University of Alberta

Grip strength and wrist load in office work

by

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Dedication

I would like to thank my supervisor, Dr. Shrawan Kumar, who knew perfectly how to combine exigency with friendship, guiding me through the PhD program and being near me during tough times.

Also, I would like to thank my family (my parents, grandparents and brother) for their love and continued support of my academic endeavors.

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Abstract

Carpal tunnel syndrome (CTS) has been the subject of a growing number of studies, most of them leading to contradictory outcomes. The objective of the thesis was to assess the relationship between various task and device designs used while performing office and industrial work and risk factors for upper extremity musculoskeletal disorders with an emphasis on Carpal Tunnel Syndrome.

Different sections of the thesis looked into different aspects as follows: the forearm muscles activity in different wrist deviated positions and neutral zone, and the self-selected resting position without visual feedback; the effect of different keyboards designs and typing training on wrist motion, overall applied force, forearm muscle activity and typing performance; the effect of wrist/forearm/elbow posture on grip strength; and, the impact of office job design on body and upper extremity musculoskeletal symptoms.

A total of over two hundred and fifty volunteers participated for the five studies. Self selected wrist neutral posture significantly decreased muscle activity. Placement of wrists in neutral zone is expected to reduce risk of injuries. Also, taking into account that the alternative keyboards and training promoted reduced wrist deviation without increasing the EMG activity or reducing the performance, they were considered to constitute valid solutions for conventional keyboard replacement. Awkward postures caused decreased grip force and increased forearm muscles' activity.

The ergonomic assessment of new devices should precede their introduction and not follow it. It is proposed that a thorough understanding of the factors that intervene in the task-CTS causal relationship, as well as the assessment of workers' adaptation

capacity will lead to ergonomic interventions that may reduce the number of work-related CTS cases.

Preface

Since all chapters included in this thesis have been accepted for publication in peer-reviewed journals, a paper format with discrete studies around a single project was chosen.

The first chapter provides an exhaustive literature review of the existing literature regarding the Carpal Tunnel Syndrome in both office and industrial work. Also, hand strength and its characteristics are discussed in this part of the thesis.

In the second part of the thesis (experimental section), first the differences between the anatomical and physiological wrist neutral zones are analyzed followed by two studies that looked into the effect of alternative keyboard design on various typing parameters and the effect of training on ergonomic keyboards on wrist posture, movement, muscle activity, overall applied force and typing performance. In Chapter 5 issues related to the effect of upper extremity joints deviation on maximum grip force exertion are addressed. In the last chapter, details of a survey describing the prevalence of musculoskeletal symptoms among office workers are presented.

The last part of the thesis integrates the separate studies into a larger project and provides general discussion and conclusions.

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List of abbreviations

ADL	Activities of Daily Living
ANSI	American National Standards Institute
APL	Abductor pollicis longus
ASHT	American Society of Hand Therapists
C_c	Cross-sectional area of the canal
C_t	Cross-sectional area of the tendons
CTD	Cumulative Trauma Disorders
CTP	Carpal tunnel pressure
CTS	Carpal Tunnel Syndrome
DT	Downward tilting
EASP	Externally applied surface pressure
ECR	Extensor carpi radialis
ECU	Extensor carpi ulnaris
ED	Extensor digitorum
EDC	Extensor digitorum comunis
EDM	Extensor digiti minimi
EI	Extensor indicis
EMG	Electromyography
EPB	Extensor pollicis brevis
EPL	Extensor pollicis longus
FCR	Flexor carpi radialis
FCU	Flexor carpi ulnaris

FDI	First dorsal interosseous
FDP	Flexor Digitorum Profundus
FDS	Flexor Digitorum Superficialis
IP	Interphalangeal
LEF	Left extension/flexion
LUR	Left ulnar/radial deviation
MCP	Metacarpophalangeal
MSD	Musculoskeletal Disorders
MVC	Maximal voluntary contraction
N	Newton
NSKS	Negative slope keyboard support
OR	Odd ratio
PST	Prosper Street Technologies
REF	Right extension/flexion
RUR	Right ulnar/radial deviation
ROM	Range of motion
RS	Relative space
RSI	Repetitive Strain Injuries
SD	Standard deviation
TH	Thenar compartment
VDT	Video display terminal
WCB	Workers' Compensation Board
WRUED	Work Related Upper Extremity Disorders

Part I

Chapter 1

Introduction – literature review

1.1. Work-Related Carpal Tunnel Syndrome:

Current Concepts

1.1.1. Abstract

Carpal tunnel syndrome (CTS) has been the subject of a growing number of studies, most of them leading to contradictory outcomes. The dual aim of this paper is to provide the foundation for a thorough understanding of CTS history, and to emphasize the strong relationship between upper extremity activities and occupational CTS. Evidence of work relatedness, as well as contradictory opinions regarding the role of job-related risk factors on CTS development are addressed. It is proposed that a thorough understanding of the factors that intervene in the task-CTS causal relationship, as well as the assessment of workers' adaptation capacity will lead to ergonomic interventions that will ensure a reduction in the number of work-related CTS cases.

Keywords: Musculoskeletal disorders; Work relatedness; Physical factors; Psychosocial factors

1.1.2. History of Carpal Tunnel Syndrome

It is highly probable that due to the poor-designed tools and work techniques the first victim of Carpal Tunnel Syndrome (CTS) was the Stone Age Man (Dionne, 1984). After thousands of years, CTS is not only present, but also due to the same reasons, has an exponential increase in incidence and prevalence from one decade to the next. Due to the clinical symptomatic diversity and because the preoccupation with the motor manifestations was far greater as compared to that with sensory signs (LaBan and Spliteri, 1987), the exact diagnosis of CTS has not been achieved or, many cases, postponed.

The first worker's disease was reported in 1717 by Ramazinni (Webreference, 2001) who noticed that during work activities factors like unnatural postures of the body, violent and irregular motions are the major contributors that cause *"the natural structure of the vital machine to become so impaired that serious diseases gradually develop"*. The first description of a CTS case is attributed to Sir James Paget (1854), who observed in a male patient with a healing fracture of the distal extremity of the radius that the ulceration of the first three fingers was caused by the pressure on the median nerve.

The major CTS symptoms were described for the first time by Putnam (1880). His observations were based on 37 female cases that presented numbness that occurred repeatedly during the night, or in some cases early in the morning. Hunt (1909) was the first to emphasize the relationship between occupational overuse and CTS occurrence. He showed that median nerve compression (motor fibers) is the major factor that leads to thenar atrophy. A major step back in the understanding of CTS development was made in early 1900s when Hunt (1911) mitigated the importance and role of sensory manifestations compared to the motor symptoms. The intrinsic relationship between motor and sensory signs has been emphasized by Wartenberg in 1939 and Zabriskie in 1935 who showed that almost all the patients presented paresthesiae.

The histological modifications were remarked for the first time by Marie and Foix in 1913 who reported the myelin sheath's absence at the constriction level. They were the first to propose the ligament transection as a suitable therapeutic method if applied in the early stages of the disease. The median nerve pressure role on thenar musculature atrophy and paresthesia was highlighted also by Abbott and Saunders in 1933. They reported chronic nerve compression after inappropriate fracture reduction. Learmonth in 1933 and

Cannon and Love in 1946 reported the first carpal ligament release for post-traumatic and for spontaneous median nerve compression, respectively.

A complete pathophysiologic mechanism for CTS development was proposed by Brain in 1947, who linked the resulting ischemia with the applied pressure that causes oedema leading to increased pressure and precipitating a vicious cycle. The term Carpal Tunnel Syndrome was first used in the early 1950; in their article about CTS, Schiller and Kolb (1954) used the terms "Tardy Median Palsy", "Median Neuritis", "Partial Thenar Atrophy" and "Carpal Tunnel Syndrome" as synonyms.

Phalen (1950, 1957) is the one who deserves the most recognition for popularizing the CTS and raising it to the attention of medical community. He proposed a provocative wrist flexion test that now is known as Phalen's test (Phalen, 1951). Chronic flexor tenosynovitis as a primary cause for nontraumatic CTS was proposed (Phalen, 1957).

Gilliatt and Sears in 1958, Simpson in 1956 and Buchthal and Rosenfalck in 1971 demonstrated the reduction of median nerve conduction in patients with CTS. The role of ischemia was noted by Gilliatt in 1980 and LaBan et al. in 1989, who noted the presence of prolonged sensory evoked potentials in transient CTS patients during wrist flexion.

Nowadays, due to the use of poor designated tools, repetitive work procedures and non-ergonomic workplaces, CTS' presence has extended in a vast area of occupational activities, being one of the most important causes of loss productivity. The term CTS is used "to describe all cases of compression neuropathy of the median nerve at the wrist", following Phalen and Kendrick's recommendation (Phalen and Kendrick, 1957).

1.1.3. Magnitude of the problem

In 1981 only 18% of all illnesses were Cumulative Trauma Disorders (CTD), in 1984 28%, in 1992 52%, and in 2000 70% of all occupational illnesses reported were RSI (BLS, 2001). The CTD burden on US economy in 1994 equalled $3.6 billion in direct workers' compensations. Including the indirect costs, the total cost was $10.8 billion with $12,000 per case (Advisor, 1996). In 1998 there were 500,000 cases of Work Related Upper Extremity Disorders (WRUEDs) that were reported as needing more than one day off work (Mani and Gerr, 2000) and from these, CTS resulted in the highest number of days lost among all work related injuries. CTS is the most commonly reported nerve entrapment syndrome (Silverstein et al., 1987). Currently, Carpal Tunnel Syndrome affects over 8-million Americans (US Department of Labor, 1999). Almost half of the carpal tunnel cases resulted in 31 days or more of work loss (NCHS, 2000). The non-medical costs of a CTS case from compensation settlements and disability average $10,000/hand. Including the medical and indirect cost, the amount is elevated to $20,000 to $100,000/hand (Szabo, 1998). Up to 36% of all Carpal Tunnel Syndrome patients require treatment for the rest of their lives (US Department of Labor, 1999), the total costs are enormous (table 1.1).

Dimmitt (1995) noted that litigations represent an important part of the total cost of CTS with lawyer fees and other legal taxes accounting for 25% of costs. Company policy should encourage return to work with subsequent job rotation. Employee expenses can reach $30,000 if the worker returns to work and $100,000 if he is unable to work again in that position (Pinkham, 1988).

1.1.4. Evidence of Work Relatedness

Although some authors (Hadler, 1987; Hadler, 1999; Nathan et al., 1992; Nilsson et al., 1995; Stevens et al., 2001) questioned the causal relationship between work exposure and CTS, there is strong evidence of the effect of repetitive and/or forceful tasks on the musculoskeletal system. The relationship between physical exposure and Work Related Upper Extremity Disorders (WRUEDs) was noted by previous authors (Armstrong et al, 1984; Armstrong and Chaffin, 1979; Armstrong et al., 1987; Hart, 1999; Marklin et al., 1999; Silverstein et al., 1987). Approximately 260,000 carpal tunnel release operations are performed each year, with 47% of the cases considered to be work related (NCHS, 2000). There is a direct correlation between increased exposure to risk factors and increased incidence.

In an evaluation of occupational and non-occupational factors associated with CTS, Roquelaure et al. (1997) noted force exertion > 1kg (OR=9.0), shortest working cycle<10s (OR=8.8), lack of rest for at least 15% of the worktime (OR=6.0) and manual supply of the worker (OR=5.0) as having an important impact on CTS occurrence. Among the personal factors, only parity of at least 3 (OR=3.2) was associated with CTS. Interestingly, no upper extremity posture was associated with CTS. Roquelaure et al. (1997) also noted a cumulative effect of risk factors on CTS development, with musculoskeletal disease increasing sharply when more than 3 factors are simultaneously present. Although the presence/absence of a specific risk factor is easy to assess, there is still a need to develop a method of quantifying the risk factors' overall effect on the probability of developing CTS. Moore and Garg (1995) proposed a semiquantitative job analysis methodology (Strain Index). It composses the assessment/appraisement of six variables (repetition, wrist posture, task duration per day, force intensity and duration per cycle, and exertion speed). While this method is very straight forward resulting in a numeric score (the product of all six ratings multiplied by a constant), it fails to account for psychophysical stress, which is an important risk factor. Also, posture, force intensity, and speed are subjectively recorded reducing the method's power.

The activities with the highest risk for CTS development are: data entry, poultry and meat processing/packaging, being a dentist, the use of vibratory tools and being a cashier (Table 1.2). The poultry workers have an increased risk for developing CTS (odd ratio 8-36) (Kurppa et al., 1991; Luopajarvi et al., 1979; McCormack et al., 1990). The claim incidence rates in meat/poultry industry between 1987 and 1995 in Washington State were 308/10,000 workers determining a major loss in poultry farms profit (Silverstein et al., 1998). All the generic work related risk factors (force, repetitiveness, localized mechanical compression, awkward posture, working with cold hands) (Armstrong et al., 1987; Loslever and Ranaivosoa, 1993; Silvertein et al., 1987) are met in poultry industry. The relationship between work postures, force, repetitiveness in poultry tasks and CTS development was studied in previous research (Kirschberg et al., 1994; Schottland et al., 1991; Yossi et al, 1996) but future extensive research is still needed in order to develop task and employee-specific ergonomic interventions.

In a review of workers' compensation board (WCB) claims in Manitoba, Yassi et al. (1996) assessed that the most frequent diagnosis (27.5%) of all accepted claims was CTS. The meat and poultry processing related industry is the highest risk activity in the area. Frost et al. (1998) assessed a prevalence ratio of 3.23 for non-deboning slaughterhouse workers and 4.91 for deboning slaughterhouse workers. Gorsche et al.

(1999) found a nonsignificant difference in CTS prevalence in modern, mechanized meat plants when compared with older plants.

Among WRUEDs, CTS has the biggest impact in the professional computer users' health and in the industrial-related medical and non-medical costs. From the 37,804 cases of CTS reported in 1994, 7897 (24%) were attributed to repetitive typing or key data entry (Szabo et al., 1998). The loss in productivity is manifested before (less typing speed), during and after (days of hospitalization) the treatment of CTS. During keyboarding the causes for CTS are: keystroke activation force, tactile and proprioceptive feedback, repetitiveness of the task (Coury et al., 1998), percentage of time typing, typing speed, the unequal distribution of finger usage, keyswitch make force and typing force (Amell and Kumar, 1999). Although typing does not lead to CTS through high forces (Rempel et al., 1999), the elevated level of repetition makes typing a major factor in CTS pathogenesis (Nordstrom et al., 1997).

During typing the posture is usually that in which the wrist is extended and ulnar deviated. Also, in order to fit the keyboard, fingers are extended leading to an elevated intracarpal tunnel pressure (Werner et al., 1997). Although the maximum acceptable rate is 30/min, fingers' movement frequencies above 38-40/min are commonly met during typing. Wendi et al. found association between work repetitiveness and CTS (OR=1.22 per unit of repetition, p=0.08). Also, significant difference between low and high repetitive activities was assessed (OR=3.11). When positive electrodiagnostic aspect in the dominant hand (difference in peak latency of 0.5 ms between ulnar and median nerves), and hand diagrams consistent with CTS (score 2 or 3 on a 0-3 scale that take into account the presence of numbness, tingling, burning, or pain in the fingers, hand, or wrists in a minimum of three episodes or one episode more than one week in the last year) were used to define CTS, there was an important difference between prevalence recorded for low (2.7%) and high (7.9%) repetition jobs.

CTS among cashiers is due to high repetition, awkward posture and localized mechanical pressure (Baron and Hobes, 1991; Morgenstern et al., 1991; Osorio et al, 1994). The use of mono-optic laser instead of a bi-optic ones elevates the repetition of the task, and forces the worker to manipulate the objects for longer periods of time (Lannerstein and Ringdahl, 1990). Although the checkstands are designated to accommodate standing postures in Asia, North America and Australia compared to Europe and South America where seated workplaces are widespread, there are no differences in the number of cumulative trauma disorders (Lehman et al, 2001). A major confounding factor in simulated studies that measure the CTS risk level assessment among cashiers is the lack of rescanning, which is highly common in the real task (Lannerstein and Ringdahl, 1990).

The mechanism by which the use of vibratory tools leads to CTS is still unclear because of the constant association between vibration, forceful and repetitive movements. Proposed mechanisms are: elevated muscle tonic vibration reflex followed by increased muscle contraction (Armstrong et al, 1987), mechanical abrasion of tendon sheaths, constricted blood flow to the nerve (Putz-Anderson, 1988) and unnecessary increase in the applied force due to the tactility impairments caused by vibration (Bovenzi et al., 1991; Viikari-Juntura and Silverstein, 1999). A decreased peripheral nerve conduction due to affected myelinated nerve-fibre activity and parasympathetic activity is likely to occur (Murata and Garg, 1995; Murata et al., 1991).

In all work activities, the risk of developing CTS is highly increased when there is an association between different risk factors. Silverstein et al. (1987) noted that tasks where both high repetition and high force are present are the most hazardous.

Recent studies (Hamann et al., 2001; Lalumandier and McPhee, 2001) noted a growing incidence of CTS among dentists. Although their assessed CTS prevalence varies within a wide range, the majority support the idea of work causation in the development of CTS among dental professionals. The risk factors are multifactorial including awkward postures, short work cycles, repetitive movements and localized mechanical pressure.

Hadler (1998) stated that psychosocial factors play an important role in cumulative trauma disorders development. He tends to overestimate the role of stress in the workplace and consider that all claimants' symptoms are not work-related. Considering that work-related CTS does not exist, one does not only disdains all the claimants and the physicians that diagnosed the cases, but also the entire system is offended. Among all WRUEDs, CTS is the disorder in which psychosocial stress plays the least important role. In CTS pathogenesis, muscle activation due to mental stress is almost inexistent. Factors such as fatigue, insecurity, organizational stress, and lack of job satisfaction are important in the initiation of litigation (Jackson and Martin, 1996). Mental factors do affect pain but they can only increase its level and cannot be initiators. Using information that arises from ergonomic studies, one can design jobs and workplaces that will allow the worker to execute tasks within the safe limits for the musculoskeletal system.

1.1.5. Discussion and conclusions

The relationship between work and CTS occurrence was stressed by previous studies. This causal link is sustained by the difference in CTS prevalence found among employees in occupations with high physical exposure/awkward posture level vs. workers performing low exposure jobs. Also, targeted ergonomic interventions succeeded in reducing the number of upper extremity musculoskeletal disorders for workers in hazardous tasks. Although the role of psychosocial factors is not fully assessed, there is strong evidence in the literature regarding the relationship between physical exposure and CTS. Ignoring the problem will determine no other result than a growth in the number of work-related disorders especially due to the maintenance of poorly designed jobs and workplaces that determine the worker to perform daily tasks at elevated risk levels.

All causal characteristics (temporal ordering, dose-response effect, absence of other plausible explanations and temporal contiguity) are present in the hazardous work-MSD relationship (Musculoskeletal Disorders and the Workplace). The occurrence of CTS *after* prolonged exposure, and the decrease of CTS cases *after* ergonomic programs implementation (reduction at risk factors exposure) stress this point of view. The assessment of the temporal relationship between exposure and outcome is jeopardized by the fact that the majority of studies are cross-sectional. Also, this type of research design fails to include the most severe cases due to their absence from the workplace. Workers non-response may be due to different reasons. Uninterested unaffected workers as well as the ones absent due to sick-leave or transfer to light exposure jobs are not included in the original data collection. The data extrapolation to non-included workers weakens the study external validity and introduces an important bias.

The examination of work-related CTS cases should address both the individual and the working population as a group. The individual approach to the problem would provide useful data regarding the personal adaptability at the work place, the effect of injury on the individual, methods of coping with the impairment, experience role in modifying work habits as well as case management information. Analyzing the high risk working population as a whole would provide an epidemiological synopsis of the situation, allowing for targeted strategies development. One should consider the effect of personal variance on musculoskeletal development. Job/device design adaptability plays an important role and ensures the ergonomic program success (the work-men interface optimization). The only valid solution is the identification of the causes that force the worker to adopt positions other than the ergonomic ones.

Due to the strong evidence that work is etiologically related with CTS several proposed modifications for workplace, device and job design are presented (Table 1.3). Since returning to the same workplace configuration would lead to the occurrence of the same pathology, all these modifications should accompany the workers' treatment.

The presence of two distinct points of view is evident. While some question the epidemiological relationship between work-related risk factors and CTS, the others, based on extensive direct research and systematic reviews, demonstrated an association between CTS and force, repetition, and awkward positions. Close interrelations between different risk factors play an important role in a job's overall hazardous level. An accurate assessment of the level beyond which a risk factor becomes hazardous is needed. One should be aware not to classify a job as generating CTS in the presence of just one risk factor. False positive classifications, followed by unnecessary job/device redesign may cause an important decline in productivity.

In view of the information from previous studies, it is suggested that future research should address on-site work activities. The need for more studies that address the effect of psychosocial factors on upper on CTS is evident. Also, a more complex classification, rather than just “yes” or “no” should be used for both risk factors assessment and disease prevalence. Binary classifications do not provide any information about intermediate levels of exposure, which are most frequently encountered. Once these questions are answered, in order to ensure the success of adopted ergonomic job and workplace modifications, there should be an increase in the workers’ awareness level that will help the future job assessments. A normal consequence is the increased productivity along with a reduction in the workers' discomfort. Through combining job/device ergonomic redesign with programs that will reduce the psychosocial stress level, one may obtain a real reduction in the number of claims.

CTS costs	**Expenditures' structure**
Direct costs (20%)	1. Medical expenses 2. Workers' compensation premiums 3. Lost and light duty workdays
Indirect costs (80%)	1. Loss of injured worker's production 2. Time lost of employee paid by employer 3. Time lost by uninjured employees 4. Temporary help 5. Training and retraining 6. Reporting and claims 7. Management time 8. Worker/management discussions 9. Litigations costs

Table 1.1. List of direct and indirect costs associated with CTD incidence as noted by Lloyd and Haslam (1998)

Occupation	**Risk Factor for CTS**	**Prevalence**	**Reference**
Poultry and meat processing/packaging	Force, localized mechanical compression, repetition, awkward posture, working with cold hands and in cold environment	37-41% 53% 27.5%	Chiang et al., 1990 Falck and Aarnio, 1983 Yassi et al., 1996
Data entry	Repetitive finger motion, awkward posture, force applied, lack of rest, muscle overuse,	13% 11.7 3.5%	Ulin et al., 1997 BLS, 1999 Stevens et al., 2001
Cashiers	Repetitive wrist motion, localized pressure, awkward posture, inadequate recovery time	12% 11% 10-63%	Morgenstern et al., 1991 Baron and Hobes, 1991 Osorio et al., 1994
Vibratory tools	Compressive force, repetitive trauma, shock absorption, elevated muscle contraction, inadequate force, work cycles < 30 sec.	21-33% 14% 38.4% 44%	Lucas, 1970 Nilsson et al., 1990 Bovenzi et al., 1991 Chatterjee et al., 1982
Dentists	Repetitiveness, localized compressive force, work cycles < 30 sec., awkward postures	56% 4.8% 11%	Lalumandier and McPhee, 2001 Hammann et al., 2001 Rice et al, 1996

Table 1.2. Occupational carpal tunnel syndrome symptoms prevalence and risk factors

Job and device proposed redesign	Poultry/meat industry	Data entry	Dentists	Cashiers	Vibratory tools
Textured surface for a better grip	X		X		X
Wide range of grip sizes	X		X		X
Equal distribution of applied pressure	X	X	X	X	X
Redesign for vibration absorption	X		X		X
Well fitted gloves	X		X		X
Wide variety of specialized tools	X		X		X
Pace task reduction	X	X	X	X	X
Task alternation	X	X	X	X	X
Microbreaks	X	X	X	X	X
Training programs for new workers	X	X	X	X	X
Apply minimum required force	X	X	X		X
Adjustable devices	X	X	X		X
Workplace below elbow level	X	X	X	X	

Table 1.3. Proposed redesign modifications in hazardous industries for a reduction in CTS prevalence

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1.2. Carpal Tunnel Syndrome Due to Keyboarding and Mouse Tasks: A review

1.2.1. Abstract

So far, many different studies have examined possible implications of typing related posture and activity on Carpal Tunnel Syndrome (CTS) incidence. Although they tend to present the findings as very apparent ones, assessing the complex relationships between the different causal factors implicated in keyboarding and in the usage of pointing devices on the one hand and, work related upper extremity disorders (WRUED), especially CTS, on the other hand, is problematic. The aim of this review paper is to outline relevant information about CTS risk factors present in data entry tasks and their implications, with a special emphasis on different extreme postures determined by conventional and alternate keyboards, pointing devices and their role in the development of CTS. Secondly, a comparison of several keyboards with respect to design of keyswitch to reduce force and its effect on carpal tunnel pressure (CTP) is provided. This review critically considers the factors implicated in the occurrence of CTS due to computer work, analyzing the determining factors from a well-rounded perspective instead of considering them as separate entities. Many "ergonomic" keyboards change the musculoskeletal region exposed to risk, instead of eliminating hazardous postures. The ergonomic assessment of new devices should precede their introduction and not follow it. Future research should be directed toward establishing a comprehensive understanding of what combinations of trigger factors should be eliminated or modified, to assess the impact of workstation redesign and to uncover the interrelationships between different factors that contribute to the development of CTS.

Keywords: Carpal Tunnel Syndrome; WRUEDs; Keyboarding; Work relatedness

1.2.2. Relevance to industry

Because of the trend in the occurrence of the Repetitive Strain Injuries (RSI), especially CTS with keyboard and mouse use, an assessment of all causal factors, as well as the interrelationship between them in the development process of CTS in data entry tasks will lead to a decrease in medical and non-medical costs. Information could be used for job redesign in order to increase ergonomic qualities and productivity.

1.2.3. Introduction

The goal of this review is to identify factors that play a role in the typing related CTS development in both conventional and alternative design keyboard. The bibliographic databases (PubMed, NLM Gateway and Cochrane Library) search identified more than 400 studies. The selection criteria included both epidemiological and laboratory-based studies with well-defined diagnostic and experiment-outcome interpretation. CTS risk factors, pathophysiological mechanisms, comparison between alternative and conventional keyboard designs and mouse role in CTS development are extensively addressed.

Keyboards have been in existence for over 100 years and were very well known long before the introduction of computer input devices. At the beginning, the refinements were for superior mechanical properties and fewer malfunctions. The next 20-25 years emphasized increasing performance and the last 20-25 years have focused on typist fatigue, perceived pain, muscular strain and ergonomics. Nowadays, the computer keyboard is the primary input device for data entry tasks. Although the keyboard is often a non-adjustable device, it is used by nearby all the computer users regardless of age, anthropometric characteristics, gender and performance leading to increased musculoskeletal problems.

1.2.4. Magnitude of the problem

1.2.4.1. Incidence

Currently, Carpal Tunnel Syndrome affects over 8-million Americans (U.S. Department of Labor, 1999). Among work related upper extremity disorders (WRUEDs), CTS has the biggest impact in the professional computer users' health and in the industrial-related medical and non-medical costs. Since 66% of the entire population spend 33% of their time at work (WHO, 1995 cited by Kumar et al., 1997), and the incidence of CTS is increasing among computer users in the USA (Hedge and Powers, 1995) an association may be argued. From the 37,804 cases of work related CTS reported in 1994, 7897 (21%) were attributed to repetitive typing or key entry data (Szabo, 1998). There is a loss in productivity before (less typing speed), during, and after (days of hospitalization) the treatment of CTS (Moore, 1992). In United States alone, approximately 260,000 carpal tunnel release operations are performed each year, with 47% of the cases considered to be work related (NCHS, 2000).

According to the U.S. Department of Labor (1999) the Carpal Tunnel Syndrome is the "chief occupational hazard of the 90's"-disabling workers in epidemic proportions.

1.2.4.2. Economic impact

CTS, the most commonly reported nerve entrapment syndrome (Silverstein et al., 1987), results in the highest number of days lost per case among all work related illnesses (Mani and Gerr, 2000). Almost half of the carpal tunnel cases resulted in 31 days or more of work loss (NCHS, 2000). CTS is the most common nerve compression and the most common and costly repetitive strain illness (Adv. Chir.-CTS, 2000). The non-medical costs of a CTS case from compensation settlements and disability average $10,000/hand. This sum is increased by the medical cost and indirect costs that raises it to $20,000 to $100,000/hand (Szabo, 1998). Up to 36% of all Carpal Tunnel Syndrome patients require life-long medical treatment (U.S. Department of Labor, 1999), the total costs are enormous.

Taking into account the increased muscle activation due to high demanding cognitive tasks, which are present in data entry activities (Viikari-Juntura and Riihimaki, 1999), increasing figures are expected in the future. These costs represent only a small portion of the total costs that are lost due to the poorly designed keyboard and pointing devices. Even when VDT users stay in a poorly designed workplace and continue to work without any complaints, they cause a loss in productivity because they are forced to stop and wait until the pain is mitigated, or the discomfort level at wrist/shoulder/trapezius decreases (Moore, 1992). This is a hidden source of loss of productivity and performance that could be decreased by primary interventions like environmental changes (Marklin et al., 1999) that are always superior in effectiveness and costs compared to secondary interventions (Viikari-Juntura and Riihimaki, 1999).

1.2.5. Risk factors

In the searched literature, a wide variety of methods to assess exposure to CTS occupational risk factors have been used. The use of direct measurements, self-reports, observations, laboratory simulations and classifications by job titles leads to incomparable results and misclassifications errors that may jeopardize the assessment of work exposure – CTS relationship.

In the general population there are many risk factors for CTS that have been described in previous studies (Armstrong et al., 1987; NIOSH, 1997; Armstrong and Chaffin, 1979; Armstrong et al., 1993; Loslever and Ranaivosoa, 1993; Adv. Chir.-CTS, 2001; Nordstrom et al., 1997; De Krom et al., 1990; Kumar, 1990; Kumar and Narayan, 1998; Kumar 2001; Kumar et al., 2001; Hagberg et al., 1995). Non-occupational factors are important in the occurrence of CTS because CTS occurred twice more frequently on both hands (Loslever and Ranaivosoa, 1993). As a general rule, early detection of the pain is considered important for control of symptoms and offers a great opportunity to minimize future risk for patients (Mani and Gerr, 2000)

Although some authors (Hadler, 1987; Hadler, 1999; Nathan et al., 1992) question CTS' work relatedness, there is strong evidence supporting the direct relationship between work related factors and CTS (Silverstein et al., 1987; Armstrong et al., 1987; Armstrong et al., 1993; Buckle, 1997; Armstrong and Chaffin, 1979; Silverstein et al., 1998). Some authors stated that just the occupational factors determine the development of CTS, other named only the anatomical features as risk factors but in reality there is a summation and a combination of all of these (Hagberg, 1997). In literature there is an abundance of risk factors for CTS and for other WRUEDs but there is no precise information as to the level of exposure at which any given risk factor begins to have a significant effect. The most important CTS risk factors are presented in table 1.4. Generally, workstations are built for average sized people (Nordstrom et al., 1997) and that is why persons that are out of the interquartile range may be predisposed to CTS. There is a strong correlation between manual activity and CTS (Silverstein and Fine, 1991; Silverstein et al., 1987; Armstrong et al., 1987; Armstrong and Chaffin, 1979;

Armstrong et al., 1984; Armstrong et al., 1993; Cullum and Molloy, 1994; Bergamasco et al., 1998; Nordstrom et al., 1997). In tasks that involve repetitive use of the upper extremity, positions of the arm and hand deemed to be unacceptable are: ulnar deviation>24°, radial deviation>15°, pronation>40°, supination>57°, shoulder abduction>67°, extension> 50° and flexion >45° (Bergamasco et al., 1998).

When a muscle acts simultaneously as a primary agonist in more than one task, the increased muscle load plays an important role in the development of musculoskeletal disorders (Coury et al., 1998). Despite the findings that the association between work and CTS is high (Hagberg et al., 1995), there is a still deficit of knowledge regarding the pattern and the causality of this relation. Extensive research needs to be conducted in order to establish the relationship between the ergonomics of work and work-related injuries (Hart, 1999) including CTS.

For VDT users, the neck and upper extremity are at a greater relative risk than other regions for musculoskeletal problems (Sauter et al., 1991). The highest risks are for hand, wrist and arm. (Rempel et al., 1999; Sauter et al., 1991). CTS was attributed to keyboarding in 8% of cumulative trauma disorders (Amell and Kumar, 1999). Sauter et al. (1991) conducted a study with 932 VDT users and assessed discomfort in wrist and right hand at 13% and 12% respective from the total sample. They also described the keyboard height as the most important variable for arm discomfort, and reported that this indirectly affects the wrist position by the effect that arm abduction has upon the arm pronation and wrist ulnar deviation (Simoneau et al., 1999; Harvey and Peper, 1997; Marklin and Simoneau, 2001).

The ergonomic environment and the nature of the task dictate the postures, movements and the repetitive character of a task (Marklin et al., 1999). This causal relationship is best seen in alphanumeric (words and numbers input) and alphabetical (words input) data entry task. Tasks that require excessive use of pointing devices (mouse and trackball) such as design work, internet navigation and the use of interactive software programs are also good examples. Keyboard usage introduces a wide range of risk factors that are present in such important cumulative and simultaneous levels only in this domain. Excessive wrist extension or flexion (Marklin et al., 1999) is present in different degrees depending on the type of keyboard used (slope angle). Also, ulnar deviation occurs directly due to the need to reach the far left or right keys (Marklin et al., 1999; Werner et al., 1997) and indirectly as a compensation of the arm abduction.

1.2.6. Pathophysiology

A large array of factors that play an important role in the CTS onset and evolution have been described. Among them one could mention: personal characteristics, awkward postures, repetitiveness and combination of these.

Carpal tunnel pressure (CTP) (pressure within carpal tunnel), which is an important factor for CTS' pathogenesis (Szabo, 1989a; Szabo, 1989b; Keir et al., 1999; Keir et al., 1998; Phalen and Kendrick, 1957; Seradge et al., 1995) when it exceeds the upper limit for a prolonged amount of time, is lowest when wrist is in neutral position, hand is relaxed with fingers flexed at 30° and forearm in a semipronated position (Werner et al., 1997). These optimum hand and wrist postures are seldom reached in a VDT data entry task due to the keyboard and mouse design. The typing posture is usually that in which the arm is abducted and pronated, wrist extended, ulnar deviated and fingers extended in order to fit the keyboard. All these working positions determine an elevated CTP (Werner et al., 1997). During the VDT tasks, extreme postures and high-repetitive actions (38-40/min per finger) are frequently met. This value exceeds the frequency of 30/min, which is the highest acceptable frequency in a repetitive motion (Bergamasco et al., 1998). Cumulative load is a risk factor for causation of musculoskeletal injuries (Kumar, 1990; Kumar, 2001).

Wrist extension has a greater effect than ulnar deviation on carpal tunnel pressure (Marklin et al., 1999). The total time when wrist is extended is increased by the use of the mouse that also strains the hand by forcing repetitive use of one finger and is awkward to hold. This effect is much more visible when VDT users are required to perform double-clicking and dragging tasks most of the time (Amell and Kumar, 1999).

1.2.6.1. Personal characteristics

There is reason to believe that patients with CTS may have some predisposing anthropomorphic characteristics (Armstrong and Chaffin, 1979; Buchholz et al., 1991). Jessurun et al. (1987) defined relative space (RS) as: $\mathbf{RS=[(C_c-C_t)/C_c]x100\%}$; where C_c is the cross-sectional area of the canal and C_t is the cross-sectional area of the tendons. The relative space available for the median nerve is significantly smaller for female cases compared with female controls (Jessurun et al., 1987). Although some previous studies have explained the high work related prevalence of CTS for women by the duration of exposure and the placement in data entry work positions (Mani and Gerr, 2000), there are important anatomical and anthropometric differences between genders that may be the source of the observed discrepancy in the number of CTS cases. The anatomical differences between males and females (Armstrong and Chaffin, 1979) (wrist circumferences, radial bone size) may be the source of the observed differences in flexibility (Marshall et al., 1999) that permits the adoption of more extreme postures by females that constitute risk factors for CTS by elevating the CTP. Armstrong and Chaffin (1979) and Matias et al. (1998) found that anthropometric factors play a role in the development of CTS when they are associated with long duration of the task and awkward postures. In using a keyboard there is a decrease in risk with increased length of arms and hands and there is an increase in risk when the wrist size decreases (Matias et al., 1998). Also, there is an indirect relationship between anthropometric differences and the risk for CTS in data entry tasks. Elevated shoulder width increases both right extension and right pronation (Serina et al., 1999) leading to elevated CTP.

1.2.6.2. Extreme postures

Buckle (1997) described mechanisms for CTS: stretching or compression of the median nerve at the wrist, ischemia and increased intracarpal pressure when the wrist is in extreme postures leading to nerve compression. The most important factor in the CTS pathogenesis for keyboard and mouse users is the CTP. CTS patients have elevated CTP compared to healthy population (Keir et al., 1998). During typing the hand and wrist adopt awkward postures that increase CTP beyond the upper safe limit. The following factors increase pressure in carpal tunnel: changes in cross sectional area (affected by wrist position), folding of skin at the distal palm and movement of lumbrical muscles into the carpal tunnel. Werner and Armstrong (1997) noted that wrist extension stretches flexor tendons and median nerve, exerting pressure on their dorsal face. They showed that compression on the median nerve and tendon flexors between the volar carpal ligament and the volar glide of the proximal row of carpal bones during wrist extension occurs also due to the carpal bones movement against the radial head. Also, the presence of the distal ends of the finger flexors in the carpal tunnel leads to elevated CTP. The flexion of the fingers will lead to an increase in the carpal tunnel pressure (Keir et al., 1998). Finger flexion is very important for CTP, and this importance is raised by typing force that may be 4-5 times greater than the force required to activate the key (Feuerstein et al., 1997). Pressure at 90° flexion is greater than pressure at 45° (Keir et al., 1998) and this difference is due to the fact that between 90° and 50° the lumbricals are always within the carpal tunnel. During typing there is an active process of fitting the hand and the fingers to the keyboard and this requires fingers to adopt straight postures and elevates CTP compared with the relaxed finger posture (Keir et al., 1998). In addition to the presence of elevated CTP in patients with CTS, Szabo (1989b) found that post exercise, the pressure remains elevated for a longer period of time when compared to healthy controls, increasing the risk for nerve damage. These findings are supported by Werner et al (1983) and Braun (1988), who assessed elevated CTP and respectively increased sensory impairment in patients with CTP post active motion of the wrist. An exception to this CTP comportment was noted in advanced CTS cases where the elevated pressure after exercise was not present (Gelberman et al., 1988).

Flexion of the wrist requires the flexor digitorum tendons to be pushed against the palmar side of the carpal tunnel, causing pressure on both the tendons and the flexor retinaculum. Because the median nerve is located between the flexor retinaculum and the flexor tendons, the pressure exerted on it will rise (Szabo, 1998; De Krom et al., 1990).

Overload of the flexor muscles due to lack of rest, leads to an imbalance between flexor and extensor muscles causing elevated pressure on the palmar surface of the carpal tunnel (Ostrem, 1995). This increased pressure exaggerates the already existing elevated CTP, exposing the tissues to greater risk. However, the situation found more frequently in the data entry tasks when using conventional keyboards is that of wrist extension that causes the tendons to be displaced against the dorsal side of the carpal tunnel and the head of the radius, leading to high pressure on the tendons. When the wrist adopts extreme postures, the resulted high pressure results in endoneurial oedema and microscopic pathological changes (Cullum and Molloy, 1994). The CTP is not uniformly distributed in the carpal tunnel. It is higher in the distal portion of the CT and that is why the sensory conduction velocity action potential amplitude is affected more in this portion (Keir et al., 1998).

1.2.6.3. Repetition

During typing, which is a highly repetitive task, the adjacent tendons are sliding one against the other. The friction force is proportional to the tension in the tendon and inversely proportional to the radius curvature (Hadler, 1987). Velocities during typing in flexion/extension plane are similar to velocities in workers involved in industrial activities with great risk for CTS (Serina et al., 1999). Many authors (Yamaguchi et al., 1965; Phalen and Kendrick, 1957) stated that the nerve is compressed by thickening of the flexor tendon sheaths. In as many as 87% of the CTS cases, Yamaguchi et al. (1965) found greater fibrosis and oedema in the tendon sheaths compared with controls. Highest velocity and accelerations occurred in flexion/extension and radial/ulnar deviation movements (Serina et al., 1999).

