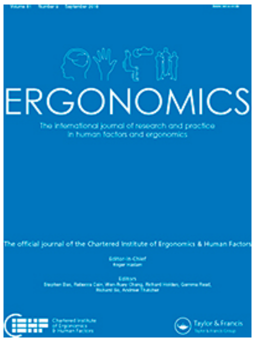

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Hand and arm injuries associated with repetitive manual work in industry: a review of disorders, risk factors and preventive measures

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Musculoskeletal disorders are the most common self-reported, work-related illness in the UK, with upper limb disorders ranking second only to back complaints. The rapid increase in disablement cases, the reduced productivity resulting from the disorders, and, perhaps, the threat of litigation which is on the increase, has led to an increased awareness of the problems and an increasing desire to reduce the incidence of such disorders. This paper reviews the problem of upper limb disorders and focuses on those disorders that could be associated with repetitive manual work in industry. The disorders are described and categorized, and potential occupational risk factors are discussed and related to the injuries. In addition, a number of preventive measures, in the form of ergonomics design changes and changes in workplace practice are reviewed. There are frequent calls for well-designed epidemiological studies, so that meaningful dose-response relationships can be drawn up. A significnat part of good study design is associated with measurement and analysis of the user-tool interface and the working environment. With this in mind, a variety of measurement techniques are described. Furthermore, this paper highlights the need for study designs to be founded on a better understanding of the potential damage mechanisms, and points the way towards which areas should be investigated.

1. Introduction

Work-related illnesses have become the curse of the twentieth century, musculoskeletal disorders being the most common self-reported work-related illness and the most frequent form of work-related ill-health in the UK (Health & Safety Commission 1997). Among musculoskeletal disorders, upper limb disorders rank extremely highly in the UK, second only to back complaints. In recent years, industry's demands for increased productivity, along with an increasing public awareness of work-related illnesses has led to a rapid increase in the number of disablement benefit cases. Many of these claims relate to the popularly named 'repetitive strain injuries' or 'cumulative trauma disorders'. In the last decade or so, a number of these types of upper limb disorders have been considered for prescription by the Industrial Injuries Advisory Council (1992), whereas previously they had not been thought to be of sufficient importance to warrant consideration. Figure 1 depicts the scale of the problem in the UK.

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A similar pattern can be observed in the USA. By the year 2000, the US government has predicted that 50% of the American workforce will have occupational injuries annually, so industries in the USA have been forced to recognize cumulative trauma disorders as their greatest risk to profitability and productivity (Melhorn 1994).

There are many costs associated with cumulative trauma injuries, including medical costs, compensation costs, loss of work days and retraining new employees, indirect costs including high absenteeism, high turnover of staff, low employee morale and poor quality of work (Carson 1993). Prevention is clearly preferable to cure, and can offer lower costs and improved quality of life, so it is of great importance that employers and employees become aware of the issues surrounding these disorders, so that prevention strategies can be effectively implemented.

There are a number of working environments in which it is possible to envisage there being a high incidence of cumulative trauma disorders, not all a product of the twentieth century, and a variety of them have been the focus of study. They include food processing plants (Streib and Sun 1984, Masear *et al.* 1986), automotive plants (Brandon 1992), quarries (Bovenzi 1994) and shipyards (Letz *et al.* 1992), to name but a few. This paper, however, focuses on the more general problem of those upper limb disorders that could be associated with repetitive manual work in industry. In general, ethical considerations preclude direct measurements of cause and effect. Well-designed epidemiological studies defining dose-response relationships relating to the various disorders are sparse at present (Viikari-Juntura 1997). There is, however, a wealth of information, in the form of workplace surveys, case studies, physiological modelling and anecdotal evidence that point the way towards which factors might contribute to which disorders. This information could well provide the grounding for study design in the future, paving the way towards which factors should perhaps be investigated more extensively. The disorders are described along with the occupationally-related factors that are thought to contribute to the disorders. A number of preventive strategies are reviewed, and suggestions as to the way forward are given, both in terms of ergonomics design considerations, and changes in working practice. Finally, given the importance of quantifying the

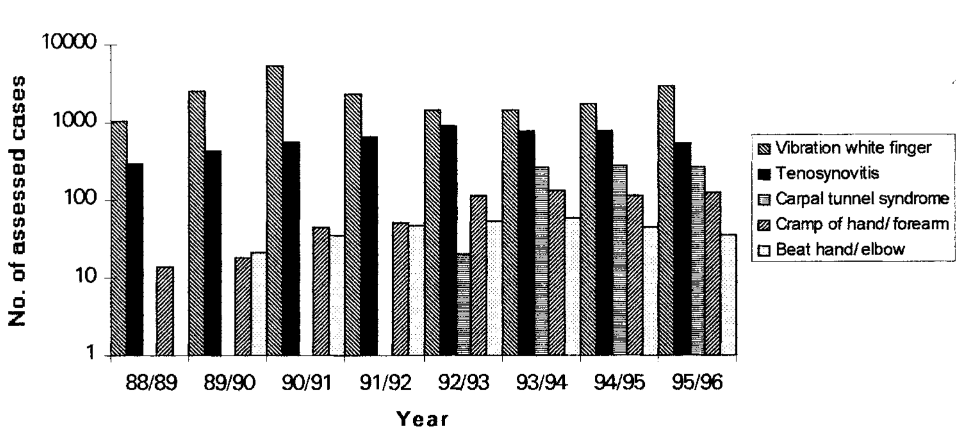

Figure 1. Prescribed upper limb diseases in the UK: number of cases assessed each year 1988/89 to 1995/96 (Health & Safety Commission 1995, 1997).

disorders and the risk potential of the various risk factors, a number of pertinent measurement and analysis techniques are described.

2. Disorders

There is a range of upper limb disorders that have been linked with occupational overuse. The injuries tend to fall into one of the three following categories: vibration whitefinger and related dysfunctions; nerve compression disorders; and tendon and tendon-related disorders. However, in addition, there are a few disorders which, although they do not fit well into the aforementioned categories, are prescribed industrial diseases in the UK and, as such, warrant some consideration. The descriptions that follow are by no means exhaustive but represent, in the authors' opinions, most of the upper limb disorders that might be currently encountered. Figure 2 shows recent statistics related to the incidence of prescribed upper limb disorders in the UK.

2.1. *Vibration whitefinger*

Vibration whitefinger, or hand-arm vibration syndrome, is a secondary Raynaud's phenomenon of occupational origin characterized by periodic blanching of the fingers accompanied by numbness and tingling. Occurring in workers exposed to vibrating equipment, it is a progressive disease with three components: circulatory disturbances (vasospasm with finger blanching); sensory and motor nerve damage (tingling, numbness, loss of finger co-ordination and hand dexterity); and musculoskeletal disorders (muscle, bone and joint changes) (Taylor 1993, Pelmear

