SHU, YU. Effect of wrist splint orthoses on forearm muscle activity and upper extremity kinematics. (Under the direction of Dr. Gary A. Mirka.)

Ergonomics is concerned with understanding the interactions between humans and other elements in a system. Physical ergonomics is concerned with the prevention of musculoskeletal disorders (MSDs), - a topic of particular importance to industry because of the high costs of MSDS in worker’ lost time, health care costs, worker’ compensation, etc. Awkward postures have been identified as a risk factor in the development of several MSDs. In particular, awkward postures of the wrist are often the focus of intervention efforts. Wrist splint orthoses (WSOs) are intended to protect the wrist by limiting wrist motions and there have been reports of relief of wrist disorders such as carpal tunnel syndrome and tendonitis when the orthoses are worn at night. However, their use in work environments should be carefully considered because of the complex interaction of required wrist postures and the work environment/task.

The focus of the current study was to evaluate the impact of wearing a wrist splint orthosis while performing tasks requiring deviated wrist postures. Ten subjects performed two experimental tasks. In the first experiment, the subjects performed a series of simple, single-plane wrist exertions at varied wrist angles (flexion/extension and ulnar deviations) with and without a wrist splint orthosis. Electromyographic (EMG) activity of three forearm muscles (flexor carpi radialis, flexor carpi ulnaris and extensor carpi ulnaris) were recorded as they performed these exertions. In the second experiment, upper extremity kinematics of the wrist, elbow, shoulder and torso were recorded as the subjects performed a simulated computer jumper installation task at varied work surface angles with and without a wrist splint orthosis.
The results of the EMG experiment revealed a strong interaction between wrist angle and wearing a wrist splint orthosis. For example, at the neutral wrist posture, wearing a WSO did not elevate the normalized EMG of the studied muscles. At 48º of wrist flexion, wearing WSO increased the normalized EMG of flexor carpi radialis by nearly 600% (32% of max vs. 5% of max, p<0.001). Similar trends were seen in deviated postures in other planes.

In the study of the upper extremity kinematics during the jumper installation experiment, the results showed a strong effect (p<0.001) of the wrist splint on the shoulder abduction angle. Wearing WSO increased the shoulder abduction angle significantly (average 43.5º vs. 32.3º, p<0.01) during the jumper experiment indicating that the subjects adapted to the limited range of motion of the wrist by increasing shoulder movement.

The results of this research provide important quantitative data relative to the recommendations of wrist splint utilization in the work environment to protect worker from occupational injuries and disorders. This study showed that wearing a wrist splint orthosis can increase the activity of the forearm muscles, thereby increasing exposure to another risk factor (force); and wearing the WSO can induce awkward postures in other parts of body, thereby increasing the risk of MSDs to other body regions. These results indicate that the practice of having a worker wear WSO during work activities should be carefully considered relative to task demands.
Effect of Wrist Splint Orthoses on Forearm Muscle Activity and Upper Extremity Kinematics

By

Yu Shu

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Approved by:

David B. Kaber    David A. Dickey

Gary A. Mirka
Chairperson of Advisory Committee
Yu Shu was born in Chengdu, Sichuan province in China. Thanks to his parents, Shaoyun Shu and Chunxiu Zhang, he spent his childhood happily in Shuanliu, a small but beautiful town near Chengdu.

Yu Shu graduated from the Tsinghua University in 2002 with a Bachelor’s of Science degree. After that, he flew around half of the earth to the United States and joined the Department of Industrial Engineering in North Carolina State University for a doctor’s degree. He worked as a Research Assistant to Dr. Mirka, while taking classes in ergonomics and biomechanics.
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1. Introduction

1.1. Ergonomics

Ergonomics is the scientific discipline concerned with understanding the interactions between human beings and other elements in a system in order to optimize overall system performance as well as protect human beings. The goal of ergonomics is to “design the job to fit people”. Based on the knowledge of the characteristics of the system, and consideration of the physical, cognitive, social, organizational, environmental and other relevant factors of human beings, the ergonomist contributes to the evaluation, improvement, and design of tasks, jobs, products, environments and systems.