1.2.6.4. Summation of factors

There is a decrease in tolerance for exposure when the wrist is deviated compared with the situation with wrist in neutral posture. Although movements in both planes (flexion-extension and radial-ulnar deviation) occur simultaneously, due to the tension developed in the carpal ligaments, the range of ulnar or radial deviation during typing is minimal when the wrist is flexed or extended (Kapandji, 1982). When the tasks require wrist extension, the ulnar or radial deviation cannot be extreme because there are limitations of movements in this plane during wrist extension. Hazardous positions at a lesser value of ulnar/radial deviation when the wrist is in extension are likely to appear. The reciprocal relationship is true (Marshall et al., 1999).

There is a statistically significant relationship between wrist extension and forearm pronation (Serina et al., 1999). Flexion and extension are maximal when the hand is not deviated in the horizontal plane. They are minimal when wrist is in pronation (Kapandji, 1982). The ANSI/HFS (1988) stated that wrist extension beyond 15° is a risk factor for CTS and therefore the keyboard slope angle should be between 0° and 15°. This recommendation should take into consideration the limiting effect of arm pronation on the maximal wrist extension angle. With the arm pronated, accompanied by shoulder abduction, there is a lower safe limit for wrist extension. The greatest intracarpal tunnel pressure was recorded in extension, which causes an increase of 1.6 mmHg/10° compared to flexion, where 10° deviation results in a 0.2 mmHg variation in pressure (Werner et al., 1997). The actual recommendation for workstation and input device design should be changed in order to maintain the wrist within the neutral zone for a longer period of time (Serina et al., 1999).

Electrodiagnosis is the gold standard (Szabo, 1998) and many studies (Visser et al., 2000; Harvey and Peper, 1997) have used this device but this will lead to a gap in the information regarding the CTS pathogenesis. One should use a large range of measurement tools (questionnaire survey, electrodiagnostic tests, sensory testing with Semmes Weinstein monofilaments, Durkan pressure test) in order to gather all the data. Using just electrodiagnosis, one will lose information from other approaches. One way is to triangulate with several simultaneous methods in a multivariate study. So, in fact the gold standard should be developed from several parallel and complementary techniques.

1.2.7. Conventional vs. alternative keyboards

1.2.7.1. Typing posture due to bad design

In using keyboards there are a lot of potential risk factors for CTD, especially CTS. (Liao and Drury, 2000; NIOSH, 2000) have found important changes in postures when using different keyboard heights. Arm discomfort increases with increase in keyboard height above elbow level (Sauter et al., 1991) because this workplace design forces the VDT user to elevate the shoulder causing high level of neck and shoulder girdle discomfort. When using a downward tilting (DT) keyboard, there is an increase of 60% in the time spent by the wrist within the neutral zone. Since CTS risk is increased when the CTP is over 40mmHg for a long period of time (Hedge et al., 1999), reduction in the CTS risk development follows. Due to the fact that DT keyboards impede the typist to see the keys, they are not suitable for non-expert data entry personnel. Because there is a strong relation between forearm angle and arm abduction dictated by keyboard height (Sauter et al., 1991), the keyboard should be about one inch above the knees so the typist can type with the forearms parallel to the floor. The keyboard should be level or tilted slightly away, with the spacebar higher than the top row of keys.

The best known and popular keyboard among VDT users is the conventional QWERTY keyboard (designated by the first six letters of the left portion of the top alphabet row). It has a slant angle (the angle between the two groups of keys measured in horizontal plane) of 0°, slope (keyboard inclination in sagital plane) ranging from 0° to 15° and tilt angle (lateral inclination of the keys) of 0° (Marklin et al., 1999). The inappropriate QWERTY layout may be due to the fact that it was initially designed for mechanical typing machines, where an elevated pace of typing would have resulted in mechanical linkage jam. Although, through the years, many proposals have been made to change the alphanumeric layout of the keyboard, none has replaced it. The best known attempt to modify the layout of the QWERTY keyboard was made by (Dvorak, 1943) on the basis of his analysis that the following defects exist in the QWERTY design:

- overloading of the weaker left hand in a right handed person
- overworking certain fingers and not assigning enough work to others
- too little typing on the home row
- fingers are required to execute an excessive amount of jumping back and forth from row to row

Many studies have been done with similar or additional outcomes ever since. When using traditional QWERTY key layout, both forearms are pronated and both wrists are in ulnar deviation and extension (Simoneau et al., 1999; Hedge and Powers, 1995; Marklin and Simoneau, 2001; Liao and Drury, 2000, Visser et al., 2000, Marklin et al., 1999; Smith et al., 1998). There are differences between left and right forearms and wrists. The forearm pronation mean is between 69°-79° with right pronation significantly greater than left pronation 65.6° ± 8.3° and 62.2° ± 10.6° ($F=12.28$, $p<.01$) respectively. In the other two planes, left hand ulnar deviation was significantly greater than right hand ulnar deviation (15.0° ± 7.7° compared with 10.1° ± 7.2°, $F=41.57$, $p<.01$) and extension in left hand exceeded the one in right hand (21.2° ± 8.8° than 17.0° ± 7.4°, $F=23.24$, $p<.01$) (Simoneau et al., 1999). All these studies failed to assess the role of anthropometric differences in the adopted posture. Also, variation in arm/forearm/wrist muscle load and in typing performance due to different hand dimensions have not been assessed. Differences between postures are due to the distribution and frequency of use of alphabetic, numeric or special keys, like *CapsLock*, *Tab* and *Shift* for left hand (Marklin and Simoneau, 2001). Another reason for the difference is that 58% of letters typed in English text are typed with the left hand.

There is a controversy about the differences in postures between alphabetic and alphanumeric tasks. Some previous studies showed that wrist and forearm position are not significantly different in alphabetic than alphanumeric typing (Marklin et al., 1999) but Simoneau et al. (1999), in a study comparing these two kind of tasks, found a significant difference between the mean ulnar deviation during alphabetic tasks (12.6°) and alphanumeric tasks (13.8°) ($F=63.25$, $p<.01$).

Big-handed users are forced to increase finger flexion and wrist extension with direct consequences on tendon travel (Treaster and Marras, 2000). On average, the tendon travel for one hour of continuous typing ranged from 30 to 59 m (Nelson et al., 2000). Repetitive sliding of tendons within their sheaths will increase the friction that is a major trigger for the disorders of the tendons, their sheaths or adjacent nerves (Moore, 1992). Taking into account the anthropometric differences between males and females (Armstrong and Chaffin, 1979; Buchholz et al., 1991), and the fact that length-tension and force-velocity relationships are shared by muscles operating the hand (Dvir, 1997), differences in wrist/muscle tendons dimensions will determine an elevated CTS prevalence in females. Although CTS is more common among females (Armstrong and Chaffin, 1979), males have a greater tendon travel (Treaster and Marras, 2000) compared to females. Extensive research is needed in order to elucidate the still unclear relationship between gender attributes and CTS pathogenesis. Also, ergonomics interventions should consider the differences between postures of right and left hands as well as the particularities of special group of users.

It is recommended that training work in a particular position should be made after the wrist neutral position has been determined. Taking into account that static load is an important factor for musculoskeletal disorders development, even after the neutral zone is assessed, one should alternate wrist positions within its limits. In a study with a standard flat alphanumeric QWERTY keyboard, Serina et al. (1999) found that typing on an "ideal" keyboard (a keyboard in an adjusted workstation), forces the users to spend 76% of their typing time (for left hand) or 73% (for right hand) with the wrist in greater then 15° extension and 28% and 9% of their time with a wrist extension greater than 30° for the left and right hand respectively. Alternate keyboards implementation should follow, not precede the ergonomic assessment of hazardous postures. Otherwise, elevated CTS prevalence and complaints will follow.

Many studies define the neutral position for wrist radial/ulnar deviation as the position where the line that is in continuation of the middle finger is parallel with the forearm, but in fact the wrist has already an ulnar deviation of 4° to 6° in the anatomical neutral position. This point of view is sustained by the findings that the intracarpal pressure is lowest when the hand is in slight pronation, 3°-5° ulnar deviation, 2°-3.5° flexion and 45° metacarpophalangeal (finger) flexion (Hedge and Powers, 1995). Marklin et al. (1999) also assessed that ulnar deviation of 10° does not increase CTP.

The ulnar deviation that occurs during typing on a conventional keyboard, if it lasts for a prolonged period of time, is an important factor in the CTS pathogenesis. Simoneau et al. (1999) measured the CTP for different angles of ulnar deviation and found that when wrist is ulnar deviated by 10° and 20° the CTP is 20 mmHg and 50 mmHg higher respectively compared with CTP for the wrist in the neutral position. Hedge and Powers (1995) described a substantial increase in the CTP when the hand is ulnarly or radially deviated by more than 15 degrees. Other studies (Seradge et al., 1995; Keir et al., 1998) found increased CTP over 30 mmHg in extreme ulnar and radial deviated postures.

1.2.7.2. Risk summation

When two or more risk factors are simultaneously present there is a synergistic effect that is more damaging than the sum of two individually (Nelson et al., 2000). This is the case with the wrist ulnar deviation and the position of the fingers while typing. Fingers undergo stresses in stretching for keys relatively far from their typing area (such as *Escape*, *End*, *Insert*, *Delete, CapsLock*). Overloading of the weakest fingers and a high number of keystrokes also increase the risk.

Flexor digitorum profundus (FDP), lumbricals and flexor digitorum superficialis (FDS) are the only muscles involved in flexion of all four fingers (Nelson et al., 2000). This overuse of a group of tendons may lead to inflammation of the tendon sheaths (Marklin and Simoneau, 2001) and a reduction in relative space (RS). The position of the fingers affects CTP (Seradge et al., 1995). The CTP was significantly higher with the finger straight (metacarpophalangeal joint angles of 0^{o}) than when the fingers were flexed at 90^{o} for wrist extension angles from 10 to 40^{o} (Keir et al., 1998). This is due to the direct relation between the flexors of the fingers and the wrist position in the flexion/extension plane that determines a stretching of the muscle in the carpal tunnel. The relation is even more evident when the wrist is in flexion (Kapandji, 1982). Wrist flexion reduces the fingers' flexion magnitude to only a quarter of what it is when the wrist is extended. CTP shows a curvilinear increase with extension/flexion and radial/ulnar deviation of the hands (Hedge et al., 1999). This increase is even more evident when the wrist is repeatedly deviated (Seradge et al., 1995), like in a typing task.

When using a keyboard, the movements in the vertical plane exceed movements in the horizontal plane. Hedge and Powers (1995) determined that the movements between flexion and extension present a greater risk for CTS than the radial/ulnar movements since they cause tendons to travel more. All these awkward positions determine an elevated CTP with effects on the conductibility (Marklin et al., 1999) and microvascularization of the median nerve, especially if the pressure that is applied on it is greater than the diastolic pressure (Seradge et al., 1995). The muscular fatigue and the level of physical stress affect the upper safe limit for the development of CTS. Pain and stiffness gradually increase during work and are worst at the end of the working day and week (Hagberg, 1997), so that extra caution including the adaptation of ergonomic postures while typing should be taken not only at the beginning of shifts, but also during these periods.

1.2.7.3. Split keyboards

The rapid increase of computer use and related keyboard CTS has lead to a wide variety of alternative keyboard designs that reduce their physical demands on the body, improve posture during use, and thus, the overall comfort. Most of the research and design efforts have focused on re-shaping the standard keyboard, or making it more adjustable, while keeping its basic shape and well-learned QWERTY key arrangement. This makes it easier for typists to switch to new keyboard designs, that assist in improving hand and arm postures, without learning a whole new typing skill. Split keyboards are the most commonly seen by most and are typically the least expensive of the alternative keyboards. They have a set horizontal split angle and possibly a slight centre raise or "tenting" of the left and right hand key segments. They have been used in many studies (Smith et al., 1998; Marklin et al., 1999; Lincoln et al., 2000; Hedge and Powers, 1995; Harvey and Peper, 1997; Marklin and Simoneau, 2001) along with QWERTY or other alternative keyboards.

In a comparative study between split and conventional keyboards (Smith et al., 1998) noted that split keyboard allow the hand, wrist and arms to be maintained in a more neutral positions. They reduce both right and left ulnar deviation and pronation. The maintenance of the wrist within the neutral zone for a longer period of time, leads to decreased force applied on carpal bones, ligaments and tendon sheaths (Armstrong and Chaffin, 1979; Armstrong et al., 1984; Marklin et al., 1999). Mitigated CTP, the major trigger for CTS follows. Taking into account that prolonged static postures represent an important risk factor for musculoskeletal disorders onset, the maintenance of the wrists within the flexion/extension and ulnar/radial deviation safe limits should be doubled by posture variation. Using split computer keyboards, Marklin and Simoneau (2001) showed that wrist ulnar deviation ranged from 7.0° to 8.5° for the left wrist and from 2.7° to 5.0° for the right wrist for alternative keyboards as compare to 15-30° for both hands for conventional keyboards. This supports the opinion that when the split keyboard is set up correctly for an individual, it reduces mean ulnar deviation by approximately 10° as compared with a conventional keyboard set-up. Therefore, it reduces the intracarpal pressure. Another advantage of split keyboards have been cited by Treaster and Marras (2000) who determined that alternative keyboard design can affect tendon travel by as much as 11%, reducing the tendon sheaths thickening process.

A particular group of keyboard users is constituted from pointers: self-taught typists who hunt and peck instead of touch-type. They usually rely instinctively on the strongest fingers (the index and middle finger) and because they have their forearms poised in midair to hunt all over the keyboard, are less likely to develop CTS because of the absence of wrist fatigue and ulnar deviation.

1.2.7.4. Split design advantage

There is a debate regarding the benefits of split design keyboards. Split keyboard configuration is more comfortable, increases relaxation and decreases fatigue of the arms and hands while typing (Lincoln et al., 2000). On the other hand, the problem of wrist-extended posture is still present (Hedge and Powers, 1995). Also, the additional width requires the VDT user to place the mouse in a position that will require elevated arm abduction (Harvey and Peper, 1997). Although people prefer split keyboard design to the flat keyboard (Smith et al., 1998), adjusting the angle for the variable split keyboard by themselves does not lead to safer postures failing to decrease the tendon travel (Treaster and Marras, 2000). There is a need for more educational and ergonomic programs to increase the awareness among VDT users regarding the safe postures that are required while typing.

There is a trade-off between wrist and finger positions: when one changes the degree of flexion or extension, the other joint must compensate in order for fingers to reach the same point of the keyboard. This interrelation is best seen with the introduction of alternative split keyboards with modified vertical and lateral angles, as well as negative slope keyboards. Nelson et al. (2000) analyzed the impact of keyboard angles, in terms of Pitch (vertical inclination), Roll (split angle between halves), and Yaw (lateral slope) on tendon travel and wrist and finger postures. They found that increasing Pitch angle produces greater radial deviation, wrist extension and more pronation; larger Roll angle produces greater radial deviation, but less wrist extension and less pronation and Yaw angle produces greater radial deviation. These outcomes support the previous findings that tendon travel is sensitive to changes in the keyboard parameters (especially changes in the three axes) (Treaster and Marras, 2000; Dvir, 1997). Future research should study different methods to decrease the tendon travel for flexor digitorum superficialis because this muscle presents greater tendon travel than flexor digitorum profundus for all keyboard angles (Nelson et al., 2000). Because these two muscles are the only muscles involved in flexion of all four fingers, the overload stress is even greater.

1.2.7.5. Other alternative keyboards

Changes in the keyboard design will affect the repetitiveness of the typing as well as the positions adopted during the typing. Taking into account the role of the tendon travel in the development of CTS (Nelson et al., 2000), and the fact that the resting position includes a degree of flexion in the MCP-IP joints (Dvir, 1997) with the wrist in a very discrete extension (Loslever and Ranaivosoa, 1993), the alternative keyboards should consider this rest posture.

Two ergonomic keyboard designs that consider this neutral posture are TONY! and OPEN keyboard. TONY! keyboard retains the QWERTY layout but has a laterally sloped, split design and a separate numeric key pad, while the OPEN keyboard has a 15° split angle and a 42° lateral inclination (Zecevic et al., 2000). Both reduce pronation and allow the hands, wrists and arms to be positioned in a more natural posture than the conventional keyboards (Smith et al., 1998; Zecevic et al., 2000). In a comparison between OPEN, conventional and FIXED (a fixed split angle) keyboard, Zecevic et al. (2000) showed that the FIXED keyboard allowed the most neutral wrist position for radial/ulnar deviation (-3°), while the OPEN keyboard resulted in an angle of –6° that, even if it represents a reduction in the ulnar deviation, is closer to the maximum safe limit for radial deviation (20°). In conclusion, more time was spent in a neutral position, moderate extension/flexion and radial/ulnar deviation typing on the FIXED keyboard compared to the other two models, making the FIXED keyboard the best option for CTS prevention.

An attempt to reduce the wrist extension problem is made by the negative slope keyboard support (NSKS) that eliminates the problem of wrist extension reducing it from

13° extension to 1.2° flexion (Hedge and Powers, 1995). A notable fact is that even if, in most of the studies, subjects choose inappropriate postures as ideal ones, in this case they have responded very favourably to the NSKS system. In this case however, the ulnar deviation remains the same or it is even greater because of the active process of fitting the finger to reach the same point. Despite the fact that the keyboards of many computers are flat, almost none of the conventional computer keyboards used on a flat work surface actually has a 0° slope, and therefore, a much more ergonomic keyboard would be a NSKS with a split angle. Several keyboard angles, as well as the interaction between different keyboard design elements, should be tried when designing job/device ergonomic modifications. This fact is even more important for the CTS pathogenesis, if we take into consideration the Nelson et al. (2000) assessment that different changes in the angles of the keyboard may reduce the tendon travel with almost 13%.

1.2.7.6. Alternative design benefits

In all the studies that compared conventional keyboard with alternative ones (Zecevic et al., 2000; Smith et al., 1998; Marklin and Simoneau, 2001; Marklin et al., 1999; Hedge and Powers, 1995), the participants have had the ability to rapidly adapt to the changes. The average speed for alternative keyboards was 10% (6 words/min.) less than the speed for conventional keyboards (Marklin and Simoneau, 2001; Marklin et al., 1999). The resulted typing performance is even more remarkable if we take into account the training time that was very short (Smith et al., 1998). Although the above mentioned studies have not had too many subjects, and not all the alternative designs have been included, there is sufficient evidence to support the superiority of alternative keyboards over conventional ones. The most important benefits of ergonomic design keyboards usage are presented in table 1.5. The immediate interests including performance, typing speed and costs have delayed the massive introduction of these ergonomic keyboards. Sooner or later, after some future adaptations, they will become more acceptable, replacing the conventional keyboards.

1.2.8. Keyboard keyswitch design

Even when the required force is not elevated, repeated loading of the fingers has been suspected to contribute to tendon and nerve disorders at the wrist. The increased level of repetitiveness leads to a total overloading of the musculoskeletal and nervous structures that exceeds the safe limit. The best example of such a task is typing.

Actual keyboards present important variations in keyswitch characteristics (keyswitch make force, key travel distance, over travel distance, stiffness) (Rempel et al., 1997). The development mechanism for CTS as well as other typing related injuries is not the result of a single triggering factor. The stress to which the structures within the carpal tunnel are exposed is influenced not only by the keyswitch make force (force required to activate the key), but also the key travel distance, over travel distance and the stiffness at the end of the key travel (Rempel et al., 1999, Rempel et al., 1997).

Several studies reported that high keyswitch make force played a role in the development of hand and wrist disorders, including CTS (Rempel et al., 1999; Feuerstein et al., 1997; Rempel et al., 1997; Radwin and Ruffalo, 1999; Dennerlein et al., 1999; Serina et al., 1997). In direct opposition with these findings are the results of Pan and Schleifer (1996) who observed that lower keyforce and keystroke rates are associated with higher discomfort in hand, elbow and shoulder.

There is a much stronger relation between applied force and keyswitch make force than between EMG measurements and keyswitch make force (Rempel et al., 1997). Also, due to the lack of electrode stability, small detection and inter-detection surface, and noise level caused by motion artefacts, the EMG technique is not suitable in this case. That is why almost all the studies have assessed the force applied by the data entry personnel. The majority of VDT users exert an excessive force while typing. This force is a determining factor in the development and/or progression of WRUEDs (Feuerstein et al., 1997). Although ANSI/HFS recommended that the force required to electrically activate the switch shall range between 0.5N and 1.5N with a preference interval of 0.5N-0.6N (Amell and Kumar, 1999), subjects generally apply a force four to five times greater than the necessary force to activate the key. Rempel et al. (1997) showed that the ratio **R** between applied force and keyswitch make force decreased with increasing make force and probably converges to 1 when the make force approaches finger maximal voluntary contraction (MVC).

Radwin and Ruffalo (1999) found that key switch make point and key switch strike force are proportional to each other: the second one increased from 0.75N to 1.10N when the other was increased from 0.31N to 0.71N. This is in contradiction to Rempel et al. (1997), who reported that the applied force is greater only when keyswitch make force is greater than 0.47N. These differences may be due to a lot of study variables, including typing angle, which have an important effect on the impact force (Dennerlein et al., 1999). An important finding was made by Serina et al. (1997), who showed that the fingertip pulp responds as a viscoelastic material, exhibiting rate-dependence, hysteresis, and a nonlinear force-displacement relationship. The ANSI/HFS recommendation regarding the keyswitch make force is sustained by the recent evidence about the relation between applied force and finger pulp compliance. The stiffening pulp attenuates high-frequency forces of a magnitude less than 1 N while the forces of larger magnitude are transmitted to the bone (Serina et al., 1997) and tendons with direct implications in the CTS development. Fingertip dimensions, subject age and gender, had little to no influence on pulp parameters.

In another study, Rempel et al. (1994) used a piezoelectric load cell and a high-speed video motion analysis system on a standard alphanumeric computer keyboard. They determined that the subject's mean peak force ranged between 1.6 and 5.3 N and the subject mean peak fingertip velocities ranged from 0.3 to 0.7 m/s. This applied force is even greater at the tendon level where Dennerlein et al. (1999), demonstrated that the average tendon maximum forces during a keystroke ranged from 8.3 to 16.6 N ($\mu = 12.9$ N, SD = 3.3 N), four to seven times larger than the maximum forces observed at the fingertip. The risk for CTS is even greater because of the particular pattern of the tendon force variation. Tendon tension during a keystroke continues to increase throughout the impact and most importantly, it is characterized by an important inertia that leads to a slower decrease rate than fingertip force. Therefore, elevated tendon tension will be present twice the time. In the above-mentioned studies, the applied force assessment has been done using a recording device placed under the keyboard. Although there are more expensive, individual recordings for each key are needed if one wants to discriminate between the forces exerted on different keys.

An exception to the relation between force applied and keyswitch make force is seen at light touch keyboards when, due to the lack of feedback, VDT users tend to apply a disproportionate force while typing (Rempel et al., 1997). Keys with a low activation force are not desired because of the high error rate caused by the fingers that are resting on the keyboard. This loss in accuracy will lead to a longer duration of the task at a high typing force.

The increase in key switch make force will affect performance, with implications in lost days and costs, both directly lessening the number of keys/min and indirectly by increasing muscle fatigue and pain over a long data entry task. The longer the travel distance, the lower the key strike force. Radwin and Ruffalo (1999) showed that an increase from 0.5 to 4.5 mm in the total key travel lead to a decrease in the force applied from 1.22N to 0.62N. These findings support the Rempel et al. (1999) results that recorded the highest applied force during the last phase of the key travel. He also showed that the key stiffness at the end of the travel distance alleviates the impact key-finger impact increasing the Phalen test time after a period of 12 weeks. The Phalen test is positive if numbness or tingling in the median nerve distribution is produced or exaggerated within one minute of maximum wrist flexion.

With the VDT users typing with five times more force than it is required, great level of repetitiveness and high association between typing and CTS, attention should be given to the application of the recommendation (0.5N – 1.5N) regarding keyswitch make force.

1.2.9. Mouse role in CTS

Because of the adoption of the graphical user interfaces, pointing devices (e.g. computer mouse, trackballs) are present in every office environment (Fogleman and Brogmus, 1995). In most applications the use of the mouse accounts for almost 60% of total time (Phillips and Triggs, 2001; Harvey and Peper, 1997; Chaparro et al., 2000) with a maximum level of usage of 65-70% in drawing applications (Keir et al., 1999). It was reported to be the most frequently used device among the VDT users both in term of number of users and in terms of daily time spent in using it (Jensen et al., 1998). Although studies that analyze the effects of keyboard use are much more common, there is previous work (Fogleman and Brogmus, 1995; Phillips and Triggs, 2001; Wahlstrom et al., 2000; Chaparro et al., 2000; Burgess-Limerick et al., 1999) that address the etiological relationship between the use of pointing devices and musculoskeletal disorders development.

The lateral position of the mouse is due to the original workstation design that took into consideration only the keyboard. This determines the abduction of the arm (Jensen et al., 1998; Karlqvist et al., 1994) with the wrist ulnar deviated (Wahlstrom et al., 2000), extended, high muscular tension and fatigue. These, plus the prolonged awkward postures have been reported as risk factors for CTS (Hagberg, 1997; Liao and Drury, 2000). Jensen et al. (1998) showed that musculoskeletal symptoms are more prevalent for the arm and hand operating the mouse than for the other arm or hand. Also, increased forces of the tendons and their sheaths produce the first factor in the CTS pathogenesis: inflammation (Marklin et al., 1999). Because most of the computer mice are set up on the right side, the left-handed persons are forced to use their nondominant hand, unless they know how to change the settings. 25% of the VDT users are using their nondominant hand (Jensen et al., 1998) for mouse control and there is not any reason to do it beside the original set up of the workstation. This leads to awkward positions (Fogleman and Brogmus, 1995; Keir et al., 1999) with a high prevalence for CTS.

During a comparative study between mouse and non-mouse users, Karlqvist et al. (1994) reported that 64% of the total mouse working time is spent with ulnar deviation more than 15°. The deviation exceeded 30° in 30% of the mouse task time. Total forearm pronation during mouse use is also common (Keir et al., 1999). Both factors play an important role in the CTS pathogenesis. Women are more affected than men (Armstrong and Chaffin, 1979; Jensen et al., 1998). This is due to higher ulnar deviation, wrist velocities, range of motion (ROM) and percentage of the maximal force applied on the mouse (Wahlstrom et al., 2000).

CTP is also influenced by the nature of the task. Keir et al. (1999) noted the highest intratunnel pressure during dragging (28.8-33.1 mmHg), followed by pointing (18.4-28.0 mmHg) and hand resting on the mouse (16.8-18.7 mmHg). These are in contradiction with Laursen and Jensen (2000), who noted that double clicking caused the highest muscle activity. It is noteworthy that simply placing the hand on the mouse increased the CTP by 13 mmHg. Although the required force is lower, the actual force applied during dragging is 1.5-2N on the buttons and 4N on the sides (Keir et al., 1999). The difference between the tasks effects on CTP is well seen in older users (age 60 to 90). The decreased ROM due to a reduction in wrist flexion (12%), wrist extension (41%) and ulnar deviation (22%) (Chaparro et al., 2000) lessens the lower safer point (Laursen and Jensen, 2000) that will be thus reached more frequently. Due to the loss in capacity of performing fine movements, older computer users apply a higher grip force (Phillips and Triggs, 2001, Chaparro et al., 2000) increasing the risk for CTS. A high level of muscle activity, as represented by EMG when there are increased demands is also common among the older users.

An alternative to the mouse is represented by the trackball. When using trackballs, 80% of the working time is spent with 2°-7° wrist radial deviation compared to the use of mouse where the 5°-15° ulnar deviation is the most adopted position. On the other hand the trackball increases wrist extension by 6° (Burgess-Limerick et al., 1999). Although the elderly are more precise when using a mouse, it is recommended for them to use trackballs (Chaparro et al., 2000) in order to avoid extreme positions that, at this age, due to the reduced ROM, are much closer to the maximum capacity in comparison to young population.

The training of users, workstations, software and tool redesign, reduction in the duration of highly risky tasks (dragging and double-clicking), and limitation of the duration and proportion of continuous mouse are measures that should be taken in order to decrease the mouse role in CTS development.

1.2.10. Discussion

Although De Krom et al. (1990) didn't find an association between carpal tunnel syndrome and typing, the majority of ergonomic literature has emphasized a strong relation between them (Amell and Kumar, 1999; Burgess-Limerick et al., 1999; Feuerstein et al., 1997; Fogleman and Brogmus, 1995; Hedge and Powers, 1995; Marklin and Simoneau, 2001; Serina and Rempel, 1999). The above-mentioned alternative designs introduce lower risks and show that they are superior to the conventional keyboard layout and pointing devices. They allow the VDT user to adopt more ergonomic postures. A decrease in performance when alternative keyboards are tested with a short training session is also common. The relative slow pace of introduction of new ergonomic computer devices may be due to the high cost and the reduction in typing speed. In almost all the studies that investigated the causal relation between keyboarding and CTS, the variables were measured just for a limited period of time and the interaction between them has been ignored. Also, the sample size was very small affecting both the external and internal validity. The replacement of old keyboards shouldn't be viewed as a trade-off between reduction in CTS risk and high costs. Allocating more funds initially may reduce the future medical and non-medical costs.

Without a thorough understanding of the configuration of skeleton framework, the degree of freedom of the joints involved in a particular task as well as the pressure that is induced on adjacent tissues when a certain force is produced, it is impossible to take proper ergonomic measures. It is also necessary to understand the relation between different joint positions and the way in which they affect each other. For example trying to reduce the wrist extension and forearm pronation could lead to prolonged arm abduction, which is the major risk factor for rotator cuff tendonitis. New technical devices are introduced without any previous assessment jeopardizing the workers' health. In order to mitigate the risk level, proper ergonomic evaluations should precede major job/device changes. A real feedback from the workers is compulsory in order to detect CTS early and to prevent the further development of existing early stages of CTS into more severe ones as well as the prevention of new cases.

A person chooses a particular working posture because he/she feels that this position is the most comfortable in relation to that particular task and work place. An important question is why users may choose a position different from the most ergonomically correct. If this question is answered, there will be a significant reduction in the number of typing related CTS. Two possible explanations are that the task requires the adoption of hazardous postures or the devices that are used are inappropriate. Future research should include studies about factors that lead to such dangerous work positions.

Repositioning of some very frequently used keys, implementation of split keyboards with adjustable angle and negative slope, keyswitch make force between 0.5N-1.0N, on the job exercises and job rotation are compulsory measures that need to be taken in order to reduce the CTS incidence and related costs. Mouse redesign (thinner, with a greater distance between the two buttons in order to reduce wrist and finger extension) and keyboard workstation modification (low placement of the keyboard) are also required. All these modifications should avoid localized compression, wrist deviation in all four directions (flexion, extension, radial and ulnar deviation) by more than 50% of its normal range and overloading of the weaker fingers.

On the basis of information found, it is suggested that future research should consider relieving the stress exerted upon the upper extremity with an emphasis on the wrist. The negative features of the conventional keyboard layout noted by Dvorak (1943) are still present. For an objective evaluation of each new design modification's impact, it is better to examine the alternative keyboards that differ in only one, not two or more set-ups. Otherwise, one will not be able to link following effects with specific design interventions. In the case of pointing devices, following studies should evaluate the effect of repeated dangerous trajectories as well as the impact of using both mouse buttons on wrist musculoskeletal system, like in a real VDT task. The assessments of wrist position when the trackball is localized in different places, the role of carpal bones in CTS occurrence and the wrist neutral zone determination in concordance with anatomic features are also possible future research directions.

1.2.11. Conclusions

Although there is a strong evidence of a causal relation between keyboarding and pointing devices on the one hand and CTS occurrence on the other, the role of every single design element is not known. Once these answers are provided, the primary aim of the environmental changes will certainly be the reduction of the risk factors regardless of the associated financial costs as these are going to be one-time expenditures. Not addressing the problem optimally will have a recurring financial, productivity and social costs. To achieve this goal future research directions are presented.

Carpal tunnel syndrome risk factors		
Personal risk factors	**Occupational risk factors**	**Data entry risk factors**
1. Gynaecological surgery 2. Age between 40 and 50 3. Varicosis 4. Female gender 5. Previous wrist fracture 6. Previous diagnosis of a musculoskeletal disorder 7. Diabetes 8. Hand preference 9. Pre-existent joint hypermobility 10. Obesity and lack of sport 11. Slimming courses 12. 6-12 months after the last menstrual period	1. Force applied 2. Repetitiveness 3. Localized mechanical compression 4. Awkward posture 5. Vibration 6. Working in cold environments 7. Working with cold hands 8. Time on task	1. Keystroke activation force 2. Proprioceptive feedback 3. Percentage of time typing 4. Typing speed 5. The use of a group of fingers 6. Keyswitch make force 7. Typing force 8. Repetitiveness 9. Keyboard height 10. Awkward postures

Table 1.4. Carpal Tunnel Syndrome risk factors

QWERTY layout keyboard	Alternative design solutions
1. wrist ulnar deviation	1. split design
2. excessive wrist extension	2. negative slope keyboard support (NSKS) lateral adjustable angle
3. forearm pronation	3. adjustable split angle lateral inclination
4. keyboard fixed size	4. two halves keyboard (with adjustable distance) split design
5. fingers' stretching	5. curved key rows (horizontal plane)
6. fingers excessive flexion	6. concave key rows (vertical plane)
7. increased tendon travel	7. adjustable lateral slope split design
8. arm/hand excessive fatigue	8. split design

Table 1.5. Ergonomic solutions for QWERTY layout induced hazardous factors

1.2.12. References

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1.3. Hand Strength

1.3.1. Ergonomic relevance

Having a complete synopsis of hand injuries risk factors, as well as tabulated data for grip and pinch force values would provide valuable information for ergonomic programs. Also, clarifying the still unknown relationship between shoulder/elbow/wrist position and hand strength, the interconnection between fingers' force, and the differences between young and older workers would allow for targeted ergonomic interventions.

1.3.2. Abstract

Despite a large number of published materials that deal with upper extremity disorders, hand muscle strength has not been extensively addressed from an ergonomic point of view. This chapter represents a review of the state of knowledge in this area. Injuries risk factors, grip and pinch force production, as well as the effect of upper extremity joints deviation on hand strength are presented. Also, older workers concerns and industrial ergonomic solutions are addressed.

1.3.3. Introduction

Although the introduction of powered tools replaced a part of physical work needed from the workers, yet the majority of work tasks that involve the upper extremities experience an elevated stress at the hand-tool interface. With 27 bones, 39 muscles from which 15 muscles serve the thumb and index finger, and more than 25 degrees of freedom of motion, the hand is the most complex musculoskeletal part of the human body. Due to its complex anatomical structure and intense usage (Muralidhar *et* *al.* 1999), and the fact that all occupational musculoskeletal injuries are biomechanical in nature (Kumar 2001), ergonomic interventions are vital. Also, due to the fact that the hand is the main vehicle of motor activity and the most important sensory and tactile organ (Napier 1956), perfect matching between tools/devices and hand characteristics is essential in all workplaces (Imrhan 1989).

Most of the injuries that occur to the hand, forearm and arm are due to poor design (Fransson and Winkel 1991). The rapid transformation in workplace and task, in both office and industrial environments cause high stress levels on hand musculoskeletal system. These include inappropriate force exertions, highly repetitive tasks and awkward postures, sometimes for a prolonged time with little rest (Kumar 2001). Work-related hand musculoskeletal disorders develop from such exposures. The continuous increase in the incidence of upper extremity disorders constitutes strong evidence supporting the idea that workers are either anatomically ill adapted to sustain such demanding tasks physically, or mentally incapable of coping with elevated psychosocial stresses (Kumar 2001).

With scarcity of information regarding submaximal grip and pinch exertions (Radwin *et al.* 1992), the interaction between different joint deviations and upper extremity muscle's loads, and fatigue onset and progression, it is hard to design safe tasks and tools. The need for reporting force application (Kroemer 1970) and hand force production data is evident. Job and device redesign that take into account ergonomic data should be implemented in order to have a reduction in both work-related musculoskeletal disorders and ensuing claims. Although the initial costs may increase the financial burden for a period of time, the ergonomic modifications will enhance both productivity and workers' safety in long term, thus affecting economy positively.

1.3.4. Magnitude of the problem

Although the majority of studies (Kumar and Simmonds 1994, Sukthankar and Reddy 1995, Gerber 1998, Muralidhar *et al.* 1999, Muralidhar and Bishu 2000, Kumar 2001) support the relationship between office/industrial work and hand/wrist musculoskeletal disorders, there is still a scarcity of specific data regarding the recommended posture and pace for any task. Many industrial and office jobs involve extensive forearm and hand/fingers repetitive movements with an important force component. Increased prevalence of musculoskeletal disorders is present in almost all these activities (Hansson *et al.* 1996). In industries where there is an extensive use of tools, such as meat processing and packaging, poultry industry and automobile upholstering, the work related upper extremity disorders prevalence is even greater (McGorry 2001).

In 1984, 9% of all compensable work-related injuries were due to tool use with over 50% from them to upper extremity (Mital 1991). From 1987 to 1989 there was a 100% increase in the number of cases of cumulative trauma disorders (Wiker *et al.* 1989) reaching over 50% of all occupational illnesses in the United States (Sommerich *et al.* 1993). Cumulative trauma disorders were one of the biggest health problems in the 1990s (Halpern and Fernandez 1996). Cumulative trauma disorders were the cause for 62% of all work-related illnesses reported in the USA in 1992 (Bureau of Labor Statistics 1994). This constitutes a 38% increase compared to figures from 1981 (Halpern and Fernandez

1996). According to NIOSH (1997), in U.S., 32% (705,800) of all work-related injuries arose from repetitive motion or overexertion. From them, 92,576 cases were due to repetition (typing, repetitive grasping, repetitive hand tool use, etc.) with 55% affecting the wrist.

In France, 38% of injuries that caused work interruption affected the upper limb (CNAMTS 1995). Although, during the last few years a slight decrease in the absolute number of WRUEDs requiring days away from work was observed (BLS, 2002), the percentage of injuries that affect wrist, hand and fingers is on rise (Table 1.6).

The impact of work-related upper extremity disorders (WRUEDs) on industrial performance has been noted by Hashemi *et al.* (1998) who assessed that, in a large workers' compensation carrier, WRUEDs accounted for 3.6% of all claims and 6.4% of all costs. Hand injuries caused the longest absence from work (Bureau of Labor Statistics 1998), hence associated with higher costs (cost per claim 13 times greater for the WRUED when compared to the overall average).

1.3.5. Risk factors for hand and wrist injuries

There are a wide variety of hand/wrist injuries risk factors that were described in several studies (Drury *et al.* 1985, Silverstein *et al.* 1986, Muralidhar *et al.* 1999, Stal *et al.* 1999, Muralidhar and Bishu 2000, Chaparro *et al.* 2000). In almost all industrial and office work activities the hand-tool interface has the most elevated hazard for the hands (Muralidhar and Bishu 2000). Fransson-Hall and Kilbom (1993) noted that the thenar area, the area around the pisiform bone and the region between thumb and index finger are the hand regions most sensitive to externally applied surface pressure (EASP). This information is suported by Muralidhar and Bishu 2000, who determined that the lowest tolerance to pressure is present at the top of finger V, between fingers I and II and the base of finger II. Localized pressure on hand and wrist has been proven to be associated with musculoskeletal disorders, with a direct relationship between continuous pressure exerted by tools on the palm base and carpal tunnel syndrome (CTS) (Ketola *et al.* 2001). Since pain in the hand caused by extensive external pressure has been stated as a limiting factor in the work performance that require hand held tools use (Fraser 1980), one should act promptly to remedy it. An adaptation to the tasks could allow one to work beyond a certain discomfort level that may elevate risks. Since the majority of occupational musculoskeletal disorders are caused by overexertion (Kumar 1994), continuous forceful hand exertions (Bernard and Fine 1997), non-neutral wrist positions and hand and finger awkward postures (Richards 1997, Ketola *et al.* 2001) constitute important risk factors for hand injuries. Due to their viscoelastic properties, prolonged loading causes permanent tissue deformation (Kumar 2001). The capacity of producing greater force in order to compensate for the decrease due to awkward postures might be absent in pathologic conditions (Richards 1997) raising the risk of injuries in such cases. Asymmetric activities lead to overload of several muscles causing disproportionate stress concentration on tissues (Kumar 2001).