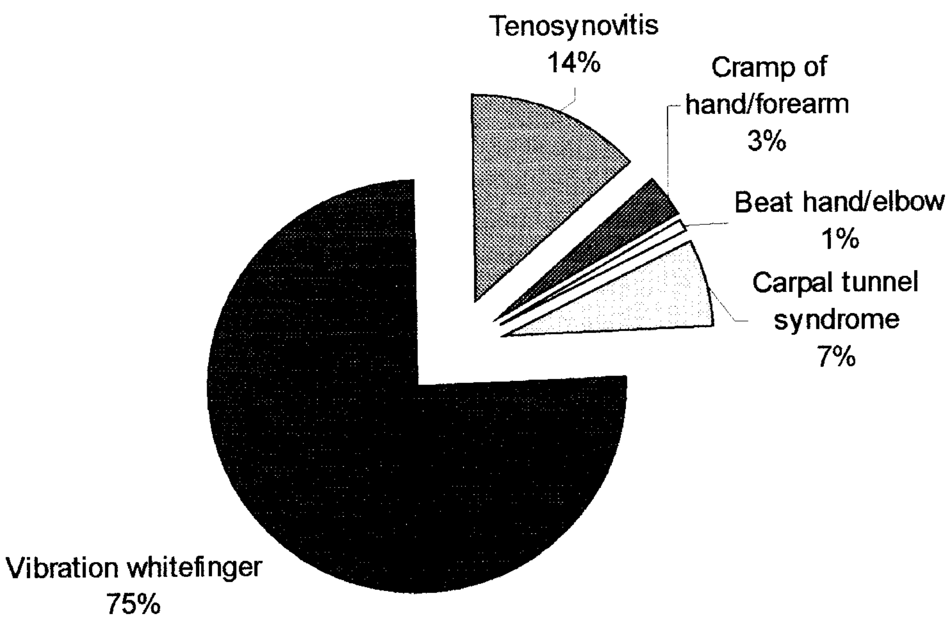

Figure 2. Prescribed upper limb diseases in the UK: proportions of each upper limb disorder as a percentage of all upper limb cases. New cases assessed in 1995/96 (Health & Safety Commission 1997).

and Taylor 1994b, Williams 1994). Vibration whitefinger is also linked with a number of autonomic dysfunctions. The effects on the autonomic nervous system can manifest themselves in a variety of ways. The hand that is not exposed directly to vibration, along with the ears, nose and the toes, can be affected with Raynaud's phenomenon (Hashiguchi *et al.* 1994, Toibana *et al.* 1994, Williams 1994). Inner ear functions can be disturbed (Pelmear and Taylor 1994b, Pyykkö *et al.* 1994), which can then lead to balance disorders (Iki 1994), and cardiac functions can also be affected (Pyykkö *et al.* 1994). The exact damage mechanisms, however, including the roles of central and local mechanisms, remain unclear (Lundborg *et al.* 1987, Olsen 1987, Greenstein and Kester 1992).

Becoming a prescribed disease in the UK in 1985, vibration whitefinger has become the most common prescribed disease (Health & Safety Commission 1997), with several thousands of applications being made each year in the UK alone (figures 1 and 2). It has been estimated that the number of workers in the UK at risk is 500 000, reaching 1.2 million in the USA (Pelmear and Taylor 1994a).

2.2. *Nerve compression disorders*

The hand and arm are innervated by three main nerves: the median nerve; the ulnar nerve; and the radial nerve. In general, compression neuropathies can arise from nerve compression at one or more of three sites; the shoulder, the elbow, and the wrist. Symptoms are exacerbated if compression occurs at more than one site, hence the aptly named 'double' or 'triple crush'. The following paragraphs outline the most common compression neuropathies, which involve the median and ulnar nerves at the sites mentioned above. Interestingly, neuropathies involving compression of the radial nerve have received very little attention in the literature, although one radial nerve compression syndrome (radial tunnel syndrome) has been named (Ranney 1993).

2.2.1. *Carpal tunnel syndrome*: Carpal tunnel syndrome is the most common entrapment neuropathy, involving the median nerve as it passes through the carpal tunnel at the wrist (Putz-Anderson 1991, Cailliet 1994). An increase in pressure within the carpal tunnel can lead to either direct nerve compression or vascular insufficiency of the nerve, nerve compression often being apparent on surgical inspection (Rankin and Rankin 1995). Symptoms include pain, numbness and tingling of the fingers innervated by the median nerve. In later stages, motor loss becomes apparent and muscles may atrophy.

Carpal tunnel syndrome became a prescribed disease in the UK in 1993 (Health & Safety Commission 1995), but only in relation to the use of hand-held vibrating tools. In the USA, it has evolved to rank with back injuries as one of the most frequently reported disorders and has resulted in costly workers' compensation claims (Hoyt 1984).

2.2.2. *Cubital tunnel syndrome*: Cubital tunnel syndrome involves entrapment of the ulnar nerve at the elbow. Tingling and numbness occur in the little finger and the ulnar side of the ring finger (those fingers innervated by the ulnar nerve) and weakness of the hand and forearm may occur (Helander 1995). It was considered for compensation by the Industrial Injuries Advisory Council in 1992 (Industrial Injuries Adivosry Council 1992), but is not a prescribed disease in the UK at the present time.

2.2.3. *Guyon's tunnel syndrome*: Guyon's tunnel syndrome is entrapment of the ulnar nerve at the wrist, as it passes through Guyon's canal (Cailliet 1994). Symptoms include difficulty in hand-grasping, numbness, motor weakness, loss of dexterity and loss of thumb pinch strength. Muscle atrophy can occur in advanced stages, as with carpal tunnel syndrome.

2.2.4. *Pronator teres syndrome*: Pronator teres syndrome is entrapment of the median nerve at the elbow. Symptoms are aching and discomfort in the forearm, weakness in the hand, and numbness in the thumb and index finger (Hartz *et al.* 1981).

2.2.5. *Thoracic outlet syndrome*: Thoracic outlet syndrome involves compression of the brachial plexus, or neurovascular bundle, in the region of the neck and shoulder (Putz-Anderson 1991). Strictly the term refers to compression caused by a specific anatomical abnormality (Barton *et al.* 1992) but its wider definition, referring to compression due to any cause, is used in this paper. Pain can be the dominant symptom, accompanied by muscle spasms in the confines of the neck and shoulder (Gorton 1994). Other symptoms include arm numbness or parathesia, and finger numbness. The pulse at the wrist may also be weakened.

2.3. *Tendon and tendon-related disorders*

There are a variety of tendon and tendon-related disorders that may be encountered in the occupational setting, the main two being tendinitis and tenosynovitis. Tendinitis refers to tendon inflammation specifically, whereas tenosynovitis is a general term describing injury involving the tendon sheath. Traumatic inflammation of the tendons of the hand or forearm or of the associated tendon sheaths is prescribed in the UK and relates to any occupation involving manual labour, or frequent or repeated movements of the hand or wrist (Department of Social Security 1991, Industrial Injuries Advisory Council 1992). The following paragraphs outline the most common of the disorders.

2.3.1. *De Quervain's disease*: De Quervain's disease, also known as clothes wringing disease, is a special case of tenosynovitis caused by stenosis of the thumb abductors (Cailliet 1994). Symptoms are pain and swelling at the thumb base, with the pain being aggravated by forceful ulnar deviation with the thumb flexed and abducted.

2.3.2. *Trigger finger*: Finger tendinitis, or trigger finger, occurs in the flexor tendons of the finger (Helander 1995). Snapping of the flexor tendons occurs during active finger flexion, and may be felt and be audible. When flexion is attempted, it is at first restricted, but then occurs suddenly. Once flexed, the finger remains locked and cannot be re-extended (Cailliet 1994). Finger movements thus become abrupt or jerky. This condition occurs most frequently in the middle or ring finger. In later stages of the disease, snapping ceases and the finger remains permanently locked.

2.3.3. *Medial and lateral epicondylitis*: Medial epicondylitis, or golfer's elbow, is an irritation of the tendon attachments of the finger flexor muscles on the inside of the elbow (Putz-Anderson 1991). A similar condition is lateral epicondylitis, or tennis elbow, which affects the outer part of the elbow, and is much more common than medial epicondylitis (Industrial Injuries Advisory Council 1992). The main symptom is pain, which may spread along the forearm as far as the wrist and is aggravated by extending (in the case of lateral epicondylitis) or flexing (in the case of medial epicondylitis) the wrist and fingers against resistance. In addition, grip is often impaired.