There are three broad domains of specialization within the discipline of ergonomics: physical ergonomics, cognitive ergonomics and organizational ergonomics. Cognitive ergonomics is concerned with mental processes, such as perception, memory, reasoning, and motor response, as they affect interactions among humans and other elements of a system. Organizational ergonomics is concerned with the optimization of the organization and processes of a social or physical system.

Physical ergonomics includes human anatomical, anthropometric, physiological and biomechanical characteristics and the application of these principles in the design of physical activity of human beings. The focus of the current work is in the area of physical ergonomics.

1.1.1. Physical ergonomics

Musculoskeletal disorders (MSDs) are a major point of emphasis in physical ergonomics because of the high cost to industry in terms of lost work days and health care and workers’ compensation costs. Statistical data from the United States Bureau of Labor
Statistics (BLS) shows that for the year 2002 there were 1.4 million cases of occupational injuries and illness that led to lost work time and 0.6 million cases were categorized as musculoskeletal injuries (BLS, 2002). Of these cases, more than 76% were related to trunk (back and shoulder) and upper extremities (finger, hand and wrist). In the United States, back disorders account for 27 percent of all nonfatal occupational injuries and illnesses involving days away from work (BLS, 2002). The direct costs of diagnosing and treating low back pain in the United States were estimated in 1991 to be $25 billion annually (Frymoyer et al. 1991). Although the causes of back disorders are complex, substantial scientific evidence identified physically heavy work, static work postures, lateral bending and twisting, lifting and forceful movements, repetitive work and whole trunk vibration as associated with back disorders. Other common MSDs are shoulder disorders, which include thoracic outlet syndrome, rotator cuff tendonitis, bursitis and prolonged traumatic shoulder muscle pain. The injuries to the shoulder caused the second largest number of days away from work (mean 12 days) (BLS, 2002). Occupational risk factors for shoulder disorders are high force, awkward postures, static loading, repetition and dynamic motions. The main focus of the current work is the hand/wrist complex and, therefore, more detail is provided in the following sections.

1.2. Work-related hand/wrist illnesses

1.2.1. Epidemiology of work-related hand/wrist illness

Carpal tunnel syndrome (CTS) and tendonitis are the most common work-related distal upper extremity MSDs (DUEMSDs). The impact and costs associated with work-related DUEMSDs are substantial. In 2001, The Bureau of Labor Statistics reported that the rate of DUEMSDs cases with “days away from work” was 26.8 per 1000 workers. The agency also reported that the injuries to the wrist resulted in the longest absences
from work - a median of 13 days. Among major disabling injuries and illnesses, median days away from work were highest for CTS (25 days) (BLS 2002). An estimated one million adults from the United States annually have DUEMSDs that require medical treatment (Tanaka et al. 1994). The average non-medical costs of a DUEMSD case from compensation settlements and disability was $10,000 per hand (Masear et al. 1986). With the medical costs and the indirect costs borne by patients and families, the total cost ranges from $20,000 up to $100,000 per case (Katz et al. 1991). Prevention and management of DUEMSDs has become an important mission for modern industry.

1.2.2. Anatomy and disorders of the hand/wrist

There are thirty separate bones in each upper limb, which may be described regionally as the arm, forearm and hand. The humerus is the sole bone of the upper arm, which is connected at the elbow with two forearm bones: the ulna and the radius. The distal ends of these two forearm bones articulate with the carpal bones (wrist bones). Most movements of the hand and wrist are promoted by the forearm muscles, which are functionally divided into two groups: the anterior and posterior muscle groups. Most of the anterior muscles are wrist or finger flexors, and innervated largely by the median nerve. Muscles of the posterior compartment are chiefly wrist and finger extensors. Most muscles of the forearm arise from a tendon on the distal end of humerus, and then they taper to long insertion tendons that travel through carpal tunnel and attach onto the destination hand or finger bones.