In a study that assessed the role of repetitiveness and force application in work-related injuries, (Silverstein *et al.* 1986) observed that the high forcefulness-high repetitiveness combination was the most hazardous followed by high repetitiveness and low forcefulness, low repetitiveness and high forcefulness, and low repetitiveness and low forcefulness. Repetitive movements of the hand wrist in both office and industrial tasks have been cited as important risk factors also by (Stal *et al.*, 1999, Ketola *et al.* 2001). Close causal relationship between age and hand performance has been assessed by previous studies (Mathiowetz *et al.* 1985, Imrhan 1989, Ranganathan *et al.* 2001). There is a significant reduction in wrist ulnar deviation, flexion and grip strength for men between age 60 and 90. For the same wrist deviations and force exertions, elderly are the end of wrist range of motion (ROM) leading to increased muscle load. (Chaparro *et al.* 2000). In long term, joint kinematics and muscle load sharing patterns different that the physiologic ones occur leading to increased risk of injury (Kumar 2001). The most important risk factors for hand and wrist injuries are presented in Table 1.7.

1.3.6. Hand force production

1.3.6.1. Factors that affect hand strength

Almost all working tasks involve a certain degree of hand force application. Both productivity and the risk of injury are affected by workers' hand performance. Between industrial design and applied force and/or hand dexterity there is a complex relationship. On one hand poor ergonomic design determine a decrease in hand force and precision, on the other hand continuous feedback from experienced workers is useful to ensure proper interaction between man and machine.

Hand force production is generated by a combination of intrinsic and extrinsic muscles. The median and ulnar nerves control the hand intrinsic muscles, which are: 7 interossei (4 dorsal and 3 palmar), hypotenar muscles (flexor digiti quinti, opponens digiti quinti and abductor digiti quinti), adductor policis muscle, the thenar muscles (oponens pollicis, abductor pollicis brevis and flexor pollicis brevis) and the lumbrical muscles

(Kozin *et al.* 1999). Hand extrinsic muscles are represented by: flexor pollicis longus (FPL), flexor digitorum superficialis (FDS), flexor digitorum profundus (FDF), abductor pollicis longus (APL), extensor pollicis longus (EPL), extensor pollicis brevis (EPB), extensor digitorum (ED), extensor digiti minimi (EDM) and extensor indicis (EI). Extrinsic muscles' principal actions are flexion and extension of the fingers and wrist deviation in sagittal (flexion and extension) and frontal plane (ulnar and radial deviation). Their names reflect the actions on the fingers. The extrinsic hand muscles roles in wrist movement are presented in Table 1.8.

Both active and passive components affect total muscle force production (Keir *et al.* 1996). This is also affected by muscle length (Keir *et al.* 1996). Muscles operating the hand have the mechanical properties of skeletal muscles: length-tension and force-velocity relationships (Dvir 1997). During manual task completion the upper extremity joints position should cause optimal length for the muscle(s) being used. L_o (optimal muscle length) is the length at which maximal isometric tension is exerted (Gordon *et al.* 1966, Close 1972). Since tendon tissue has two orders of magnitude higher stiffness than that of the muscle tissue (Keir *et al.* 1996), the most part of the segment excursion is due to muscular tissue elongation. Because the angles of pennation in all forearm muscles, except flexor carpi ulnaris (FCU), are less than 10°, the differences in the passive force present in these muscles are not due to pennation variability (Keir *et al.* 1996). Precise force application is caused by balanced forearm muscles contractions. The maximum applicable muscle force is directly proportional to the physiologic cross-sectional area (Kozin *et al.* 1999). Chau *et al.* 1997 stated that the hand strength was more correlated with arm muscle cross sectional area than the gender and body mass index.

Hand performance is affected by burden level. Pfitzer *et al.* (1972) noted that different loading affects the hand performance variably. A 40% increase in the strength corresponds to 10% increase on an efficiency impairment scale, while a 60% and 80% increase corresponds to 17% and 18% increase, respectively. Ergonomic interventions should consider required force exertion. The maximum strength application is limited by the weakest segment or joint implicated in that particular activity (Wells and Greig 2001). Moreover, the optimal solutions are not universal. Due to different daily use, there is an alteration in the mechanical and physiological properties of skeletal muscle. In the dominant first dorsal interosseous (FDI) muscle there were lower values for recruitment threshold, initial firing rate, discharge variability and target force firing rate when compared to non-dominant FDI muscle. This may be due to an increased percentage of slow twitch fibers in the preferentially used (dominant) muscle (Adam *et al.* 1998).

Although the difference in force between dominant and non-dominant hand was assessed to be between 10% and 13% in dominant hand's favor (Lunde *et al.* 1972), the non-significant effect of hand laterality on hand strength is sustained by the majority of studies (Reikeras 1983, Mathiowetz *et al.* 1986, Imrhan 1989). Rice *et al.* (1998) found no significant differences between dominant and non-dominant hand for grip and pinch strength. Since according to Schmidt and Toews (1970) 28% of the subjects had higher grip strength values in non-dominant hand, the use of "10% rule" (the dominant hand is 10% stronger than the non-dominant hand) is not well established.

Hand use capacity is influenced also by: anatomic integrity, strength, coordination, mobility, age (Mathiowetz *et al.* 1986, Chau *et al.* 1997), gender (Swanson *et al.* 1978, Mathiowetz *et al.* 1986), associated diseases (McPhee 1987, Rice *et al.* 1998) and shoulder, elbow and wrist condition and postures (McPhee 1987). During grasping muscles acting on shoulder and elbow joints (upper extremity spatial positioning) and distal (hand) muscles (fingers shaping in according to object weight and height) are used (Kuhtz-Buschbeck *et al.* 1998). Table 1.9 presents the most important factors that affects hand performance. The peak hand strength is reached in mid twenties (Fisher and Birren 1947, Schmidt and Toews, 1970) with a force decrease of 16.5% after 60 years age (Chau *et al.* 1997). In children, development (Ager *et al.* 1984) achievement in physical education and breathing capacity (Weiss and Flatt 1971) are correlated with hand performance. Christ *et al.* (1992) noted an important decrease in wrist and finger flexor muscles maximal voluntary contraction (MVC) for women in the 45-49 age group. For all age groups, women exert less force than men (Conti 1998, Mathiowetz *et al.* 1986), with 35% of the gender difference being explained by hand size (Fransson and Winkel 1991).

Associated pathology causes an important decrease in hand force. Rheumatoid arthritis causes a 90% decrease in the grip strength compared to a healthy person. For pinch strength, there is a 75% decrease (Rice *et al.* 1998). Although severe stages are incompatible with work, the acute drop in hand abilities leads to lessened hand force and precision, increasing the risk of injuries. Median nerve paralysis presents in CTS suffering workers, determines a loss in thumb motion and coordination leading to perturbed opposition during pinch and grasp applications (Kozin *et al.* 1999). Also, hand imbalance with metacarpophalangeal hyperextension and interphalangeal flexion are present in cases with ulnar nerve paralysis. Since intrinsic muscles extend the interphalangeal joints and are the prime flexors of the matacarpophalangeal joint, a loss in their performance causes extrinsic muscle overload with asynchronous grasp exertions. In order to design ergonomic job and devices, one should bear in mind the effect of each factor on hand performance. Given the important variability among workers, adjustable tools are essential.

1.3.6.2. Hand muscles fatigue

Although the introduction of mechanized tools reduced the necessary force, there are still many tasks that require excessive physical exertion. In these cases fatigue is a common phenomenon among workers. In order to understand its development, intimate fatigue mechanisms and difference among workers should be studied.

Endurance is the ability to sustain continuous dynamic contraction or isometric contraction for a prolonged period of time. When analyzing endurance one should take into account duration, intensity and frequency. Without these, comparison between different outcomes is impossible (Wallstrom and Nordenskiold 2001). Endurance can be studied either maintaining a certain percentage of MVC for a period of time or measuring the strength magnitude that follows repetitive or sustained contractions for a predetermined time. Previous studies assessed endurance levels determining repetitive submaximal (75% and 50% of the MVC) contractions (Wolf *et al.* 1996), sustained submaximal (40% and 50% of the MVC) contractions (Aniansson *et al.* 1983, Chatterjee and Chowdhuri 1991) or sustained maximal contractions (Nwuga 1975). During the first repetitive contractions there is an important decrease in muscle strength, named by Ohtsuki (1981) as the fatigue phase. Once a certain level is reached, muscle strength decreases at a lower rate (the endurance level) (Wallstrom and Nordenskiold, 2001).

Rohmert (1960) proposed the equation T_s=-90+126/P-36/P^2+6/P^3 as the relationship between human static strength and endurance time, where T_s represents the endurance time expressed in seconds, –90 is a constant, and P is the percentage of maximum strength. Kroemer (1970) questioned this equation noting that its utility depends upon its usefulness in isometric exertions tasks.

During muscle fatigue, decline in the maximal contractile force, inability to maintain targeted force and increased effort during muscle contraction occur (Blackwell *et al.* 1999). The maintenance of constant force is accomplished either by recruiting more motor units or increasing the discharge frequency in the active ones (Carpentier *et al.* 2001). During muscle fatigue, for constant force, higher activation rates are required leading to increased risk of injury due to lack of rest (Fuglevand *et al.* 1999). In contradiction with these findings, Zijdewind and Kernell (2001) noted important decrease in the activation rate due to fatigue. Although there is a consensus in the literature regarding the recruitment of new motor units, contradictory information are reported about the change in discharge frequency in active motor units during fatiguing contractions. Frequency has been reported to increase (Dorfman *et al.* 1990), remain constant (Maton and Gamet 1989) or decrease (Gantchev *et al.* 1986). Fatigue is not greatest in the motor units that exerted the largest forces. Fast-contracting motor units are not more exposed to fatigue or stronger than slowly contracting units (Fuglevand *et al.* 1999). In addition to the local feedback and regulatory mechanisms, the central control plays an important role in the motor units adaptation (Carpentier *et al.* 2001).

Muscles not directly involved in the force production undergo fatigue, too (Aymard *et al.* 1995, Zijdewind *et al.* 1998). Activation in both ipsilateral and contralateral muscles occurs during prolonged muscular contractions (Gandevia *et al.* 1993). Zijdewind and Kernell (2001) reported an increase in force and electromyographic activity in the contralateral muscle during both submaximal and MVC fatiguing contractions. This coactivation increases the risk of injury by two mechanisms: 1. due to accumulated fatigue in muscles that are not primary effectors during a specific task, the change in position and/or pattern would find the new primary muscle already fatigued and would cause an increased stress resulting in muscle overload and overexertion, 2. due to fatigue in muscles other than the target one, unintended contractions of fatigued muscles could induce loss of precision increasing the risk of errors and accidents. Proportional relationship between contralateral activation and targeted muscle activity was also demonstrated (Zijdewind and Kernell 2001). Differences in moment arm determine higher forces at the proximal site when compared to forces at the distal site (Danion *et al.* 2001). Since at the upper extremity level, the distal regions are more vulnerable, even forces lower than those exerted at proximal levels could induce musculoskeletal injuries. This causal relationship is even more evident if one works in awkward postures and highly repetitive tasks in which muscle overload and coactivation are ubiquitous.

Due to its particular characteristics, adductor pollicis muscle was extensively studied (Fulco *et al.* 1999, Fulco *et al.* 2001, Carpentier *et al.* 2001). Its unique properties are: high proportion of slow-twitch high oxidative fibers and complete motor unit recruitment (Fulco *et al.* 2001). Merton (1954) noted that in adductor pollicis muscle, voluntary activation account for all force produced in both rested and fatigued muscle. During fatigue, for low-threshold (<25%MVC) motor units, the first dorsal interosseus presents an increase in both mean twitch force and recruitment threshold. For high-threshold (>25%MVC) motor units, both twitch force and activation decreased (Carpentier *et al.* 2001). Afferent feedback differences in muscle implicated in sustained contraction may explain the different behavior of low and high threshold motor units. Although Herbert and Gandevia (1996) showed that 90% of adductor pollicis force was explained by voluntary activation and there are no differences between genders, Fulco *et al.* (2001) were the first to assess a gender difference in muscle performance under hypoxic conditions. If in normoxia and hypoxia, men had higher MVC force for rested muscle when compared to women (Fulco *et al.* 2001), during sustained muscle contractions, women present a slower decrease in force. The fatigue rate in men was approximately 2 fold shorter in normoxia (-8 +/- 2 vs. –4+/- 1 N/min, respectively, $p<0.01$) and approximately 2.5 fold shorter in hypoxia (-13+/- 2 vs. –5+/- 1N/min, respectively, $p<0.01$) than for women. Furthermore, the decrease in adductor pollicis force after one minute of exercise for women was less (93+/- 1%) compared to men (80+/- 3%). Also, the endurance time to exhaustion was double in women compared to men (14.7 +/- 1.6 min vs. 7.9+/- 0.7 min, $p<0.05$). Wallstrom and Nordenskiold (2001) noted that during the first 90 seconds there was a decrease of 33% and 30% for women and men respectively, whereas the decrease between seconds 90 and 180 was 12% for women and 13% for men.

Since the slow-twitch high-oxidative fibers proportion in adductor pollicis muscle is equal in both men and women, the women's superior muscle performance in tasks requiring total motor unit recruitment might be due to an fast-twitch fibers lowered capacity for oxidative phosphorylation in men (Fulco *et al.* 2001). Another point of view is that in women the adductor pollicis muscle contains a higher percentage of slowly fatigable fast-twitch oxidative fibers than in men with differences in adductor pollicis muscle properties determined by muscle generating capacity variance (Fulco *et al.* 1999). Gender differences demonstrated in adductor pollicis determine a higher oxidative capacity in women and a less impaired muscle capacity under hypoxic conditions. The assessment of differences between women and men should lead to ergonomic modifications for demanding activities where males are predominant. All these findings dictate the need for important differences between devices and workplaces for men and women. Also, differences in task completion pattern should be taking into account.

Due to the anatomy of hand, changing the force application point along the finger axis might provide an important variation in the muscle participation for force exertion, protecting them from overload and overexertion (Danion *et al.* 2001). Fatigue can be avoided implementing training programs that would increase awareness among workers. Rest pauses and alternative postures could also avoid muscle overload. Decreased injury rate due to better hand force production and precision follows.

1.3.7. Grip force

1.3.7.1. Classification

In the past, different criteria have been used in order to classify grip force application. Significant diversity led to difficult-to-compare results and testing procedures. McBride (1942), considering the parts of the hand used, proposed grasping with hand as a whole, grasping with both the thumb and fingers and a combination of the palm and finger grasping as the most important subtypes of gripping applications.

Griffiths (1943), based on the object shape, classified hand prehension into cylindrical grip, ball grip, ring grip, pincer grip and pliers grip. Also, Cutkosky and Wright (1986) divided gripping exertion into circular, when the thumb and fingers are placed radially around the object, and spherical in which the fingers oppose the thumb. Napier (1956) introduced for the first time the terms hook grip, power grip, precision grip and combination grip. During power grip the thumb is adducted at the carpo-metacarpal and metacarpalphalangeal joints, fingers are ulnarly deviated, laterally rotated and flexed (Pryce 1980). In precision grip the thumb is abducted and rotated and the fingers are flexed and abducted at the metacarpalphalangeal joints (Napier 1956). There is not a distinct separation between power and precision grip while working. Often they are combined during job task completion. (Landsmeer 1962) proposed the substitution of the term precision grip with precision handling.

Kamakura *et al.* (1980), in a study involving healthy volunteers, noted 14 patterns: 5 for power grip (involving areas of the palm, hand and volar surfaces of the digits with the finger IV and V flexed more than the radial fingers), 4 intermediate grips patterns (the contact area with the object is represented by the radial faces of the index and middle fingers), 4 prehension grip patterns (with the object between the fingers and the pulp of the thumb) and one prehension without the thumb. Kapandji (1970), in terms of digital segments involved in the force exertion, proposed the introduction of the following terms: palmar prehension, prehension by digito-palmar opposition, prehension by subtermino-lateral opposition, prehension by subtermino opposition, prehension by termino opposition and prehension between two sides of the finger.

Finally, Sollerman and Sperling (1978) proposed the Hand-Grip Classification in which four prehension patterns were described: transverse grip (the object is held between the thumb and fingers at 90° to the hand margins), diagonal grip (the object is held between thumb and all four fingers with a diagonal object-palm contact interface), extension grip (the object is held with interphalangeal extension) and spherical volar grip (the object is surrounded by the thumb and fingers with palm contact). None of the above grip classifications are better than the others. They are suitable for describing grip applications regarding the tool being used, hand position, required force and/or precision and hand regions involved in force exertion. In order to ensure unbiased data, grip classification should be chosen in concordance with particularities of the task being analyzed.

1.3.7.2. Force exertion

Grip strength is widely used in many industrial tasks. During grip exertion the most exposed areas are the metacarpal regions (Muralidhar and Bishu 2000). Also, elevated stress on the common extensor tendon is present due to the increased passive forces in the digital extensors (Keir *et al.* 1996). Grip force is produced by the thumb flexors exerting force in opposition to the total force produced by other fingers' flexors. Imrhan (1989) noted that since the force is applied at metacarpophalangeal joints level, during gripping the finger flexors are more advantaged than the thumb flexors. There is an important variation among different reporting regarding the most exposed hand and fingers areas while gripping. Table 1.10 presents the zones of the hand with maximum risk of being injured during gripping applications. Given that some regions (distal phalanges for fingers II-V, thenar area) are cited by the majority of authors, grip applications could be significantly limited by localized pressure in these regions.

The most important factors that influence grip force are: age (Mathiowetz *et al.* 1985, Carmelli and Reed 2000), gender (Desrosiers *et al.* 1995, Richards, 1997), handedness (Crosby *et al.* 1994, Richards 1997), tool handle surface (Westling and Johansson 1984, McGorry 2001), object shape, intended use (Pryce 1980), body position (Teraoka 1979, Martin *et al.* 1984), object weight and size (Frederick and Armstrong 1995, Kinoshita *et al.* 1996), dynamometer setting, time between tasks (Netscher *et al.* 1998), upper extremity posture (Dawson *et al.* 1998), total number of muscle fibers, percentage of fibers activated, muscle section area, fiber tension (Carmelli and Reed 2000) and hobby demand (Crosby *et al.* 1994). In all studies men were consistently stronger than females (Desrosiers *et al.* 1995, Richards, 1997, Wallstrom and Nordenskiold 2001). Dawson *et al.* (1998) found lower values in females for all wrist positions. Su *et al.* (1994) noted that for males, the 20 to 39 years age group had the highest grip strength. For women, the peak was recorded in the 40 to 49 years age interval with an ulterior decrease due to age. After 60 years of age there is a 20% decrease in grip force for both genders (Carmelli and Reed 2000). Grip strength values obtained in different studies are presented in Table 1.11. Important variations among reportings are due to sample characteristics, experimental setup and recording measurements being used.

Grip force is also subject to variation due to body and upper extremity position. Previous studies showed that grip forces while supine are weaker than grips measured in standing posture (Teraoka, 1979, Martin *et al.* 1984). Although Martin *et al.* (1984) and

Richards (1997) determined no difference between grip force measured in supine and sitting subjects, Teraoka (1979) recorded higher values for the later posture. Decrease in gripping force has been reported for supination greater than 70 degrees. No effect of supination on force exertion has been noted. All these influences are explained by the muscles length-tension relationship (LaStayo *et al.* 1995). Also, the force produced on gripping is directed in order to stabilize the upper extremity (Richards 1997). An important condition for grip force exertion is the presence of wrist stiffness. During finger flexion, the flexor tendons, which cross the wrist, provide an increase in wrist stabilization (Dawson et al. 1998). If the upper limb needs to be stabilized, less force may become available for producing grip force. Thus the safer limits may be crossed leading to musculoskeletal disorders.

The grip force necessary to work with a certain tool is equal to the grip force component normal to the handle surface multiplied by the coefficient of static friction between the hand and the tool. Cutkosky and Wright (1986) noted a significant decrease in the applied force using a screwdriver when a high-friction handle was used compared with an aluminum (low-friction) handle. In order to avoid acute accidents, the workers exert more grip force than required. Westling and Johansson (1984) saw the difference between necessary and applied force as a buffer. At high loads, workers exert no more than required force because of fatigue considerations. At low-loads, the available wide area of variation between the required force and the MVC value determine an important increase in the applied force (Frederick and Armstrong 1995) keeping the risk elevated. The risk of injury is even more increased for subject with CTS. In their case, due to decreased sensibility, the coordination is almost absent leading to significantly greater grip-moment ratio (Kozin *et al.* 1999, McGorry 2001).

LaStayo *et al.* (1995) found drop in grip strength due to fatigue. There was a significant drop of 17.2 pounds in grip force after 5 seconds of force exertion. The decrease was not linear, with a 4.8 pound decrease in the first second. Due to the high force required during industrial work, more important than the maximum grip force exerted, is the rate of fatigue that occurs during prolonged/repetitive gripping activities. During repetitive grip exertions, muscle contraction is highly influenced by both the anaerobic metabolism and the proportion of type II (fast twitch) muscle fibers (Capodaglio *et al.* 1997). Grip endurance time depends on the fiber type composition, muscle blood flow, maximum force for the muscle being used and individual range of motion. Given that all these factors are improved by training, different tasks should be assigned to experienced workers when compared to new employee. Mitigated strength capacity may lead to injuries that could possibly be prevented using training programs and introducing rest pauses.

Information regarding muscle activity during grip force application could be used in order to ergonomically design new devices and/or working techniques. Berguer *et al.* (1999) noted that the muscle electrical activity amplitude while using the palm grip was decreased in the flexor digitorum superficialis (FDS), thenar compartment (TH) and extensor digitorum comunis (EDC), unchanged in the extensor carpi ulnaris (ECU) and flexor carpi ulnaris (FCU) and elevated in flexor digitorum profundus (FDP) compared with the finger grip during laparoscopic instruments use. More visible differences between EMG aspects were seen during high force conditions. Furthermore, for the same object the use of above radial grip requires less force than lateral grasping from the side (Kinoshita *et al.* 1996). In radial grip, in addition to the distal phalanx, the middle phalanx pulp was used, decreasing the localized mechanical pressure on the hand surface (Kinoshita *et al.* 1996). One should use 4 or 5 finger grips in order to be protected by muscle finger overload. Tool diameter is very important in grip strength application (Imrhan and Loo 1988). Since the muscle cross-bridge attachments are at their maximum level when the muscle is near resting length, moderate diameters determine highest grip forces. When the muscle is very short or very long, the number of attachments decreases and the resulting force is lessened (Blackwell *et al.* 1999). Kinoshita *et al.* (1996) noted that there was an increase in the grip force with the increase in object weight and variations of diameter above and less than 7.5 cm. Also, smallest grip forces were assessed when extreme diameters were used (Blackwell *et al.* 1999). Based on available data, moderate diameters of handles with high friction coefficient should be used at the workplace. In this way, through inexpensive ergonomic modifications, important reduction in muscle load as well as safer working techniques are promoted.

1.3.8. Pinch force

1.3.8.1. Classification

Sollerman and Sperling (1978) classified pinch applications in four finger grips (pinches) types: pulp pinch (involve thumb and index or middle finger), lateral pinch (thumb and radial side of the index finger), tripod pinch (thumb, index and middle fingers) and five-finger pinch, which occurs when the thumb and all the fingers are used. Brorson *et al.* (1989) divided three-point pinch in tip pinch and palmar pinch. In tip pinch the device/tool is grasped between the tips of the thumb, index and middle finger, whereas in palmar pinch the pinch meter is grasped between the pads of the thumb, index and the middle finger. Two-point pinch includes tip, palmar and lateral pinch. In lateral pinch (key pinch) the force is exerted between the pad of the thumb and the lateral side of the middle phalanx of the index finger. The interaction between intrinsic and extrinsic muscles is evident during lateral pinch applications. Both thumb and intrinsic muscles act for thumb positioning and force exertion against the *flexor pollicis* during pinch exertion (Kozin *et al.* 1999).

1.3.8.2. Force exertion

The use of pinch force is needed in majority of industrial tasks. During pinch, the most exposed hand regions are the top of fingers I, II and III (Muralidhar and Bishu 2000). Imrhan (1989) noted that during pinching, the force is applied at the tips or pads of the fingers, increasing the risk of injury at these levels. Localized reduction in sensibility may develop leading to lack of feedback and inappropriate force exertions. Previous studies assessed the ratio between pinch and grip force of being 1:4 (Imrhan 1989) to 1:5 (Kumar and Simmonds 1994). Crosby *et al.* (1994) noted that pulp pinch was 16% and key pinch was 22% of maximum grip values.

Pinch strength is influenced by: hand dominance (pinch grip force is consistently less in the non-dominant hand compared to dominant hand), occupation, range of motion, pain sensation and, self-perception of function (Fowler and Nicol 2001). Also, pinch strength could be highly influenced by experimental conditions (Imrhan 1989) with learning effects affecting both MVC and submaximal contractions. The ratio between dominant hand and non-dominant hand was 1.12, 0.13 (mean, SD) for both males and females, with no effect of age on its value (Brorson *et al.* 1989). Chong *et al.* (1994) found pinch (tip, palmar and key) strength positively correlated with gender, body height and weight, mid-arm and mid-forearm circumference and negatively correlated with age and triceps skinfold thickness. Positive correlation between finger length and pinch strength is also reported (Brorson *et al.* 1989). Armstrong and Chaffin (1979) proposed the $F_t=kF_L$ *equation for* the finger flexor tendon force estimation, where F_t=finger flexor tendon force, F_L=pinch force and k=2.8-4.3 being influenced by the object and person hand sizes. Data could be used for the estimation of stress at the wrist level. According to Chau *et al.* (1997), for pinch strength the highest correlation was obtained with gender and muscle area. These anthropometric values are easy and not costly to assess and should be included in the hand strength assessment techniques. In all studies males were stronger compared to females in terms of pinch strength application (Brorson *et al.* 1989, Imrhan, 1989, Chau *et al.* 1997). The difference between pinch strength in males and females is smaller in children (female-male ratio=0.89) than in adults (0.69), with force values increasing in this order: female children, male children, female elderly, male elderly, female adults, male adults (Imrhan 1989). Pinch mean values assessed in previous studies for different age intervals are presented in Table 1.12.

During key handling, the lateral pinch forces are in a constantly maintained balance (Wells and Greig 2001). Due to their important role in stabilizing thumb-tip force during unstable pinch, there is an important increase in abductor pollicis brevis and extensor pollicis longus. Their action is independent of force magnitude (Johanson *et al.* 2001). If prolonged precision tasks are performed, there is an elevated risk for abductor pollicis brevis and extensor pollicis longus overload with consecutive musculoskeletal injury. One should alternate between high-force and precision tasks in order to avoid the risk for localized fatigue/discomfort/injury.

Among all pinch types, the strength values were from the highest to the lowest: key pinch, palmar pinch and tip pinch (Chong *et al.* 1994). Imrhan (1989) found the same magnitude order and noted that the relationships between forces exerted in different pinch types are constant regardless experimental conditions. The finger used in opposition to the thumb influences the force exerted during pulp pinch. The force increases in the following order: digit 5 (little finger), digit 4 (the ring finger), digit 2 (the index finger) and digit 3 (the middle finger) (Swanson *et al.* 1970). Similar finger strength proportion was found during the fixed total pinch force task. The average contribution of each finger was 33%, 33%, 17% and 15% for index, middle, ring and small finger respectively (Radwin *et al.* 1992). During pinch exertion with index finger opposing the thumb, the joint position is balanced in order to optimize the posture in which slipping is almost impossible (Radwin *et al.* 1992). This reduces MVC and increases safety. Imrhan (1989) noted the need for proper size handles if safe lateral and chuck pinches are desired. Armstrong and Chaffin (1979) showed that the index finger pinch strength was 42% to 93% greater when the digits 3,4 and 5 were flexed and extended respectively. Also, increasing the force exertion level from 10% to 30% MVC causes an elevation of middle finger contribution from 25% to 38% from total finger force exertion (Radwin *et al.* 1992). The uneven load distribution among fingers leads to increased risk for stronger fingers, while little and ring fingers remain exposed due to anatomical characteristics.

In order to implement valid ergonomic interventions, one should be aware not only of hand musculoskeletal structures exposed to elevated stresses during repetitive and forceful applications but also of pinch variability among workers. The wide variety of job factors that influence force exertion should also be considered. For example, Frederick and Armstrong (1995) noted that increasing tool handle friction reduces required pinch force for tasks requiring more than 50% of pinch strength MVC. Pinch strength assessment provide an accurate determination of hand function (Fowler and Nicol 2001). Information could be used for targeted tool/task design as well as for choosing the most appropriate muscle-tendon load transfer technique.

1.3.9. Differences due to shoulder, elbow and wrist position

The majority of work and daily living activities require positions different than the neutral one (Richards *et al.* 1996). The influence of upper extremity joint position was extensively noted in ergonomic literature (Mathiowetz *et al.* 1985, Drury *et al.* 1985, Marley and Wehrman 1992, LaStayo *et al.* 1995, Keir *et al.* 1996, Berguer *et al.* 1999). The further away the joint is, compared to the hand, the less well documented is its relation to hand performance. Furthermore, body posture has been shown to influence grip strength (Kuzala and Vargo 1992). McPhee (1987) noted that the hand functional capacity is closely correlated with the upper extremity proximal portion capacity to position the hand in an ergonomic posture. Also, there is a strong relationship between awkward posture leading to indirect vision of the tool/working place and decreased performance (Berguer *et al.* 1999). Since long flexors and extensor muscles of the fingers act at the same time for intermediate joints stabilization and for maximum force exertion, any variation in their total length leads to important decrease in the ability to contract with maximum performance (Richards *et al.* 1996). The extrinsic finger and wrist musculature influence on hand movement and posture was also studied by Keir et al. (1996) during wrist and finger flexion. Since the hand muscles are multiarticular fully deviated joints cause muscle to overstretch.

Due to the dynamic aspect of almost all the tasks required during work, the relationship between grip force exertion and wrist/forearm position is very important (LaStayo *et al.* 1995). Previous studies addressed the impact of wrist position on grip strength (Melvin 1977, Pryce 1980, Drury *et al.* 1985, O'Driscoll *et al.* 1992, Lamoreaux and Hoffer 1995, Fong and Ng 2001). Outcomes are not consistent. Wrist extension was shown to either increase (Mathiowetz *et al.* 1985) or decrease (O'Driscoll *et al.* 1992) grip strength. Kraft and Detels (1972) demonstrated that the grip strengths recorded at 0°, 15°, and 30° wrist extension were not significantly different. Also, Pryce (1980) noted no differences in grip strength for the 0° and 15° wrist ulnar and/or extension deviation. For the 15° wrist flexion and 30° ulnar deviation, the values were significantly lower when compared to the neutral position. Both Pryce (1980) and Kraft and Detels (1972) noted significantly lower values at 15° wrist flexion when compared to the neutral position. Contrary to these findings is the study in which no differences in grip strength were found between neutral, 15° and 30° wrist extension (Kraft and Detels 1972). Hazelton et al. (1975) noted that 21° ulnar deviation and 14° radial deviation determine an increase in grip strength and the 30° ulnar deviation allow for the highest grip strength. In contrast, Terrell and Purswell (1976) found a decrease in grip strength of 15% and 18% for 20° ulnar deviation and 20° radial deviation respectively.

Because larger moment arms characterize wrist flexors compared to extensors, larger forces would require active extensors to maintain the wrist posture (Keir *et al.* 1996) leading to increased risk of injury for the extensors' group while working with flexed wrist. Passive muscle forces, always present in antagonist muscles, elevate the risk even more. The tensions recorded in wrist extensors were between 5 and 10N. These values represent between 5% and 36% of the maximal force. Berguer *et al.* (1999) noted ineffective finger grip while wrist is flexed at 90°. When the wrist is fully extended or flexed there is a loss of flexor tendon force due to friction and contact with the wrist structure. This causes a significant decrease in pinch strength (Halpern and Fernandez 1996). Furthermore, wrist deviation in coronal plane decreases grip strength due to the change in angles between the tendons and their insertions. Compression of tendons against the carpal tunnel structures is present as well (Fong and Ng 2001). The risk of injury is raised, especially when repetition and/or high forces are present. Extensor muscles overload is likely to appear during grips involving large wrist flexion angles, such as tip pinch, briefcase grip and key pinch. Alternating between these hand/finger positions and working postures that require wrist extension could reduce muscle fatigue, alleviating the risk of injury. In order to maintain a balance between wrist extensors and finger flexors during large objects grasp, there is a need for wrist flexion, whereas during grasping smaller objects, the wrist is extended (O'Driscoll *et al.* 1992). When designing jobs and devices, one should allow for the role of tool shape and size on hand function. Deviations from the wrist neutral position cause compression of carpal tunnel elements against the surrounding structures. Muscle length variations followed by hand/finger mechanical disadvantage are also present (Pryce 1980). Adjustable and/or customized utensils should be promoted at workplace for the worker safety.

According to Pryce (1980), the wrist positions that led to the highest grip strength values were: 0° ulnar deviation and 15° extension, 15° ulnar deviation and 15° extension, 15° ulnar deviation and 0° extension, and 0° ulnar deviation without wrist extension. The differences between them were not significant. In the contrary, Fong and Ng (2001) reported that the grip strength recorded at 15° or 30° wrist extension and 0° ulnar deviations were significantly higher than the grip strength at 0° ulnar deviation and 0° wrist extension or 15° ulnar deviation with or without wrist extension. Maximum grip strength was recorded in the self-selected posture (35+/- 2° extension and 7 +/- 2° ulnar deviation) without any effect of gender on the subjectively selected wrist posture (O'Driscoll *et al.* 1992). The beneficial effect of moderate wrist ulnar deviation on gripping force is also supported by Lamoreaux and Hoffer (1995), who noted that there is a decrease in grip strength when wrist is radially deviated. No effect on pinch strength was recorded. There is a tied relationship between the wrist deviations in extension-flexion and ulnar-radial deviation planes. Pryce (1980) reported a significant interaction between ulnar deviation and wrist flexion-extension. Although the wrist might be positioned in the proper position in one plane, in order to obtain maximum force, there is a necessity of keeping it within the appropriate deviation range in the other plane, too. Differences in strength exertions among studies may be due to different elbow and/or shoulder position, which represent an important factor in hand performance (Kuzala and Vargo 1992, Su *et al.* 1994, Fan and Ng 1999).

In order to maintain gripping stability and strength, the wrist muscles contract in a balanced manner positioning the wrist in the optimal posture for a given task (Dawson *et al.* 1998). During wrist stabilization, an important role is played by the wrist musculature, carpal bones and ligaments (LaStayo et al. 1995). The finger flexors muscles EMG was approximately the same for wrist deviation within the 5° radial deviation – 10° ulnar deviation range with significant increase in myoelectrical activity for extremely deviated postures (Drury *et al.* 1985). Furthermore, the EMG activity in left hand was 27% higher than for the right hand with wider variations as a function of wrist angle. The increased variation in non-dominant hand could be explained by the effect of "occupational training" on the dominant hand in a world designed for right-handed workers.

Hand performance is also highly affected by forearm position (degree of supination or pronation). Grip and pinch strengths are increased or not changed by supination (Agresti and Finlay 1986) and decreased by forearm pronation (Marley and Wehrman 1992). Richards *et al.* (1996) assessed grip force exertion in pronation as being the weakest followed by neutral position and forearm supination. The drop in gripping force during forearm pronation is explained by the loss in force generation of the long finger flexors (LaStayo *et al.* 1995). In this position the muscles are stretched leading to mitigated strength. Fraser (1980) noted that the maximum pinch strength during supination is due to biceps brachii's role of forearm stabilization. This provides support for forearm digital flexors to contact at their maximum capacity. High risk of musculoskeletal injury is present during work that involves repetitive changes from supination to pronation concomitant with important force demand. During the shift between supination and pronation, the direction of pulls of the flexor muscles that originate from the radius and rotates around the ulna changes (Richards *et al.* 1996) making it even more difficult to maintain the muscular balance. Almost all studies test hand force in set-ups that lead to maximum strength. Due to variability of forearm positions used during work, forearm supination should not be the only position tested in grip strength tests.

Both grip and pinch forces are significantly affected by elbow and shoulder posture (Kuzala and Vargo 1992, Marley and Wehrman 1992, Su *et al.* 1994, Halpern and Fernandez 1996, Capodaglio *et al.* 1997, Fan and Ng 1999). No consensus has been reached regarding the upper extremity position that provides the highest hand force. Because the flexor digitorum superficialis crosses the elbow joint, elbow position influences its strength performance. Although Kuzala and Vargo (1992) and Marley and Wehrman (1992) reported significantly stronger grip strength with extended elbow (0° flexion) when compared to elbow flexion (90° flexion has been shown to allow for the highest force values by other studies). Mathiowetz *et al.* (1985) found higher grip values when elbow was 90° deviated compared to 0° position. Also, Fan and Ng (1999) demonstrated that grip strength was higher at 90° elbow flexion than at 130° elbow flexion or no flexion. Maximum hand force recorded at 0° elbow flexion could be the explained by the relation between joint deviation and muscle length. The more flexed the elbow is, the shorter is the flexor digitorum superficialis leading to a decrease in force exertion (Kuzala and Vargo 1992). Shoulder and/or body stabilization could account for elevated hand force exertion with flexed elbow. Higher torque mean values were recorded during grip with the elbow adducted (no shoulder flexion) and flexed at an angle of 90° than in the tests performed with arm abducted (shoulder flexion) and extra-rotated and the elbow flexed at an angle of 90°. This difference might be due to a better hand/forearm stabilization and wrist maintenance within the neutral zone (Capodaglio *et al.* 1997). In a study that assessed hand strength in four different positions (elbow fully extended with 0°, 90° and 180° shoulder flexion and elbow 90° flexed with 0° shoulder flexion), Su *et al.* (1994) showed that 180° shoulder flexion with elbow fully extended was the position which provided the highest grip force, whereas the weakest strength was recorded during 90° elbow flexion with 0° shoulder flexion. The most used positions while performing working tasks, 90° elbow flexion with 45° and 90° shoulder flexion were not studied.

Extensive studies in this area are urgently needed in order to assess the most appropriate upper extremity position while exerting hand force. Joints should not be viewed as individual entities. Their interrelation is the one that allows for the significant upper extremity mobility and, more important, for posture compensation when working in awkward postures. The majority of studies are static with subjects adjusting their upper extremity in order to exert maximum grip strength (LaStayo *et al.* 1995). In order to obtain applicable data, dynamic studies in which industry-like postures and frequency are present should be carried out. Once the relationship between hand force and upper extremity musculoskeletal complex is established, job/workstation redesign could be performed based on scientific data. Lessened hazard levels and increased productivity may follow.

1.3.10. Individual finger strength

Individual finger contribution to the total hand force has been studied by different authors (Fransson and Winkel 1991, Radwin *et al.* 1992, Li *et al.* 1998, Danion *et al.* 2000) yielding inconsequential results. There is a consensus regarding the index and middle finger being stronger than the ring and little finger (Swanson *et al.* 1970, Ejeskar and Ortengren 1981) with the middle one being the strongest (Ejeskar and Ortengren 1981). Ring finger contribution greater that index finger was assessed only by Fransson and Winkel (1991), who described the distribution of forces as being 21.2, 33.6, 26.5, and 18.1% for digits II, III, IV and V respectively. Radwin *et al.* (1992) showed that for object weights below 1 kg, the finger force magnitude from the highest to the smallest was: index, middle, ring and little fingers. For weights above 2 kg, the order was middle, index, ring and little fingers with thumb force equal to the others four fingers' force sum. Also, an increase of 1.5 kg force demand, from 0.5kg to 1.5kg, determined an increase in the thumb, middle and ring fingers' contribution and a decrease for index and little fingers (Kinoshita *et al.* 1996). Although the load reduction on little finger is a useful protective tool against overexertion, the redistribution of elevated force on the other fingers including the ring one could lead to increased risk of injury.