Both lateral and medial epicondylitis were considered for compensation in 1992, but insufficient evidence was found to justify its inclusion in the list of prescribed diseases (Industrial Injuries Advisory Council 1992). The Industrial Injuries Advisory Board continues to review the evidence on these two conditions.

2.3.4. *Rotator cuff syndrome*: In rotator cuff syndrome, the tendons or bursa of the muscles that rotate the shoulder joint become irritated or swollen (Helander 1995). Symptoms are pain, burning sensation and swelling. Reduced muscle power often results although the range of active movement can remain unimpaired (Herberts and Kadefors 1976). Rotator cuff syndrome was considered for compensation in 1992 (Industrial Injuries Advisory Council 1992) but at the present time it is not a prescribed disease in the UK.

2.4. *Other disorders*

The following disorders are not covered by the previous paragraphs, but are prescribed industrial diseases in the UK relating to the hand and arm, and so are included here for the sake of completeness.

2.4.1. *Cramp of the hand or forearm*: This condition, as prescribed (Department of Social Security 1991), relates specifically to repetitive movements. It is characterized by muscular spasm and tremor or pain in the hand or forearm when attempting to perform a familiar act involving a frequently repeated muscular action. Diagnosis must be on symptoms and history alone as there are no physical signs or detectable abnormalities.

2.4.2. *Subcutaneous cellulitis of the hand*: Known as 'beat hand' (Department of Social Security 1991), this condition involves bruising and devitalization of the tissues of the hand. Mineral or other particles may become implanted causing inflammation or bacterial infection. Symptoms are mainly pain or loss of function, accompanied by tenderness, swelling, redness and heat, and possibly stiffness or deformity.

2.4.3. *Subcutaneous cellulitis of the elbow*: Known as 'beat elbow' (Department of Social Security 1991), this condition is similar to beat hand, but refers to trauma at or around the elbow. Symptoms include pain and swelling, accompanied by tenderness and possibly signs of infection.

3. Contributing factors

There is a range of factors that are known or thought to contribute to upper limb disorders, both occupationally-related and non-occupational. In this paper, only occupational risk factors will be considered. They can broadly be categorized as: load-related (including vibration); posture-related (including repetitiveness); and environmental. How the contributory factors interact will also be discussed. Several forms of evidence are considered: epidemiological; anecdotal; and that based on physiological/mathematical modelling. No claim is made as to the definitive nature of the links; rather they serve as a basis from which further investigations could take place, as well as highlighting the nature of potential injury pathways.

3.1. *Load-related risk factors*

3.1.1. *Vibration*: Of all the relationships between occupational diseases and occupational risk factors, the link between vibration whitefinger and exposure to vibration must be one of the most firmly established. That there is a link is not disputed. Although not definitive, the International Standards Organisation has drawn up a set of guidelines for the measurement and assessment of human exposure to hand-transmitted vibration (ISO 1986). Based on consensus of opinion within the field, it includes dose-response relationships in the form of weighted acceleration versus exposure time in years before the onset of vibration whitefinger for different population percentiles. The International Standards are continually being reviewed to reflect the best guidance based on research evidence available at any given time.

The fact that vibration contributes to the onset of vibration whitefinger is clearly no surprise. What is perhaps more interesting is that vibration appears to contribute to other of the aforementioned disorders, both compression syndromes and tendon-related disorders. Epidemiological evidence suggests that carpal tunnel syndrome is significantly correlated with exposure to vibration from hand-held tools (Cannon *et al.* 1981, Conner and Kilisek 1986, Sieslander *et al.* 1989), and not only because more wrist force is required to hold a vibrating tool, as has been surmised (Tanaka *et al.* 1995). The fact that vibration can contribute to carpal tunnel syndrome is acknowledged by the Health and Safety Executive as carpal tunnel syndrome is now a prescribed disease in relation to the use of hand-held vibratory tools (Industrial Injuries Advisory Council 1992) although there is some concern that hand-arm vibration syndrome is often mis-diagnosed as carpal tunnel syndrome (Miller *et al.* 1994, Pelmear and Taylor 1994a,b). Carpal tunnel syndrome is not the only compression neuropathy to be linked with vibration. There is also some epidemiological evidence of a link between both cubital tunnel syndrome and thoracic outlet syndrome and vibration (Kakosy 1994). Regarding tendon-related disorders, rotator cuff tendinitis has also been found in a number of workers exposed to vibration under high load conditions (Stenlund *et al.* 1993, Hagberg 1996) as have a number of neck and shoulder complaints (Dimberg *et al.* 1989). In addition, a number of cases of trigger finger in workers exposed to vibration have been found, suggesting a link between trigger finger and vibration (Conner and Kolisek 1986).

Furthermore, vibration can contribute to the onset of upper limb conditions indirectly. It is well known that muscles exposed to vibration can exhibit a tonic vibration reflex in the form of a gradually increasing involuntary contraction (Armstrong *et al.* 1987b, Radwin *et al.* 1987). This, combined with the fact that vibration interferes with proprioception (Ranney 1993), can cause the worker to grip the tool harder than if the vibration were not present. This harder gripping not only exposes the worker to larger muscle stresses, but also it generally leads to better vibration coupling between the tool and the hand-arm system. (Increasing grip force will cause the impedance of the hand-arm system to increase. Except for extremely light tools, the impedance of the hand/arm will in general be less than that of the tool for all frequencies of interest. Increasing the hand/arm impedance will therefore lead to better impedance matching between the tool and the hand/arm, thus effecting better vibration coupling.) A vicious circle might thus develop. This could explain the high incidence of shoulder and upper arm disorders observed in workers exposed to vibratory tools (Dimberg *et al.* 1989).

3.1.2. *Mechanical shocks*: On one level, exposure to mechanical shocks could be seen as exposure to short bursts of vibration with a wide range of frequency components, and, as such, any disorder that is affected by vibration would be affected by exposure to mechanical shocks. However, apart from being of short duration, wide band vibration, mechanical shocks to the hand and arm seem to do damage in their own right. This belief is supported by a number of epidemiological studies but also by the widely held view that shocks are not covered adequately by the ISO 5349 standard (ISO 1986) for hand-arm vibration (Starck *et al.* 1990, Nelson and Griffin 1992, Louda *et al.* 1994) and vibration whitefinger is exacerbated by the use of highly impulsive tools (Starck *et al.* 1990). Furthermore, the use of impulsive or pounding tools is specifically cited as a risk factor in the description of vibration whitefinger as a prescribed disease (Department of Social Security 1991). Carpal tunnel syndrome has been linked to use of a staple gun, in which repeated shocks are transmitted to the hand and arm (Louda *et al.* 1994). In addition, both tenosynovitis and the pronator teres syndrome have been linked to repetitive hammering (Thompson *et al.* 1951, Hartz *et al.* 1981, Department of Social Security 1991). As the name suggests, the beat conditions are associated with mechanical shocks. Repeated direct trauma to the hand (beat hand) or elbow (beat elbow) is the main causative factor for these disorders (Department of Social Security 1991). Finally, although little epidemiological evidence is available for epicondylitis, it is interesting to note that the sports with which is is traditionally associated (tennis for lateral epicondylitis, and golf for medial epicondylitis) are themselves characterized by repeated hand-arm shocks.