The carpal tunnel is a space cradled within the concave arch of the carpus (wrist) bones and is enclosed by the transverse carpal ligament. Nerves and tendons of forearm muscles travel through this tunnel. The median nerve is the most superficial structure located within the carpal tunnel. It normally enters the carpal tunnel either in the middle or slightly to the radial side of the midline. The nerve itself can shift to the radial or ulnar
direction while traveling through the tunnel (Rotman et al. 2002). The nerve can also
glide in the carpal tunnel during wrist flexion/extension exertions with a maximum of
9.6mm (Millesi et al. 1990). “In compression, with the presence of fibrosis, this nerve
gliding would be inhibited. Injury to or scarring of the mid-nerve will cause the nerve to
adhere to surrounding tissue. Subsequent movement will then cause traction on the nerve,
which will further compromise nerve function.” (Makinnon, 2002)

1.2.3. Physical risk factors for DUEMSDs

There have been many studies that examined physical workplace factors and their
relationship to DUEMSDs. The factors reported to be associated with DUEMSDs include
high grip/pinch force, repetitive wrist exertions, exposure to vibration and awkward wrist
postures.

Force

There is evidence of a positive association between forceful work and DUEMSDs
(NIOSH, 1997). While muscles in hand and forearm contract, the tendons in carpal tunnel
will generate a force to press the median nerve. The motion of hand will make these
tendons slide relative to the stationary structures in the wrist, creating stress and
inflammation of the tendons. When high tendon force levels are added, the normal force
of the tendons on these structures increases the stress, inflammation and carpal tunnel
pressure (CTP). A number of studies (e.g. Chiang et al. 1993, Moore et al. 1994, Osorio
et al. 1990) have shown a relationship between forceful work and development of
DUEMSDs. Some of the studies concentrated on CTS, and some were focused on other
common hand/wrist disorders. For example, Chiang et al. (1993) studied 207 workers
from eight fish-processing factories in Taiwan. Jobs were divided into three groups based
on levels of force and repetitiveness. He found a statistically significant trend of increasing CTS prevalence from the lowest exposure group to the highest exposure group (8.2% to 28.6%, p<0.01). Moore and Garg (1994) evaluated 32 jobs, which were categorized as hazardous or safe by force, wrist posture, grasp-type, vibration and some other factors in a pork processing plant. Subsequently they reviewed past OSHA illness and injury logs and plant medical records for CTS cases in these job categories. The hazardous jobs had a relatively higher risk (23% vs. 3%) for CTS as compared to the safe jobs. McCormack et al. (1990) compared the tendonitis and related DUEMSDs among 1,579 textile production workers to 468 non-production textile workers from jobs with less hand/wrist movements as a reference group. The textile production workers were reported as being exposed to repetitive finger, wrist and elbow motions based on knowledge of jobs. They were divided into four broad job categories: boarding, sewing, packaging, and knitting. The over all prevalence of DUEMSDs in the textile workers was 1.7 times (3.75% vs. 2.1 %) the prevalence for the reference workers. For textile workers in the boarding job, which was noted to require forceful work as well as the repetitive hand-intensive work, the prevalence was 3 times larger than the reference workers (6.4% vs. 2.1%). Though most of these studies didn’t categorize the jobs by force alone, jobs which require forceful hand/wrist exertions were widely recognized as dangerous.

Repetition

Previous researches on the relationship between repetition and DUEMSDs (e.g., Moore et al.1992, Chiang et al. 1990, 1993; Silverstein et al. 1987, Stetson et al. 1993, Barnhart et al. 1991, Osorio et al. 1994) have found high repetition of wrist exertions alone can induce DUEMSDs. Chiang et al. (1990) studied 207 workers from two frozen food processing plants. Investigators observed job tasks and divided them into low or high repetitiveness categories of wrist movement based on cycle time. It was found that
the prevalence of CTS was five times larger in the high repetitiveness group than in the low repetitiveness group. The combination of repetition with other risk factors, such as force was found to be much more dangerous. Silverstein et al. (1987) found high force combined with high repetition appeared to have more than a multiplicative effect, increasing the risk more than 5 times that of either factor alone. Another recent study also showed that low force with repetitive motions causes more damage than long duration continuous low force. Watanabe et al. (2001) studied the effect of repeated versus continuous nerve strain in a rat forelimb model. Continuous stretching of the nerve at 2N for 1 hour resulted in no functional abnormality. By contrast, abnormalities were noted when this small stress (2N) was applied 60 or 120 times during 1 hour.