The sum of each finger's maximum force is bigger than the force of fingers II, III, IV and V acting in parallel (Danion *et al.* 2000). The sum of each finger maximum force yields 183N, which is 83% bigger than the average pinch strength using all five fingers simultaneously (Radwin *et al.* 1992). The fingers act as a veritable complex (tied communication between its components) when hand force demand variations and/or change in hand and fingers posture take place. There is a consistent force sharing among fingers regardless the total force production (Danion *et al.* 2001). When a finger is removed from the grasping application, the biggest variation in applied force is seen in the fingers adjacent to the removed finger (Kinoshita *et al.* 1996). Injury due to sudden change in loading may develop. During maximal voluntary contractions, the activation of one finger inhibits the activity of adjacent fingers (force deficit). This sharing pattern could be explained by the reduction of load per digit leading to decreased muscular activation. The sharing pattern among fingers may be explained by a minimization of secondary moments about the longitudinal functional axis of the hand (Li *et al.* 1998a, Li *et al.* 1998b). Central neuromuscular control could also play a role in individual finger force exertion.

Due to their highly repetitive and intensive force component, work-related hand activities determine localized muscular fatigue with important changes in muscles strength production pattern. Danion *et al.* (2000) noted an enslaving process in which during finger contraction, the other fingers produced force, too. Enslaving remain unchanged during fatiguing exercises when force was measured at the site involved in fatigue and increased when other site was the zone for force production. Increased risk of injury is present due to a lack of rest and muscle overload. The central contribution to force exertion control is supported by Danion *et al.* (2001) who found large transfer of fatigue across fingers, culminating with the removal of the fatigued finger from force application complex. Excluding the fatigued finger from the force production, allows it to recover and to enter later into the synergy.

Both enslaving and force deficit phenomena might be due to the presence of multifinger forearm muscles and intertendinous connection (Danion *et al.* 2000). When designing tools and working techniques, one should consider that due to their interaction, fingers constitute a musculoskeletal complex. The flexor digitorum profundus and flexor digitorum superficialis muscles that contribute to several fingers flexion, and juncturae tendinum that links together the digits (Fransson and Winkel 1991) allows fingers to act in a simultaneously and complementary manner. Taking into account the significant drop (25%) in finger strength for all fingers due to fatigue (Danion *et al.* 2000) and the fact that individual finger strength was decreased by the participation of more fingers (Radwin *et al.* 1992), it is indicated to design tasks that involve the simultaneous use of fingers. This protective technique should be applied even when the job could be completed using only one or two fingers. In this way the force exerted will be split between all fingers reducing the muscle load and allowing the work within safer limits.

1.3.11. Older workers

The proportion of elderly in the working population is increasing, stressing the importance of preventive interventions for this specific group. The baby boom generation trend will continue in the 21st century (Rahman *et al.* 2002). In U.S., in 2030 the number of elderly will reach 70 million, twice the number in 1996 (Resources Services Group 1997). In order to work at its best and in a safe environment, this segment of working population requires customized workstations. Targeted design modifications based on scientific data are the only valid solution that could address this issue. Nowadays, when designing jobs and workstations, it is assumed that the same movement and force patterns are used by elderly and young population alike (Shiffman 1992).

Although Crosby *et al.* (1994) did not find a significant effect of the age on the hand force exertion, many studies (Mathiowetz *et al.* 1985, Brorson *et al.* 1989, Desrosiers *et al.* 1995, Chaparro *et al.* 2000) have shown differences between old and young workers in both force/endurance and precision. From the last years of the first decade of life, which is the period when the hand prehensile development ends (Kuhtz-Buschbeck *et al.* 1998), to death the hand force capacity is in a continuous transformation with periods of both development and involution. A curvilinear relationship between grip strength and age, with a peak between 25 and 59 years and decline thereafter, was noted (Shiffman 1992, Desrosiers *et al.* 1995). Also, for tip, key and palmar pinch the values were constant within the 20 to 59 years range with a decline from 60 to 79 years (Mathiowetz *et al.* 1985). Ranganathan *et al.* (2001) noted a reduction of 30% for gripping force in elderly (65-79 years) compared to young subjects (20-35 years). The decrease in grip and pinch strength occurs in both genders (Voorbij and Steenbekkers 2001).

Females exert less grip force than males with the difference between forces increasing with age. Age does not affect the greater grip strength values in men (Crosby *et al.* 1994). Female grip strength was 61.8% of the male value for the 60-69 years age group and decreased to 46.7% for age 90+ (Chaparro *et al.* 2000). Furthermore, Ranganathan *et al.* (2001) found a 43% grip strength decrease in older women compared to older men, versus 34% less grip strength in young women when compared to young men. The relationship between age and force exertion control was stressed by Ranganathan *et al.* (2001), who showed that ageing not only reduces the MVC but also mitigates the ability to maintain steady submaximal force. The impact of magnitude is not similar on pinch and grip strengths. The effect of age on hand strength was more pronounced in grip compared to pinch applications (Mathiowetz *et al.* 1985, Chong *et al.* 1994, Ranganathan *et al.* 2001). Due to its ubiquitous usage, pinch strength does not vary as much as grip strength as a function of age. This could be explained by the training effect of daily activities on pinch force (Chong *et al.* 1994). This idiosyncrasy could be viewed as an advantage for elderly and should be used to replace, when possible, the grip force demand. The degenerative effect of age on hand performance might be due to changes in both peripheral (muscle, nerves) and central (central nervous system, circulator system) regulation mechanisms. A complete list of changes that determine the important drop in hand performance is presented in table 1.13. According to some studies, body weight is a good indicator for hand strength (Desrosiers *et al.* 1995). The assessment of the relationship between age and grip/pinch maximum force should allow for the possible increase in weight that counterbalances the decreasing effect of age on strength (Boatright *et al.* 1997). In this case, although the muscle suffered degenerative modification due to age, the values are inflated due to increase body weight.

The decline in hand strength interferes with both office/industry responsibilities (hand tool handling, typing, etc.) and daily tasks activities, such as opening a medicine bottle, drinking, eating, etc. The impact is even more important if one takes into account the important reduction in joints mobility at this level. Ageing could account for up to 40% reduction in ROM compared to a younger worker (Chaparro *et al.* 2000) elevating the risk of injury, especially while working in awkward postures for a prolonged period of time. All these modification affect pinch and grip precision, and determine an increase in task completion time (Rahman *et al.* 2002) leading to a drop in performance if appropriate ergonomic modifications are not implemented.

When designing jobs for elderly workers, one should consider that during fine motor movements, the muscle activation is increased even more at this age (Chaparro *et al.* 2000). The force applied by the older group is bigger than the one applied by younger group in the same task, especially in activities that require high precision movements (Rahman *et al.* 2002). These differences could be explained by changes in muscle activation pattern, skin properties and central nervous system, which lead to lack of feedback and confidence during precise tasks. The risk for localized muscle fatigue and overload that follows high physical and mental stress is even more pronounced than in the general working population. Also, the decrease in hand sensibility in elderly causes a drop in their capacity to assess the objects' slipperiness increasing the risk of errors and accidents (Ranganathan *et al.* 2001). The introduction of exercises/training methods for elderly would lead to a reduction in the risk involved in different tasks. Increase in performance and productivity due to a mitigated completion time and lack of unsuccessfully repetitive movements will follow.

1.3.12. Hand performance measurement techniques

In order to implement ergonomic changes based on valid data, the need for hand performance measurement devices is evident. Their usefulness is proven by the wide usage. In order to objectively measure the hand function, the Jebsen Test of Hand Function (JTHF) was proposed in 1969 in the United States (Jebsen 1973). The test includes hand movements that are present in Activities of Daily Living (ADL). Grip and pinch strength assessment tools were used in the past in order to study the neuropsychological status of brain-damaged patients and the effectiveness of surgical treatment. Return to work capacity used these tests, too (Chong *et al.* 1994). Also, isokinetic dynamometry has been proved to be efficient in identifying feigned efforts (Dvir 1999), playing an important role in legal issues. Giampaoli *et al.* (1999) showed that handgrip assessment tools are valid for incident disability prediction in men 77 years or older.

For grip strength measurement, among all devices, Jamar dynamometer and Martin vigorimeter are the most known. The Jamar dynamometer has a sealed hydraulic system with a gauge calibrated in pounds and kg and five different settings. It was shown to give the most accurate measure of grip strength by the majority of studies (Mathiowetz *et al.* 1985, Chong *et al.* 1994, Desrosiers *et al.* 1995, Ashford *et al.* 1996, Shechtman *et al.* 2001). Moreover, The California Medical Association Committee recommended the Jamar Dynamometer as the best measuring device for grip strength (Kuzala and Vargo 1992). Ashford *et al.* (1996) noted inaccuracy less than +/-3% for Jamar dynamometer, which is even lower than the one indicated by the manufacturer (+/-5%). These results stress its accuracy. The other grip strength assessment device is the Martin vigorimeter. It is not as well known as Jamar dynamometer, but several studies used this tool. It has a rubber bulb connected to a tube to a manometer calibrated in kilopascals. It is very suitable for grip force measurement in people with arthritis since it eliminates any stress on joints (Melvin 1977). Because the subjects have to compress the rubber bulb, muscle isometric activity is involved during strength measurement (Desrosiers *et al.* 1995). Desrosiers *et al.* (1995) noted that although the Martin vigorimeter measures the grip pressure, not the force applied, a high correlation between Jamar dynamometer and vigorimeter was found. For pinch strength measurement B&L pinch gauge presents the highest accuracy. Due to the wide variety of devices that were used, it is very difficult to compare results from different studies. For example the Osco pinch meter is no longer commercially available (Mathiowetz *et al.* 1985). Although it may be more convenient to use a certain type of measurement device, researchers should take into account that only using compatible tools outcomes could gain usefulness and applicability. Also, Chadwick and Nicol (2001) noted that from all types of grip measuring devices (pneumatic, hydraulic, mechanical and strain gauge), the ones that are designed to assess only the maximal force and have only one degree of freedom and are not valid.

The American Society of Hand Therapists (ASHT) concluded that upper extremity position influences the hand strength tests. They recommended that during testing the subject should be seated with the shoulder adducted and 0° rotation, 90° elbow flexion and the forearm and wrist in neutral position (Mathiowetz *et al.* 1985). Given that there is no difference in grip force between supine and sitting positions when the upper extremity is maintained in the position recommended by the ASHT (Richards 1997), the two positions could be interchanged when one is not available. Although ASHT recommended the posture for grip assessment, grip strength assessment in different positions is needed in order to determine which are the safest and the most hazardous postures. In order to be able to compare data from different studies, standardized alternative postures should be used (Mathiowetz *et al.* 1985). Obtaining high grip values is not everything. The upper limb posture during force exertion is even more important. Introducing design modifications based only on maximal hand force values, without correlating the outcome with the posture in which it was recorded, would determine long-term musculoskeletal problems.

During maximum strength assessment subjects should gradually increase the exertion until the maximum is reached and to maintain this level for three seconds (Caldwell *et al.* 1974). Also, considering that as any index of human performance, there is an important variation in strength applications, repeated measurements are essential (Young *et al.* 1989). The majority of studies recommend the use of three recordings (Mathiowetz *et al.* 1985, Desrosiers *et al.* 1995). Chaparro *et al.* (2000) proposed to repeat the exertions until two maximum values vary within 10%. The greater value is used. The use of three trials' means provide a higher reliability (0.89 and 0.93 for the right and left hand respectively) compared with only one trial (0.79 for right and 0.86 for left). This procedure is even more important if one consider that no learning or fatigue effects are present during the use of three consecutive trials (Mathiowetz *et al.* 1985). Crosby *et al.* (1994) noted that repeated testing procedure is not necessary because over 50% of the subjects had decreased values when the test was repeated. The consistent decline in force might be due to short resting breaks between trials. When the study is carried out over a prolonged period of time, serial measurements are even more needed. Young *et al.* (1989) assessed a variation between 5.1 and 8.4 pounds (19.2%-23.7%) for grip strength for 6 measurements performed in 3 weeks. For lateral pinch strength, the fluctuation was between 2.6 and 3.8 pounds (13.8% and 17.6%).

There is an important interindividual variation in terms of device setting. Although the Jamar dynamometer has five settings, in order to save time the majority of studies used only one setting (II). This choice is made based on previous data and does not take into account the subjects' characteristics. The proportion of research participants that exerted maximum force when setting II was used varies from 60% (Crosby *et al.* 1994) to 89% (Firrell *et al.* 1996). It has been shown that individuals that had maximal values at setting I had lower body weight and height (Firrell *et al.* 1996). Preliminary hand and body measurements should be made in order to designate the right setting for a certain worker. If only setting II is used, biased (decreased) values will be obtained for subjects that would have exerted higher forces if proper setting had been available to them (Firrell *et al.* 1996). O'Driscoll *et al.* (1992) found a linear and inverse correlation between the Jamar dynamometer setting and wrist extension. This relationship was not true for ulnar and radial deviations. The resting length position for fingers flexors coincides with a moderate flexion in MCP-IP joints (Dvir 1997). All the positions that require excessive joints deviations, such as Jamar dynamometer positions I and V determine a decrease in the number of filaments' overlapping with a consecutive drop in strength. While different settings should be used in order to match various hand sizes, due to variability in force direction and hand-device interaction surface, only data obtained from the same setting should be compared. Even when the same settings are used, differences between manufacturers determine various grip dimensions, leading to incompatible data. For example, the dynamometer used in Bechtol's study measures 1.50 in. at setting II while the Jamar dynamometer has 1.75 in. at setting II (Firrell *et al.* 1996).

In order to assess hand/wrist position while exerting force, joint deviation measurements are also essential. The goniometer outcome for wrist deviations differs significantly from data obtained manually (Marshall *et al.* 1999). Observers underestimate wrist non-neutral postures (Ketola *et al.* 2001). Therefore, the use of electrogoniometers is indicated. Obtaining research-based force limits for the most used wrist deviations would provide vital data for ergonomic design programs. In addition to the above-mentioned devices, electromyography and subjective magnitude estimation are used for grasping exertion level assessment. Due to its incapacity of measuring muscle activity during complex manual work and considering that it is not specific for individual finger activity, electromyography is suitable only for static exertions and fixed postures (Radwin *et al.* 1992). Also, McGorry (2001) noted that the EMG-grip ratio wide variation determined by wrist/upper extremity posture and grip type makes the use of electromyography in grip force estimation unreliable. Self-rating introduce an important bias in hand performance assessment. Subjective magnitude estimation is very inaccurate and depends on the participant objectivity (Radwin *et al.* 1992). Porac and Coren (1981) showed a 74% concordance between the responses given in a questionnaire regarding hand preference and the actual skill performance. This outcome reveals that there is a bias in self-reporting.

Hand performance and hand proficiency vary considerably from one type of task to another (Borod *et al.* 1984). Therefore, the use of several hand performance assessment tests is better in order to have a complete hand capability assessment. For example the difference between dominant and non-dominant hands is very well seen in handwriting test but presents an important overlap in gripping strength test (Provins and Magliaro 1993). This outcome comes in contradiction with Reikeras (1983) results who noted that under pathological conditions when it is impossible to determine both hand performance, the assessment of the other hand with consequent use of data is a useful procedure. Although both dynamic and static phases play a role in dexterity hand capacity, the majority of prehension patterns assess only the static components. Including tasks present in work and daily life activities would increase the test validity. In order to obtain a comprehensive overview of the subject hand function, the grip/pinch strength and range of motion assessment should be accompanied by questionnaire regarding other aspects of work/daily living tasks (Fowler and Nicol 2001).

One should be aware that all the time when volunteers are involved in a study, there are high chances to have subjects that thought they might do well. A biased outcome with higher hand strength force values is possible to appear. Rigorous sample size formation increases the external validity of the study, assuring a superior power and generalizability. Another concern when using hand strength measurement tools is the lack of attention given to the quality of movements that are performed (Conti 1998). Triangulating with different parallel measurement techniques (hard tools, observations, etc.) would ensure an objective assessment (Fagarasanu and Kumar 2002). Although standard testing positions are required in order to have comparable data, alternative postures with different wrist/elbow/shoulder deviations should be performed in order to have normative data regarding the grip strength during deviated working postures (Fong and Ng, 2001). Considering higher correlation between hand strength/range of motion and biomechanical trial data, the force assessment represents a cost and time efficient method of hand-function assessment. Normative data for grip and pinch force exertions could be used in engineering design, rehabilitation programs parameters, performance assessment and training programs development (Giampaoli *et al.* 1999, Chaparro *et al.* 2000).

1.3.13. Industry relatedness – ergonomic solutions

The work-men interface is influenced by both task/workstation design and worker's individual characteristics (adaptation capacity, endurance, maximum strength, skills, dexterity). Targeted ergonomic interventions based on valid data as well as training programs that increase awareness among workers, represent legitimate solutions for work-related primary and secondary prevention.

Both in industry and office activities the limits are set arbitrarily and no connection between applied force and awkward posture is made (Ketola *et al.* 2001). During industrial tasks, poor ergonomic design determines elevated localized pressure leading to increased risk of injury. For example, the use of laparoscopic instruments for a prolonged time leads to thenar nerve palsies (Kano *et al.* 1993, Majeed *et al.* 1993, Horgan *et al.* 1997), arms muscle fatigue and increased forearm muscle overload compared to laboratory experiments (Berguer *et al.* 1997). The effect of design on performance is highlighted also by the difference between the laparoscopic instruments (tip force transmission of 1:3) (Sukthankar and Reddy 1995) and the standard surgical instruments where the transmission ratio is 3:1 (Gerber 1998). Perceived hand pain is a limiting factor in work with hand held tools. The most sensitive regions are the most likely to be injured if one exceeds the safer limit during repetitive and/or forceful tasks (Muralidhar *et al.* 1999). There are wide variations in the force applied on the tool's handle: for cylindrical handles, a radial force is present while for an elliptical or rectangular handle cross section the maximum grip force is exerted along the major axis with unequal force along its length. Finally, a shearing force component is present during the use of tools that produce a moment about the long axis (screwdriver) (McGorry

2001). Although it is very difficult to assess the amount of forces applied with or by hand tools, because of its importance, the quantification of force exerted at hand-tool interface should be included in the ergonomic evaluations. Kumar and Simmonds (1994) noted that with the exception of 40% MVC level, there was a consistent bias in perception of force exerted at all graded contractions. The 60% and 80% of MVC were lower and 20% was higher compared to their objective values. As a consequence, repetitive tasks requiring forces below 40% MVC will lead to overestimation of applied force, to hazardous levels of exposure, promoting musculoskeletal injuries. Also, tasks that require force application beyond the 40% level will be performed with force exertions lower than the strength necessary to handle the tool under safe conditions. Accidents due to drops and inappropriate grip are likely to appear.

Force applied is highly influenced by tool handle surface and shape (Berguer *et al.* 1999, Muralidhar *et al.* 1999, Kinoshita 1999, Chadwick and Nicol 2001). For tool slips to be avoided, forces greater than the tangential loads should be applied. Safer limits could be easily crossed (Jenmalm *et al.* 2000), especially when using tools with inappropriate handles. Due to the hand glabrous skin properties (high density of specialized mechanoreceptors) (Salimi *et al.* 1999), tactile sensors are very important in the grip force maintenance above slip force level (Kinoshita 1999). The gripping force is adjusted for both the weight and the object texture, with elevated grip forces being recorded for lower coefficient of friction (Salimi *et al.* 1999). The important role of hand sensibility is demonstrated by the fact that anesthesia of a digit increases force production in the other fingers. This may be due to lack of sensitive feedback and/or to shifting to nonanesthetized digits as a compensation for the lack of sensitive information from that finger. This is very important for workers suffering from CTS and which continue to work with partial/total sensory loss of one or more fingers. The still unaffected fingers will exert compensatory force being overloaded and at high risk for musculoskeletal injury (Kozin 1999). The equation $F_f=\mu F_n$ (Amonton's Law of Friction), in which friction force is equal with normal contact force multiplied by coefficient of friction, could be used for applied force prediction in tasks that involve frictional coupling between object handle and hand. The modified equation would be: $F_p=W/2\mu$, where friction force equals weight divided by the coefficient of friction multiplied by 2. This equation is valid only in cases in which the frictional force is equally distributed on handle's both sides (Frederick and Armstrong 1995). Using this equation, one could predict the required force, being able to take the necessary actions in order to reduce the stress level on hand musculoskeletal system.

Tool's handle shape causes important variations in working patterns and posture. Considering that the middle finger is the strongest and the little finger is the weakest, during cross-action tools usage, the small finger has the longest lever arm and the index finger, has the shortest lever arm. Reversed grip, although may not increase the grip force exertion, constitutes a safer working technique, reducing the risk of injury (Fransson and Winkel 1991). Kadefors *et al.* (1989) noted spontaneous use of reverse grip among workers. A certain size diameter cannot be used for all tools. Consideration of applied forces, required postures, moment and force applications should be taken into account. Also, adjustable handles should be implemented in workplace. In this way, small fingers will be at their proper position. If not, high load requirements are present on a finger that is not capable of maximal contraction due to poor design (Blackwell *et al.* 1999). The lesser grip strength values for females are due to both muscle force and hand size. Therefore, ergonomic redesign interventions should not only promote a reduction of the amount of force required to complete the task but also a tool resizing (Muralidhar *et al.* 1999). Jenmalm *et al.* (2000) noted lessened grip force with increased handle tool curvature. This may be due to deviated working postures during which the wrist stabilization process is extremely complicated, especially if dynamic movements are involved (LaStayo *et al.* 1995). Data regarding applied grip force and moments during hand tool use would bring important information about the individual adaptation, individual responses to exposures and elevated-risk office and industry activities.

Although gloves have been used in many industrial tasks as protective devices, their extensive exploit also has negative features. Gloves affect hand performance influencing: task time (Muralidhar and Bishu 1994), dexterity (Bradley 1969, McGinnis *et al.* 1973, Banks and Goehring 1979), grip strength (Hertzberg 1955, Cochran *et al.* 1985) and range of motion (Griffin 1944). Uniform thick gloves introduce more hazards such as insecure grasp, loss of sensory feedback, reduction of range of motion and mitigated hand dexterity (Muralidhar *et al.* 1999). These modifications produce changes in working patterns leading to elevated musculoskeletal and mental stress and awkward postures. Although thick gloves provide better protection against vibration and toxic agents, due to the cutaneous sensation mitigation, increased applied force was recorded (Kinoshita 1999). Ergonomic (selective thickness) gloves provide an elevated protection especially for exposed areas, without increasing bulk, increases grip strength and does not mitigate productivity compared to conventional gloves. They represent the solution that permits the work at higher pressure for a longer period of time before discomfort appears

(Muralidhar and Bishu 2000). Moreover, considering the wide variation in pressure-discomfort threshold over the palm, it is suggested to have proper protection in the critical areas than having several complete layers of material. Even with selective thickness gloves there are several exposed hand areas. Further work is needed in order to eliminate the low pressure-discomfort threshold assessed for the top of finger IV and V and the base of finger IV (Muralidhar and Bishu 2000).

In addition to workstation/tool redesign, job rotation programs should also be used in order to reduce the prevalence of occupational musculoskeletal injuries. A relocation of workers suffering from work-related disorders is desirable. In its absence, employees that continue to work in the same job position as the one that caused the injury, will suffer continued tissue degradation leading to decreased productivity, an increase in work claims and lost days (Sande *et al.* 2001). Also, training programs that promote minimum required force applications should be implemented in order to educate workers to work within the safe limits. Finally, the cumulative effect of prolonged awkward postures and extensive force application must be emphasized.

1.3.14. Summary and conclusions – future research

Hand strength has not been thoroughly addressed from an ergonomic point of view. The majority of studies support the relationship between work and hand musculoskeletal disorders. Wrist, hand and finger musculoskeletal disorders due to work are still on rise with all industrial and office risk factors still acting at elevated levels. Hand performance is affected by muscle strength, hand size, gender, body weight and height, age, associated diseases and hand dominancy. Fatigue is a common phenomenon among workers causing decline in the maximal contractile force, increased effort during muscle contraction, and inability to maintain targeted force. Owing to the dynamic aspect of almost all the tasks performed during work, there is tied relationship between wrist/elbow/shoulder position and hand strength. There is not any consensus regarding the optimal upper extremity posture. There is a consensus regarding the index and middle fingers being stronger than the ring and little fingers. The thumb force equals the other four fingers' force sum. Older workers represent an important and growing segment of the actual working force. In order to avoid an increase in musculoskeletal pathology, their special needs should be addressed from an ergonomic point of view. Evidence based ergonomics intervention should stay at the forefront of all device and/or job (re)design.

Almost all studies use "healthy university students". Different study samples should be used in order to ensure an increased external validity. The use of real workers could reveal aspects that are not obvious in university students. Both on site workers' musculoskeletal adaptation and changes in posture while performing specific tasks due to prolonged work are important factors that modify the risk factors exposure level.

Although previous studies determined grip and pinch strength in several elbow and shoulder positions, more research is needed in this area in order to assess the force application during positions that are used in real work. An increment of 5^0 should be used for wrist/elbow/shoulder deviations with different combinations between them. Recording data only while the upper extremity is in the standard posture recommended by ASHA will not provide data that can be applied for further ergonomic job and workstation design. Furthermore, almost all studies focused on static measurements. While this setting is more easy to use, the utilization of dynamic recordings would provide the difference between static and dynamic force exertions. While the hand and fingers areas are exposed to high risk for musculoskeletal injuries, extensive work is required in order to reduce the elevated hazard for injury due to localized pressure for the area between thumb and digit II, distal end of digit IV metacarpal bone and tip of finger V. The hand protection should be accomplished using combinations of different glove materials in order to ensure an important reduction in localized pressure at hand-device interface, without consecutive precision mitigation. To facilitate both the perfect glove fit and the adjustability between workers, stretchy materials seem a suitable solution and should be tested.

The well-documented differences between right and left hand should not be viewed only in terms of applied force. In order to ensure an appropriate grip or pinch, the fingers/wrist/elbow postures present important variations between right and left sides. Living in a right hand designed world, the use of the same devices and workstations impose a greater risk for left handed workers. Further research in this area is needed in order to ensure targeted ergonomic interventions. The data difference in hand muscle fatigue and recovery pattern between men and women should be used to facilitate gender-customized devices. A closer collaboration between data generators (researchers) and data users (designers) would allow a reduction in work related musculoskeletal injury with consequent cost saving.

Finally, follow-up study addressing the capacity of returning workers to cope with the new/modified jobs are of extreme importance in order to reduce company's costs and to ensure successful return to work.

Year	WRUEDs per 10,000 workers	Wrist injuries	Hand injuries (except fingers)	Fingers + fingernails injuries	Total (wrist, hand and fingers)
1998	45.2	21.01%	18.36%	36.72%	**76.09%**
1999	43.9	21.18%	17.76%	37.58%	**76.52%**
2000	41.7	22.30%	18.22%	36.21%	**76.73%**

Table 1.6. Wrist, hand and fingers nonfatal injuries as percentages from total number of Work Related Upper Extremity Disorders (WRUED) involving days away from work for 1998-2000 interval (Adapted from BLS, 2002).

Hand and wrist injuries risk factors		
Personal	**Occupational**	
	Industrial	**Office**
- age over 50 years - female gender - previous injuries - hand preference - menopausal women - obesity	- localized pressure - repetitive movements - awkward postures - excessive hand force production - working with cold hands - vibration - fatigue	- repetition - prolonged deviated postures - percentage of time typing - lack of rest - preference for certain fingers

Table 1.7. Personal and occupational risk factors for hand and wrist injuries

MUSCLE	ACTION AT WRIST LEVEL			
	Flexion	Extension	Radial dev.	Ulnar dev.
1. Thumb' extrinsic muscles				
- flexor pollicis longus (FPL)	X		X	
- abductor pollicis longus (APL)	X		X	
- extensor pollicis brevis (EPB)	X		X	
- extensor pollicis longus (EPL)		X	X	
2. 2^{nd}-5^{th} fingers' extrinsic muscles				
- flexor digitorum superficialis	X			
(FDS)	X			
- flexor digitorum profundus (FDP)		X		
- extensor digitorum (ED)		X		
- extensor indicis (EI)		X		X
- extensor digiti minimi (EDM)				

Table 1.8. Extrinsic hand muscles role in wrist movements

Factors positively correlated	Factors negatively correlated
1. Muscle strength	1. Age over 50
2. Movement coordination	2. Female gender
3. Body height	3. Associated disease
4. Muscle optimal length	4. Small hand size
5. Body weight	5. Non-dominant hand
6. Mobility	6. Triceps skinfold thickness
7. Overall development (children)	7. Young age (children)
8. Breathing capacity	
9. Back extensor strength	

Table 1.9. The correlation between personal factors and hand performance.

Author(s)	Exposed zones	Comments
Yun et al., 1992	- thenar area - metacarpophalangeal joints - distal phalanges fingers I-V - proximal phalange digit II	Zones exposed to risk of injury while executing gripping tasks involving power tools, a knife and hammer.
Chao et al., 1989	- distal phalanges for digits II-V - proximal phalange for finger II	Outcome is based on calculations regarding force applied while using different phalangeal distribution.
Cochran and Riley, 1986	- distal phalanges of the II, III and IV finger	They used force sensing resistors and adjustable handles.
Fellows and Freivalds, 1989	- index and thumb metacarpophalangeal joints - thumb proximal phalange - distal phalanges digits I-IV	EMG, force sensing resistors and subjective measurements were performed.
Iberall, 1987	- distal phalanges digits I, II, III - II, III, IV metacarpophalangeal joints - proximal and middle phalanges for finger II (lateral side) - proximal and middle phalanges for finger III	The degree of stress on a certain hand region is influenced by the nature of grip being used.
Fransson-Hall and Kilbom, 1993	- thenar area - pisiforme bone - area between digits I and II	These areas are the most likely to present pain during localized high pressure.

Table 1.10. Hand and finger areas most exposed to injury

due to grip force applications.

<table>
<tr><th rowspan="2">Study</th><th rowspan="2">Gender</th><th colspan="16">Force</th></tr>
<tr><th>5</th><th>10</th><th>15</th><th>20</th><th>25</th><th>30</th><th>35</th><th>40</th><th>45</th><th>50</th><th>55</th><th>60</th><th>65</th><th>70</th><th>75</th><th>80+ years</th></tr>
<tr><td rowspan="2">Chaparro et al., 2000</td><td>Male</td><td colspan="12">-</td><td colspan="2">41.29</td><td>32.55</td><td>16.09</td></tr>
<tr><td>Female</td><td colspan="12">-</td><td colspan="2">25.52</td><td>17.83</td><td>10.58</td></tr>
<tr><td rowspan="2">Mathiowetz et al., 1985</td><td>Male</td><td colspan="4">-</td><td>54.0</td><td>53.9</td><td>54.3</td><td>53.4</td><td>52.1</td><td>49.0</td><td>50.7</td><td>45.1</td><td>40.0</td><td>40.6</td><td>33.6</td><td>29.3</td></tr>
<tr><td>Female</td><td colspan="4">-</td><td>31.4</td><td>33.2</td><td>35.1</td><td>33.0</td><td>31.4</td><td>27.7</td><td>29.3</td><td>25.5</td><td>24.5</td><td>22.1</td><td>22.1</td><td>19.0</td></tr>
<tr><td rowspan="2">Imrhan, 1989</td><td>Male</td><td colspan="2">15.2</td><td>-</td><td colspan="5">49.7</td><td colspan="4">-</td><td colspan="4">30.0</td></tr>
<tr><td>Female</td><td colspan="2">12.9</td><td>-</td><td colspan="5">31.4</td><td colspan="4">-</td><td colspan="4">21.5</td></tr>
<tr><td rowspan="2">Voorbij and Steenbekkers, 2001</td><td>Male</td><td colspan="4">-</td><td colspan="2">54.08</td><td colspan="2">53.57</td><td colspan="2">52.04</td><td colspan="2">48.97</td><td colspan="2">43.36</td><td>38.26</td><td>31.63</td></tr>
<tr><td>Female</td><td colspan="4">-</td><td colspan="2">33.67</td><td colspan="2">33.16</td><td colspan="2">31.63</td><td colspan="2">29.08</td><td colspan="2">26.53</td><td>21.42</td><td>18.36</td></tr>
<tr><td>Kumar et al., 1994</td><td>Female</td><td colspan="3">-</td><td colspan="5">25.0</td><td colspan="8"></td></tr>
<tr><td rowspan="2">Desrosiers et al., 1995</td><td>Male</td><td colspan="12">-</td><td colspan="2">45.6</td><td>42.4</td><td>34.5</td></tr>
<tr><td>Female</td><td colspan="12">-</td><td colspan="2">25.3</td><td>23.7</td><td>20.0</td></tr>
<tr><td rowspan="2">Mathiowetz et al., 1986</td><td>Male</td><td>18.7</td><td>34.5</td><td>48.2</td><td colspan="13">-</td></tr>
<tr><td>Female</td><td>15.7</td><td>25.9</td><td>31.9</td><td colspan="13">-</td></tr>
<tr><td rowspan="2">Shiffman, 1992</td><td>Male</td><td colspan="4">-</td><td colspan="4" rowspan="2">41.2</td><td rowspan="2">-</td><td colspan="4" rowspan="2">39.5</td><td colspan="2" rowspan="2">27.9</td><td rowspan="2">25.5</td></tr>
<tr><td>Female</td><td colspan="4">-</td></tr>
<tr><td rowspan="2">Ager et al., 1984</td><td>Male</td><td>8.4</td><td>16.1</td><td>23.5</td><td colspan="13">-</td></tr>
<tr><td>Female</td><td>7.3</td><td>14.5</td><td>21.4</td><td colspan="13">-</td></tr>
<tr><td rowspan="2">Boatright et al., 1997</td><td>Male</td><td colspan="4">-</td><td colspan="2">57.1</td><td colspan="2">53.57</td><td colspan="2">52.23</td><td colspan="2">53.1</td><td colspan="2">35.71</td><td>37.05</td><td>31.25</td></tr>
<tr><td>Female</td><td colspan="4">-</td><td colspan="2">33.48</td><td colspan="2">33.03</td><td colspan="2">32.14</td><td colspan="2">32.58</td><td colspan="2">23.21</td><td>22.32</td><td>19.19</td></tr>
</table>

Table 1.11. Grip strength values for different age intervals

Study	Pinch type	Force 5	10	15	20	25	30	35	40	45	50	55	60	65	70	75+ years
Mathiowetz et al., 1985	Tip (pulp)	-			8.0M 4.9 F	8.1M 5.3 F	7.8M 5.6 F	8.0M 5.1 F	7.9M 5.1 F	8.3M 5.8 F	8.1M 5.5 F	7.4M 5.2 F	7.0M 4.5 F	7.5M 4.7 F	6.1M 4.5 F	6.2 M 4.2 F
	Key (lateral)	-			11.6 M; 7.8 F	11.9 M; 7.9 F	11.7 M; 8.3 F	11.6 M; 7.4 F	11.4 M; 7.4 F	11.5 M; 7.8 F	11.9 M; 7.4 F	10.8 M; 7.0 F	10.3 M; 6.9 F	10.4 M; 6.6 F	8.6 M; 6.4 F	9.1 M; 5.6 F
	Palmar (chuck)	-			11.8 M; 7.6 F	11.6 M; 7.9 F	11.0 M; 8.6 F	11.6 M; 7.8 F	10.9 M; 7.5 F	10.7 M; 7.9 F	10.6 M; 7.7 F	10.5 M; 7.1 F	9.7 M; 6.6 F	9.5 M; 6.3 F	8.0 M; 6.4 F	8.3 M 5.3 F
Imrhan, 1989	Tip (pulp)	2.7 M 2.4 F		-	7.3 M 4.7 F				-				4.3 M 3.0 F			
	Key (lateral)	4.2 M 3.6 F		-	9.4 M 6.5 F				-				6.7 M 4.9 F			
	Palmar (chuck)	4.0 M 3.6 F		-	9.4 M 7.0 F				-				5.9 M 4.6 F			
Kumar et al.1994	Key (lateral)	-			6.3 F					-						
Mathiowetz et al., 1986	Tip (pulp)	3.2M 2.9 F	4.4M 4.3 F	6.6M 5.3 F	-											
	Key (lateral)	5.0M 4.2 F	6.8M 6.3 F	10.4 M; 7.7 F	-											
	Palmar (chuck)	4.4M 4.0 F	6.2M 6.0 F	9.9M 7.9 F	-											
Shiffman, 1992	Tip (pulp)	-				6.0			-	5.4				-	4.7	4.2
	Key (lateral)	-				9.3			-	9.1				-	7.6	6.7
	Palmar (chuck)	-				8.3			-	8.3				-	6.7	6.0

Table 1.12. Pinch types values (Kg) in previous studies. M=male, F=female

Study	Pinch type	Force 5	10	15	20	25	30	35	40	45	50	55	60	65	70	75+ years
Ager et al., 1984	Tip (pulp)	1.6M 1.3 F	4.1M 4.1 F							-						
	Key (lateral)	2.9M 2.4 F	6.4M 5.5 F							-						
	Palmar (chuck)	2.7M 2.2 F	7.4M 7.0 F							-						
Boatright et al., 1997	Tip (pulp)							-								
	Key (lateral)			-		8.4 M 6.6 F		8.0 M 6.2 F		8.4 M 5.8 F		10.2 M 7.5 F		6.6 M 4.9 F		4.9 M 3.1 F
	Palmar (chuck)							-								
Chong et al., 1994	Tip (pulp)				-			6.7 M 4.3 F		6.4 M 4.2 F		5.8 M 4.1 F			5.3 M 3.5 F	
	Key (lateral)				-			9.8 M 6.5 F		9.6 M 6.6 F		9.0 M 6.4 F			8.8 M 5.6 F	
	Palmar (chuck)				-			9.0 M 6.5 F		8.4 M 6.2 F		8.1 M 5.9 F			7.9 M 5.3 F	
Halpern and Fernandez, 1996	Tip (pulp)			-		6.2 M						-				
	Key (lateral)			-		8.8 M						-				
	Palmar (chuck)			-		8.3 M						-				

Table 1.12. Pinch types values (Kg) in previous studies. M=male, F=female (cont.)

Peripheral	Central
1. Central nervous system degradation (loss in muscle coordination capacity) 2. Endocrine changes (decrease endocrine communication among apocrine and epicrine systems) 3. Protein metabolism perturbation (decrease in protein quality) 4. Perturbation in circulatory system (intramuscular flux reduction, mitigated effort capacity)	1. Reduction in hand tactile sensation (lack of feedback) 2. Muscle fibers reduction (especially fast twitch fibers – type II) (selective atrophy) 3. Muscle mass atrophy (changes in muscle size) 4. Local vascular degenerative changes (arteriosclerosis) 5. Incomplete muscle inervation 6. Muscle-nerve plate junction degenerative changes 7. Contractile proteins degradation 8. Drop in functional muscle fibers proportion

Table 1.13. Central and peripheral causes for reduced hand muscle performance in elderly.

1.3.15. References

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1.3.16. Additional reading

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1.4. Integration of literature review leading to research questions

In the view of literature review findings, there is an acute need for concrete outcome that would address the cause of the problem leading to elevated levels of musculoskeletal complains in both office and industrial settings.

In order to work under safe conditions, among other requirements (e.g. force limits guidelines, shift duration), one should perform within the safe margins for joints deviation. Since wrist is extensively used in any work task, the first experiment was designed in order to assess the wrist neutral zone in both planes (flexion-extension and ulnar-radial deviation). Knowing the range of motion segment within which workers are at lowest risk would ensure reduced injuries and complains.

During typing on the conventional keyboard, as concluded in the extensive literature review, there are important risk factors. In order to reduce the associated risk when performing typing tasks, a study was designed in order to compare different keyboard designs and to provide guidelines for an ergonomic keyboard that would address typing tasks from a wide perspective (EMG muscle activity, overall applied force, wrist deviation, wrist repetition, typing performance). Moreover, due to the fact that the existing alternative keyboards and not very well accepted by office workers, a consequent study is included in which the effect of training on typing on two alternative keyboards is assessed.