3.1.3. *Palmar and gripping loads*: Apart from the effect on vibration coupling, as outlined above, forceful gripping has been linked to the onset of a number of upper limb disorders. A high incidence of carpal tunnel syndrome has been found in occupations that require forceful grasping such as in the meat cutting and sewing industries (Armstrong and Chaffin 1979, Masear *et al.* 1986). This can perhaps be explained by the effects that palmar loading has on carpal tunnel pressure. A cadaver study undertaken by Cobb *et al.* (1995a) mapped the entire palmar suface of the hand for the effects of loading on carpal tunnel pressure. They found that loads applied at the base of the palm, particularly in the region of the median nerve, produced signficiantly larger pressure changes than for the same loads applied more distally. Forceful gripping tends to involve loads at the base of the palm and so high carpal tunnel pressures could result. The ulnar nerve at the wrist can also suffer compression, resulting in Guyon's tunnel syndrome, the suggestion being that a tight hand grip can cause direct compression of the nerve against the bony structure of Guyon's canal (Streib and Sun 1984). High palmar or gripping loads can also contribute to the bruising associated with beat hand. Symptoms of the pronator teres syndrome have been found to occur following periods of repetitive grasping (Hartz *et al.* 1981) and trigger finger and De Quervain's disease have been found in workers undertaking forceful gripping (Thompson *et al.* 1951, Armstrong *et al.* 1987a). Again, data regarding epicondylitis is sparse, but an unusual case study has been reported in the *British Medical Journal* (Price 1982). Two incidences of lateral epicondylitis were diagnosed in police officers acting as jailers at a magistrate's court. New locks, which were extremely stiff, had been installed at the jail. The forceful gripping, combined with elbow rotation, required to operate the locks up to 80 times daily was enough to provoke symptoms in both officers within a reasonably short space of time. The symptoms subsided after the locks were attended to.

3.1.4. *External loads*: It is not a straightforward matter to distinguish the effects of gripping or palmar loads and external loads. In general, grip force increases with increased weight or pull resistance (Grant and Habes 1993), and the effect of increased grip and increased load bearing can often be similar in physiological terms. This is a particular problem when considering trigger finger and De Quervain's disease as the loads of interest are loads taken directly by the hand. Likewise, the loads involved in the case of jailer's elbow (see above) were directly related to gripping. With regard to vibration, to the extent that load effects gripping, vibration coupling will be affected, so load will be linked to vibration whitefinger and the associated autonomic disturbances. In addition, epidemiological studies have revealed a link between forceful exertions and carpal tunnel syndrome (Armstrong and Chaffin 1979, Loslever and Ranaivosoa 1993). High force work has also been linked with thoracic outlet syndrome (Sällström and Schmidt 1984, Kakosy 1994) and rotator cuff tendinitis (Herberts and Kadefors 1976, Hagberg 1996).

3.1.5. *Hard/sharp edges*: The main effect of a hard or sharp edge in direct contact with part of the body is to locally increase the load in that area. That is of particular relevance to the compression neuropathies where load at or near the nerve site can contribute to their onset but also to trigger finger and De Quervain's disease (Thompson *et al.* 1951, Armstrong *et al.* 1987a), and beat elbow. The ulnar nerve at the elbow is particularly prone to this kind of onslaught and cubital tunnel syndrome can result from leaning the elbow on a hard or sharp surface (Helander 1995). Indeed it has been suggested that this is the only mechanism that contributes to the disorder (Barton *et al.* 1992), although this is open to debate. It seems that thoracic outlet syndrome can also be exacerbated by stress concentrations at the shoulder, caused by shoulder straps for example (Guidotti 1992).

3.2. *Posture-related risk factors*

Not only the loads to which the human body is subjected, either static, or dynamic, are important when considering cumulative trauma disorders. Postures that are adopted to undertake any particular task also significantly contribute to the risk of injury. Owing to the nature of the way in which skills are learnt, the same activity may tend to be performed by a given individual in exactly the same way once an effective motion pattern has been established. Posture is, in fact, the most frequently cited risk factor for cumulative trauma disorders (Hoyt 1984, Armstrong 1996).

3.2.1. *Wrist flexion/extension*: Of all the hand/arm postures that could be adopted, flexion/extension of the wrist has received the most attention in the literature, and this is almost exclusively in relation to carpal tunnel syndrome.

One of the earliest studies into the effects of wrist postures on the incidence of carpal tunnel syndrome was undertaken by Armstrong and Chaffin (1979) on sewing machine operators. They found that diseased subjects used a wrist position more deviated from neutral than non-diseased subjects. Wrist deviation was only measured in the flexion/extension plane. More recent studies relating biomechanical measuremens to epidemiological data have confirmed the view that flexion and extension can be a problem (Schoenmarklin *et al.* 1994) with flexion being particularly so (Loslever and Ranaivosoa 1993). The high incidence of carpal tunnel syndrome in the meat-cutting industry where extremes of wrist motion are used, particularly flexion and ulnar deviation for boning activities, supports these findings (Maesear *et al.* 1986). In addition, in a US survey of self-reported carpal tunnel syndrome a high incidence was found in workers exposed to 'bending' or 'twisting' of the hands (Tanaka *et al.* 1995). The finding that wrist flexion and extension contribute to carpal tunnel syndrome is supported by *in vivo* measurements of carpal tunnel pressure. Significant pressure rises are reported for both flexion and extension (Seradge *et al.* 1995, Weiss *et al.* 1995), the pressure varying in a parabolic fashion with the minimum at a few degrees of extension (Weiss *et al.* 1995).

There is also some anecdotal and epidemiological evidence to suggest that wrist flexion and extension contribute to the onset of both medial and lateral epicondylitis (Price 1982, Dimbert 1987, Putz-Anderson 1991), although it is difficult to separate the effects of wrist movements from other factors.

In principle, wrist movements could also contribute to the pronator teres syndrome at the elbow. An interesting *in vitro* study by Cobb *et al.* (1995b) revealed that while the carpal tunnel appears to function as a relatively closed compartment with respect to transfer of pressure from the flexor compartment of the forearm, pressures are transmitted in the reverse direction, from the carpal tunnel to the forearm flexor compartment. As such, raised pressures in the carpal tunnel could result in raised pressures around the median nerve at the elbow thus promoting nerve compression.

3.2.2. *Wrist radial/ulnar deviation*: Not only do flexion and extension of the wrist contribute to carpal tunnel syndrome, but also radial and ulnar deviations have been implicated (Masear *et al.* 1986, Tanaka *et al.* 1995). Again, *in vivo* pressure measurements inside the carpal tunnel show that pressures increase, in a parabolic manner with radial and ulnar deviations (Weiss *et al.* 1995). The lowest pressure was found to be at a few degrees of ulnar deviation.

Of all the upper limb disorders reviewed in this paper, De Quervain's disease is the disorder most strongly associated with radial and ulnar wrist positions (Armstrong 1996). Again, the clothes wringing associations provide a clue in this respect, along with acecdotal associations with activities such as manual screwdriving (Ross 1994).

As for flexion and extension, lateral epicondylitis has been associated with radial and ulnar wrist deviations (Price 1982, Dimberg 1987).

3.2.3. *Elbow movements*: In general there is very little documented evidence on the role of elbow movements in the genesis of upper limb disorders. Job movement analysis studies have tended to focus on the wrist almost exclusively. However, not surprisingly, most of the disorders that have been associated with elbow movements are those that actually involve the elbow directly. Pronator teres syndrome has been linked with elbow pronation and flexion (Hartz *et al.* 1981). Both medial and lateral epicondylitis have been associated with elbow movements, a fact that can be deducted from the common terms alone (golfer's & tennis elbow), but particularly with rotations (Price 1982, Putz-Anderson 1991). The movements required for manual screwdriving might also suggest a link between De Quervain's disease and elbow rotation, but it is quite likely that the involvement of the elbow itself is incidental.

3.2.4. *Shoulder movements and postures*: The only disorders that have been linked with shoulder movements *per se* are thoracic outlet syndrome (Ohlsson *et al.* 1995) and rotator cuff tendinitis (Herberts and Kadefors 1976), rotator cuff tendinitis being associated with shoulder abdunction and forward shoulder flexions particularly (Hagberg 1996). Interestingly, however, a high rate of shoulder movement in some circumstances has been found to be characteristic of workers who remained healthy (Moore *et al.* 1991).