**Vibration**

Vibration was found to be an important risk factor in the development of DUEMSDs, especially when it was combined with other factors. Bovenzi et al. (1991) found a strong relationship between vibration and DUEMSDs based on symptoms and physical exams in comparing vibration-exposed forestry operators using chain-saws to maintenance workers performing manual tasks. The DUEMSD prevalence in the vibration exposed workers was ten times higher than the control workers (38.4% vs. 3.2%, p=0.002). Cannon et al. (1981) found that the incidence of DUEMSDs in the workers who self-reported use of vibrating tools, in combination with reported forceful and repetitive hand motions, was two times larger than that in the workers working with repetitive motions alone, indicating that exposure to vibration may have an interactive effect with other risk factors.
Posture

Some studies have shown that extreme wrist postures are a significant risk factor for some DUEMSDs, and can be more dangerous when combined with other risk factors, such as high force and highly repetitive motions (e.g. Luopajarvi et al. 1979, Hagg et al. 1997, Kuorinka et al. 1979, Bystrom et al. 1995). Luopajarvi et al. (1979) compared the prevalence of hand/wrist tendonitis among 152 female assembly line packers in a food production factory to 133 female shop assistants in a department store. The assembly line packers were noted to have awkward postures and repetitive work. Exposure to awkward hand/arm postures work and repetitive work was assessed by observation and videotape analysis. The ratio of prevalence of tendonitis among the assembly line packers compared to the shop assistants was 4.13 (55.9% to 13.5%). Armstrong and Chaffin (1979) studied eighteen female sewing machine operators with symptoms and/or signs of CTS and compared them to eighteen other female sewing machine operators without history of CTS. They observed that CTS-diagnosed subjects used deviated wrist postures more frequently than non-diseased subjects, particularly during forceful exertions. These results indicated the combination of awkward hand/wrist postures and highly repetitive or forceful hand/wrist motions was dangerous. Some studies also point out that extreme wrist motions alone could be related to the development of wrist disorders. Hagg et al. (1997) studied forearm and hand disorders among twenty automobile assembly line workers which were divided into two groups by prevalence of wrist hand symptoms. Wrist angles of these workers during normal work were recorded using a biaxial goniometer. It was found that the tasks and jobs performed by workers with high level of prevalence of wrist/hand disorder symptoms required larger wrist ulnar deviation angles and higher absolute angular velocity compared to the jobs done by workers with low level of prevalence of wrist/hand disorder symptoms.
1.2.4. Control studies to reduce exposure to awkward wrist postures

Many studies evaluating the risk factor of awkward wrist posture also suggested methods and strategies to reduce it. These methods and strategies can be classified into three groups: engineering, administrative, and personal protective equipment (PPE).

Engineering strategies are defined as “change or alternate the equipment or working process to eliminate the source of the hazard” (Goldenhar and Schulte, 1996). Keyboard and mouse wrist supports are interventions using an engineering strategy to eliminate awkward wrist postures because they reduce wrist extension angles during typing and keep the wrist nearer to a neutral posture as compared to a traditional keyboard and mouse pad. Bent handled pliers are another example of successful engineering design using the ergonomics principle: “bending the tools instead of bending the wrist”. The benefit of these kinds of interventions has been shown by many researchers (e.g. Smith et al. 1998, Hedge et al. 1995, Damann and Kroemer 1995, Schoenmarklin, 1988, Tichauer, 1973).

Administrative strategies include management of the work process or work schedule to reduce the time of exposure to the hazard. Typical administrative interventions include job rotation, rest pauses, job enlargement, etc. Administrative interventions usually can only reduce the cumulative stress because they do not eliminate the source of stress, so they are usually combined with other strategies when applied to real working environments. Hakkanen et al. (1997) developed and applied an ergonomic program consisting of engineering (improved designs of workstations) and administrative (changes in work method, job rotation) interventions into a furniture manufacturing factory, and found that the combination of engineering and administrative controls reduced the cumulative exposure to deviated wrist posture. The combination of these two controls is an effective way to address risk exposures.
Personal protective equipment is often the last shield for workers against the job risk factors. The function of PPE is to cut the path from the source of hazard to the worker. Safety glasses, hearing protection earplugs and gloves are the most common PPEs in industry. One recognized weakness of PPE is that they must be worn to be effective, often resulting in an additional management activity: enforcement. Wrist splint orthoses are a kind of PPE yet essentially a little different from others. Instead of a shield that separates the worker from the hazard, wrist splint orthoses are more like a boundary that restricts the wrist from reaching the hazard (awkward posture). It is designed to limit the range of motion of the wrist and keep the wrist at a neutral position. Basic wrist splint orthoses include a hard plastic or metal board that is located under the forearm and palm, and some elastic fabric that binds the forearm and palm with the board. The board is bent at one end and curved to fit palm shape. The angle of the curve is designed to keep the wrist at a neutral position. The elastic fabric then wraps the palm and forearm with the board with appropriate tension force to restrict wrist motions.