Almost all industrial tasks are performed in assimetrical postures. As presented in the literature review, these are the positions with the highest risk for musculoskeletal injuries. The need for creating guidelines regarding the safest and most performant gripping posture is evident. A study in which grip maximum force and forearm muscle activity in different wrist/forearm and elbow deviations follows.

The aim of the last study is to provide an overview of the prevalence of musculoskeletal disorders symptoms prevalence among office workers. It looks into symptoms frequency, intensity and their effect on work ability.

Having these study completed would provide valuable data that could be applied in order to reduce the associated risks, reducing vompany loses due to claims and lost days.

Part II

Experimental part

Chapter 2

Measurement of angular wrist neutral zone and forearm muscle activity

2.1. Abstract

Objectives. To determine the forearm muscles activity in different wrist deviated positions and neutral zone, and to assess the self-selected resting position without visual feedback.

Background. Wrist deviation occurs in almost all industrial and office jobs. This has been deemed hazardous for Carpal Tunnel Syndrome. Proper resting wrist position is likely to decrease the hazard for carpal tunnel pressure.

Methods. Twenty blindfolded subjects without history of hand/forearm musculoskeletal disorders participated in the study. The EMG of the forearm muscles (flexor carpi radialis, flexor carpi ulnaris, extensor carpi radialis and, extensor carpi ulnaris) in deviated and neutral wrist postures was recorded at a sampling rate of 1kHz. Also, wrist neutral zone at rest was measured using a calibrated custom-made uniaxial electrogoniometer. Two-way ANOVA with repeated measures was used in order to find the impact of wrist deviation on muscles activity.

Results. The participants positioned their wrist in 7°-9° extension and 5°-7° ulnar deviation. Statistically significantly higher EMG activity was recorded for each muscle in the wrist deviated postures when compared to EMG activity for the same muscle in neutral position ($P<0.001$).

Conclusions. Self selected wrist neutral posture significantly decreased muscle activity. Placement of wrists in neutral zone is expected to reduce risk of injuries.

Keywords: Wrist neutral zone; Wrist deviation; forearm muscles EMG.

2.2. Relevance

A knowledge of wrist neutral zone and associated muscle activity is likely to be of assistance in treating patients that require wrist reconstruction. Also, these results would assist job and workstation design/redesign.

2.3. Introduction

In the last decade, cumulative trauma disorders (CTD) were the fastest growing occupational health problem. According to the Bureau of Labor Statistics (1994), in 1992, almost two third of all work related illnesses reported in the United States were CTD. In 1981 only 24% of all occupational musculoskeletal disorders were CTD. Changes have occurred in many jobs during recent years (characterized by less force demands and increased mental load, higher social load leading to a sustained increase in muscle load) (Viikari-Juntura and Riihimaki, 1999). This trend is expected to continue. The treatment costs and human suffering continue to increase in addition to productivity losses due to the growth of work-related hand and forearm injuries. Hence, ergonomic intervention becomes very important.

The neutral zone is defined as "the part of the range of physiological motion, measured from the neutral position, within which the motion is produced with a minimal internal resistance" (Kumar and Panjabi, 1995).

Highly repetitive movements of the wrist, hand and forearm in office and industry jobs play an important role in the development of CTD (Kuorinka and Forcier, 1995). In order to mitigate the risk of musculoskeletal injuries, one should avoid the postures that force wrist deviation close to the limit of its range of motion (RoM) (Bernard, 1997). Rempel and Horie (1994) and Werner et al. (1997) demonstrated that the carpal tunnel pressure increases proportionally with the increase in wrist deviation. The risk level increases even more when repetition and/or high-force exertion occur (Keyserling et al., 1982).

Because the wrist, with deviation, permits the hand to adopt an optimal posture in order to perform the required tasks (Kapandji, 1982), the forearm muscles tendons become stressed. Deviated wrist postures have been demonstrated to decrease hand force (grip and pinch strength) (Fernandez et al., 1991; Marley, 1990; Lamoreaux and Hoffer, 1995; Dempsey and Ayoub, 1994; Terrell and Purswell, 1976), forcing the worker to exert greater effort while maintaining the wrist in unsafe postures in order to do his job. Also, hand performance is also highly affected by forearm position (degree of supination or pronation). Grip and pinch strengths are increased or not changed by supination (Agresti and Finlay 1986) and decreased by forearm pronation (Marley and Wehrman 1992). Richards *et al.* (1996) assessed grip force exertion in pronation as being the weakest followed by neutral position and forearm supination. Muscle overexertion follows (Kumar, 2001). The drop in hand strength may be due to the change in the angle between tendons and the finger bones (Hazleton et al., 1975), compression of the finger flexor tendons against the intratunnel structures (Tichauer, 1966; Armstrong and Chaffin, 1979) or changes in the musculotendinous units' length and orientation (Pryce, 1980). Also, during office work the wrist is maintained in extreme flexion or extension (Szabo and Chidgey, 1989) and radial or ulnar deviation (Smith et al., 1998), leading to increased carpal tunnel pressure followed by stress on the median nerve, blood vessels and forearm muscles tendons.

All these awkward postures result in an increased load level on the hand/wrist/forearm musculoskeletal structures. Information on wrist neutral zone, and muscle activity needed to deviate or maintain deviated the wrist, could be used to design products (e.g. manual wheelchairs, keyboards) that may minimize risk of wrist/hand injuries. Also, wrist surgical correction may need such biomechanical information.

Consequently, an experiment was designed where blindfolded subjects were asked to position their wrist in the neutral posture starting from a randomly chosen wrist deviated postures (45° for flexion and extension, 30° for ulnar deviation, and end of range of motion for radial deviation). An additional aim of the study was to measure the forearm muscle activity in both deviated and neutral wrist positions. Although muscles assessed in this study do not play a role in the CTS' pathogenesis, knowing their activity level is of great importance as they deviate and stabilize the wrist during office and industrial tasks.

2.4. Methods

2.4.1. Sample

The experimental population consisted of ten normal young adult males (age 27.5 (4.7) years, height 177.5 (7.2) cm, and weight 74.8 (12.6) kg) and ten normal young adult females (age 29.4 (9.8) years, height 165.7 (8.5) cm, and weight 62.1 (5.0) kg. All subjects were in good health, free of wrist/forearm pain and without history of upper extremity musculoskeletal disorders. Nineteen subjects were right-handed. Ethics approval was granted by the Human Research Ethics Board.

2.4.2. Tasks and measurements

2.4.2.1. Apparatus

Wrist motion angles were measured using a calibrated custom-made electrogoniometer. It consisted of two mobile plastic arms articulated with a central potentiometer. The uniaxial electrogoniometer was calibrated before each experiment.

The EMG forearm muscle activity was measured using DelSys Bagnoli™ (Boston, USA) EMG system (active surface electrodes, electrode cables, preamplifiers and amplifiers). The DE-2.1 single differential electrodes had 99.9% pure silver contacts 10 mm apart for ion flow maximization. Preamplification of the EMG at the source and low impedance active output reduced signal noise. The system had low noise (less than 5 μV) and exceptionally low leakage currents (less than 10 μA).

2.4.2.2. Experimental procedure

An informed consent was obtained from each volunteer. Age, gender, weight, height and hand dominance were recorded for the subjects. They were seated upright into a straight-back chair with feet flat on the floor and looking straight ahead. The forearm was rested on the table, being fully pronated (the forearm volar side was parallel to the table) when wrist deviation in the ulnar-radial deviation plane was measured and semipronated (the forearm lateral side was parallel to the table) for the flexion-extension plane (Figure 2.1).

The electrogoniometer was adjusted across the wrist with goniometer's arms aligned to the long axes of the hand and the lower arm. For radial and ulnar deviation assessment, the electrogoniometer's fulcrum was centred over the middle of the dorsal aspect of the wrist over the capitate. The proximal arm was aligned with the dorsal midline of the forearm, using the lateral epicondyle of the humerus for reference and the distal arm was aligned with the dorsal midline of the third metacarpal bone. For flexion and extension measurement, the fulcrum of the electrogoniometer was centred over the radial aspect of the wrist (trapezium level) with the proximal arm aligned with the medial side of the radius and the distal arm aligned with the midline of the second metacarpal bone. The device was adhered using Velcro closures. For EMG recording, the subject's forearm was shaved, where needed, and the skin was cleaned with alcohol. Four bipolar silver-silver chloride active surface electrodes with knife edge configuration 10 mm apart were applied bilaterally. The electrodes were applied 5-7 cm distal to the line connecting the medial epicondyle and biceps tendon for flexor carpi radialis (FCR), above the shaft of ulna in the middle of forearm for extensor carpi ulnaris (ECU), at 2-3 cm volar to ulna at the junction of the upper and middle thirds of the forearm for flexor carpi ulnaris (FCU), and at 3 cm medio-distal to lateral epicondyle for extensor carpi radialis (ECR).

In order to ensure the lack of feedback, subjects were blindfolded. For each muscle a 5 seconds maximum isometric contraction against a fixed obstacle was performed. The muscle testing order was computer randomized. Participants received training on how to perform the maximal voluntary contractions (MVC) for each muscle building up the maximum force for the first two seconds and maintaining it for the next three seconds. Starting from the wrist position with 0° deviation for both planes, and with the forearm resting on the table, volunteers were asked to deviate the wrist against the fixed obstacle as hard as they could, while trying to extend and adduct the wrist for ECU, extend and abduct for ECR, flex and adduct for FCU and flex and abduct for FCR. The highest muscle activity level was used to normalize the EMG data for each subject. After completing the isometric contractions (MVCs), the wrists were passively deviated to 45° flexion, 45° extension, 30° ulnar deviation, or at the end of range of motion for radial deviation, and volunteers were asked to bring the wrist in the subjective neutral zone. The sequence was randomized in order to avoid the carry-over effect. Each condition was repeated once (two trials). Between conditions a 2 minutes resting period was given. The forearm muscles' EMG activity was measured in both wrist deviation and wrist neutral zone.

2.4.2.3. Data acquisition

The EMG and electrogoniometer output were sampled at 1 kHz using a DAQ 700 National Instrument data acquisition card. The signals were collected at a sampling frequency of 1 kHz. The data were collected by a specially written software, which stored them on a Toshiba laptop.

2.4.2.4. Data analysis

The peak EMG amplitudes of FCR, ECU, FCU, and ECU (left and right) in isometric MVC for activities in which muscles were primary effectors were measured and considered as 100%. The EMG amplitudes measured with both deviated and neutral wrist positions were normalized against peak MVC. When analyzing the effect of wrist deviation on muscle activity, angle of deviation was the independent variable and the EMG values were the dependant variables. Wrist deviation acted as dependant variable when the effect of lack of feedback on wrist resting position was studied. The normalized data were analyzed using SPSS 11.0 statistics software. The group data were subjected to two-way ANOVA with repeated measures in order to find the effect of wrist deviation on forearm muscles activity. Also, differences between genders/sides in terms of wrist neutral zone were analyzed. For significance, an alpha level of $P<0.05$ was chosen.

2.5. Results

Since there was no statistical significant difference between the two trials, data were pooled and analyzed together.

2.5.1. EMG in wrist deviation. Figures 2.2 presents the normalized average EMG (% isometric maximal voluntary contraction (MVC)) for each recorded forearm muscle in each wrist deviation (ulnar and radial deviation, flexion and extension). FCU required significantly higher activity in females when compared with males ($P=0.03$). For the other muscles, although females had somewhat higher % MVC in all wrist deviated postures, gender did not have a statistically significant effect on muscle activity normalized magnitude ($P>0.05$). Also, no differences were found between sides for all muscles and wrist deviations ($P>0.05$).

For ulnar deviation, the maximum activity was observed for ECU (26.9-35.7 % of MVC) and FCU (16.5-29.1 % of MVC). Along with FCR (19.9-26.8 % of MVC), FCU (18.3-23.6 % of MVC) was among the most active muscle while the wrist was maintained in flexion. ECR presented the maximum activity in both wrist radial deviation (25.5-36.8% of MVC) and extension (29.4-38.3% of MVC). It was followed by FCR in radial deviation (19.8-24.2 % of MVC) and ECU in extension (17.3-34.1 % of MVC).

2.5.2. EMG in wrist neutral zone. In the neutral zone muscle activity was significantly lower than that of the deviated postures ($P<0.05$). Table 2.1 presents significance levels for differences between each muscle activity in the neutral position and deviated postures where it is the primary muscle. For both genders, all four forearm muscles demonstrated a similar pattern with ECR being the most active (9.2-11.1% of MVC), followed by ECU, FCR, and FCU with normalized average EMG values varying between 7.7-9.3%, 6.9-8.4% and 4.8-8.5% of MVC, respectively (fig. 2.3). These represent a drop of up to 75% in the muscle activity in the neutral zone when compared to normalized average EMG values in wrist deviated postures (16.5-38.3% of MVC). Although %MVC values for all muscles were higher in females, no significant differences were found between genders. Also, laterality did not have a significant effect on muscle activity in neutral zone.

2.5.3. Self-selected wrist neutral zone. All subjects consistently positioned their wrist in 5.°-7° ulnar deviation and 7° to 9° extension. Males tend to adopt more deviated postures (8°-9° extension and 7° ulnar deviation compared to 7°-8° extension and 6° ulnar deviation for females) while keeping the wrist in the neutral posture. The differences between genders were not statistically significant. Also, no significant differences in terms of wrist position in the neutral posture were found between the left and right sides for both genders.

2.6. Discussion

This study reports the relationship between wrist deviation and forearm muscle activity. Significant lower muscle activity was found in the neutral zone compared to muscle activity in all four deviated postures. Each movement direction caused wrist muscle co-activations in different pairs and proportions (ECU and FCU for ulnar deviation, ECR and FCR for radial deviation, FCR and FCU for flexion, and ECR and ECU for extension). The 20-35% of MVC recorded for forearm muscles during wrist deviations, demonstrate a significant muscle load. Our results are supported by Hoffman and Strick (1999), who noted that there was co-activation of wrist muscles. This co-activation included both synergists and antagonist muscles. Because wrist flexors have larger moment arms compared to extensors, larger forces will be required by extensors to maintain the wrist posture (Keir et al., 1996) leading to possible increased risk of injury for this muscle group while working with flexed wrist position. Passive muscle forces in antagonist muscles may further increase the risk. The deviated joints cause muscle overload, thus pose a greater risk for musculoskeletal injury.

The secondary effectors (FCR in extension and ulnar deviation, FCU in extension and radial deviation, ECR in flexion and ulnar deviation, and ECU in flexion and radial deviation) presented activity between 8 and 17% of MVC. These levels demonstrate their concomitant dual role in wrist stabilization and force exertion. Muscle's prolonged loading results in fatigue. Therefore, due to lack of rest, the risk of musculoskeletal injury is increased (Kumar, 2001). The effect of wrist deviation on muscle EMG activity was also noted by Drury et al. (1985) in manual materials handling tasks. Authors noted an important increase in EMG at extreme wrist deviations, whereas the muscle activity for wrist angles between 5° radial deviation and 10° ulnar deviation was low and almost constant.

ECR was the most active muscle in both radial deviation (25.5-36.8%) and extension (29.4-38.3%) making it vulnerable in activities that require this combination of wrist deviations (e.g. manual wheelchair propulsion). In addition to being the primary muscle in wrist extension and radial deviation, ECR also acts as a wrist stabilizer. Therefore it is exposed more to static load than flexor muscles. This may explain a higher prevalence of epicondilites on the extensor side. A 20-25% activity of FCR during flexion and radial deviation suggests it to be an important risk factor in tasks such as grasping and packing of products. One should bear in mind that these force magnitudes were obtained in passively deviated wrist postures and any active contractions would require significantly greater muscle activity.

All subjects positioned their wrists in extension and ulnar deviation while in the neutral zone. The recorded postures (5-7° ulnar deviation and 7-9° extension) had a significant effect on all four forearm muscles, causing a 66-75% decrease in muscle activity. This demonstrates that with additional training that would increase the percentage of working time spent within the safe limits for wrist deviation, and design modifications, workers would be able to carry out tasks more safely. The results may assist physical therapists, surgeons, and ergonomists in their evaluations of office and industrial workstations and in making recommendations for interventions (e.g. job/device design/redesign, final wrist joint position following reconstructive interventions).

Additional to the effect on forearm muscle activation, sustained extreme wrist position poses significant risk for CTS development. Extreme wrist extension cause the finger flexors' tendons to slide in the area between volar carpal ligament and the carpal bones increasing tissue crowding. Wrist flexion cause the tunnel elements to be close together on the volar side of the wrist and spread apart on the dorsal side. Also, the flexor retinaculum presses the flexor tendons and bursae against the head of the radius. Although the carpal tunnel cross section decreases in ulnar and radial deviations, it is not so acute owing to constrained range of motion to cause significant problem.

Our results are supported by Hedge and Powers (1995) who demonstrated that the lowest carpal tunnel pressure (CTP) is recorded when the hand is 5° ulnar deviated. Also, O'Driscoll et al. (1992) reported the same self-selected wrist posture with extension and ulnar deviation. It is suggested that completing tasks with a wrist position within neutral zone would lessen carpal tunnel pressure, helping those with a diagnosis of carpal tunnel syndrome or exposed to increased risk.

The results show that the EMG or the wrist neutral zone were not significantly different on two sides. Contrary to our findings, Drury et al. (1985) noted that EMG for the left hand was consistently higher (by 27%) than for the right hand. Also, the wrist angle deviation determined a more pronounced variation in the right hand. This may be due to the training effect of daily work in which most of the tasks determine an overload of the right upper extremity muscles.

Studies that will measure simultaneously forearm muscle activity and carpal tunnel pressure should be performed in order to see if the selected wrist posture corresponds to the lowest values for both EMG and carpal tunnel pressure. One should consider that although during rest, wrist posture would present minimal muscle activity and carpal tunnel pressure, in some stages of industrial work, due to applied force and required awkward postures, the forearm muscle activity may be significantly changed.

2.7. Conclusions

The aim of this paper was to record the self-selected wrist neutral position for both flexion-extension and radial-ulnar deviation planes and the forearm muscle activity in deviated and neutral wrist postures. The neutral zone varied between 7^{o} and 9^{o} extension and between 5^{o} and 7^{o} ulnar deviation. The recommended work zone should be a range +/- 5^{o} from these deviation angles. Significantly lower EMG muscle activity was recorded while the wrist was positioned within neutral zone as compared to deviated postures. Also, the effect of adaptation following daily activities that require extensive wrist ulnar deviation and extension (office work, industrial pinch and grip exertions), on wrist resting posture, should also be determined. Encouraging workers to perform with wrist positions within neutral zone as it could reduce job-associated musculoskeletal disorders risks. The measurement of wrist deviation and forearm muscle activity during force applications also requires exploration. A balance between performance and safe postures should be considered for design solutions.

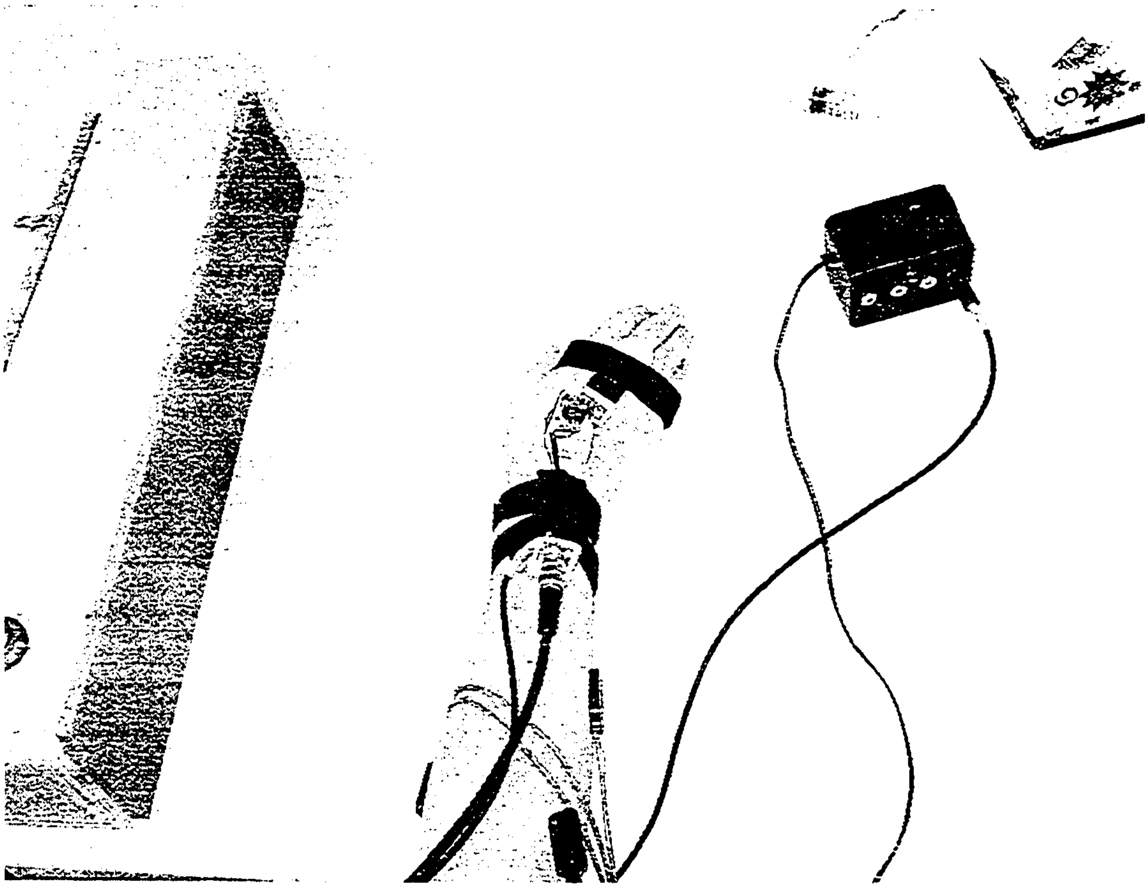

Fig 2.1. Experimental set-up

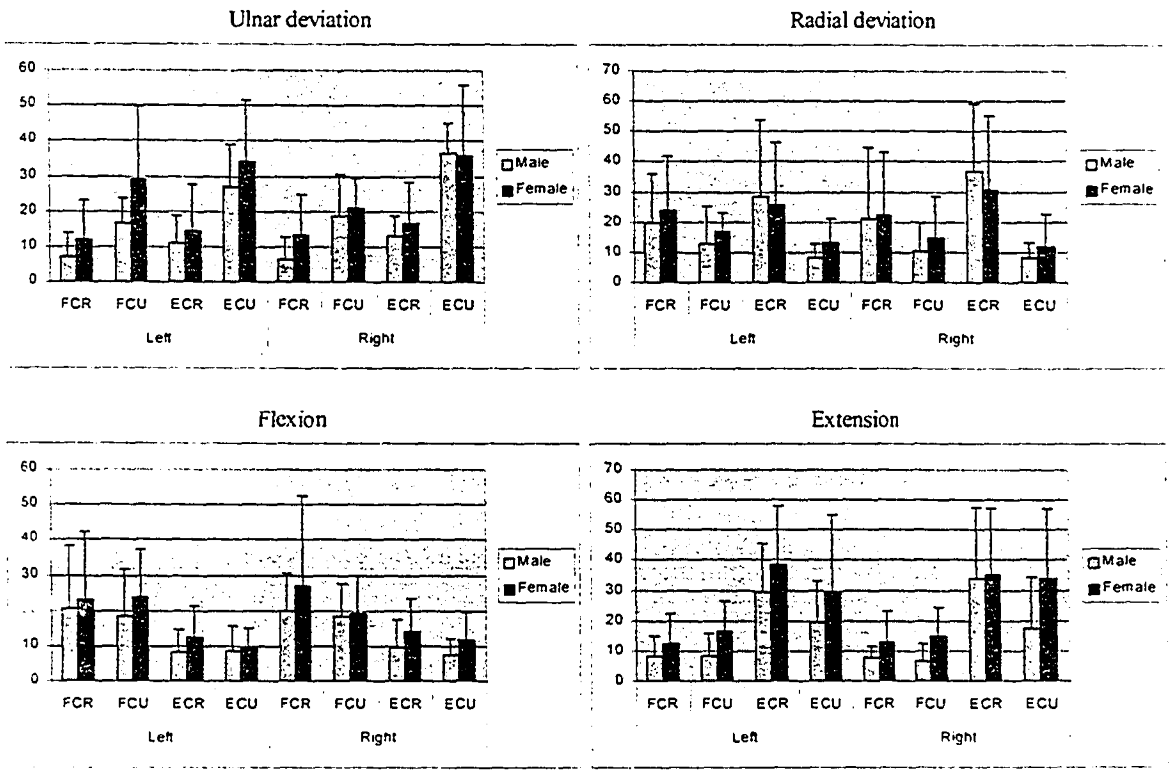

Fig 2.2. The forearm muscles normalized average EMG (% isometric MVC) in wrist deviation postures (FCU: flexor carpi ulnaris; FCR: flexor carpi radialis; ECR: extensor carpi radialis; ECU: extensor carpi ulnaris).

Muscle	Male		Female	
	Right	Left	Right	Left
FCR	□ 0.013 ✱0.028	□ 0.038 ✱ 0.024	✱ 0.023	□ 0.020
FCU	▲<0.001 ✱<0.001	▲0.028 ✱0.006	▲0.001 ✱0.006	▲<0.001 ✱0.005
ECR	□ <0.001 ● <0.001	□ 0.002 ● 0.001	□ 0.004 ● <0.001	□ 0.01 ● <0.001
ECU	▲<0.001	▲<0.001 ● 0.005	▲<0.001 ● <0.001	▲<0.001 ● <0.001

Table 2.1. Significance level of the differences between each muscle activity in the neutral zone and its activity in wrist deviations in which it acts as a primary muscle

*□ = radial deviation
▲= ulnar deviation
● = extension
✱= flexion
FCR = flexor carpi radialis
FCU = flexor carpi ulnaris
ECR = extensor carpi radialis
ECU = extensor carpi ulnaris

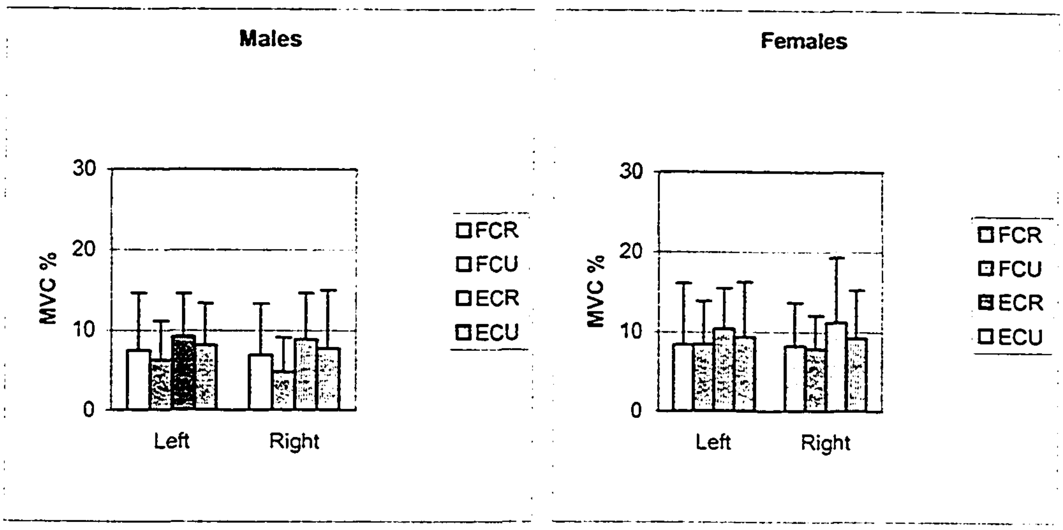

Fig 2.3. The forearm muscles normalized average EMG (% isometric MVC) for both genders in the self-selected neutral position (FCU: flexor carpi ulnaris; FCR: flexor carpi radialis; ECR: extensor carpi radialis; ECU: extensor carpi ulnaris).

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Chapter 3

An ergonomic comparison of four computer keyboards

3.1. Abstract

The effect of different keyboards designs on wrist motion, overall applied force, forearm muscle activity and typing performance was assessed. Twenty subjects typed a standardized text on each keyboard. Wrist electrogoniometers were used to measure wrist deviation and repetition in two planes. Electromyography and force plate were used to quantify forearm muscle activity and overall applied force. Also, for typing performance, words per minute and number of errors were assessed. Wrist deviation was sensitive to keyboard design for all four movement planes with Maltron keyboard different than the other three keyboards. Statistically significant higher overall applied force and lower typing performance values were recorded for Maltron keyboard. No significant differences were found between the four keyboards in terms of EMG muscle activity for all six channels. Taking into account that the alternative keyboards promoted reduced wrist deviation angles without increasing the EMG muscle activity, they are a valid solution for conventional keyboard replacement. The effect of different ergonomic keyboard designs on the musculoskeletal diseases risk factors associated with computer work is discussed.

Keywords: Ergonomic evaluation; Wrist deviation; Typing performance; keyboards comparison

3.2. Introduction

Wrist awkward postures and repetition have been shown for typing with a conventional keyboard. Keyboarding has been associated with excessive wrist ulnar deviation and extension, forearm pronation and shoulder adduction. The average values for wrist deviation when using the traditional QWERTY layout has been assessed to vary between 9° and 25° for ulnar deviation (Smith and Cronin, 1993; Rempel et al. 1994; Serina et al. 1994; Sommerich and Marras, 1994) and between 15° and 33° for wrist extension (Serina et al. 1994; Chen et al. 1994; Sommerich and Marras, 1994).

Although the increase in prevalence of typing-related cumulative trauma disorders (CTD) caused a proliferation of alternative keyboards designs, none of these keyboards have been exhaustively studied and compared. Most of the design efforts have focused on reshaping the conventional keyboard or making it adjustable. Previous studies assessed the influence of various ergonomic designs on typing only from a limited perspective: wrist/forearm posture and typing performance (Marklin et al. 1999) and wrist joint motion and subjective preference (Tittiranonda et al. 1999). Wrist extension and ulnar deviation was noted to be reduced when typing on the Microsoft Natural keyboard compared to Apple Extended™ (Honan et al. 1995). Hedge and Powers (1995) demonstrated a total reduction in wrist extension when negative slope keyboard was used. However, no effect on wrist ulnar deviation was reported. In a comparative study between conventional and split keyboards, Smith et al. (1998) found that split design promoted a more neutral posture for hands, wrists and arms. Also, typing on a split keyboard was shown to reduce wrist ulnar deviation by 12.3° to 21.5° compared to conventional keyboard (Marklin and Simoneau, 2001). All of the above-mentioned studies presented static information (average wrist deviation values) without analyzing the effect of keyboard design from a dynamic point of view (e.g. number of wrist repetitions in a given amount of time).

Only a few studies addressed the effect of alternative keyboard design on typing performance (Marklin and Simoneau, 2001; Marklin et al. 1998; Swanson et al. 1997; Zecevic et al. 2000; Chen et al. 1994). The results vary with decrease in performance that ranges from 10% to 60%. For long training periods the initial decline in performance was followed by an increase, which partly compensates the early loss in productivity.

Although several studies assessed the relationship between applied force while typing and keyswitch characteristics (key travel distance, over travel distance, stiffness, and keyswitch make force) (Rempel et al. 1997; Radwin and Ruffalo, 1999; Dennerlein et al. 1999), there is scarcity of data regarding the influence of keyboard design on overall typing force. Also, while finger flexors and extensors electrical activity have been studied, EMG activity of forearm muscles controlling the wrist movement/position while typing on different keyboards has not been assessed in the past.

The aim of this study was to perform a comparison of four keyboards (three alternative and one conventional) in terms of wrist average repetition and posture for both ulnar-radial and extension-flexion planes, overall applied typing force, EMG forearm muscle activity and typing performance (words per minute and number of errors). No study could be identified in the literature that has assessed the effect of various keyboard designs on all these variables simultaneously.

3.3. Methods

3.3.1. Approach

The approach of this study was to carry out a laboratory testing in which wrist motion, forearm muscle activity, applied force, and performance were measured during a standardized typing task. Four different keyboard designs were used in a randomized order. Wrist repetition and average deviation, EMG activity, overall typing force, typing speed and typing errors were computed in order to determine the effect of different keyboard design.

3.3.2. Recruitment

Enrolment posters were used throughout university campus to recruit volunteers. Subjects willing to participate in the study were screened in order to have a sample that met the inclusion criteria: no history of hand and forearm musculoskeletal problems, touch-typing ability, minimum typing speed of 45 words per minute, and ability to read and write English well.

3.3.3. Subjects

The experimental population consisted of twenty normal young adults: fourteen women and six men. They ranged in age from 21 to 53 years (M=34.1; SD=8.80). The mean height and weight of the volunteers were 165.48 cm (SD=10.54) and 71.18 kg (SD=17.21). The participants were informed of the study objectives and experimental procedure and signed a consent form preceding the investigation. Ethics approval had been obtained from the Human Research Ethics Board.

3.3.4. Apparatus

3.3.4.1. Keyboards. Four different keyboards (one conventional and three alternative) were used in this study (Fig 3.1.). The conventional keyboard was a Fujitsu 105-keys traditional QWERTY layout with 5° positive slope. The alternative keyboards were: Maltron E-Type (fixed split design, tilted keys and pads, straight vertical key columns, central number pad, and slightly modified layout such as thumb keys for *Enter*, *Space* and *Backspace*), Goldtouch Adjustable Ergonomic Keyboard (adjustable split angle and lateral slope with lacking ball and socket latch mechanism), and Prosper Street Technologies (PST) LLC Wave Keyboard (QWERTY slim design with row vertical curves for longer fingers). Although Goldtouch® keyboard lateral inclination could have influenced both pronation and ulnar deviation, in order to be able to assess the impact of split angle design on typing posture, the authors choose a fixed split angle of 25° (in order to have a split angle of 12.5° on each side, which is the cited wrist ulnar deviation while typing on the conventional keyboard) and a 0° lateral slope. These keyboards were chosen in order to cover a large spectrum of keyboard designs (conventional, fixed split design, adjustable split angle design and key rows curvature design).

3.3.4.2. Electrogoniometers. Wrist motion and number of wrist repetition greater than 10° (changes in wrist movement) were measured bilaterally using two SG 65 Biometrics Ltd electrogoniometers (15 g, crosstalk < ±5%, measuring range of ±150°).

3.3.4.3. EMG System. The EMG forearm muscle activity was measured using DelSys Bagnoly™ EMG system (surface electrodes, electrode cables, preamplifiers and amplifiers). The DE-2.1 Single Differential electrodes had 99.9% pure silver contacts for ion flow maximization. Preamplification at the EMG source and low impedance active output reduced signal noise. Electrode cables had all conductors protected in order to minimize line interference. The signals were collected at a frequency bandwidth of 20-450 Hz per channel, extremely low noise, less than 5 uV (p-p, r.t.i.), and exceptionally low leakage currents, less than 10 uA.

3.3.4.4. Force plate. An AMTI force plate was placed under the keyboards in order to assess the overall applied typing force. Using a 12bit a/d card, with the gain set at 4000, the resolution would be about 0.7N. Noise was not a problem as the platform was well isolated and there was an EMI filter in the power circuit. Vibration was also minimized because the platform mounting plate was well secured, so movement and other artifacts were negligible.

3.3.5. Workstation configuration

The computer workstation (adjustable desk and chair, document holder, Pentium Pro 200 computer and 14" Sony monitor) was adjusted for each subject anthropometric characteristics. Seat height and backrest, desk height and monitor angle, were adjusted in order to comply with American National Standards Institute (ANSI, 1988) recommendations (typist's both feet flat on the floor, knees angle at 90°, upright torso and elbow angle of 90° with both forearms parallel to the floor).

3.3.6. Experimental design

A repeated measures experimental design was used. The fixed (independent) variable was the keyboard type. The differences in features among the four tested keyboards were expected to affect the dependant variables assessed in this study (wrist deviation and repetition, overall typing force, forearm muscles EMG activity, number of typed words per minute and number of mistakes) These variables are very important in a typing task, dictating the wotk performance, workers' confort and ability to sustain the prolonged typing sessions.

3.3.7. Text paragraph

Four different text paragraphs with both alphabetic (upper and lower cases) and numerical characters were used. Also, hyphens, commas, spaces, periods, colons, semicolons, and quotation marks were included. The texts had a Times New Roman 12 pitch font with a font size and were long enough (224-238 words) for 2 minutes typing. All four paragraphs met the required readability level (Flesch-Reading Ease between 60 and 70; Flesch-Kincaid Grade Level Score between 7 and 8).

3.3.8. Procedure

After reading the information letter and signing the consent form, the subjects underwent a total of 24 hours of practice (eight hours on each of the alternative keyboards). Special attention was paid to ensure that every subject used the entire practice duration. Prior to the beginning of the experiment, a series of descriptive measurements (age, gender, weight, height, and dominant hand) were recorded.

The electrogoniometers were positioned according to the Biometrics Ltd. recommendations (the subject's shoulder in 90° abduction, elbow flexion of 90° and the forearm fully pronated). The distal endblock was attached to the hand dorsal surface over the third metacarpal bone with the centre axis of the hand and endblock coincident. The proximal endblock was attached to the forearm dorsal surface so that the axes of the forearm and endblock were coincident. After the examiner prepared the subject's forearm by shaving hair and cleaning with alcohol, three EMG bipolar silver-silver chloride surface electrodes were applied bilaterally with an inter-electrode distance of 2 cm. Their positions were: 5-7 cm distal to the line connecting the medial epicondyles and biceps tendon for flexor carpi radialis (FCR), above the shaft of ulna in the middle of forearm for extensor carpi ulnaris (ECU), and at 2-3 cm volar to ulna at the junction of the upper and middle thirds if the forearm for flexor carpi ulnaris (FCU). Although thse muscles do not play a role in the CTS pathogenesis their activity is greatly influenced by wrist position and external force applied on the wrist while working.

The subjects were then seated with the investigator adjusting the workstation in order to have 90° elbow, knee and hip flexion. Also, to alleviate the detrimental effect of monitor position on torso posture and neck discomfort, the centre of the monitor was placed 20° below the subject's horizontal line of sight. Three 5-seconds maximum isometric contractions against a fixed obstacle (resistance) were performed on each muscle. Participants received training on how to perform the maximal voluntary contractions (MVC) for each muscle. The provocative manoeuvres were performed with 90° elbow flexion and neutral forearm posture (between full pronation and full supination). Starting from the wrist neutral position, volunteers were asked to push against the fixed obstacle as hard as they can, while trying to extend and adduct the wrist for ECU, extend and abduct for ECR, flex and adduct for FCU and flex and abduct for FCR. The muscle testing order was computer randomized. The highest EMG activity level among the three MVCs trials was used to normalize the data for each muscle. For the typing tasks, subjects were instructed to type at their normal speed correcting the mistakes, if any. Being limited by the goniometers' data logger memory capacity (1MB), participants typed for 2 minutes a different text on each keyboard. Both text and keyboard testing order were randomly assigned. Between tasks a 15 minutes rest was given.

3.3.9. Data collection

The EMG and force output were sampled at 1 kHz using a DAQ 700 National Instrument data acquisition card. The data collection was managed by developing a special software, which collected data from all seven (6 for EMG and 1 for force) channels and stored them on a Toshiba laptop. During the typing tasks electrogoniometer data from all 4 channels was recorded by the Biometrics Ltd DL 1001 data logger. After each trial, due to data logger limited memory capacity, data was downloaded to a Pentium Pro 200 computer. Repetitive values were calculated using the graphs generated by the Biometrics Ltd software. A 10° movement (distance between two consecutive graph's peaks) was counted as repetition. Typing performance was determined during (number of *Backspace* strokes representing number of mistakes) and after the typing sessions (number of typed words). *Backspace* strokes were visually kept track of by two observers. The average between the two recordings was used in the data analysis. Typed words were counted on the computer screen at the end of each trial (2 minute typing session) and the value was divided by 2 in order to compute the typing speed per minute.

3.3.10. Data analysis

The processed data were further analyzed using SPSS 11.0 statistics software. The group data were subjected to two-way ANOVA with repeated measures in order to find the impact of different keyboards designs on studied variables. Scheffé post hoc multiple comparisons was used to find the differences between keyboards in terms of studied variables. For significance, an alpha level of $p<0.05$ was chosen.