Working with the arms continuously raised above the shoulders poses additional problems. When combined with hand/arm vibration, it has also been implicated in the development of the sensorineural stage of hand-arm vibration syndrome (Letz *et al.* 1992).

Rotator cuff injuries have been strongly associated with overhead working (Herberts and Kadefors 1976, Hagberg and Wegman 1987, Welch *et al.* 1995, Hagberg 1996), but also it appears that thoracic outlet syndrome, and neck and shoulder disorders in general, can be exacerbated by working in this posture (Ohlsson *et al.* 1995).

3.2.5. *Repetitive movements and exposure time*: In anthropological terms, man is not designed to perform highly repetitive tasks involving relatively few different operations and, as such, seems disposed to suffer from cumulative trauma disorders given exposure to these kinds of tasks. The term 'cumulative trauma disorder' suggests an injury mechanism whereby repeated exertions over a period of time contribute to the illness, and, although some of the disorders discussed thus far can be caused by a single traumatic event, that is not the subject of this paper. This section briefly considers what is perhaps obvious — that it is the repetitive nature of some tasks that can ultimately result in disability.

Separating the effects of repetition and total exposure time from other risk factors is, however, particularly difficult. The repetition must always refer to some particular activity which will, of itself, involve certain postures and exposures to particular loads, all of which could be seen to be instrumental in causing a disorder. For example, in one survey, a low incidence of carpal tunnel syndrome was found (Ohlsson *et al.* 1995). This was attributed to the fact that although some of the jobs assessed were highly repetitive, none involved frequent flexion and extension of the wrist, or forceful gripping. However, notwithstanding these difficulties in interpretation, repetition can be considered a risk factor in its own right.

That tendons suffer if subjected to rapid repetitive movements is well documented. Early work by Hammer (1934) revealed that demands for increased speed in manual industries often resulted in an increased incidence of tenosynovitis. He concluded that, as a rule of thumb, human tendons will not tolerate more than 1500 to 2000 manipulations per hour. Wilson (1983) also concluded that a person manipulating objects thousands of times a day can often develop tenosynovitis, even if the individual objects themselves are quite light. Thompson *et al.* (1951), in a study of tenosynovitis in industry, attributed a significant proportion of cases to repetitive stereotypical movements. The finding that loads need not be particularly high is supported by more recent work linking the playing of joystick-controlled video games with De Quervain's disease (Reinstein 1983). It was found that symptoms could be reproduced after only half an hour of playing games such as Space Invaders (corresponding to approximately 900 thumb or wrist movements). Playing a slower game, such as video chess, did not reproduce the symptoms. The case study citing the incidences of lateral epicondylitis in jailers (Price 1982) adds further weight to the importance of repetitiveness in these types of injuries. Furthermore, the notion that high repetition rates can result in tendon injury is bolstered by notions of materials and muscle fatigue (Moore *et al.* 1991). Interestingly trigger finger is not so much associated with continuous finger movements as with continually holding the finger in the same position under load, such as when operating the switch of a power tool (Ross 1994).

Given that tendons can suffer the effects of high repetition rates, it is no surprise that nerve compression disorders are also linked. Guyon's tunnel syndrome has been linked with highly repetitive work, requiring stereotypical movements, such as gold and brass polishing and shoemaking (Streib and Sun 1984). Again, high loads appear not to be a prerequisite. Carpal tunnel syndrome has also been linked with repetitive work. Highly repetitive motions are predominant in the meat cutting industry, which also has a high incidence of carpal tunnel syndrome (Masear *et al.* 1986). Furthermore, studies investigating the occupational causes of carpal tunnel syndrome show the repetitive motion to be a significant factor (Wieslander *et al.* 1989, Monsivais *et al.* 1994), often when the loads incurred are not heavy. Mathematical modelling work on the carpal tunnel supports the notion that adequate recovery time is important if injury is to be avoided as pressures in the carpal tunnel can escalate (Cheever *et al.* 1995).

With regard to vibration whitefinger, although 'repetitiveness' is not a term that can be meaningfully applied to vibration exposure, cumulative exposure can be. ISO 5349 (ISO 1986) includes dose-response relationships in the form of weighted acceleration versus exposure time in years before the onset of vibration whitefinger for different population percentiles. However, cumulative exposure is not the only important factor; adequate recovery time between repeated exposures is also relevant. This is demonstrated in a number of surveys, for example by Saito (1987). Particularly in high vibration scenarios, workers have been shown to exhibit some recovery after a number of years with reduced operating hours. Thus, although the total exposure continues to increase, suitable rest periods permit the recovery process.

A number of studies have specifically investigated the incidence of hand and wrist cumulative trauma in industry in relation to exposure to various risk factors. Armstrong *et al.* (1987a) found the risk of tendinitis to be 29 times greater in workers performing high force, high repetition jobs compared with low force, low repetition jobs. High repetition jobs were defined as those with a cycle time of less than 30 s or with more than 50% of the cycle time involved in the same kind of motion pattern. This definition, then, takes into account both the effects of actual high repetition rates and also cumulative exposure without necessarily a high repetion rate. In this study, however, the effects of force and repetition were not separated. Silverstein and colleagues investigating cumulative traumas in general (Silverstein *et al.* 1986a) and carpal tunnel syndrome specifically (Silverstein *et al.* 1987), using the same definition of high repetitiveness found the risk of injury for high force, high repetition jobs to be much higher than for low force, low repetition jobs. In these studies, an attempt was made to separate the effects of force and repetition rate, and high repetition rates were indeed found to have a significant impact. Ohlsson *et al.* (1995) found a significant association between exposure to repetitive work and the diagnoses of both neck/shoulder and elbow/hand problems. Interestingly, and contrary to most findings, in a study carried out in Norway on female office and production workers (Westgaard *et al.* 1993), researchers found repetition rate not to be a high risk factor.

Furthermore, piece work, often linked with an increased work pace, is associated with neck and arm disorders compared with work paid by the hour (Ohlsson *et al.* 1995, Hagberg 1996).

Perhaps the most convincing evidence linking high repetition rates to injury can be found in work in which actual postural measurements are made. In a study to assess the discriminatory powers of different wrist postures as risk factors for cumulative trauma disorders, Schoenmarklin, Marras and co-workers (Marras and Schoenmarklin 1993, Schoenmarklin *et al.* 1994) showed that, using position, velocity and acceleration data in all three primary planes, flexion/extension plane acceleration discriminated best between groups of low and high incidence rates, and highlighted the importance of dynamic components. The view that dynamic components are important is supported by work investigating the spectral components of movements in which frequency weightings were derived (Radwin and Lin 1993, Radwin *et al.* 1994). The frequency weightings showed that the human stress response was proportional to differentiated wrist flexion. However, as Viikri-Juntura (1997) has pointed out, the relationship between short-term stress response and risk of injury has not yet been established.

3.3. *Environmental risk factors*

Although there are many environmental factors that could contribute to the onset of some of the upper limb disorders described, only three are described here. These, in the authors' opinions, are the most significant and widespread factors that are likely to be encountered in an industrial setting.

3.3.1. *Temperature*: In general, there is very little evidence on the effect of temperature extremes on the incidence of upper limb disorders, although it is cited as being a causative factor for cumulative trauma disorders (Ross 1994). Cold stress on the circulatory system is known to aggravate symptoms of vibration whitefinger (Pelmear and Taylor 1994b), but it is not known whether exposure to cold is instrumental in the genesis of the disorder (Silverstein *et al.* 1986b). There is no evidence that low temperatures above freezing cause direct soft tissue damage but substantial evidence that low temperatures reduce circulation thus causing impairment of hand sensory and motor function (Gerwatowski *et al.* 1992, Armstrong 1996). These effects reduce manual dexterity and accentuate the symptoms of nerve end impairment. A minimum working hand temperature of 25°C (Gerwatowski *et al.* 1992, Armstrong 1996), and a minimum atmospheric temperature of 10°C (Yamada *et al.* 1993) have been recommended.

