Carpal tunnel syndrome due to keyboarding and mouse tasks: a review

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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 task 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, analysing the determining factors from a well-considered perspective instead of considering them 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 to establish 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.

Relevance to industry

Because of the trend in the occurrence of the Repetitive Strain Injuries (RSI), especially CTS with keyboard and mouse use, the assessment of all the 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.

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1. Introduction

The goal of this review is to identify factors that play a role in the typing related carpal tunnel syndrome (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 nearly all the computer users regardless of age, anthropometric characteristics, gender and performance leading to increased musculoskeletal problems.

2. Magnitude of the problem

2.1. Incidence

Currently, CTS 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 (National Center for Health Statistics, 2000).

According to the U.S. Department of Labor (1999) the CTS is the “chief occupational hazard of the 90’s”-disabling workers in epidemic proportions.

2.2. 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 (National Center for Health Statistics, 2000). CTS is the most common nerve compression and the most common and costly repetitive strain illness (Advance Chiropractic, 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–$100,000/hand (Szabo, 1998). Up to 36% of all CTS 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. All these costs represent only a small portion of the total costs that are lost due to the poorly designed keyboard and pointing devices. Even the VDT users that are staying in a poorly designed workplace and continue to work without any complaints 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).
3. 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 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, 1993; NIOSH, 1997; Armstrong and Chaffin, 1979; Loslever and Ranaivosoa, 1993; Advance Chiropractic, 2000; Nordstrom et al., 1997; de Krom et al., 1990; Kumar, 1990, 2001; Kumar and Narayan, 1998; 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 greater opportunity to minimize future risk for patients (Mani and Gerr, 2000).

Although some authors (Hadler, 1987, 1999; Nathan et al., 1992) questioned the 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, 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.

Generally, workstations are built for average sized people (Nordstrom et al., 1997) and that is why the 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., 1984, 1987, 1993; Armstrong and Chaffin, 1979; Cullum and Molloy, 1994; Bergamasco et al., 1998; Nordstrom et al., 1997). In a task that involve repetitive use of the upper extremity, positions of the arm and hand deemed to be unacceptable are: ulnar deviation $>24^\circ$, radial deviation $>15^\circ$, pronation $>40^\circ$, supination $>57^\circ$, abduction $>67^\circ$, extension $>50^\circ$ and flexion $>45^\circ$ (Bergamasco et al., 1998).

Always 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.

4. Pathophysiology

A large number 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,b; Keir et al., 1998, 1999; Phalen and Kendrick, 1957; Seradge et al., 1995) when it exceeds the upper limit for a prolonged 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 flexed, 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, 2001).

Wrist extension has a greater effect than ulnar deviation on CTP (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).

4.1. Personal characteristics

There is reason to believe that patients with CTS may have some predisposing anthropomorphic characteristics (Armstrong and Chaffin, 1979; Buchholz and Armstrong, 1991). Jessurun et al. (1987) defined relative space (RS)
as: \[ RS = \frac{[C_c - C_t]}{C_c} \times 100\% \], where \( C_c \) is the cross-sectional area of the canal and \( C_t \) is the cross-sectional area of the tendons. The \( RS \) 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 anthropometrical 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.

4.2. 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. 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 exceeding 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 CTP (Keir et al., 1998). Finger flexion is very important for CTP, and this importance is raised by typing force that may be four to five 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).

4.3. 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 so 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).

4.4. 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 wrist 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 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, electrophysiological 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.
5. Conventional vs. alternative keyboards

5.1. Typing posture due to bad design

In using keyboards there are a lot of potential risk factors for CTD, including 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 40 mmHg 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 1 in 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 sagittal 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 since then. 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; Markau 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° and 79° with right pronation significantly greater than left pronation (65.6°±8.3° and 62.2°±10.6° (F = 12.28, p < 0.01), 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<0.01) and extension in left hand exceeded the one in right hand (21.2°±8.8° than 17.0°±7.4°, F = 23.24, p < 0.01) (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.
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°) \( (F = 63.25, \ p < 0.01) \).

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 1 h 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 and Armstrong 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 (Treater 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, ergonomic 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 should follow, not disregard the ergonomic assessment of hazardous postures. Otherwise, elevated CTS prevalence and complaints will continues.

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 4–6° 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 ulnar deviation and found that when wrist is ulnar deviated by 10° and 20° the CTP is 20 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 than 15°. Other studies (Seradge et al., 1995; Keir et al., 1998) found increased CTP over 30 mmHg in extreme ulnar and radial deviated postures.

### 5.2. 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) 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 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°) than when the fingers were flexed at 90° for wrist extension angles from 10° to 40° (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 conductivity (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.

5.3. 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° 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 fore-arms 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.

5.4. 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) analysed 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 FDS because this muscle presents greater tendon travel than FDP 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.

5.5. 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 keyboards. 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; Zecic et al., 2000). In a comparison between OPEN, conventional and FIXED (a fixed split angle) keyboard, Zecic 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° flexion (Hedge and Powers, 1995). A notable fact is that even if, in most of the studies, subjects choose inappropriate postures aside from 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 by almost 13%.

5.6. 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 2. 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.

6. 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). Because there is a strong correlation between them, the development mechanism for CTS as well as other typing related

<table>
<thead>
<tr>
<th>Ergonomic solutions for QWERTY layout induced hazardous factors</th>
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<tbody>
<tr>
<td>QWERTY layout keyboard</td>
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<tr>
<td>1. Wrist ulnar deviation</td>
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<tr>
<td>2. Excessive wrist extension</td>
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<td>3. Forearm pronation</td>
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<td>4. Keyboard fixed size</td>
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<td>5. Fingers’ stretching</td>
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<td>6. Fingers excessive flexion</td>
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<td>7. Increased tendon travel</td>
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<td>8. Arm/hand excessive fatigue</td>
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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 as well as the key travel distance, over travel distance and the stiffness at the end of the key travel (Rempel et al., 1997, 1999).

Several studies reported that high keyswitch make force played a role in the development of hand and wrist disorders, including CTS (Rempel et al., 1997, 1999; Feuerstein 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 0.5 and 1.5 N with a preference interval of 0.5–0.6 N (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 0.75 to 1.10 N when the other was increased from 0.31 to 0.71 N. 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 0.47 N. 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 non-linear 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 over 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 1.22 to 0.62 N. 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 1 min 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 (0.5–1.5 N) regarding keyswitch make force.

7. 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). Mice were reported to be the most frequently used devices 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 analyse 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; Karlvist 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 non-dominant hand, unless they know how to change the settings. Of the VDT users 25% are using their non-dominant hand (Jensen et al., 1998) for mouse control and there is no 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 more than 15° ulnar deviation. 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 1.5–2 N on the buttons and 4 N on the sides (Keir et al., 1999). The difference between the tasks effects on CTP is well seen in older users (age 60–90). 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° (Chaparro-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.

8. Discussion

Although de Krom et al. (1990) did not find an association between CTS 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; Fogelman and Brogmus, 1995; Hedge and Powers, 1995; Marklin and Simoneau, 2001; Serina et al., 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 should not 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 0.5 and 1.0 N, 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 over-loading 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 track-ball 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.

9. Conclusion

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.

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