3.4. Results

3.4.1. Wrist deviation

For all four keyboards, the wrist was ulnarly deviated and extended for typing. Table 3.1 presents the wrist deviation angles for extension/flexion and ulnar/radial deviation planes while typing on each of the four tested keyboards.

Keyboard design had a statistically significant effect on angle of wrist deviation for all four planes (left extension/flexion=LEF, left ulnar/radial deviation=LUR, right extension/flexion=REF, and right ulnar/radial deviation=RUR) ($p<0.001$). When compared to conventional keyboard, Maltron and Goldtouch keyboards significantly reduced the wrist ulnar deviation for both left and right sides ($p<0.001$). The PST keyboard required 9-13° more ulnar deviation than Maltron and Goldtouch keyboards for both LUR and RUR planes ($p<0.001$). There were no significant differences in wrist ulnar deviation angles between Maltron and Goldtouch keyboards ($p=0.77$ and $p=0.158$ for LUR and RUR, respectively) as well as between the conventional and PST keyboards ($p=0.771$ and $p=0.837$ for LUR and RUR, respectively). Table 3.2 shows the significant p-values for multiple comparisons for wrist deviation angles. While typing on the conventional keyboard 65% of subjects maintained the left or right wrist in greater than 15° ulnar deviation as compared to 0% for Goldtouch and Maltron and 60% for PST.

The Goldtouch keyboard design forced 80% of subjects to type with the left or right wrist in greater than 20° extension as compared to 70% for the conventional and PST and 30% for Maltron. Within keyboards, no significant differences were found between sides for all four planes.

3.4.2. Wrist repetition

Wrist excursions greater than 10° were taken into account when repetitive values were computed (Table 3.3). Scheffé post hoc multiple comparisons revealed that for the LEF plane, when compared to the other keyboards, the Maltron keyboard significantly reduced the wrist repetition ($p=0.002$, $p=0.040$, and $p=0.017$ for the conventional, Goldtouch, and PST, respectively). Although Maltron caused decreased wrist repetition for REF, LUR, and RUR, the differences were not significant at 0.05 level. No significant differences were found between the conventional, Goldtouch, and PST keyboards for all four movement planes. Also, there were no significant differences between sides for all four keyboards.

3.4.3. Applied force

Keyboard design had a significant effect on overall applied typing force ($p<0.001$). Compared with the conventional keyboard, only Maltron had a statistically significant difference in applied force ($p<0.001$). The mean typing force for participants using the conventional keyboard was 1.91N (SD=1.05), as compared to Maltron (M=5.84; SD=4.16). The mean applied typing forces for Goldtouch and PST were 0.97N (SD=0.52) and 1.28N (SD=0.85), in that order, which were 4.87N, respectively 4.56N lower than the Maltron's average force ($p<0.001$). No significant differences were found between the conventional, Goldtouch, and PST keyboards ($p=0.633 - 0.980$).

3.4.4. EMG muscle activity

No significant differences were found between the six recorded muscles (ECU, FCR, FCU bilaterally) for all four keyboards. The mean values and standard deviations for percentage of MVC used to type on each keyboard are presented in table 3.4.

Compared to the other keyboards, the least forearm muscle activity was needed when typing on Maltron for all six muscles (5.73-21.57%MVC). The conventional keyboard design caused the highest muscle activity for all recorded muscles.

3.4.5. Typing performance

Table 3.5 shows the average values for typing speed and accuracy for each keyboard. The Maltron keyboard was associated with significantly lower performance compared to other three keyboards for both typing speed and error rate ($p<0.001$). There was no significant difference in typing speed and accuracy between the conventional, Goldtouch and PST keyboards ($p>0.05$). While the conventional and PST keyboard were statistically similar in terms of accuracy, Goldtouch keyboard showed significantly higher error rate than the conventional, with 89% level of confidence.

3.5. Discussion

It has been shown that typists have difficulties adapting to the new posture and motor patterns required by the new keyboard designs (Hertting-Thomasius et al. 1992). The current data demonstrates that after a relative short practice session typists were able to adjust their posture, performing as well with some of the tested alternative keyboards as with the conventional keyboard. This study indicated that keyboard design had an important effect on typing in terms of musculoskeletal diseases risk factors.

The fact that the majority of subjects typed maintaining the left or right wrists in greater that 15° ulnar deviation (65% conventional and 60% PST) and wrist extension beyond 20° (80% Goldtouch, 70% conventional and 70% PST) suggest hazard in prolonged computer tasks. The ergonomically designed Maltron keyboard required significantly less wrist deviation for both radial-ulnar and flexion-extension planes. The mean wrist extension recorded in this study for the Maltron keyboard varied between 13.29 (R) and 15.01° (L), compared with the average hand extension of 12° reported for the Kinesis keyboard (similar design as Maltron) (Smith and Cronin, 1993).

Both Maltron and Goldtouch keyboards reduced wrist ulnar deviation by approximately 10° as compared with the conventional set-up. These results are similar to those reported by Marklin and Simoneau (2001), who noted wrist ulnar deviation of 2.7-5° for the right wrist and 7-8.5° for the left for split keyboards as compared to 15-30° for conventional keyboards. Theoretically, the split keyboard design should reduce the average wrist ulnar deviation by 50% of the keyboard split angle. This causal relationship has been validated in our study. The difference between the ulnar deviation recorded for conventional and Goldtouch keyboards was exactly ½ of the Goldtouch split angle. Knowing that the traditional QWERTY design forces the user to maintain the wrist in more than 15° ulnar deviation, a split angle of 25-30° is required.

Although split design configuration is more comfortable, decreasing hands and arms fatigue while typing (Lincoln et al., 2000), the problem of wrist extension is still present. In the present study, Goldtouch keyboard caused the greatest wrist extension between the four tested keyboards (23.56° (R) and 25.76° (L) with 80% of the participants typing with one of the wrists extended more than 20°). Subjects with sustained awkward working postures are of greater risk for developing upper extremity musculoskeletal problems. A strong relationship between wrist deviated postures and increased intracarpal pressure was noted (Weiss et al. 1995). The more neutral posture recorded in the ulnar-radial plane while typing on Goldtouch is expected to decrease both intracarpal pressure and tendon travel, as noted by Treaster and Marras (2000). In order to reduce the risk of musculoskeletal problems at this level, wrist extension should be lowered at 5-10°. A split design QWERTY layout with 25-30° split angle, 0° lateral slope and horizontal or negative slope is needed. While lateral slope tends to decrease forearm pronation, it also reduces typing productivity and user's acceptance. The reduction in both ulnar deviation and shoulder external rotation due to split angle design promote a safe forearm pronation while typing.

One should take into account the trade-off between wrist and finger positions: when one joint changes the degree of deviation, the other one must compensate in order for the fingers' tips to reach the same keys. Hazardous postures could occur.

The reduction in wrist repetition for all four movement planes while typing on the Maltron keyboard can be explained by its unique design. The key-column vertical curvature and the thumb keys for *Enter*, *Backspace*, *Delete* and other frequently used keys reduced the hand movement in the extension-flexion plane. For the ulnar-radial deviation plane, the wrist repetitive movements over 10° were reduced by the presence of the central numeric pad, which could be used by either hand, as preferred. Also, straight vertical key-columns reduced wrist excursions. Some of these design features should be further evaluated and, if valid, adopted by other keyboards. Although there were no significant differences in wrist repetition between the conventional, PST, and Goldtouch keyboards, one should take into account that the repetitive values for the traditional design were produced while maintaining the wrists in the highest wrist ulnar deviated posture among all keyboards. As shown by previous studies (Nelson et al. 2000; Treaster and Marras, 2000), alternative keyboard design can affect tendon travel by as much as 11-13%, reducing the tendon sheaths thickening process. While the number of keystrokes is a consequence of the task complexity, both wrist posture and repetition are highly influenced by the keyboard design. Promoting safer wrist postures and repetition rates without increasing the forearm muscle activity, ergonomic keyboards represent a valid alternative to the widespread traditional design.

The elevated EMG values recorded in this study may be due to the fact that participants did not exert their maximal contraction during MVC trials. Also, the short typing session (2 min on each keyboard) under experimental conditions and the pressure of typing speed recordings could have imposed an additional stress on subjects increasing the tension. While there is a possibility that the absolute EMG values would have been diminished under different study conditions, the relationship between different EMG values among tested keyboards would have remained unchanged with conventional and Maltron keyboards causing the highest, respectively the lowest muscle activity. Since subjects were not allowed to rest their wrists during typing, decreased EMG values while using the Maltron keyboard were not a consequence of hands being supported. Although decreased productivity, not only the wrist posture, could have accounted for the lower muscle activity, its effect would have been more pronounced if finger, not wrist flexor and extensors had been recorded. Typing speed is closer correlated with fingers' movement (fingers' flexor/extensor activity) than it is with wrist movers (muscles recorded in this study). Maltron design imposed a closer to neutral wrist posture (decreased wrist muscles activity) within which fewer finger strokes (lower typing productivity) were performed.

In the current study, overall applied typing force recorded while using the conventional and Maltron keyboards exceeded the ANSI/HFS recommendations (0.5-

1.5N). These results are similar to those of Rempel et al. (1994), who using a piezoelectric load cell determined that the subject's mean peak force ranged between 1.6 and 5.3N. The differences in overall typing force can be explained by important variations in keyswitch characteristics (key travel distance, over travel distance, stiffness and keyswitch make force). Radwin and Ruffalo (1999) noted that rising the keyswitch make force (force required to activate the key) by only 46% caused a 129% increase in key strike force. The applied force at the tendon level was noted to be four to seven times higher than the maximum force recorded at the fingertip (Dennerlein et al. 1999). Due to the tendon inertia and force magnitude that leads to a slower decrease speed compared to fingertip force, the risk for musculoskeletal problems is increased by higher required typing force. Both Goldtouch and PST keyboards had typing force within the recommended levels. Relationship between applied force and typing performance can be speculated. In our study, subjects exerted lower strike force when typing on keyboards promoting higher performance. Elevated stress as well as frustration could play an important role in force generation.

Our study indicates that the participants were able to rapidly adapt to two of the alternative keyboards (Goldtouch and PST). For the Maltron keyboard the productivity was significantly reduced (58% decrease in typing speed and 149% increase in error rate, when compared to the conventional keyboard). On the Goldtouch keyboard, subjects reached 86% and on the PST keyboard 90%, of their typing speed on the traditional keyboard. Also, the error rate for these keyboards was statistically identical when compared to the conventional design. Marklin and Simoneau (2001) and Marklin et al (1999) found similar performance results, with an average speed for alternative keyboards 10% (6 wpm) less than the speed for traditional design. The adaptation to these new keyboards is even more promising if one takes into account the relative short (8 hours) training time. The decrease in productivity of 58% for the Maltron keyboard represents an important impediment for its acceptance. However, one should note that the Maltron keyboard has the option to switch to an alternate Maltron layout, which has not been tested in this study. If additional training time was given and the Maltron layout was used, it is possible that typing productivity would have been improved.

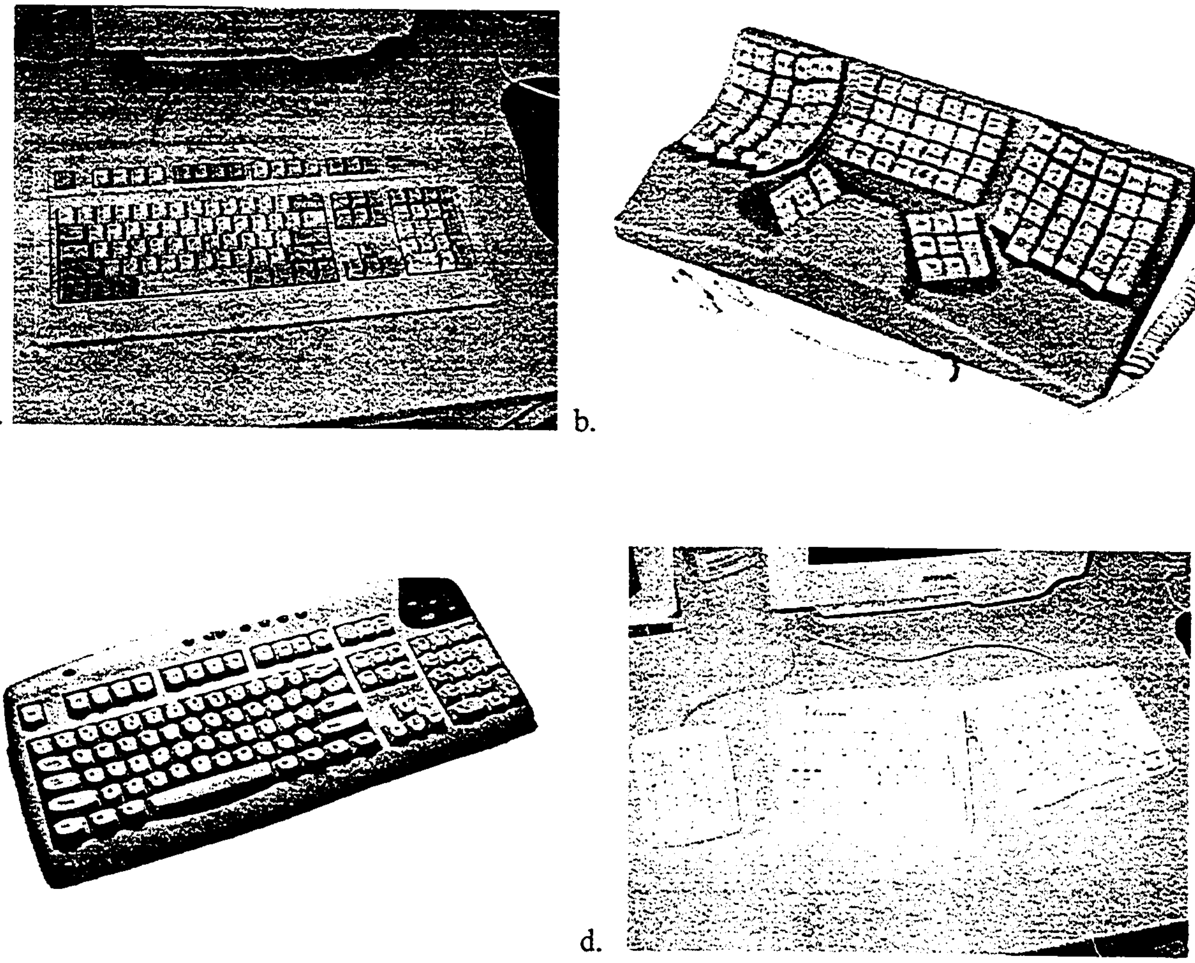
3.6. Conclusions

As presented in table 3.6, all three alternative keyboards were better in at least one typing parameter when compared with the conventional keyboard.

The actual results demonstrate that:

- the design changes for Goldtouch and Maltron keyboards promoted a more ergonomic wrist posture while typing.
- due to its discrete design modifications, the PST keyboard had changed the typing force when compared with the conventional keyboard.
- the trade-off between drastic design modifications and typing performance was evident for the Maltron design. While maintaining the wrist in a more neutral posture without increasing the forearm muscle activity, the Maltron keyboard impaired typing performance.
- In view of the findings that drastic design reshaping causes decreased productivity, the authors suggest that alternative designs that maintain the QWERTY layout but introduce discrete design modifications should be tested in the future.

- Taking into account the important ulnar deviation assessed while typing on the conventional keyboard, modifying the position of some extreme, but very frequently used keys (e.g. *Tab*, *Backspace*, *Caps Lock*, *Esc*) may reduce the wrist deviation.
- not only that ergonomic keyboards are able to meet the immediate requirements such as performance, typing speed, and short training time, but they also promote safer hand postures. Additional research is mandatory in order to see if prolonged office work on alternative keyboards supports these findings.
- future research is needed to determine if longer training time will compensate for the lost productivity due to radical keyboard redesign.



a. b.

c. d.

Fig. 3.1. The keyboards that have been used in the experiment: a. Conventional; b. Maltron; c. Prosper Street Technologies and d. Goldtouch

Keyboard	Extension (+)/flexion (-)		Ulnar (+)/radial (-) deviation	
	Left	Right	Left	Right
Conventional	21.80 (4.89)	21.73 (6.12)	15.67 (3.63)	16.91 (4.33)
Goldtouch	25.76 (4.67)	23.56 (5.87)	0.55 (6.44)	3.62 (5.61)
Maltron	15.01 (5.55)	13.29 (5.45)	4.69 (4.11)	7.00 (4.80)
PST	21.00 (5.46)	21.78 (4.45)	14.04 (4.81)	15.58 (3.32)

Table 3.1. Means and standard deviations for average wrist angles while typing on the four different keyboard designs.

Keyboard	Goldtouch	Maltron	PST
Conventional	□<0.001; ▲<0.001	●=0.001; □<0.001; ✶<0.001; ▲<0.001	
Goldtouch		●<0.001; ✶<0.001;	●=0.048; □<0.001; ▲<0.001
Maltron			●=0.006; □<0.001; ✶<0.001; ▲<0.001

Table 3.2. Significant p-values for wrist deviation angles

for multiple comparisons between keyboards.

Legend: ● = LEF; □ = LUR; ✶ = REF; ▲ = RUR.

Keyboard	Movement plane			
	LEF	REF	LUR	RUR
Conventional	51 (13)	44 (15)	9 (3)	12 (5)
Goldtouch	43 (10)	39 (14)	12 (6)	10 (5)
Maltron	26 (8)	29 (12)	7 (3)	10 (5)
PST	46 (14)	41 (12)	9 (6)	12 (4)

Table 3.3. Mean values and standard deviations for wrist repetition >10°

per minute for all planes and keyboards

Keyboard	Forearm muscle					
	ECUL	ECUR	FCRL	FCRR	FCUL	FCUR
Conventional	15.39 (7.51)	29.25 (19.13)	23.63 (8.87)	34.76 (16.64)	11.40 (10.56)	8.13 (5.18)
Goldtouch	13.22 (10.52)	27.15 (20.44)	22.18 (10.13)	21.72 (25.04)	8.05 (7.93)	6.91 (4.84)
Maltron	9.02 (4.85)	21.28 (18.67)	20.06 (7.86)	21.57 (24.41)	8.05 (7.54)	5.73 (3.36)
PST	13.49 (7.18)	24.69 (19.43)	21.49 (6.89)	34.70 (27.99)	8.95 (6.78)	7.48 (5.00)

Table 3.4. Percentage of maximal voluntary contraction (%MVC) muscle activity needed to type on each keyboard.

*Standard deviation values are presented in brackets.

**ECUL=extensor carpi ulnaris left; ECUR=extensor carpi radialis right; FCRL=flexor carpi radialis left; FCRR=flexor carpi radialis right; FCUL=flexor carpi ulnaris left; FCUR=flexor carpi ulnaris right

Keyboard	Typing speed	Typing accuracy
Conventional	69.67 (19.61)	7.61 (4.09)
Goldtouch	58.92 (21.40)	11.38 (5.37)
Maltron	29.26 (8.86)	19.29 (5.88)
PST	62.37 (17.28)	8.39 (3.72)

Table 3.5. Typing speed (wpm) and accuracy (*Backspace* strokes per 100 typed words) for each keyboard

Keyboard	Wrist posture		Wrist repetition	Applied force	Muscle activity	Typing performance	
	Ulnar deviation	Extension				Wpm	Error rate
PST	↔	↔	↔	↓	↔	↔	↔
Goldtouch	↓	↔	↔	↓	↔	↔	↔
Maltron	↓	↓	↓	↑	↔	↓	↑

Table 3.6. Changes in typing parameters for the tested alternative keyboards when compared with the conventional design

Legend: ↔ = no statistical significant difference; ↓ = statistical significant decrease; ↑ = statistical significant increase.

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Chapter 4

The Training Effect on Typing on Two Alternative Keyboards

4.1. Abstract

Problem: Although alternative keyboards promote safer postures, their implementation is impeded by the initial reduced productivity. The objective of this study was to assess the effect of training on typing efficiency on two ergonomic keyboards (Maltron and Goldtouch). *Method:* Thirty volunteers (20 trained and 10 untrained) typed a standardized text on each keyboard. Bilateral wrist motion, overall applied force, surface electromyography (EMG), and typing performance were continuously monitored. *Results:* The multivariate analysis of variance revealed that training decreased the applied force significantly for both Maltron ($p<0.031$) and Goldtouch ($p<0.022$). Training increased the typing speed ($p<0.027$ and $p<0.008$ for Goldtouch and Maltron respectively) and decreased the error rate ($p<0.039$ and $p<0.007$ for Goldtouch and Maltron, respectively). However, training did not influence wrist motion and EMG muscle activity. *Conclusions:* Due to the fact that the increase in performance following the training period did not cause higher muscle activity, ergonomic keyboards may constitute a solution for reducing typing related musculoskeletal problems.

Keywords: Human-computer interaction; Ergonomic keyboards; Training; Performance;

4.2. Relevance to industry

While ergonomic keyboards have been developed in order to reduce the computer work-related injuries, their introduction has been delayed due to economic reasons. Proving that after a relative short training session, the majority of typing parameters have improved would ensure a rapid replacement of traditional keyboard design.

4.3. Introduction

Cumulative trauma disorders (CTDs) caused by poor job and device design are on rise (Tittiranonda et al. 1999). Nowadays, work-related musculoskeletal disorders (WRMSDs) are one of the ten most significant health problems (Barthel et al. 1998). The total costs for new personnel training, workers' compensation, and management costs exceeds $90 million for one year (NIOSH, 1996). The increase in computer usage led to a higher prevalence of typing-related upper extremity musculoskeletal problems. Between 1988 and 1993 there was a 1000% increase in number of CTDs among office workers (BLS, 1993). Szabo (1998) noted that from all cases of work-related carpal tunnel syndrome (CTS), 21% were attributed to keyboarding. Therefore, the actual keyboard design poses high risk for WRMSDs development.

The typing posture while using the conventional keyboard requires arms abduction, pronation of forearms, extension of wrists, ulnar deviation and finger extension in order to fit the keyboard. These result in elevated carpal tunnel pressure (CTP) (Werner et al. 1997). A high-repetitive movement in the task (38-40/minute), exceeds the tolerance frequency in a repetitive task (30/minute) (Bergamasco et al. 1998). Left hand overloading, insufficient typing on the home row, excessive finger travel, and uneven finger work distribution occur while typing on a traditional QWERTY layout (Dvorak, 1943).

In an attempt to reduce the impact of extensive office work on CTDs incidence, a wide variety of alternative keyboard designs have been developed. Although previous studies showed an improvement in wrist posture (Hedge and Powers, 1995; Marklin and Simoneau, 2001; Smith et al. 1998), forearm pronation (Smith et al. 1998; Zecevic et al.

2000), and tendon travel (Treaster and Marras, 2000), when typing on ergonomic keyboards compared to conventional one, the replacement costs and early decreased performance become considerations. Also, dramatic design modifications caused resistance from companies and/or data entry personnel. The average typing speed for ergonomic keyboards was 10% lower than the speed for traditional keyboards (Marklin et al. 1999; Marklin and Simoneau, 2001). In another study, Zacevic et al. (2000) found that after 10 hours of training, the decline in productivity was 10% for the FIXED keyboard (split angle of 12° and a lateral slope of 10°) and 20% for the OPEN keyboard (split angle of 15° and lateral inclination of 42°) when compared to the standard keyboard. In contrast, Smith et al. (1998) showed no difference in typing performance between conventional and split design keyboards. Moreover, subjects did not undergo any typing training session. The majority of studies (Liao and Drury, 2000; Simoneau et al. 1997; Smith et al. 1998) used a very short training sessions (5 minutes – 2 hours per set-up), leading to biased outcomes. In order to have a valid comparison between a new/modified and the conventional keyboard, one should use a training session long enough to reduce the experimental stress. In a study that assessed the impact of different keyboard designs on performance and comfort, Swanson et al. (1997) described typing performance for alternative keyboards as a curve with an initial decline that is 85-90% recovered through the session.

While data comparing typing performance when using alternative keyboards versus conventional one is available, no study has compared all the important typing variables before and after training session. The aim of this study was to assess whether training has an effect on wrist posture and repetition, overall applied force, typing performance in terms of number of typed words per minute and number of mistakes per one hundred typed words, and EMG forearm muscles activity for two different ergonomic keyboards.

4.4. Methods

4.4.1. Subjects

A total of thirty (twenty trained and ten untrained) normal young adults were included in the study. Participants' descriptive statistics data are presented in Table 4.1. The volunteers signed the informed consent form preceding the experiment. Subjects included in the study met the following inclusion criteria: no history of hand and forearm musculoskeletal problems, touch-typing ability, minimum typing speed of 25 words per minute, and ability to read and write English well. Although factors as smoking, endocrine pathology (e.g. diabetes, hyperthyroidism), and obesity may be implicated in upper extremity musculoskeletal problems, they have not been included in the exclusion criteria.

4.4.2. Devices

4.4.2.1. Keyboards. Three different keyboards (one conventional and two alternative) were used in this study (Fig 4.1.). The conventional keyboard was a Fujitsu 105-keys traditional QWERTY layout with 5° positive slope. The alternative keyboards were: Maltron E-Type (fixed split design, tilted keys and pads, straight vertical key columns, central number pad, and slightly modified layout such as thumb keys for *Enter*, *Space* and *Backspace*) and Goldtouch Adjustable Ergonomic Keyboard (adjustable split angle and lateral slope with lacking ball and socket latch mechanism). In the current study, a fixed split angle of 25° as well as 0° lateral slope was chosen for the Goldtouch® keyboard.

4.4.2.2. Electrogoniometers. Wrist motion was measured bilaterally using two SG 65 Biometrics Ltd electrogoniometers (15 g, crosstalk < ±5%, measuring range of ±150°).

4.4.2.3. EMG System. The EMG forearm muscle activity was measured using DelSys Bagnoly™ EMG system (surface electrodes, electrode cables, preamplifiers and amplifiers). The DE-2.1 Bipolar differential electrodes had 99.9% pure silver contacts for ion flow maximization. Preamplification at the EMG source and low impedance active output reduced signal noise. Electrode cables had all conductors protected in order to minimize line interference. The signals were sampled for two minutes within frequency bandwidth of 20-450 Hz per channel at a rate of 1000 Hz. The system had extremely low noise (less than 5 μV) and exceptionally low leakage currents (less than 10 μA).

4.4.2.4. Force plate. Also, an AMTI force plate was placed under the keyboards in order to assess the overall applied typing force.

4.4.3. Workstation configuration

The computer workstation (adjustable desk and chair, document holder, Pentium Pro 200 computer and 14" Sony monitor) was adjusted for each subject's anthropometric characteristics. Seat height and backrest, desk height and monitor angle, were adjusted in order to comply with American National Standards Institute (ANSI, 1988) recommendations.

4.4.4. Experimental design

A repeated measures design was used. The independent variables were training and keyboard type. Dependent variables in this study were: wrist deviation and repetition, overall applied typing force, forearm muscles EMG activity and typing performance. The effect of training on these variables when typing on two alternative keyboards was studied.

4.4.5. Text paragraph

Three different alphanumeric paragraphs were used. The texts had a Times New Roman font with a size of 12 pitch and 224-238 words for the 2 minutes of typing. The readability level for all three texts ranged from 60 to 70 for the Flesch-Reading Ease Score and between 7 and 8 for the Flesch-Kincaid Grade Level Score.

4.4.6. Procedure

Twenty subjects underwent eight hours of practice on each of the alternative keyboards. Although the remaining sample (ten participants) typed without any practice, they were introduced to the new keyboard designs.

Descriptive measurements (age, gender, weight, height, and dominant hand) were recorded at the beginning of the experiment for each subject. The electrogoniometers were positioned with the subject's shoulder in 90° abduction, elbow flexion of 90° and the forearm fully pronated. The distal endblock was attached to the hand dorsal surface over the third metacarpal bone with the centre axis of the hand and endblock coincident. The proximal endblock was attached to the forearm dorsal surface so that the axes of the forearm and endblock were coincident. For EMG recording, the subject's forearm was prepared by shaving hair and cleaning with alcohol at the electrode placement sites. Three EMG bipolar silver-silver chloride surface electrodes were used bilaterally with an inter-electrode distance of 2 cm. Their positions were: 5-7 cm distal to the line connecting the medial epicondyles and biceps tendon for flexor carpi radialis (FCR), above the shaft of ulna in the middle of forearm for extensor carpi ulnaris (ECU), and at 2-3 cm volar to ulna at the junction of the upper and middle thirds if the forearm for flexor carpi ulnaris (FCU).

The subjects were then seated with the investigator adjusting the workstation in order to have 90° elbow, knee and hip flexion. In order to provide a more comfortable typing posture the centre of the monitor was placed at 20° below the subject's horizontal line of sight. A 5 seconds maximum isometric contraction was performed for each muscle. The muscle testing order was randomly chosen. The highest activity level was used to normalize the data for each subject. For the typing tasks, subjects were instructed to type at their normal speed correcting the mistakes, if any. Participants typed for 2 minutes a different text on all three keyboards. Both text and keyboard testing order were randomized. A 15 minutes rest was given between tasks.

4.4.7. Data collection

The data collection was managed by using a special software, which acquired data from all seven (6 for EMG and 1 for force) channels and stored them on a Toshiba laptop. During the typing tasks, electrogoniometer data from all 4 channels was recorded on the Biometrics Ltd DL 1001 data logger. After each trial, the data were downloaded to a Pentium Pro 200 computer. Typing performance was determined during (number of Backspace strokes) and after the trials (number of typed words).

4.4.8. Data analysis

The processed data were further analyzed using SPSS 11.0 statistics software. In order to assess the effect of training on studied variables, the group data were subjected to nested one-way ANOVA with repeated measures. For significance, an alpha level of $p<0.05$ was chosen.

4.5. Results

No significant differences were found between trained and untrained volunteers in terms of wrist deviation and repetition, overall applied force, EMG forearm muscles activity and typing performance when typing on the conventional QWERTY design, ensuring statistical similarity between the two tested groups. Table 4.2 presents the effect of practice on studied variables.

4.5.1. Typing performance

Practice had a statistically significant effect on typing performance (words per minute and typing accuracy). Typing speed improved by 48% for both keyboards, increasing from 39.77 to 58.92 wpm for Goldtouch ($p=0.027$) and from 19.71 to 29.26 wpm for Maltron ($p=0.008$). For the Goldtouch keyboard, the accuracy rate for the trained group was 11.38 errors per one hundred typed words ($SD=5.37$), as compared to 15.39 ($SD=3.14$) for the untrained subjects ($p=0.039$). Training on Maltron keyboard significantly reduced the error rate from 26.58 ($SD=7.40$) to 19.29 ($SD=5.88$) ($p=0.007$).

4.5.2. Wrist deviation and repetition

Training did not have a significant effect on wrist angle of deviation for all four movement planes (left extension/flexion=LEF, left ulnar/radial deviation=LUR, right extension/flexion=REF, and right ulnar/radial deviation=RUR) for both Maltron and Goldtouch keyboards ($p>0.05$). Wrist deviation values for trained and untrained subjects are presented in Table 4.3. Compared with the conventional design, both groups maintained safer typing postures while typing on the alternative keyboards. For the Maltron keyboard the more ergonomic working postures found in untrained participants (less wrist ulnar deviation and extension) when compared with the traditional design, were maintained after the training session. Working on Goldtouch tented to reduce ulnar deviation in both untrained and trained groups. Although training decreased wrist motion repetition (number of wrist excursions greater than 10°) with 2-6 repetitions per minute, the difference was not significant ($p>0.05$).

4.5.3. Applied force

Training significantly reduced the overall applied force for both Goldtouch ($p=0.022$) and Maltron ($p=0.031$) keyboards. The mean typing force was reduced by 58% from 2.27N (SD=2.26) to 0.97N (SD=0.52) for Goldtouch and by 42% from 9.92N (SD=5.47) to 5.84N (SD=4.16) for the Maltron keyboard.

4.5.4. EMG activity

Forearm muscles activity for the trained group was not significantly different when compared to untrained subjects for both Maltron and Goldtouch keyboards ($p>0.05$). The percentage of maximal voluntary contraction (%MVC) muscle activity needed to type on each keyboard varied between 6.91 and 24.15 %MVC for trained and 5.02 to 25.00 %MVC for untrained when typing on the Goldtouch keyboard and between 5.73 and 21.57 %MVC for trained and 4.43 to 22.86 %MVC for untrained when Maltron keyboard was used.

4.6. Discussion

The introduction of ergonomic keyboard designs has been delayed due to concerns such as performance preservation and high training costs. Although previous studies assessing alternative keyboard designs also included various training sessions (5 min-10 hours per day for 1 week), there is a lack of data regarding the improvement in typing parameters induced by subjects' adaptation to the new designs (Hedge and Powers, 1995; Marklin et al. 1999; Smith et al. 1998; Treaster and Marras, 2000; Yoshitake et al. 1997). The actual study demonstrates that after a relative short training period, subjects were able to significantly improve their typing style and performance.

Even if, when compared to performance values for the conventional keyboard, the untrained group's typing performance equalled 60.25% and 29.86% for the Goldtouch and Maltron keyboards, respectively, the 8 hours of training increased the performance by 51% for Goldtouch and 54% for Maltron. The fact that trained participants were able to type at 89% of their baseline typing speed when using the Goldtouch keyboard constitutes a strong evidence that with additional experience, alternative keyboards could easily replace the widespread traditional design without any loss in productivity, or perhaps even may improve it. While the performance recorded in the trained group for Maltron represents only 44.33% of their typing speed when using the conventional keyboard, the 54% increase in performance between the two groups demonstrated that participants were able to adapt even to dramatic design changes. These results differ from those reported by Treaster and Marras (2000), who noted a decrease of only 14% when typing on the Kinesis™ keyboard (similar design to Maltron). Regarding typing performance, Smith et al. (1998) noted values similar to those recorded for the traditional keyboard after only 2 hours of training on a split angle keyboard. Previous research indicated that the initial decline in typing productivity was recovered after two days of training (Swanson et al. 1997).

The subjects' rapid adjustment for alternative keyboards was demonstrated also by the significant improvement in error rate. A reduction of 27% in error rate following training was recorded for both keyboards. There is a strong relationship between typing speed, error rate, and wrist repetition. Customization with the new keyboards design leads to decreased error rate, which eliminates wrist repetitions needed to correct the mistakes and to retype the accurate word. However, future research is needed in order to assess if all design modifications are required. If not, eliminating the unnecessary ones would increase performance even more, making these ergonomic keyboards more likely to be accepted.

For the Goldtouch keyboard the training session was enough in order to reduce the typing force below the values for the conventional design (from 2.27N to 0.97N, as compared with 2.17N recorded for conventional). Also, through training, the values were brought within the ANSI/HFS (1988) recommendations (0.5-1.5N). For Maltron, although even after training the force was high (5.84N), the drop of 4.08N (42%) is promising. Similar results were noted by Rempel et al. (1994), who assessed that subjects' mean peak force varied between 1.6 and 5.3N. Radwin and Ruffalo (1999) showed that a 46% increase in keyswitch make force (force needed to activate the key) induced a 129% raise in key strike force. In order for the Maltron keyboard to promote forces within the acceptable limits, changes in key switch mechanism are needed.

The decrease in overall applied force following training could be explained by a reduction in associated stress. Working under time pressure, especially with keyboard designs totally different than the one subjects are used to, spending more time in order to find the right keys leads to higher key stroke force (increased finger velocities) when the key is found. Training makes devices more familiar, eliminating unnecessary actions.

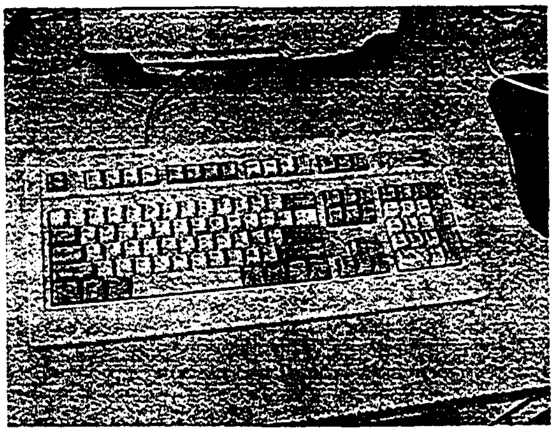
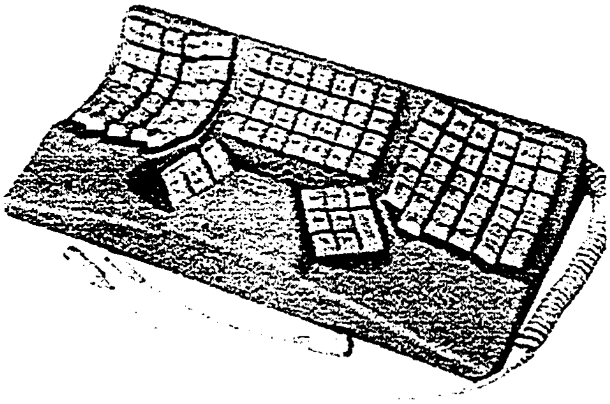
Since the force at the tendon level was noted to be four to seven times higher than the force applied at the fingertip (Radwin and Ruffalo, 1999), the reduction in mechanical stress present at the tendon level is even bigger. As expected, the decrease in applied force was not associated with a decline in forearm muscles EMG activity. While forearm muscles maintain the forearm and hand in a certain posture, finger flexors are the muscles responsible for the force applied by the fingers. Additional research of the effect of training on finger flexor muscles is needed.

The 10% decrease in wrist repetition for flexion-extension and ulnar-radial deviation planes (2-5 wrist movements/min) due to training, although not significant, it was consistent among all four planes for both keyboards. These could represent a significant decrease in risk factors associated with prolonged typing (e.g. tendon travel, tendon sheaths friction). After training, for one day of work the decline in wrist repetition would be of 2400 movements per movement plane (5 repetitions/min x 60 min per hour x 8 hours of work). For one hand (both ulnar – radial deviation and flexion – extension planes) a total of approximately 4800 unnecessary wrist movements would be avoided through training. For the Maltron keyboard, training produced values below 30/min, which is the recommended highest acceptable frequency in a repetitive motion[7]. Subjects being more familiar with the new keyboards could be one explanation for the drop in hand repetition. Cumulative load is a risk factor for musculoskeletal injury development (Kumar, 1990; Kumar, 2001).

It is important to mention that for both groups (trained and untrained), these decreased values for repetition were obtained while maintaining the wrists in safer postures. For the Maltron keyboard, although not modified by training, both wrist ulnar deviation and extension were reduced when compared with the traditional design. Also, typing on the Goldtouch keyboard promoted lower ulnar deviation. Due to the additive effect of decreased wrist motion repetition combined with safer wrist postures, decline in associated musculoskeletal disorders risk factors as well as an increase in productivity could be expected after longer training periods. Further research is needed in order to assess the training time required by each alternative keyboard in order to reach the plateau typing speed. This will help optimization of training.

4.7. Conclusions

Eight hour training resulted in lower wrist motion repetitions, decreased overall applied force, and increased performance (words per minute and number of errors). The current results show that with additional training or experience, alternative keyboards may represent an alternative for the conventional keyboard design reducing risk of musculoskeletal injuries.

a.  b. 

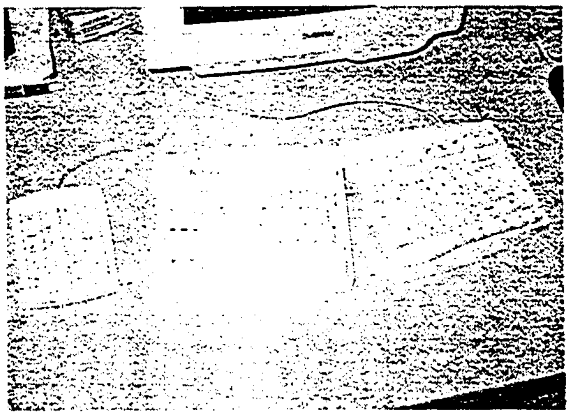
c. 