3.3.2. *Humidity*: Likewise, there is little data available on the effects of humidity. The predominant effect, however, is likely to be related to grip. At very low levels of humidity, hand moisture can be reduced to such an extent that grip is impaired (Falkenburg and Schultz 1993). Similarly, at extremely high humidity, excess moisture can degrade grip quality. In both circumstances, more grip force will be required to maintain an effective grip. Interestingly, beat hand has been linked with work in wet conditions, so high humidity is likely to encourage the onset of the condition. In addition, humidity extremes can subject workers to emotional stress.

3.3.3. *Psychological stress*: Psychological and social factors are held to be more strongly associated with back pain than with other types of musculoskeletal pain (Hagberg 1996), and more strongly for non-specific pain than for that with a specific diagnosis. However, that does not mean to say that stress and upper limb pain could not be linked. It is well known that stress can exacerbate the symptoms of Raynaud's phenomenon (Cailliet 1994), but it is not clear whether or not stress exacerbates vibration whitefinger symptoms or contributes to the onset of the disorder. A link has been found between psychological stress at work, emotional well-being, and the tendency towards muscular tension, and neck and shoulder problems (Westgaard *et al.* 1993, Ohlsson *et al.* 1995), a link not found for elbow/hand complaints. Furthermore, piece work has been associated with neck and arm disorders compared with work paid by the hour (Ohlsson *et al.* 1995, Hagberg 1996). Although this could be linked with an increased work pace, the psychological demands of the work pace being directly related to remuneration could be implicated.

3.4. *Defining dose-response relationships*

Much work has been done in an attempt to link a number of risk factors with cumulative trauma disorders. However, demonstrating their exact hierarchy in relation to a particular condition remains largely intractable. Evidence is generally gathered from retrospective workplace surveys and a limited number of epidemiological studies. For most of the disorders there is a poor understanding of the physiological mechanisms involved in the injury processes, so modelling work has been restricted. Notwithstanding these drawbacks, given the large number of potential risk factors for each disorder, the dimensionality of the problem is such that it is unlikely that definitive dose-response relationships can be drawn up.

Most of the work investigating the relative importance of different risk factors has concentrated on the effects of force and repetition rate. In principle, a clue could be found in studies reporting the incidence of both hands being affected compared with the dominant hand alone. However, in studies where the majority of cases occurred bilaterally, for example (Chatterjee 1992, Loslever and Ranaivosoa 1993), the hands were subjected to globally equivalent efforts and movements. Work by Silverstein *et al.* (1986a, 1987) has attempted to unravel the problem of force and repetition by defining jobs as one of the four combinations of low/high-force/ repetition rate. In their study of carpal tunnel syndrome (Silverstein *et al.* 1987), high repetion rate appeared to be the greater risk factor, whereas for the study on cumulative trauma disorders in general (Silverstein *et al.* 1986a) force appeared to be a greater risk. However, while separating their effects is a non-trivial matter, and by no means a solved problem, there is agreement that the combination of high force and high repetition rate results in a particularly high risk. The 1988 National Health survey in the USA (Tanaka *et al.* 1995) concluded that the risk factor most strongly associated with carpal tunnel syndrome was repetitive bending or twisting of the hand and wrists at work, the risk factor being much larger than for the use of vibratory tools. Unfortunately, the force levels used were not assessed in this study. There have also been a few modelling attempts to separate the effects of different risk factors, mainly to evaluate the risk factors associated with particular tasks (Moore and Garg 1995), but also to be able to define optimum rate-rest profiles (Fisher *et al.* 1993), but no clear-cut conclusions have been forthcoming.

Intrinsic in the idea of defining dose-response relationships is the notion of how much a human being can be exposed to without sustaining damage. At present, what is perhaps more important than attempting to define such relationships is to move towards a clearer understanding of the mechanical and physiological mechanisms involved in establishing a diseased state. Not only is this approach likely to result ultimately in more meaningful dose-response relationships, but it could perhaps lead towards a way of thinking in which the aim is not to ascertain human limits and then try to stay just within them, but to introduce modes of working which, at a fundamental level, are more appropriate to the overall human constitution.

4. Preventive measures

The fact that hard evidence of the roles of different factors in the genesis of cumulative trauma disorders is sparse has not prevented a surge of enthusiasm regarding a variety of different strategies for reducing the incidence of such diseases, particularly in industry. These measures include ergonomics design changes (particularly related to tools), changes in workplace practices, and more recently, the development of measurement methods to quantify the risk potential of different activities. These three areas will be considered in the following paragraphs.

4.1. *Ergonomics design considerations*

A number of different ergonomics design changes intended to reduce the incidence of upper limb injuries have been reported in the literature. In the main, changes have focused on reducing the requirement for deviated wrist positions and reducing the loads on the hand and wrist.

One of the areas of tool design, which has received particular attention, is handle design. Curved handles to reduce awkward wrist postures, particularly flexion and ulnar deviation, have been used to good effect in many industries (Anon 1992, Johnson 1993). This is not a new idea. Curved handles were often used on hand tools in the nineteenth century to facilitate use (Armstrong 1996), and can often be seen in museums displaying tools designed much earlier. Suitable handle designs can also reduce the stress concentrations that result in compressed digital arteries and nerves (Johnson 1993), by facilitating a more even pressure on the hand and fingers. Handle straps can be beneficial in allowing release of muscle tension between repetitions (Johnson 1993). A new custom-mouldable handgrip aimed at reducing carpal tunnel syndrome is proving to be successful in the automotive industry (Anon 1995). Featuring a non-mouldable inner layer to reduce shock and vibration transmission, it incorporates a custom-moulded outer part that remains tacky to improve the grip surface. Such a custom grip enables less grip force to be used and allows for a more even pressure distribution over the hand. Grand and Habes (1993) investigated incorporating flanges onto tool handles as a way of reducing manual effort. They found that adding a flange did not significantly reduce the grip force used for any of the tasks they investigated. This is probably due to the fact that unless the gripping surface permits only poor contact between the hand and the tool, it is unlikely that the flange will be used at all. In addition, a poorly designed flange may make matters worse by introducing sharp edges onto the contacting surface.

Tool manufacturers are also beginning to realize the importance of a tool grip being the correct size for the operator. The effects of differing hand sizes and tool sizes have been studied in a variety of contexts. An *in vitro* study by Cobb *et al.* (1996), simulating active grip, showed that tool grip size can have a significant effect on carpal tunnel pressure. Furthermore, grip size can affect grip strength and hand forces, dependent on the size of the operator's hands (Fransson and Winkel 1991, Oh and Radwin 1993).

Wrist braces are now becoming commonplace as part of the treatment for conditions like carpal tunnel syndrome, and their use has been suggested to help to prevent the disorder. However, this approach is of questionable value. While wrist flexion and extension are undoubtedly reduced (Anon 1992), conflicting reports exist as to whether the carpal tunnel pressure is actually reduced or increased under such circumstances. The reduction in carpal tunnel pressure expected by the restricted wrist motion can be cancelled by the increase due to the static load on the wrist caused by wearing the split itself (Rempel *et al.* 1994).