Fig.4.1. The keyboards that have been used in the experiment: a. Conventional; b. Maltron;
c. Goldtouch

	Trained		Untrained	
	Mean	St. dev.	Mean	St. dev.
Age	34.1 yrs	8.80	26.8 yrs	4.82
Height	165.48 cm	10.54	170.78 cm	7.77
Weight	71.18 kg	17.21	64.38 kg	8.09

Table 4.1. Demographic data of experimental sample

Keyboard	Wrist posture	Wrist repetition	Applied force	EMG activity	Typing performance	
					WPM	Accuracy
Goldtouch	↔ p>0.05	↓ p>0.05	↓*p=0.022	↔ p>0.05	↑*p=0.027	↓*p=0.039
Maltron	↔ p>0.05	↓ p>0.05	↓*p=0.031	↔p>0.05	↑*p=0.008	↓*p=0.007

Table 4.2. The effect of training on studied variables.

* = statistical significant difference

↓= decreased; ↑= increased; ↔= no difference.

KEYBOARD		LEF		REF		LUR		RUR	
		Angle	Repet	Angle	Repet	Angle	Repet	Angle	Repet
Conventional		22.22 (5.30)	52 (13)	21.65 (5.78)	42 (15)	15.86 (2.78)	8 (4)	16.66 (3.97)	13 (5)
Maltron	**Trained**	15.01 (5.55)	27 (8)	13.29 (5.45)	29 (12)	4.69 (4.11)	7 (3)	7.00 (4.80)	10 (5)
	Untrained	13.37 (4.13)	32 (13)	13.82 (5.91)	31 (13)	4.91 (4.14)	8 (5)	6.49 (4.60)	10 (5)
Goldtouch	**Trained**	25.76 (4.67)	43 (10)	23.56 (5.87)	39 (14)	0.55 (6.44)	12 (6)	3.62 (5.61)	10 (6)
	Untrained	25.99 (5.67)	44 (20)	23.46 (4.74)	43 (16)	1.05 (3.66)	14 (4)	4.70 (3.20)	12 (5)

Table 4.3. Average wrist angle of deviation and repetition for all four movement planes.

*LEF=left extension/flexion; REF=right extension/flexion; LUR=left ulnar/radial deviation; RUR=right ulnar/radial deviation.

**Standard deviation values are presented in brackets.

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Chapter 5

Grip strength and forearm muscles activity variation due to upper extremity deviated postures

5.1. Abstract

The purpose of this study was to assess the effect of wrist/forearm/elbow posture on grip strength. Also, the effect of deviated postures while gripping, on EMG activity of four wrist stabilizer muscles (Flexor Carpi Radialis (FCR), Flexor Carpi Ulnaris (FCU), Extensor Carpi Radialis (ECR) and Extensor Carpi Ulnaris (ECU)) was examined. Twenty volunteers were tested while exerting eighty maximal grip contractions in different upper extremity postures. The highest grip force was recorded in neutral wrist posture with supinated forearm in both females (29.03-36.20 kg) and males (61.92-70.90 kg). Wrist total flexion and pronation promoted the lowest grip force (14.28-18.98 kg for females and 23.46-27.21 for males). Males exerted significantly higher grip force for all conditions ($p<0.001$-0.040). In wrist extension the grip force was low, but the EMG activity was increased in FCR, ECU, and ECR. Similarly, higher activities were recorded for ECU in wrist ulnar deviation, FCU in wrist flexion, and ECR in wrist radial deviation. In view of these findings that awkward postures cause decreased grip force and increased forearm muscles' activity, redesign and interventions should take this into account for reducing the risk for musculoskeletal injuries.

Keywords: Grip strength; EMG; Wrist deviation; Forearm muscles; Elbow flexion;

5.2. Relevance to industry

Knowing the relationship between upper extremity joints posture and grip force exertion would ensure targeted industrial job and device redesign.

5.3. Introduction

Even though many physical works have been replaced by powered tools, high force applications with the upper extremity in awkward postures is still surprisingly common in everyday activity and industrial work. Owing to the biomechanical nature of all occupational musculoskeletal injuries (Kumar 2001), ergonomic interventions that address the device-hand interaction are desirable (Imrhan 1989).

While the vast majority of studies (Kumar 2001, Muralidhar and Bishu 2000, Muralidhar *et al.* 1999, Gerber 1998, Sukthankar and Reddy 1995, Kumar and Simmonds 1994) support the relationship between industrial work and hand/wrist musculoskeletal disorders, the recommended posture and repetition pace are not entirely resolved. High prevalence of musculoskeletal disorders in almost all tasks that involve extensive forearm and hand/fingers repetitive movements with a force component is commonly observed (Hansson *et al.* 1996). In poultry industry and automobile upholstering, meat processing and packaging, where there is a widespread use of tools, the upper extremity disorders prevalence is even greater (McGorry 2001). The increase in the upper extremity disorders demonstrates that workers are not adapted to cope with associated risk factors (repetitive tasks, lack of rest, inappropriate force exertions, and awkward postures) (Kumar 2001).

In contrast to Lunde et al. (1972) findings that hand strength is 10-13% higher in the dominant hand, the non-significant difference between sides in terms of grip force was demonstrated by the majority of studies (Rice 1998, Imrhan 1989, Mathiowetz 1986, Reikeras 1983). Furthermore, Schmidt and Toews (1970) noted that 28% of the subjects exerted higher grip force in the non-dominant hand. Therefore, the use of "10% rule" (the dominant hand is 10% stronger than the non-dominant hand) is not well supported.

Among factors that influence grip force, one can enumerate: gender (Richards, 1997, Desrosiers et al., 1995), age (Carmelli and Reed, 2000, Mathiowetz et al., 1985), tool handle surface (McGorry, 2001, Westling and Johansson, 1984), dynamometer setting, time between tasks (Netscher et al, 1998), intended use, object shape (Pryce, 1980), object weight and size (Kinoshita et al, 1996, Frederick and Armstrong, 1995), percentage of fibers activated, muscle cross-sectional area, total number of muscle fibers, fibre tension (Carmelli and Reed, 2000). All studies reported higher grip force values in males (Wallstrom and Nordenskiold, 2001, Dawson et al, 1998, Richards, 1997, Desrosiers et al, 1995).

Grip force is also influenced by body and upper extremity position (Berguer et al., 1998, Dawson et al., 1998, Keir et al., 1996, Martin et al., 1984, Teraoka, 1979). The American Society of Hand Therapists (ASHT) recommended that grip testing should be performed with the subject seated, with the shoulder adducted and neutrally rotated, elbow flexion of 90°, and the wrist in neutral position (Mathiowetz et al., 1985). Supination greater than 70° has been shown to decrease grip force (Martin et al., 1984, Teraoka, 1979). Even though grip force was not different in supine and sitting subjects (Martin et al., 1984, Richards, 1997), Teraoka (1979) obtained higher values for the latter posture. McPhee (1987) noted a tied relationship between hand ergonomic posture and its functional capacity. Wrist positions that promoted the highest grip strength were: 0° ulnar deviation and 15° extension, 15° ulnar deviation and 15° extension, 15° ulnar deviation and 0° extension, and 0° ulnar deviation without wrist extension (Pryce, 1980). Contrary to these findings, Fong and Ng (2001) obtained higher values at 15° or 30° wrist extension without ulnar deviation when compared to 0° or 15° ulnar deviation and 0°

extension. Changes in angles between tendons, as well as their compression against the carpal tunnel structures are caused by extreme wrist deviation. The risk of injury is increased even more when repetition and high forces are involved. Because of their smaller moment arms, extensor muscles are more likely to be injured during grips involving excessive wrist flexion (Keir et al., 1996). The passive forces present in antagonist muscles elevate the risk even more.

Grip force is decreased by pronation and increased or not affected by supination (Marley and Wehrman, 1992). These results are sustained also by Richards et al. (1996) who assessed grip force in supination as being the strongest followed by neutral position and pronation. The elevated values in supination may be due to biceps brachii' role in forearm stabilization (Fraser, 1980). Marley and Wehrman (1992) and Kuzala and Vargo (1992) reported significantly lower grip strength with 90° flexed elbow when compared to elbow extension. In contrast, Fan and Ng (1999) and Mathiowetz et al. (1985) noted that grip strength was higher at 90° elbow flexion than 130° flexion or extension.

Despite the fact that information regarding the grip force in different postures is available, there is a lack of data concerning the muscle overload while griping with the upper extremity in awkward postures. The aim of this study was to assess the effect of different wrist/forearm/elbow postures on maximum grip force application. Also, the relationship between wrist stabilizers muscles activity and grip strength exertion was studied.

5.4. Methods

5.4.1. Subjects

A total of twenty (10 males and 10 females) normal young adults participated in the study. The demographic data for the experimental sample were: mean age: 28.8 years (SD=4.8), mean height 170.4 (9.2) cm, and mean weight 70.2 (16.0) kg. All subjects were in good health, free of wrist/forearm/arm pain and without history of upper extremity musculoskeletal disorders. All subjects were right-handed. The volunteers read the information letter, and informed consent was obtained preceding the experiment. Ethics approval had been obtained from the Human Research Ethics Board.

5.4.2. Apparatus

5.4.2.1.Dynamometer. Jamar hand dynamometer was used. This recording system was calibrated by placing known weights on a platform connected to the dynamometer for linear response within the test range (maximum error 1% full scale).

5.4.2.2.EMG System. The EMG forearm muscle activity was measured using DelSys Bagnoly™ EMG system (surface electrodes, electrode cables, preamplifiers and amplifiers). The DE-2.1 Single Differential electrodes had 99.9% pure silver contacts for ion flow maximization. Preamplification at the EMG source and low impedance active output reduced signal noise. Electrode cables had all conductors protected in order to minimize line interference. The signals were collected at a frequency bandwidth of 20-450 Hz per channel, extremely low noise, less than 5 uV, and exceptionally low leakage currents, less than 10 uA.

5.4.3. Experimental design

The fixed (independent) variable was the upper extremity position. Dependant variables measured in this study were maximum grip force exertion and forearm muscles EMG activity.

5.4.4. Experimental procedure

A series of descriptive measurement (age, gender, weight, height, dominant hand) were recorded from each participant. Subjects were seated with both feet flat on the floor, knees angle at 90°, upright torso, and with shoulder adducted and neutrally rotated. For EMG recording, the examiner prepared the subject's forearm by shaving hair and cleaning with alcohol. Taking into account previous data indicating that from the five dynamometer's settings, the majority of research participants exerted maximum grip force when dynamometer's setting II was used (Firrell et al. 1996; Crosby et al. 1994), setting II was used for the Jamar dynamometer. Four EMG bipolar silver-silver chloride surface electrodes were used bilaterally ensuring minimum 2 cm between electrodes. Their positions were: 5-7 cm distal to the line connecting the medial epicondyle and biceps tendon for flexor carpi radialis (FCR), at 2-3 cm volar to ulna at the junction of the upper and middle thirds of the forearm for flexor carpi ulnaris (FCU), above the shaft of ulna in the middle of forearm for extensor carpi ulnaris (ECU), and at 3 cm medio-distal to lateral epicondyle for extensor carpi radialis (ECR). Figure 5.1 presents the experimental set-up.

The Maximal Voluntary Contractions (MVCs) test conditions were combinations of: wrist neutral position, maximal ulnar deviation, radial deviation, flexion, and extension (for hand position); forearm pronation and supination (forearm); elbow extension and 90° flexion (elbow). The neutral zone is defined as "the part of the range of physiological motion, measured from the neutral position, within which the motion is produced with a minimal internal resistance" (Kumar and Panjabi, 1995). Both right and left sides were tested. Volunteers had to maintain the designated upper extremity position for each tested contraction and to grip as hard as they could without modifying the joints deviation. Joints angles were monitored in order to ensure that each volunteer maintained maximal deviation for each posture. Participants were instructed to gradually build the force for 2 seconds until the maximum is reached, and then to maintain this level for another 3 seconds. The condition sequence was randomized in order to avoid the carry-over effect. No visual feedback was provided to volunteers during these force applications. Two maximum grip exertions (5 seconds each) were made in each upper extremity posture with the highest grip force value being included in the analysis. Between conditions a 2-minute resting period was given. Due to rest periods given, and taken into account the feedback received from the volunteers, one can assume that fatigue was not an issue. The tested conditions are presented in figure 5.2. The maximum grip force as well as forearm muscles' EMG activity were measured in all conditions twice for both arms resulting in a total 80 measurements.

5.4.5.Data acquisition

The Jamar dynamometer and EMG output were sampled at 1 kHz using a DAQ 700 National Instrument data acquisition card. The data collection was performed by a especially developed software that gathered data from all five (1 for grip force and 4 for EMG muscle activity) channels and subsequently stored them on a Toshiba laptop hard drive.

5.4.6. Data analysis

EMG peak values were normalized against the peak values obtained for each muscle in the position recommended by the American Society of Hand Therapists (ASHT) for grip force measurement (shoulder adducted, 90° elbow flexion and wrist in neutral position) (Mathiowetz *et al.* 1985). The processed data were statistically analyzed using SPSS 11.0 statistics software. The group data were subjected to one-way ANOVA with repeated measures in order to find the effect of upper extremity posture on maximum grip exertion and forearm muscles EMG activity. The Scheffe post-hoc analysis was not sensitive enough to discriminate between both force and EMG values, even though the general linear model indicated statistical differences between conditions. The least square difference (LSD) was used to differentiate between tested conditions. Also, differences between genders/sides in terms of grip strength and muscle activity were assessed. For significance, an alpha level of $p<0.05$ was chosen.

5.5. Results

5.5.1. Grip force. Wrist and forearm deviation had a statistically significant effect on exerted maximum grip force ($p<0.001$). The difference between grip values recorded while keeping the elbow at 0° and 90° flexion was not statistically significant for all ten forearm and wrist positions ($p>0.05$). Table 5.1 presents maximum grip strength for all tested conditions. The highest grip force was recorded while keeping the wrist in neutral position and forearm in supination for both females (29.03-36.20 kg) and males (61.92-70.90 kg). When compared to these values, keeping the upper extremity in wrist total flexion and forearm pronation caused a significantly lower grip force (14.28-18.98 kg for females and 23.46-27.21 for males) ($p<0.001$). The drop in maximum grip strength represented 53.3% and 64.5% for females, respectively males. Also, forearm supination with wrist flexion (19.38-20.33 kg for females and 28.39-32.06 kg for males) ($p<0.001$-$p=0.01$) and forearm pronation with wrist radial deviation (21.04-24.22 kg for females and 38.48-43.36 kg for males) ($p<0.001$-$p=0.033$) caused significantly lower grip force. Males exerted statistically significant higher force for all conditions ($p<0.001$-0.040). No differences were found between sides for all conditions and genders, data being pooled together.

5.5.2. EMG muscle activity. As expected, elbow flexion magnitude (0° and 90°) and forearm position (pronation and supination) did not have an effect on recorded forearm muscles (wrist stabilizers) EMG activity for both genders and sides. Wrist extension caused higher EMG activity in Flexor Carpi Radialis (FCR) (8.6-54.0% increase), Extensor Carpi Ulnaris (ECU) (7.1-56.1%), and Extensor Carpi Radialis (ECR) (14.2-43.0%) when compared to muscles activity in the normalizing condition. Similarly, an increase of 3.1-22.2% for ECU and 2.6-24.7% for Flexor Carpi Ulnaris (FCU), while exerting maximum grip strength in wrist ulnar deviation, was recorded. FCU was overloaded also by grip force application concomitant with total wrist flexion (7.7-39.6% increase), while wrist radial deviation had a similar effect on ECR activity, increasing its activity by 2.2-24.8%. Table 5.3 presents activity levels for muscles overloaded by deviated wrist postures. Gender did not have a statistically significant effect on muscle activity ($p>0.05$). Also, no differences were found between sides for all muscles and upper extremity postures.

5.6. Discussion and conclusions

The current study demonstrates the importance of proper upper extremity working postures during force applications. The highest grip force was obtained while the upper extremity was positioned in 90° elbow flexion, forearm supination, wrist ulnar deviation 0°, and extension 0°. Similar results were obtained by Marley and Wehrman (1992) and Agresti and Finlay (1986) who indicated supination as the forearm position promoting the highest grip force. Also, Pryce (1980) noted wrist neutral position as the position that led to the highest grip strength. Future job redesign should be promoted in order to incorporate this posture into tool use and task completion.

Significantly lower maximum grip force was recorded while the wrist was deviated. The significant drop in grip strength (34-64.5%) noted while positioning the upper extremity in forearm supination and pronation combined with total wrist flexion, and pronation with radial deviation emphasize the significant stress on musculoskeletal system during high-force exertion and demanding tasks. The effect of upper extremity deviated posture on maximum grip force is illustrated in figure 5.3. Our results are supported by Pryce (1980) and Kraft and Detels (1972) who also noted significantly lower values at 15° wrist flexion when compared to the wrist neutral position. Also, Lamoreaux and Hoffer (1995) and Terrell and Purswell (1976) indicated an 18% decrease in grip strength for fully radially deviated wrists. Contrary to these findings, O'Driscoll et al (1992) recorded highest grip strength in the 35+/-2° extension and 7+/-2° ulnar deviation. The non-significant difference between grip force generated by dominant and non-dominant hands noted in the present study is supported by the majority of studies (Rice at al, 1998; Imrhan, 1989; Mathiowetz et al. 1986). The fact that wrist deviation in any direction (ulnar and radial deviation, flexion and extension) caused decreased maximum grip force, regardless of elbow and forearm position, demonstrate that the closer the joint is to the hand, the more important is its impact on force production.

Not only wrist deviated postures decreased the maximum grip force, they also caused a significant increase in forearm muscles EMG activity. The effect of deviated upper extremity joints on maximum grip force application and EMG muscle activity for each tested conditions are presented in figures 5.4 and 5.5. The increased fatigue and MSDs' risk factors level while performing demanding tasks maintaining deviated upper extremity postures is illustrated by the significant drop in the capacity of exerting maximum grip force with accompanying increase in EMG forearm muscles' activity. For both genders, the decrease in grip force (35-64%) while keeping the wrist in flexion was associated with a 14-34% increase in FCU muscle activity. Also, grip force application in wrist extension was the most demanding condition. Three muscles (ECU, ECR, and FCR) presented increased EMG activities when compared to their activity when upper extremity was positioned in 90^{o} elbow flexion, forearm supination and wrist neutral position. The increased muscle activity for FCR (8.6-54.0% increase), ECU (7.1-56.1%) and ECR (11.2-43.0%) while the wrist was positioned in total extension showed their role in wrist stiffness when the joint is deviated in flexion-extension plane. The higher activity recorded for FCR in wrist extension (108.8-154.0%) compared to wrist flexion (71.3-118.0%) was due to its important role as joint stabilizer. The increased EMG activity recorded for FCU in both wrist flexion (up to 39.6% increase) and wrist ulnar deviation (up to 24.7%) exposes it to overexertion in activities that require grip force with wrist deviations (e.g. screwdriving). Also, owing to their increased muscle activity while gripping with the wrist deviated in extension and radial deviation (ECR) and extension and ulnar deviation (ECU), these muscles are at a considerable risk of injury in activities such as using a wheelchair and manoeuvring devices with oversized handles, respectively. One should bear in mind that the muscles studied in the current experiment acted as wrist stabilizers during grip force exertions and not as wrist movers. During industrial tasks, in which wrist deviation is performed against tool/device resistance, the forearm muscle activity is increased further. From the foregoing account it is clear that while the job demands remain unchanged a non-neutral posture decreases the workers' capacity but increases the effort required. Such repeated exertions are likely to accelerate the process of injury causation by increasing the loads on tissues disproportionately (Kumar, 2001).

Both contractile and passive components affect total muscle force production. This is also affected by muscle length (Keir et al., 1996). During manual task completion the upper extremity joints position should cause optimal length for the muscle(s) being used. L_o (optimal muscle length) is the length at which maximal isometric tension is exerted (Gordon et al., 1966, Close, 1972). Since tendon tissue has two orders of magnitude higher stiffness than that of the muscle tissue (Keir et al., 1996), the most part of the segment excursion is due to muscular tissue elongation. Because the angles of pennation in all forearm muscles, except flexor carpi ulnaris (FCU), are less than 10°, the differences in the passive force present in these muscles are not due to pennation variability (Keir et al., 1996). Precise force application is caused by balanced forearm muscles contractions. The maximum applicable muscle force is directly proportional to the physiologic cross-sectional area (Kozin et al., 1999) and is highly influenced by joints deviation.

The force produced during gripping is partially directed to stabilize the upper extremity (Richards, 1997). Wrist stiffness constitutes an essential condition for proper grip exertion. While flexing the fingers, the flexors' tendons, which traverse the wrist joint, increase the wrist stabilization. Given that fingers' flexor and extensor muscles have a dual role (intermediate joints stabilization and force exertion), variations in their total length cause decreased performance (Richards et al. 1996). Muscle resting length is the position in which cross-bridge attachments are at their maximum level. Therefore, moderate joint deviations increase grip force. With muscle length variations, there can be significant decrease in the number of muscle fibres' attachments resulting in a drop in exerted force. When the need for force application is doubled by a necessity of keeping the upper extremity in a stable position, less force may become available for generating grip force. Consequently, during task completion that requires increased force applications while keeping the wrist in awkward postures, the safer limits may be crossed sooner and repetitive exertion will tend to accentuate cumulative loading promoting musculoskeletal disorders development.

Almost all industrial tasks require positions different than the optimal one. Upper extremity deviated postures cause a significant drop in maximum grip force coupled with a significant increase in wrist stabilizers' activity. This clearly emphasises the risk level under which workers have to work. Ergonomics interventions targeting both device and job redesign are needed. Also, training program emphasizing the role of working posture on musculoskeletal disorders development would reduce the risk even more.

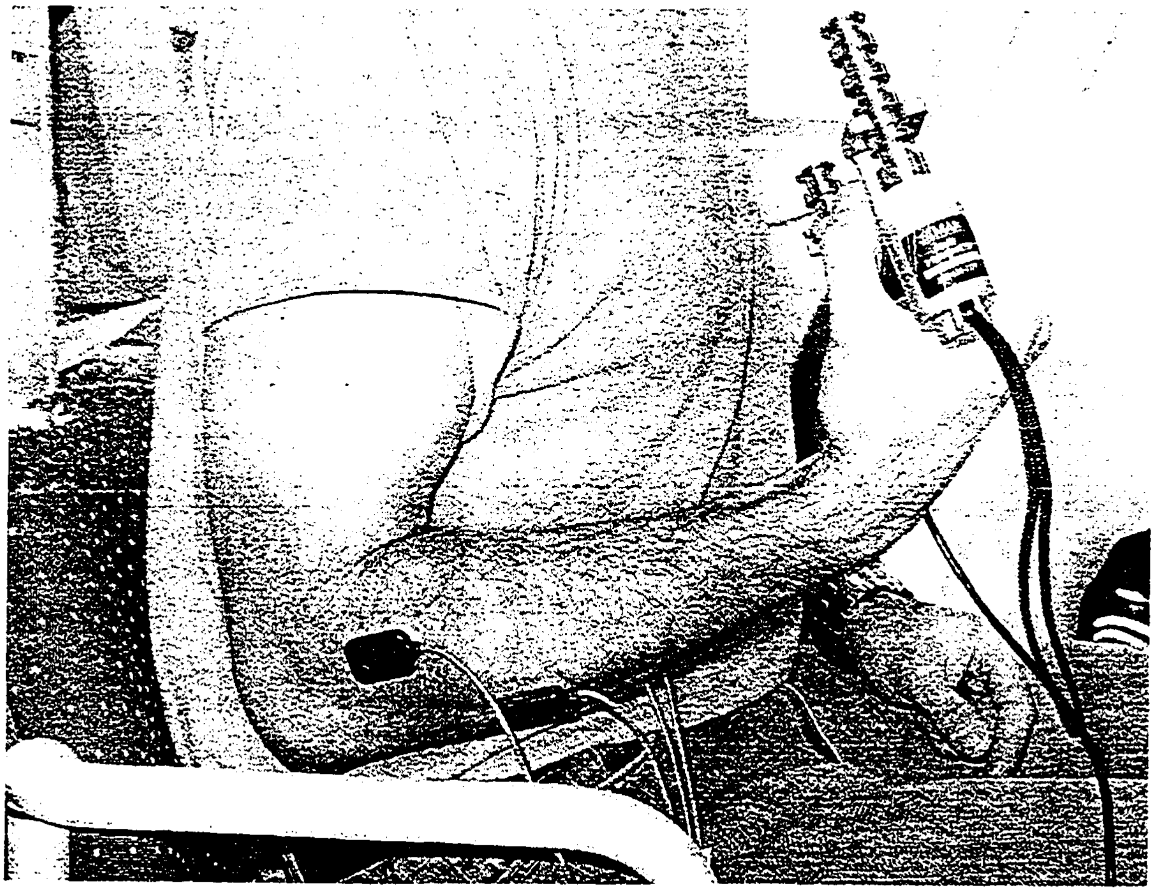

Figure 5.1. Experimental set-up.

The upper extremity position with 90^0 elbow flexion, forearm supination and maximum wrist flexion is presented.

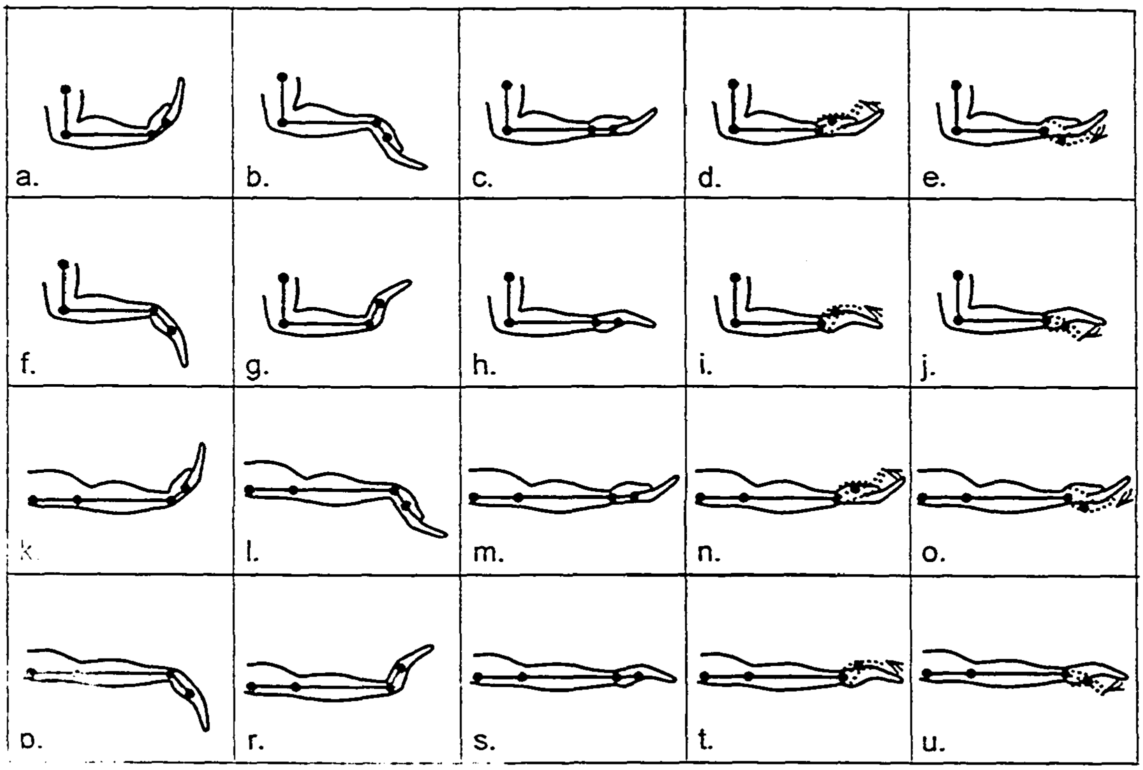

Figure 5.2. Upper extremity deviated postures tested in the study.

a. 90° elbow flexion, supination, wrist flexion; **b.** 90° elbow flexion, supination, wrist extension; **c.** 90° elbow flexion, supination, wrist neutral position; **d.** 90° elbow flexion, supination, wrist ulnar deviation; **e.** 90° elbow flexion, supination, wrist radial deviation; **f.** 90° elbow flexion, pronation, wrist flexion; **g.** 90° elbow flexion, pronation, wrist extension; **h.** 90° elbow flexion, pronation, wrist neutral position; **i.** 90° elbow flexion, pronation, wrist radial deviation; **j.** 90° elbow flexion, pronation, wrist ulnar deviation; **k.** 180° elbow flexion, supination, wrist flexion; **l.** 180° elbow flexion, supination, wrist extension; **m.** 180° elbow flexion, supination, wrist neutral position; **n.** 180° elbow flexion, supination, wrist ulnar deviation; **o.** 180° elbow flexion, supination, wrist radial deviation; **p.** 180° elbow flexion, pronation, wrist flexion, **r.** 180° elbow flexion, pronation, wrist extension; **s.** 180° elbow flexion, pronation, wrist neutral position; **t.** 180° elbow flexion, pronation, wrist radial deviation; **u.** 180° elbow flexion, pronation, wrist ulnar deviation.

Upper extremity position			Females		Males	
Elbow	Forearm	Wrist	Right	Left	Right	Left
0° flexion	Pronation	Extension	23.9 (6.3)	21.9 (6.6)	42.5 (15.5)	34.5 (16.1)
		Flexion	18.9 (6.1)	14.2 (6.0)	25.1 (9.0)	27.2 (11.1)
		Neutral	29.0 (8.8)	27.6 (7.7)	64.1 (24.4)	59.2 (18.4)
		Radial dev	21.5 (7.3)	21.0 (5.9)	43.3 (20.7)	38.4 (14.4)
		Ulnar dev	24.4 (8.8)	24.1 (6.2)	45.0 (17.0)	45.2 (20.2)
	Supination	Extension	25.5 (8.0)	22.6 (10.4)	54.5 (16.7)	45.3 (15.3)
		Flexion	19.3 (6.5)	20.1 (6.6)	30.9 (11.0)	28.3 (13.2)
		Neutral	36.2 (9.4)	29.0 (11.2)	70.9 (19.7)	61.9 (18.7)
		Radial dev	23.7 (8.7)	20.6 (3.8)	41.7 (13.0)	39.2 (10.5)
		Ulnar dev	24.8 (7.9)	20.2 (8.6)	48.9 (16.6)	43.4 (15.3)
90° flexion	Pronation	Extension	26.3 (7.4)	23.7 (7.1)	48.0 (15.7)	42.4 (12.2)
		Flexion	15.9 (6.8)	14.4 (6.2)	26.8 (9.1)	23.4 (11.3)
		Neutral	29.9 (9.0)	27.1 (8.5)	58.2 (14.7)	57.8 (17.9)
		Radial dev	24.2 (7.8)	21.6 (5.1)	41.9 (16.6)	39.2 (16.7)
		Ulnar dev	24.5 (8.9)	22.4 (8.3)	43.8 (14.9)	44.9 (19.1)
	Supination	Extension	26.0 (7.6)	24.2 (6.7)	48.5 (17.6)	45.2 (16.6)
		Flexion	20.3 (5.6)	19.5 (7.6)	32.0 (11.4)	30.3 (11.9)
		Neutral	34.0 (9.1)	30.3 (9.7)	64.0 (26.2)	62.3 (23.0)
		Radial dev	24.9 (8.3)	23.3 (5.2)	42.9 (16.0)	39.8 (13.4)
		Ulnar dev	27.8 (9.3)	24.1 (9.9)	49.0 (16.4)	41.2 (14.1)

Table 5.1. Maximum grip force (kg) for each upper extremity position

Wrist position	Muscle	Upper extremity position							
		180p		180s		90p		90s	
		Left	Right	Left	Right	Left	Right	Left	Right
Extension	ECR	F:114.0(41.5) M:136.5(53.1)*	F:143.0(58.7)** M:124.5(41.47)	F:114.2(42.9) M:126.4(58.9)	F:125.2(42.7)* M:114.4(53.8)	F:117.1(37.0) M:118.2(36.2)	F:124.1(32.4)* M:120.6(35.8)	F:113.7(29.3) M:120.2(43.2)	F:124.4(35.5)* M:131.7(43.3)**
	ECU	F:135.9(46.3)** M:156.1(73.8)**	F:126.8(51.8)* M:155.7(67.8)***	F:115.3(54.9) M:154.0(93.4)**	F:153.0(49.6)*** M:132.6(47.2)*	F:109.8(27.0) M:121.8(50.3)	F:125.9(52.7) M:130.5(52.9)*	F:107.1(33.5) M:122.0(74.1)	F:109.6(56.2) M:109.2(64.0)
	FCR	F:124.7(47.2) M:133.9(48.7)*	F:142.8(38.0)** M:108.7(59.8)	F:132.0(73.9)* M:120.1(35.4)	F:154.0(65.4)*** M:113.4(40.4)	F:146.5(51.3)*** M:131.0(46.6)*	F:125.7(56.6) M:113.1(40.0)	F:125.4(51.2)** M:126.2(51.9)	F:132.1(31.2)* M:108.0(35.6)
Flexion	FCU	F:129.4(56.4)* M:108.3(50.6)	F:123.1(58.1) M:120.5(55.5)	F:139.6(68.7)** M:112.6(60.8)	F:130.1(88.35) M:131.9(40.38)*	F:118.7(46.7) M:114.9(41.3)	F:129.3(51.0)* M:133.6(42.43)*	F:130.5(34.0)* M:107.7(50.7)	F:124.0(53.8) M:122.7(36.3)
Radial deviation	ECR	F:112.2(52.9) M:104.1(49.7)	F:115.4(43.8) M:106.4(23.6)	F:102.3(62.2) M:108.7(62.4)	F:124.8(35.0)* M:106.5(51.4)	F:112.7(63.5) M:111.0(62.4)	F:119.9(42.0) M:105.5(35.2)	F:108.7(34.1) M:132.7(42.2)*	F:105.1(30.8) M:114.5(51.9)
Ulnar deviation	FCU	F:109.6(38.22) M:105.7(51.5)	F:115.0(37.4) M:106.9(36.6)	F:116.6(56.0) M:105.8(46.3)	F:107.9(38.3) M:121.9(65.7)	F:116.2(48.1) M:105.8(24.9)	F:130.9(34.1)* M:134.7(40.4)*	F:108.9(41.6) M:102.6(21.7)	F:130.0(32.0)* M:133.9(48.5)*
	ECU	F:131.9(35.8)* M:105.6(42.1)	F:129.4(36.4)* M:108.5(24.1)	F:104.0(37.8) M:115.5(44.7)	F:111.0(45.5) M:103.1(35.2)	F:114.3(49.0) M:132.2(48.7)*	F:108.7(44.2) M:127.5(36.0)*	F:110.0(45.2) M:116.5(57.3)	F:108.6(40.5) M:103.4(55.3)

Table 5.3. Normalized peak EMG activity for muscles overloaded by deviated wrist postures, where 100=muscle activity in the reference condition (90° elbow flexion, supination and wrist neutral position)

ECR=Extensor Carpi Radialis; ECU=Extensor Carpi Ulnaris; FCR=Flexor Carpi Radialis; FCU=Flexor Carpi Ulnaris; 180=extended elbow; 90=90° elbow flexion; p=pronation; s=supination; F=females; M=males.
*=difference significant at 0.1 level
**=difference significant at 0.05 level
***=difference significant at 0.01 level

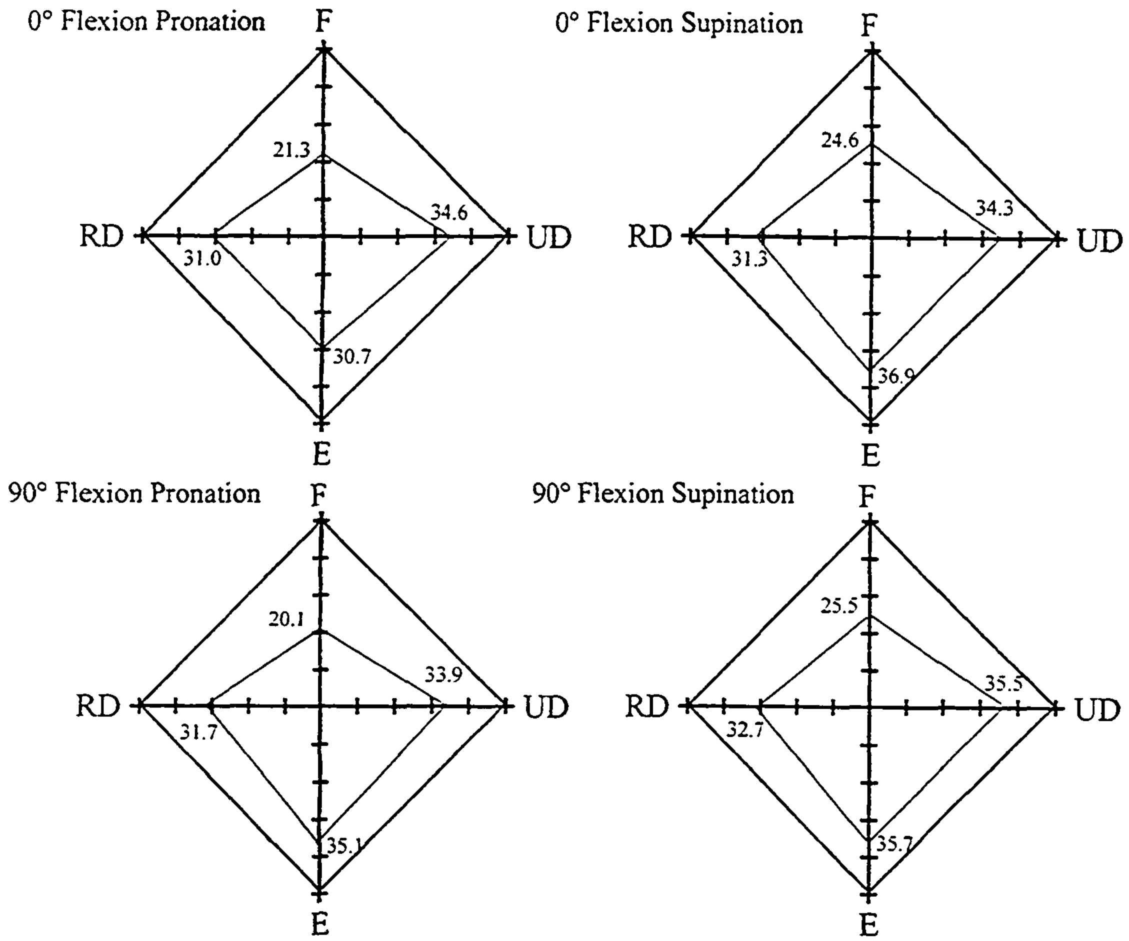

Figure 5.3. Gripping force in upper extremity deviated postures when compared to the reference posture (90^0 elbow flexion, supination and wrist neutral position) (49.65 kg)

*F = wrist flexion; E = wrist extension; RD = wrist radial deviation; UD = wrist ulnar deviation

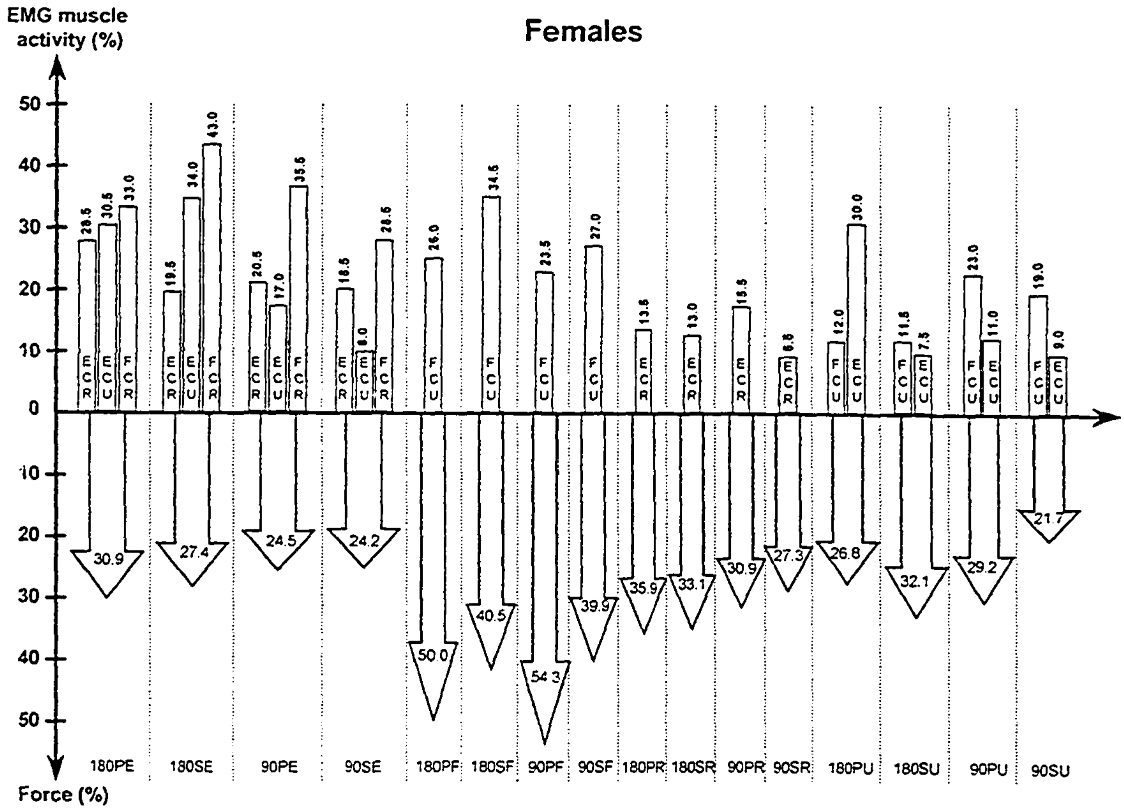

Figure 5.4. The effect of upper extremity deviated postures on maximum grip force application and EMG muscle activity for muscles that presented an increase in activity in females when ASHT position (90^0 elbow flexion, forearm supination and wrist neutral position) is used as reference.