The use of gloves in a variety of scenarios has also been investigated. Wearing gloves to reduce vibration to the hand is an area where there is not universal agreement. Vibration transmission can be significantly reduced in principle, but loss of tactile feedback can be a problem and cause the operator to grip the tool harder (Siebel and Mosher 1984), thus generally increasing transmitted vibration. Furthermore, inappropriate selection of gloves can cause vibration transmission to the hand and arm to increase. The use of gloves with non-vibrating tools has also been studied (Mital *et al.* 1994). A number of gloves were assessed and it was found that, in general, torque capability was enhanced by their use while muscle activity remained unaffected.

The use of cushioned abrasives in some applications has addressed many of the ergonomics problems associated with sanding and finishing (Archer 1993). Higher grit sizes may be used and still produce a fine scratch pattern due to the abrasive crystals being able to recede slightly. The larger crystals result in a rapid removal rate, thus reducing the total sanding time for the operator. Furthermore, less pressure is required than with traditional abrasives. This in itself is of benefit to the operator, but in addition, lighter pressure combined with the cushioning reduces the effects of shocks transmitted to the hand and arm. An energy flow divider to attenuate hand-transmitted vibration from an orbital sander has been investigated analytically (Cherian *et al.* 1996). It was shown that the hand acts as a low-pass filter with most of the vibration localized to the hand itself at higher frequencies. The use of a tuned flow divider was found to reduce frequency-weighted, hand-transmitted vibrations but the vibrations transmitted to the forearm and elbow tended to increase.

Trigger design has also received some attention. Trigger length can affect hand forces (Oh and Radwin 1993, Lee and Cheng 1995), mainly due to the number of fingers being employed to operate the trigger, an extended trigger reducing exertion levels. The use of touch-sensitive switches reduces the force required to operate a tool (Morris 1992). Often, however, the tool cannot then be operated while wearing gloves (Poeth and Frievalds 1996).

To reduce general loads on the body while using a tool, tool balancers are now commonly used. Supporting the tool weight, they are generally hung above the workstation, although a number of pantograph devices are now being marketed. An interesting support stand for use in overhead working has also been developed.

Specifically designed for use with a staple gun (Wos *et al*. 1992), load is transferred to the hips via the support, so that impacts are diverted away from the arm and the force required to operate the tool is taken mainly by the legs.

4.2. *Changes in workplace practices*

In addition to actual tool design modifications, consideration is now being given to how workers routinely undergo their daily activities and how working practices might be modified to minimize the incidence of cumulative trauma disorders. When considering such changes, it is clearly important to consult workers who are going to be the end users. This type of approach has been found to be extremely successful at UAW Ford, where changes are often suggested and monitored by the factory workers (Brandon 1992). Ford in the UK have implemented major ergonomics modifications at one site in Essex (Chatterjee 1992). The incidence of new cases of upper limb disorders dropped by a factor of $\sim$20 after the introduction of the changes, which included regular work breaks, job rotations, increased manpower, automation of some tasks and tool and workstation modifications.

The message to reduce task frequency and to enable job rotation is often repeated, aimed at a variety of industries and professions (Gerwatowski *et al*. 1992, Carson 1993, Cullum and Molloy 1994), although there might be an understandable reluctance to rotate workers once they are highly proficient at a particular task. Psychological as well as physiological variability in tasks has been highlighted as being important (Goldoftas 1991, Hagberg 1996). Even if loads are low, job rotation is important. If only low level contractions are used, only type 1 fibres (low threshold motor units) will be engaged, and may be subject to selective fatigue (Hagberg 1996), resulting in damage. Alternating between standing and sitting has been cited as beneficial since maintaining a single posture for prolonged periods can be stressful (Carson 1994). In general, however, standing is good if high forces are required. Furthermore feet may be used instead of hands for providing forceful exertions (Carson 1994). In some circumstances, it may be possible to ensure the use of different muscle groups for performing essentially the same task. The Biocentric Technique (Meador 1993), originally developed as an instrumentation technique in dental hygiene, does just this. It employs a basic two-fold strategy: to keep the joints in a neutral position as much as possible; and to maintain sufficient flexibility to shift the work load to different large muscle groups in order to avoid fatigue. The method thus focuses on assessing the ultimate action required, and cycling through the different possible combinations of body postures required to achieve this action. Unfortunately, where higher muscle loads are being taken, this type of approach may not be feasible. In a recent study investigating the postures used while drilling (Rancourt and Hogan 1995) it was found that all subjects tested used similar postures and upper limb kinematics. An analysis of the results suggested that humans endeavour to minimize joint torques. The similarity of the postures observed suggested that only one posture met the criterion of minimum joint torques for that particular activity. One study has attempted to use biofeedback to discourage the use of the awkward hand postures associated with carpal tunnel syndrome (Thomas and Vaidya 1993). Biofeedback has been shown to be beneficial in reducing the symptoms of vibration whitefinger (Taylor *et al*. 1993). In this study, however, no effect was measured. Interestingly, some participants felt that they had benefited from the feedback signals by being made aware of the musculoskeletal effects of different hand postures, even if these postures were not subsequently modified.

Recently, there has been an increasing amount of evidence that exercise can prevent the onset of conditions like carpal tunnel syndrome (Carson 1994). The effect of a number of avocational activities on the prevalence of carpal tunnel syndrome has been studied (Nathan and Keniston 1993). It was found that, in general, activities that tend to involve light physical exertions (e.g. driving, sewing) increase the risk, while activities that involve vigorous aerobic exertions that increase heart rate and induce perspiration (e.g. running, dancing) reduce the risk. Lack of physical muscular strength has also been correlated with neck/shoulder disorders and those of the elbow/hand (Ohlsson *et al.* 1995). One study, undertaken in the USA, revealed that the introduction of an on-site exercise programme in a racquet manufacturing plant helped to reduce the incidence of carpal tunnel syndrome significantly (Sawyer 1987). The 10-min routine carried out twice daily in works time, incorporated upper body flexibility exercises and hand and finger strengthening exercises. Ostrem (1995) argues that, given that a precipitator of carpal tunnel syndrome is overuse and subsequent overdevelopment of the flexor muscle group in the hand and arm, then the problem can be prevented by development of the extensors. He warns against 'squeeze toy' gadgets that only exercise the flexor muscle groups. Unfortunately, no specific exercise programme is elucidated. However, a putty ball exercise programme for use by dental hygienists has been described (Gerwatoski *et al.* 1992). Nine exercises are included, four to exercise the flexor muscles, three to exercise the extensors (one including abductor strengthening) and two to exercise the abductors alone. Suitable weight training exercises have also been found to be particularly effective as preconditioning exercises for new or return to work employees (Hoyt 1984).

An alternative method to reduce the incidence of injuries brought about by repetitive activity is job automation. Although the primary driver for this kind of change is usually increased productivity, automation can release workers onto tasks that might be less detrimental to health. However, while complete automation of some tasks might be desirable, semi-automation has the potential to make matters worse. Reducing loads merely so that the worker may operate faster increases the repetition rate and, as such, poses a potential risk. Transferring loads to different body parts may reduce the injury potential to one part of the body but at the cost of an increased risk to another part.

4.3. *Job analysis and measurements*

In order to be able to quantify job risk, as well as providing a scientific basis for the observations made regarding the factors contributing to upper limb disorders, a number of measurements are now starting to be made. The measurements focus on vibration, loads, and postures adopted.