*180 = 180^0 elbow flexion; 90 = 90^0 elbow flexion; P = pronation; S = supination; E = wrist extension; F = wrist flexion; R = wrist radial deviation; U = wrist ulnar deviation.

**ECR = Extensor Carpi Radialis; FCR = Flexor Carpi Radialis; ECU = Extensor Carpi Ulnaris; FCU = Flexor Carpi Ulnaris.

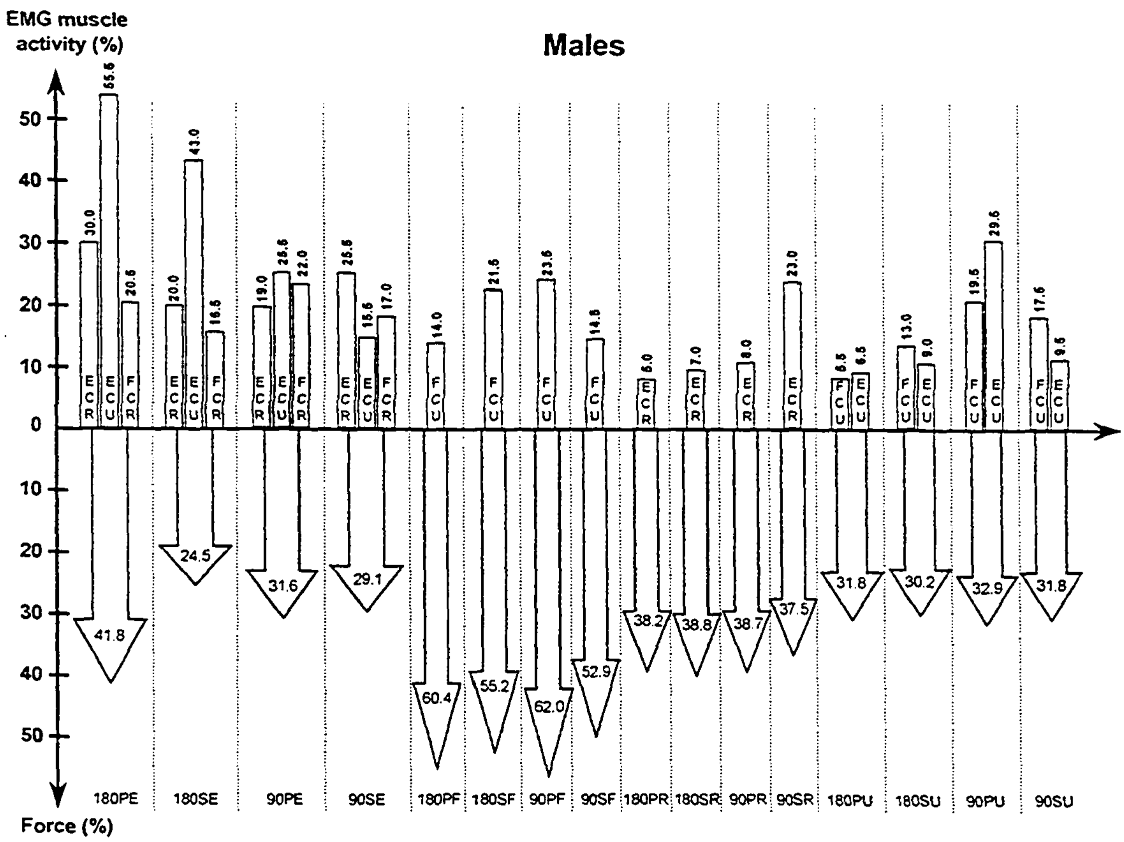

Figure 5.5. The effect of upper extremity deviated postures on maximum grip force application and EMG muscle activity for muscles that presented an increase in males when ASHT position (90^0 elbow flexion, forearm supination and wrist neutral position) is used as reference.

*180 = 180^0 elbow flexion; 90 = 90^0 elbow flexion; P = pronation; S = supination; E = wrist extension; F = wrist flexion; R = wrist radial deviation; U = wrist ulnar deviation.

**ECR = Extensor Carpi Radialis; FCR = Flexor Carpi Radialis; ECU = Extensor Carpi Ulnaris; FCU = Flexor Carpi Ulnaris.

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Chapter 6

The prevalence of musculoskeletal symptoms among office workers

6.1. Abstract

Due to the increase in computer keyboards following the replacement of intensive industrial tasks with automated operations, the prevalence of musculoskeletal symptoms and complaints have been increasing. Also, in many cases, the daily office work is doubled at home by an increased time spent in computer related activities (e.g. shopping, games, tax returns, internet browsing, etc), elevating even more the risk of musculoskeletal injuries. To quantify the magnitude of the problem, a survey was conducted. It assessed the prevalence of musculoskeletal disorders' symptoms , their intensity and interaction with ability to work among office workers. The Cornell Musculoskeletal Discomfort Questionnaire and Cornell Hand Discomfort Questionnaire developed by the Human Factors and Ergonomics Laboratory at Cornell University were used on a sample of 140 office workers. 86.5% for the left side and 95.5% for the right side reported discomfort/pain/ache at the wrist level, 77.5% for neck and 31% for the left side and 50% for the right side in the shoulder region. At the hand site, the area in the distal proximity of the wrist was the most affected site being indicated in 90% of cases for left side and 95% of cases for the right side. Having a compete overview of body segments that are affected by office work, future design modifications can be targeted towards these areas.

Keywords: Office work; Musculoskeletal symptoms; Upper extremity; Survey;

6.2. Introduction

Due to the continuous industry automation, there is an increase in the proportion of working time spent in a static posture and an increase in the repetitive movements (Bergamasco et al, 1998). Therefore a concentration of efforts to develop the background knowledge for targeted ergonomic interventions is needed. The shift in job characteristics caused a sharp increase in the time spent working in computer-related tasks.

Due to extensive computer usage, increase in musculoskeletal disability among data entry workers was reported (Sauter et al., 1991). This includes Work Related Upper Extremity Disorders (WRUED) like: Carpal Tunnel Syndrome (CTS), De Quervain's Disease, epicondylitis and shoulder disorders (Lincoln et al., 2000). Musculoskeletal symptoms are common among data entry personel and may be linked to both workstation ergonomic configuration as well as psychosocial factors such as elevated stress, time constrains, decision making (Hagberg et al., 1995; NIOSH, 1997; Bongers et al., 2002)

Although several names are used for job-related injuries (Cumulative Trauma Disorders, Work Related Musculoskeletal Disorders, Repetitive Motion Injuries, Repetitive Strain Injuries), they all reflect the causal relationship between work and musculoskeletal problems. Moreover, the general early symptoms are similar among different disorders affecting the same body areas.

Previous studies reported association between computer work and pain and/or discomfort in different upper extremity regions (Hagberg, 1995; Aaras et al., 1998; Jensen et al., 2002). The keyboard design has been proven to influence the typing position modifying the shoulder rotation, forearm supination and wrist angle of deviation in both ulnar-radial deviation and flexion-extension planes (Hedge and Powers, 1995; Honan et al., 1995; Smith et al., 1998; Marklin et al., 1999; Tittironanda et al., 1999; Marklin and Simoneau, 2001). Also, using numeric keypads requires the operator to position the shoulder in greater abduction in order to fit the workstation design (Cook and Kothiyal, 1998). All these awkward working postures combined with the need for typing for long periods of time without having microbrakes, increase the risk of presenting musculoskeletal symptoms followed by injury development. The neck and upper extremity are the most exposed areas for musculoskeletal problems in data entry operators (Sauter et al., 1991). The highest risks are for hand, wrist and arm (Rempel et al., 1999; Sauter et al., 1991). Excessive wrist extension or flexion (Marklin et al., 1999) is present in different degrees depending on the type of keyboard used (slope angle). Also, ulnar deviation occurs indirectly as a compensation of the arm abduction, and directly due to the need to reach the far left or right keys (Marklin et al., 1999; Werner et al., 1997). Also, workstation configuration (desk height, chair design, computer screen angle) has an important effect on the neck and back stress level.

Continuing to work without any complaints in a poorly designed workstation/job causes a loss in productivity because the need for spontaneous breaks in order to mitigate the pain cannot be overlooked (Moore, 1995). Primary ergonomic interventions (e.g. introduction of microbrakes, task rotation and, device redesign) that address the problem before it appears can decrease the productivity loss. Moreover, they are superior in effectiveness and costs when compared to secondary interventions (Viikari-Juntura and Riihimaki, 1999).

The actual study provides a complete overview of the musculoskeletal disorders symptoms prevalence and their exact characteristics (intensity level, localization, their effect on work performance, etc) among office workers. The outcome will help in targeted ergonomic interventions. The following research questions will be addressed:

- What are the body parts and hand regions exposed at highest risk due to computer work?
- Does the presence of discomfort/pain in a certain area interact with the subject's work ability?
- What is the effect of age, hours per day working an a PC, percentage of time working on a keyboard, hours per shift and years of experience on the presence/absence of musculoskeletal symptoms on various body regions and hand areas as well as .symptoms intensity level and their interaction with subjects' ability to work?

6.3. Methods

6.3.1. Subjects

All employees performing extensive typing in an important Canadian telecommunication company were potential subjects for the study. The questionnaires were mailed out to the researcher on site. Sample size calculation: $\alpha = 0.05$, $\beta = 0.20$, E.S. = 0.40; 3 variables and 8 conditions $\Rightarrow$ 24 cells; $n_c = [(n'-1)(u + 1)/\text{nr of cells}] + 1$; $u = (\text{variables}-1)(\text{conditions}-1) = (3-1)(8-1) = 14$; $n_c = [(11-1)(14+1)/24] + 1 = 7$ subjects/cell; Total subjects required = 112 subjects.

Out of the 140 potential subjects, 89 questionnaires were returned completed, accounting for a response rate of 69.6%. The female to male ratios were similar in the respondent and non-respondent groups, making the data representative of the population under study. Data regarding non-respondents (22 women with a mean age of 25.5 years and 29 men with a mean age of 25.1 years) were provided by the company. There were 39 women (mean age: 24.8 years, range: 19-40 years) and 50 men (mean age: 23.5 years, range: 19-49 years). Based on the assumption that the population under study was homogenous, the non-respondents were considered to be similar to the respondents. Subjects included in the study met the following inclusion criteria: computer usage of at least 4 hours/day and 5 days/week, touch-typing ability and ability to read and write English well. All these inclusion criteria were part of the requirements for the job in which they were employed. The volunteers read the information letter preceding the investigation. Ethics approval was obtained from the Human Research Ethics Board.

6.3.2. Experimental procedure

The volunteers read the Information form. They were explained the 4-page questionnaire. The Cornell Musculoskeletal Discomfort Questionnaire and Cornell Hand Discomfort Questionnaire developed by the Human Factors and Ergonomics Laboratory at Cornell University were used in order to gather data from office workers. The questionnaires begun with a few demographic questions regarding gender, age, hand dominance, years of practice, number of hours per shift, percentage of work spent typing. Also a question regarding their knowledge of proper ergonomic settings for the workstation was included. Appendix 1 contains the administered questionnaires. Subjects were allowed to spend as much time as they needed to answer each question and, any concerns/questions that aroused during the experiment were answered by the researcher on site. The subjects were not able to consult other responses or to discuss with other volunteers before or during the study. This was avoided by having all the participants filling in the questionnaires in the same time in cubicals.

6.3.3. Data analysis

All categorical answers for every subject were entered into a SPSS spreadsheet and encoded with numerical values. Mean and standard deviation (SD) were used to present the demographic data such as age, number of years of experience, hours per shift, percentage of work time spent typing. Data regarding prevalence of symptoms, as well as their intensity and impact on job tasks were presented as percentages of subjects reporting pain/discomfort for each hand region and body part. Ordinal regression was used in order to assess the effect of age, hours per day working an a PC, percentage of time working on a keyboard, hours per shift and years of experience on the presence/absence of musculoskeletal symptoms on various body regions and hand areas as well as symptoms intensity level and their interaction with subjects' ability to work. Both significance level and odd ratios are reported. Data were coded by assigning numbers to the answers and were analysed using the SPSS software. An alpha level of 0.05 was chosen.

6.4. Results

The percentage of respondents indicating symptoms for each body part and hand region, as well as the symptoms' intensity and their interaction with ability to work (the need for taking a break due to the presence of dicomfort/pain presence) are presented in tables 6.1 and 6.2. Neck, shoulder, low back and wrist were the body regions with the highest prevalence of musculoskeletal disorders' simptoms. For neck, 77.5% of the subjects reported symptoms with 7.9% having one or more than one episode of discomfort/pain per day. 34.8% of respondents reported an interaction between symptoms presence and their ability to work. At the shoulder level 30.3% (for the left side) and 49.4% (for the right side) of the respondents reported pain, with 14.6% (left) 21.3% (right) of them having moderate or very uncomfortable levels. In 15.7% of cases, work was affected and performance impaired. Wrist was the body part with the highest prevalence of musculoskeletal symptoms. 95.5% of the respondents for the right side and 86.5% of the respondents for the left side reported pain/discomfort/ache. In as many as 33.7% (for the left side) and 44.9% (for the right side) of cases, work was affected by the presence of musculoskeletal symptoms at this level.

Also, the thenar area and the area distal to the wrist were the hand regions with the highest prevalence of ache/pain/discomfort. As many as 90% for left side and 95% for the right side of the subjects indicated area F (distal border of the wrist) as the site for musculoskeletal disorders symptoms, with 48% for the right side and 58% for the left side for females and 38% for the right side and 30% for the left side for males having work ability decreased by the symptoms. These figures relates to the ones above in which similar MSDs' symptoms prevalences and percentage of workers reporting work ability being afected by the presence of symptoms were found.

The effect of age, hours per day working an a PC, percentage of time working on a keyboard, hours per shift and years of experience on the presence/absence of musculoskeletal symptoms on various body regions and hand areas as well as symptoms intensity level and their interaction with subjects' ability to work was assessed running an ordinal regression in SPSS. Age, hours of PC work per day and hours per shift did not have a statistically significant effect on the presence of musculoskeletal symptoms, their intensity level, and ability to work ($p>0.05$).

Both percentage of total working time using a keyboard ($p<0.001$, OR = 0.033-0.086) and number of years of experience ($p=0.002$, OR = 0.149-0.645) had a statistically significant effect on the presence of musculoskeletal symptoms at the neck area. Also, they had a statistically significant effect on neck symptoms' intensity level ($p<0.006$, OR = 0.014-0.086 and $p<0.014$, OR = 0.072-0.624, respectively) and their interaction with work ability ($p<0.001$, OR = 0.055-0.153 and $p=0.002$, OR = 0.179-0.799, respectively). For the shoulder level, musculoskeletal symptoms presence was statistically significant influenced only by the percentage of total working time spent using a keyboard ($p=0.003$, OR = 0.014-0.068). Also, the same variable had a statistically significant effect on symptoms intensity at the shoulder level ($p=0.025$, OR = 0.007-0.100) and symptoms-work interaction ($p=0.011$, OR = 0.016-0.129). At the wrist level, the percentage of total working time spent typing had a statistically significant effect on the presence of musculoskeletal symptoms for both right and left hands ($p=0.05$, OR = 0.001-0.052 and $p=0.014$, OR = 0.007-0.059, respetively). Wrist symptoms intensity and ability to work were not affected by the percentage of total working time spent typing ($p>0.05$).

From the six hand areas included in the questionnaire, only at the area F (the area surrounding the distal border of the wrist) level, the symptoms presence was statistically significant influenced by the percentage of total working time spent typing ($p=0.001$, OR = 0.19-0.076 for the right hand and $p=0.025$, OR = 0.005-0.068 for the left hand). Also, at the right side, both symptoms' intensity level and symptoms-work ability interaction were influenced by the percentage of time typing ($p<0.001$, OR = 0.032-0.104, and p=0.004, OR = 0.016-0.080, respectively). For the other hand areas (A to E), the effects were not statistically significant (p>0.05).

6.5. Discussion

Several limitations existed in this study. Not meeting the sample size calculation requirements, the results of this study cannot be generalized due to decreased external validity. Also, it is possible that office workers with symptoms were more likely to respond, yielding an overestimate of musculoskeletal symptoms prevalence. On the other hand, is is possible that workers present in the tested job positions at the moment of this survey to be the ones who managed to adapt to specific tasks' requirements (awkward postures, repetitive movements, or extensive force application) and to reduce the number of recorded symptoms. Also, psychosocial stress has not been addressed although the relationship between job satisfaction, lack of job control, lack of social support by colleagues, working under deadlines and musculoskeletal disorders development has been demonstrated. There is a posiblity that the most stressed people, unsatisfied with their job, participated.

The study outcome demonstrate that in a population of office workers, the most exposed body parts for development of MSD are the neck, left and right shoulder, lower back and wrist. Not having a comparison group (a group of people with the similar characteristics who are not exposed to office work), one cannot infer that the symptoms are entirely attributed to working on a PC. The fact that symptoms are grouped by body regions (neck, shoulders, upper back and low back and hips) demonstrate that interventions, although have to be targeted to certain problematic body regions, should be designed in order to address the body as an interconnected structure with joints and muscles that tend to compensate when adjacent structures are deviated and/or contracted. The actual study just noted the presence of symptoms (discomfort/pain) in bordering body regions. In order to develop ergonomic interventions that would address the affected areas, one should carry out biomechanical analysis of joints position during office task completion.

Every company, where people are forced to perform for a prolonged period in awkward postures or under repetitive patterns, should act in order to reduce the level of risk factors for MSD. Primary interventions such as detection of risk factors and addressing them before the injury occurence are preferred in both terms of money and time compared to secondary interventions (e.g. treatment) that involve lost work days, training for the new workers and compensations. In addition to risk factors assessment, training programs that would increase the awareness level are needed.

All the respondents who indicated that ability to work was impaired continue to work ignoring the symptoms and considering the pain as part of their job. Although it might seem expensive at the beginning, implementing training programs and measures that would address the associated risk factors, would decrease the number of days lost to injury abd associated claim expenditures.

Having the area E and F (thenar eminence and distal border of the wrist) as the sites with the highest prevalence of MSD symptoms, demonstrate the important impact of keyboarding on upper extremity structures, especially distal joints. Less than 50% of the respondents had adjustable keyboard/mouse. The absence of adjustable imput devices might have played an important role in the presence on symptoms in the tested group. Only adjustable devices are able to fit the wide pallete of anthropometric characteristics and to decrease the risk of excessive wrist extension and ulnar deviation. Future research should look into the differences between MSDs symptoms prevalence levels for data entry workers with and without adjustable devices.

Although 87.6% had adjustable chairs, low back was one of the body regions with the highest incidence of MSD symptoms prevalence (70% for females and 80% for males). This might be due to the fact that 66.3% of the subjects did not know how to adjust and set-up their workstations in order to meet the ergonomic guidelines.

The job related risks are doubled by repetitive leisure activities with more than two thirds of the respondents (67.4%) using the home computer on a regular basis. Only accompanying the redesign interventions with training programs that would explain the necessary modifications, one would persuade workers to adapt the same changes on their home computers (e.g. split keyboard with negative slope, knee, hip and elbows at 90°, mouse close to the keyboard in order to reduce shoulder abduction and external rotation).

Future research should look into the effect of work related-psychological stress on MSDs symptoms prevalence level. Also, comparing the symptoms prevalence and intensity between work settings with different workstation layout would provide useful data regarding the necessary desk and keyboard modifications.

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Region	Ache/pain/discomfort frequency					Intensity level			Interference with work		
	Never	1-2/w	3-4/w	1/day	>1/day	Slightly uncomf.	Moderately uncomf.	Very uncomf.	No	Slightly	Substantially
Neck	22.5	48.3	13.5	7.9	7.9	31.5	33.7	12.4	42.7	28.1	6.7
Shoulder right	50.6	38.2	2.2	2.2	6.7	29.2	14.6	6.7	33.7	11.2	4.5
Shoulder left	69.7	20.2	2.2	2.2	5.6	20.2	10.1	4.5	22.5	7.9	4.5
Upper back	64.0	21.3	2.2	5.6	6.7	15.7	15.7	6.7	20.2	15.7	2.2
Upper arm right	82.0	12.4	5.6	0	0	10.1	5.6	4.5	10.1	7.9	2.2
Upper arm left	91.0	5.6	3.4	0	0	7.9	1.1	2.2	6.7	2.2	2.2
Lower back	25.8	44.9	12.4	9.0	7.9	20.2	42.7	12.4	34.8	36.0	4.5
Forearm right	84.3	10.1	1.1	0	4.5	10.1	3.4	4.5	12.4	3.4	2.2
Forearm left	87.6	10.1	0	0	2.2	10.1	2.2	2.2	11.2	2.2	1.1
Wrist right	4.5	58.4	29.2	4.5	3.4	31.5	58.4	7.9	55.1	40.4	2.2
Wrist left	13.5	60.7	21.3	2.2	2.2	42.7	42.7	5.6	66.3	23.6	1.1
Hip/Buttocks	73.0	15.7	6.7	1.1	3.4	15.7	9.0	4.5	24.7	2.2	2.2
Thigh right	92.1	2.2	2.2	0	3.4	6.7	1.1	2.2	5.6	2.2	2.2
Thigh left	92.1	2.2	2.2	0	3.4	6.7	1.1	2.2	5.6	2.2	2.2
Knee right	80.9	9.0	4.5	0	5.6	6.7	12.4	2.2	7.9	13.5	21.3
Knee left	80.9	10.1	3.4	1.1	4.5	5.6	11.2	2.2	5.6	13.5	0
Lower leg right	91.0	4.5	1.1	2.2	1.1	6.7	4.5	0	5.6	5.6	0
Lower leg left	89.9	5.6	1.1	2.2	1.1	6.7	5.6	0	9.0	3.4	0

Table 6.1. The percentage of respondents indicating symptoms for each body part, symptoms' intensity level and their interaction with work performance

Hand area	Ache/pain/discomfort frequency					Intensity level			Interference with work		
	Never	1-2/w	3-4/w	1/day	>1/day	Slightly uncomf.	Moderately uncomf.	Very uncomf.	No	Slightly	Substantially
A right	87.6	5.6	0	1.1	5.6	5.6	4.5	2.2	5.6	2.2	4.5
A left	95.5	0	0	2.2	2.2	0	2.2	2.2	0	2.2	2.2
B right	84.3	11.2	0	0	4.5	6.7	7.9	1.1	9.0	2.2	4.5
B left	94.4	1.1	0	2.2	2.2	0	3.4	2.2	0	3.4	2.2
C right	85.4	4.5	4.5	3.4	2.2	3.4	9.0	2.2	5.6	9.0	0
C left	91.0	4.5	2.2	0	2.2	2.2	6.7	0	2.2	4.5	2.2
D right	74.2	18.0	2.2	3.4	2.2	13.5	12.4	0	15.7	10.1	0
D left	91.0	5.6	2.2	0	1.1	5.5	3.4	1.1	4.5	3.4	1.1
E right	58.4	32.6	3.4	2.2	3.4	20.2	22.5	1.1	32.6	10.1	1.1
E left	84.3	10.1	4.5	0	1.1	5.6	9.0	1.1	7.9	6.7	1.1
F right	4.5	66.3	19.1	9.0	1.1	27.0	66.3	3.4	58.4	34.8	3.4
F left	10.1	78.7	10.1	0	1.1	51.7	34.8	3.4	69.7	16.9	3.4

* Area A: index, middle finger and the medial half of the ring finger
Area B: lateral half of the ring finger and the fifth finger
Area C: thumb
Area D: the palmar side of the hand bordered by the metacarpophalangeal joints (distal) and the thenary and hypothenary eminences (proximal)
Area E: thenary eminence
Area F: the distal border of the wrist

Table 6.2. The percentage of respondents indicating symptoms for each hand region, symptoms' intensity level and their interaction with work performance

Chapter 7

General Discussion and Conclusions

After an extensive literature review and in the view of the thesis' outcome (the presence of MSD risk factors due to bad design in office work, muscle imbalance present while performing industrial tasks such as gripping with deviated joints, musculoskeletal disorders symptoms prevalence among office workers), the causal relationship between work and MSD, especially UEMSD is evident. Atributes such as temporal sequence (first the cause, followed by the effect) and dose-response relationship constitute strong proof of the effect of bad design on MSD development. Also, targeted ergonomic interventions succeded in reducing lost work days and claims, followed by an increase in productivity.

As shown by the study assessing forearm muscle activity in different wrist deviated postures versus neutral positions, even when no external force was applied, there is a significant difference in forearm muscle activity between deviated postures and neutral position (3-5° ulnar deviation, 7-9° extension). The difference is expected to increase even more during occupational tasks, especially industrial tasks, where all the movements are performed against external resistance. The need for promoting safe working postures is evident.

As demonstrated by the study addressing wrist neutral zone, wrist position with minimum internal resistance was when the wrist was extended 7-9° and ulnarly deviated to 5-7°. The muscle activity was significantly lower when compared to wrist deviated positions, even when external resistance was absent. This position is the area that should be targeted when typing or handling various tools while performing industrial tasks. Moreover, when the wrist is deviated beyond the safe limits (neutral zone) for a prolonged time, both hand force and precision are affected due to a change in the angles between muscles involved as primary movers and stabilizers. In view of these findings, keyboards with split angle and lateral slope are recommended for any office setting. This would ensure a decreased muscle load on ECU and FCU when wrist ulnar deviation will be kept within neutral zone margins, and on ECU and ECR consequent to wrist extension reduction. The decrease in forearm muscles activity following the reduction in wrist deviation, is due not only to the need of lesser force in order to maintain the wrist in a more ergonomic position, but also, to the fact that the closer a joint is to the neutral posture, the lesser the muscle load is required to generate a certain force.

In the keyboard studies included in the thesis, none of the keyboards presented all the advantages of ergonomic modifications. When ulnar deviation was reduced, performance (e.g. Maltron), or wrist extension (e.g. Goldtouch) were an issue, when performance was maintained at higher levels, wrist deviation in both planes was not reduced. Designing a keyboard that would use all of the findings described in the above mentioned studies (split design, negative slope, QWERTY layout, lateral slope, keys row curvature) would ensure a safe typing technique. Even safe activities performed for a prolonged time an a daily basis become unsafe, so job task alternation or stretching exercises would be a valuable addition.

Keyboard dramatic changes are not desired since their initial acceptance is shadowed by poor typing performance. Also, when typists are forced to work on a keyboard completely different than the one they are used to (e.g. Maltron design vs. the QWERTY conventional design), they tend to use only a group of fingers (index and middle fingers) and to apply a typing force 3-5 times higher. Increase in localized pressure at the fingertip and hand joints follows.

The improvement in typing posture (reduction of 25-30% in the number of errors and increase of 48% in typing speed) recorded after a relative short training session (8 hours) demonstrate that if alternative keyboard designs retain the necessary design modifications without incorporating drastic reshaping changes, they are valid candidates in replacing the actual outdated conventional keyboard in the near future. The increase in performance is doubled also by a reduction in wrist repetitive movements. A better knowledge of the keyboard layout and design features would ensure less hand movements for key hunting.

It is better to provide sufficient training prior the implementation of new keyboard designs. Although there will be a delay in the beginning, and the tasks will be delayed, the consequent advantages are evident. Not only typing speed would be improved but also there will be an important alleviation in the stress level and increase in confidence followed by a reduction in the overall applied force when typing. This is demonstrated in Chapter 4 when training caused a drop in overall typing force of 58% for Goldtouch and 42% for the Maltron keyboard. The results from Chapters 2, 3 and 5 point towards the same optimal hand posture. In order to reduce the risk of MSDs one should try to perform within the joint neutral zone. By doing this, the number of peoples reporting discomfort/pain in the wrist area (Chapter 6) related to work would decrease.

The closer is a joint to the force exertion site, the bigger is its deviation impact on force magnitude. This relation could be seen in Chapter 5 when wrist and forearm deviation had a statistically significant effect on exerted maximum grip force. The same relation is expected to be present in office work with the fingers and wrist deviation closely related to typing precision and overall applied typing force. The more time is spent within the ROM's safe limits (neutral zone), the lesser are the chances for developing CTD. The difference between force exertion magnitude in neutral and deviated positions for a certain joint is increased with the increase in external applied resistance. Special attention should be paid when designing tools/devices, especially in industrial settings where external resistance is always present and workers are forced to work in awkward postures.

In view of the findings that the middle finger is the strongest and the little finger is the weakest, while using cross-action tools, the small finger is the most exposed having the longest lever arm, while the index finger has the shortest lever arm. A safer technique would be to use a reversed grip reducing the risk of injury.

Research data is worthless unless it meets certain requirements (reliability and validity). In order to ensure that data used reflects the real variables being measured (e.g. symptoms prevalence, range of motion, productivity, pain level) one should simultaneously use various data collection procedures (triangulation). Only in this way research errors could be minimized and validity and reliability maintained at high levels.

In order to be efficient, ergonomic interventions should be based on solid data with direct application in the field. Although more expensive, it is desirable to collect data instead of using already gathered one (databases). In this way, the researcher is capable of customizing the research design and measured variables according to the job/device intervention final goal.

All in all, the formula for successful ergonomic interventions comprises of a thorough understanding of the occupational health and safety problem, customization of research design and data collection technique according to the final goal, implementation of the data at the worksite along with training programs for workers that would ensure an understanding of the problem and a higher acceptability of the new job structure and/or device redesign.

APPENDIX I

OFFICE ERGONOMIC QUESTIONNAIRE

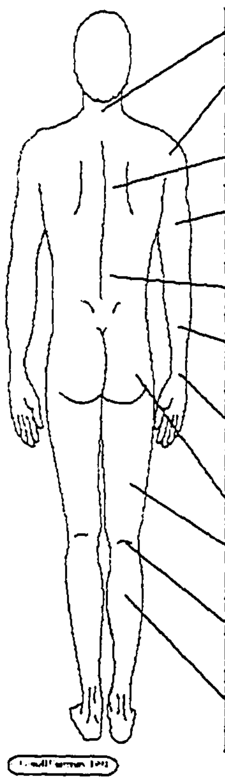
Employee Name: _____________ **Department:** _______________
Location: Room _______, Building ________ **Date:** __________

List of Current Ergonomic Tools/Furniture - Chair Adj.__ or Non-Adj. __, (Adj. Armrests)__; Desk Type _____________; Soft Keyboard and Mouse Wristrests ___; Adj. Keyboard and Mouse tray ___; Monitor Risers ___; Non-Adj. keyboard/mouse tray ___; Footrest ____; Headset _________; Other ____.

Brief Job Task Description - Works on PC __ hours a day requiring __% keyboard and __% mouse work. Intensive telephone or filing work ____. #Hrs. on job _____. Current job __ yr. Past job w/PC __ yr. Bifocals ___. Other ____.

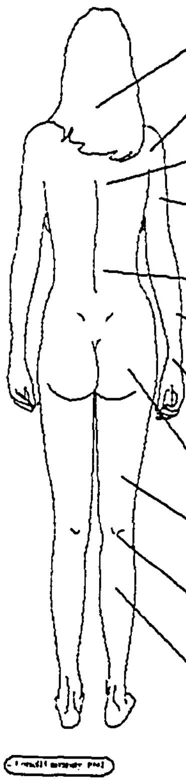
Employee Input (health complaints/workstation improvements) - Chronic Pain: __wrist; __hand; __shoulder; __foot; __back; __neck; __arm; __eye. Other ____.
Past health issues __________. Repetitive hobby/activity (__home PC work, __piano, __knit, __tennis, __racquetball, ______other).

The diagram below shows the approximate position of the body parts referred to in the questionnaire. Please answer by marking the appropriate box

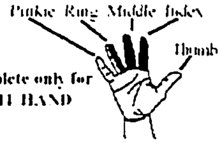


		During the last work <u>week</u> how often did you experience ache, pain, discomfort in:					If you experienced ache, pain, discomfort, how uncomfortable was this?			If you experienced ache, pain, discomfort, did this interfere with your ability to work?		
		Never	1-2 times last week	3-4 times last week	Once every day	Several times every day	Slightly uncomfortable	Moderately uncomfortable	Very uncomfortable	Not at all	Slightly interfered	Substantially interfered
Neck		☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Shoulder	(Right)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
	(Left)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Upper Back		☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Upper Arm	(Right)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
	(Left)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Lower Back		☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Forearm	(Right)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
	(Left)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Wrist	(Right)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
	(Left)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Hip/Buttocks		☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Thigh	(Right)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
	(Left)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Knee	(Right)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
	(Left)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Lower Leg	(Right)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
	(Left)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

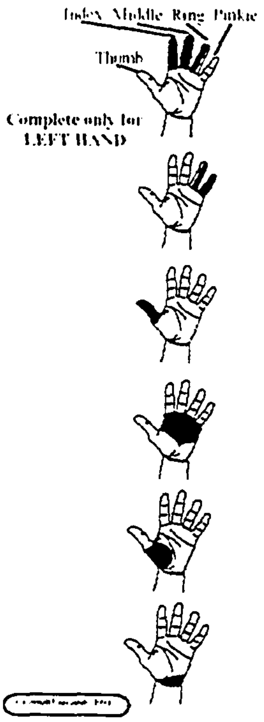
The diagram below shows the approximate position of the body parts referred to in the questionnaire. Please answer by marking the appropriate box.



		During the last work week, how often did you experience ache, pain, discomfort in:					If you experienced ache, pain, discomfort, how uncomfortable was this?			If you experienced ache, pain, discomfort, did this interfere with your ability to work?		
		Never	1-2 times last week	3-4 times last week	Once every day	Several times every day	Slightly uncomfortable	Moderately uncomfortable	Very uncomfortable	Not at all	Slightly interfered	Substantially interfered
Neck		☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Shoulder	(Right)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
	(Left)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Upper Back		☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Upper Arm	(Right)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
	(Left)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Lower Back		☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Forearm	(Right)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
	(Left)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Wrist	(Right)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
	(Left)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Hip/Buttocks		☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Thigh	(Right)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
	(Left)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Knee	(Right)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
	(Left)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Lower Leg	(Right)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
	(Left)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

The shaded areas in the diagrams below show the position of the body parts referred to in the questionnaire. Please answer by marking the appropriate box.		During the last work week how often did you experience ache, pain, discomfort in:					If you experienced ache, pain, discomfort, how uncomfortable was this?			If you experienced ache, pain, discomfort, did this interfere with your ability to work?		
Complete only for RIGHT HAND 	Area A (Shaded area)	Never ☐	1-2 times last week ☐	3-4 times last week ☐	Once every day ☐	Several times every day ☐	Slightly uncomfortable ☐	Moderately uncomfortable ☐	Very uncomfortable ☐	Not at all ☐	Slightly interfered ☐	Substantially interfered ☐
	Area B (Shaded area)	Never ☐	1-2 times last week ☐	3-4 times last week ☐	Once every day ☐	Several times every day ☐	Slightly uncomfortable ☐	Moderately uncomfortable ☐	Very uncomfortable ☐	Not at all ☐	Slightly interfered ☐	Substantially interfered ☐
	Area C (Shaded area)	Never ☐	1-2 times last week ☐	3-4 times last week ☐	Once every day ☐	Several times every day ☐	Slightly uncomfortable ☐	Moderately uncomfortable ☐	Very uncomfortable ☐	Not at all ☐	Slightly interfered ☐	Substantially interfered ☐
	Area D (Shaded area)	Never ☐	1-2 times last week ☐	3-4 times last week ☐	Once every day ☐	Several times every day ☐	Slightly uncomfortable ☐	Moderately uncomfortable ☐	Very uncomfortable ☐	Not at all ☐	Slightly interfered ☐	Substantially interfered ☐
	Area E (Shaded area)	Never ☐	1-2 times last week ☐	3-4 times last week ☐	Once every day ☐	Several times every day ☐	Slightly uncomfortable ☐	Moderately uncomfortable ☐	Very uncomfortable ☐	Not at all ☐	Slightly interfered ☐	Substantially interfered ☐
	Area F (Shaded area)	Never ☐	1-2 times last week ☐	3-4 times last week ☐	Once every day ☐	Several times every day ☐	Slightly uncomfortable ☐	Moderately uncomfortable ☐	Very uncomfortable ☐	Not at all ☐	Slightly interfered ☐	Substantially interfered ☐

The shaded areas in the diagrams below show the position of the body parts referred to in the questionnaire. Please answer by marking the appropriate box



Area	During the last work week how often did you experience ache, pain, discomfort in:	If you experienced ache, pain, discomfort, how uncomfortable was this?	If you experienced ache, pain, discomfort, did this interfere with your ability to work?
Area A (Shaded area)	☐ Never ☐ 1-2 times last week ☐ 3-4 times last week ☐ Once every day ☐ Several times every day	☐ Slightly uncomfortable ☐ Moderately uncomfortable ☐ Very uncomfortable	☐ Not at all ☐ Slightly interfered ☐ Substantially interfered
Area B (Shaded area)	☐ Never ☐ 1-2 times last week ☐ 3-4 times last week ☐ Once every day ☐ Several times every day	☐ Slightly uncomfortable ☐ Moderately uncomfortable ☐ Very uncomfortable	☐ Not at all ☐ Slightly interfered ☐ Substantially interfered
Area C (Shaded area)	☐ Never ☐ 1-2 times last week ☐ 3-4 times last week ☐ Once every day ☐ Several times every day	☐ Slightly uncomfortable ☐ Moderately uncomfortable ☐ Very uncomfortable	☐ Not at all ☐ Slightly interfered ☐ Substantially interfered
Area D (Shaded area)	☐ Never ☐ 1-2 times last week ☐ 3-4 times last week ☐ Once every day ☐ Several times every day	☐ Slightly uncomfortable ☐ Moderately uncomfortable ☐ Very uncomfortable	☐ Not at all ☐ Slightly interfered ☐ Substantially interfered
Area E (Shaded area)	☐ Never ☐ 1-2 times last week ☐ 3-4 times last week ☐ Once every day ☐ Several times every day	☐ Slightly uncomfortable ☐ Moderately uncomfortable ☐ Very uncomfortable	☐ Not at all ☐ Slightly interfered ☐ Substantially interfered
Area F (Shaded area)	☐ Never ☐ 1-2 times last week ☐ 3-4 times last week ☐ Once every day ☐ Several times every day	☐ Slightly uncomfortable ☐ Moderately uncomfortable ☐ Very uncomfortable	☐ Not at all ☐ Slightly interfered ☐ Substantially interfered