Vibration measurements have been made for a number of years, and these, along with the current understanding of the pathophysiology of vibration whitefinger have enabled international standards to be defined. ISO 8662 (ISO 1988) describes test methods for evaluation of vibration in the handles of hand-held power tools, the output being a weighted acceleration. ISO 5349 (ISO 1986) covers the measurement and assessment of human exposure to hand-transmitted vibration. It includes dose-response relationships in the form of weighted acceleration versus exposure time in years before the onset of vibration whitefinger for different population percentiles. It is generally agreed that ISO 5349 does not adequately deal with the problem of hand–arm shocks (Starck *et al.* 1990, Louda *et al.* 1994). This failing, along with other shortcomings of the standard, has been addressed in a number of studies

(Starck *et al.* 1990, Nelson and Griffin 1992), and the standards are continually being reviewed. As well as making measurements of weighted accelerations, a number of other measurements, relating to vibration, have been made. Hand–arm impedance measurements have been made, under a variety of different conditions (Griffin *et al.* 1982, Burgström and Lundström 1994, Rossi and Romasini 1995, ISO 1996). This, along with knowledge of the vibration characteristics of a particular tool, enables calculation of the vibrational power absorbed by the hand and arm. Furthermore, electromyographic (EMG) measurements have enabled muscle exertions, associated with the operation of vibrating tools, to be investigated (Rohmert *et al.* 1989, Hartung *et al.* 1993).

There are a number of different measurement techniques available for studying the various hand and arm loadings to which a person is subjected when undertaking a task, in addition to measurements that reflect physiological response to a particular situation. Caution is advised, however, when interpreting such measurements since, as Viikari-Juntura (1997) has pointed out, the relationship between short-term responses and the onset of disease has not been established. Of the physiological measurements, EMG measurements and measurements of carpal tunnel pressure are perhaps the most common. Carpal tunnel pressures have been measured both *in vitro* (Cobb *et al.* 1996) and *in vivo* (Rempel *et al.* 1994, Weiss *et al.* 1995), but the technique is invasive, and in general, impractical, as it involves insertion of a catheter directly into the carpal tunnel. Surface EMG measurements, which in general give an indication of muscular effort, have been used to good effect in a number of studies. Both Armstrong and co-workers (Armstrong *et al.* 1979, Silverstein *et al.* 1987) and Loslever and Ranaivosoa (1993) used EMG measurements to estimate hand forces; Gurram *et al.* (1995) have measured finger flexor forces with EMG signals. Moore *et al.* (1991) found measurements of dynamic EMG activity to be well matched to the injury outcomes of an epidemiological study. Exertion levels and perceived discomfort have also been assessed using psychophysical measures, where the users themselves rate the effort required to perform a particular task. The Borg scale is often used (Harber *et al.* 1994, Kihlberg *et al.* 1994), where users rate a number of different aspects of a task, e.g. force, exertion level, discomfort on a numerical scale. More direct measurements of hand forces can be obtained with strain gauge (Rohmert *et al.* 1989, Grant and Habes 1993, Nordgren *et al.* 1994, Lee and Cheng 1995) or resistance devices (Smith and Hudson 1993, Yun and Frievalds 1995), and these types of transducers have been used to measure both grip forces and triggering forces. The disadvantage of using individual force cells is that the measured force is limited to that which is applied over the force cell. Forces that are distributed, for example, over the length of a tool handle might be difficult to measure in this way. However, a linear force summing dynamometer, which is independent of the point of application, has been designed specifically for ergonomics type use (Radwin *et al.* 1991, Radwin and Oh 1992). In addition, a conductive polymer sensor, modified to measure force rather than pressure, has been used to measure individual finger forces (Jenson *et al.* 1991, Radwin and Oh 1992). Force plates have also been used to good effect, to measure ground reaction forces when carrying out a particular task (Wos *et al.* 1992, Kihlberg *et al.* 1994). More specifically, ground reaction forces have been found to be well correlated with perceived exertions when tool operators are exposed to torque reactions (Kihlberg *et al.* 1994, 1995). One further measurement possibility is to use contact thermography to investigate the distribution of palmar loads while performing an activity. Microtrauma sustained during application of pressure can be detected using thermography as local temperature changes are related to the circulatory disturbances produced by the damage. An advantage of using this approach is that measurements could be made following a period of activity, rather than during the activity, and the pressure distributions obtained could be easily mapped onto the hand contours, as these would form part of the image obtained.

Postural measurements are usually undertaken using electrogoniometers or some kind of optical system. Gross movement patterns can be assessed with single plane video. Slow motion playback has been used to assess repetitiveness (Silverstein *et al.* 1987), monitor time spent in various postures (Armstrong *et al.* 1979), identify key events in a movement sequence (Radwin *et al.* 1994), confirm methods used to perform a particular task (Harber *et al.* 1994) and as a general aid to data interpretation (Moore *et al.* 1991). Biplanar or stereo videography can also be used. Motion is recorded on video simultaneously in two planes. Identification of common points in each view allows calculation of the position in 3-D space of those points. Using a normal video camera, common points must be identified manually, which can be time consuming if a large amount of data is to be analysed. Systems that use infra-red light and reflective markers, however, can be used to investigate upper limb movement (Peterson and Palmerud 1996), and with these kinds of system, a large degree of automation is possible. In addition, optical systems that use reflective markers and synchronized beams to locate anatomical landmarks in 3-D space can be used (Kihlberg *et al.* 1994). A drawback to the use of optical systems is that the camera(s) must have the markers in view at all times in order to compute positional information, although interpolation is sometimes possible. An electrogoniometer is an angle measuring device that can be attached to a joint of interest to record both static and time-varying joint angles. Two axis transducers are available that can record, for example, flexion/extension and ulnar/radial deviation at the wrist simultaneously. Along with the optical devices, this type of measurement system is among the most common of the postural measurements systems, and has been used in a variety of studies, mainly to evaluate wrist movements (Moore *et al.* 1991, Loslever and Ranaivosoa 1993, Marras and Schoenmarklin 1993, Radwin and Lin 1993, Radwin *et al.* 1994, Schoenmarklin *et al.* 1994), but could be used to investigate motions of the elbows and shoulders (Radwin *et al.* 1994). Data gloves have also been used, fitted with a number of joint angle sensors (Wise *et al.* 1990), and sometimes incorporating force measuring transducers as well (Lucas 1990, Yun and Frievalds 1995).

Apart from providing direct measurements of hand loads and positions, force and posture measurements can be used to determine other biomechanical quantities. Repetition rates can be inferred from goniometric measurements. Velocity and acceleration levels have been calculated (Marras and Schoenmarklin 1993, Schoenmarklin *et al.* 1994), but also spectral analyses have been carried out (Radwin and Lin 1993, Radwin *et al.* 1994). Examination of the frequency components provides insights into the repetition rates encountered, zero frequency component giving the mean posture. Furthermore, once external forces and postures have been determined, biomechanical models can, in principle, be used to calculate joint torques (for example Runge *et al.* 1993, Yun and Frievalds 1995), thus facilitating a fuller understanding of the loads to which the body is being subjected.

5. Conclusions

Repetitive manual work in industry can, undoubtedly, contribute to the onset of upper limb disorders, and it is evident that the problems caused by these injuries are on the increase. Industry is becoming increasingly aware of the issues surrounding these problems and a climate is emerging where the desire to understand the mechanisms causing damage, and the wish to reduce the incidence of the disorders is assuming considerable significance.

This paper has described and categorized those disorders that could be associated with repetitive manual work in industry. Occupational risk factors have been discussed and related to the injuries. In addition, a number of preventive measures have been reviewed, and suggestions have been made as to the way forward, both in terms of ergonomic design and changes in workplace practice.

In 1992 the Industrial Injuries Advisory Council (1992) made a plea for further research to be undertaken to establish the occupational risk of these types of disorders. In order to be able to quantify such risk, epidemiological studies need to be able to quantify not only the incidence and extent of these injuries but the occupational risk factors to which injured workers are exposed. The final section of this paper describes a number of measurement techniques that have been used, and which could be exploited yet further, to provide this much needed information. At present, mathematical modelling work on injury mechanisms is extremely limited, but, combined with appropriate measurements, could point the way forward to a genuine understanding of those disorders that have become some of the most costly occupational complaints of our time.

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