Previous epidemiology studies have found positive effects of wearing wrist splint orthoses on patients with DUEMSDs. Walker et al. (2000) compared the effects of night-only with full-time splint use. After 3 months of wearing the wrist splint orthoses, the patients in both groups (as a combined sample) showed significant improvement in some measurements of CTS (e.g., subjective perception of symptom severity reduced from 28.5% to 22.0% in a questionnaire, p<0.0001). The author also suggested the patients wear wrist splint orthoses full time to get better results. Kruger et al. (1991) reviewed the medical records of 105 adult patients with CTS, who had been treated with a neutral-angle wrist splint, and found that 67% of the patients reported obtaining symptomatic relief by wearing wrist splint orthoses.
However, some researchers also point out that wrist splints have little or even negative effect on DUEMSDs when patients wear it at daytime, especially when patients wear the splint during work. Li et al. (1999) did a three-month follow-up study for the effectiveness of splinting. They found that though 77% of the subjects had reduced symptom severity, some subjects had increased symptom severity with splinting treatment. Of note is the observation that many of these subjects were employed in clerical occupations or sales and service occupations, working 12 to 14 hours per day with their hands.

1.2.5. Previous studies of the biomechanical effects of wrist splints

Some studies have evaluated the biomechanical impact of wrist splint orthoses on workers, and considered their effects on wrist motion range, carpal tunnel pressure (CTP), EMG activity of the forearm muscles, adaptation and period of use.

Carpal tunnel pressure

Weiss et al. (1995) found that wrist deviation increased CTP. The curve of CTP versus wrist flexion/extension/deviation angles followed a “U” shape as a function of deviation from neutral with CTP lowest at wrist neutral position and increasing with increasing deviation. It is reasonable to expect from this relationship that less range of wrist motion will induce lower CTP. Since the function of the wrist splint is to reduce the range of motion of the wrist, it would be expected that wearing wrist splint orthoses will reduce CTP. Rempel et al. (1994) studied the effect of wrist splints on carpal tunnel pressure during repetitive hand activity. The subjects were asked to perform a repetitive task, which consisted of loading and unloading a box containing 1 lb. cans at a rate of 20 cans per minute for a period of 5 minutes, with and without wrist splint orthoses. He found the wrist splint elevated the resting CTP, probably because of direct external
pressure on the carpal tunnel. Even through the wrist splint did reduce the wrist motions, the CTP was increased during task performance while wearing a wrist splint. Some other researchers have shown that increased forearm muscle forces will induce higher CTP (Keir et al. 1997, 1998). This result indicates that the side effect of wearing wrist splint orthoses, which can be increasing muscle activity, was not negligible. This concept of the worker fighting against the wrist splint to finish the task in this study was shown to increase muscle activity and bring about increased CTP.

**Kinematics**

Other studies have shown that wrist splint orthoses do, in fact, reduce the range of motion of the wrist. Collier et al. (2002) studied the range of wrist flexion and extension while shooting a basketball with 4 different kinds of wrist splints and free hand, and found the range of wrist movement with wrist splints is significantly lower than in free hand (<30° versus 98°). A similar result was also found by Rempel et al. (1994). The wrist motion range was reduced by about half for splinted hands compared to bare hand. However, they also pointed out that the wrist splint orthoses did not “substantially change the average wrist position (4°±6° extension and 4°±4° ulnar deviation with the splint, compared with 3°±13° extension and 7°±8° ulnar deviation without the splint)”. This indicated that the average wrist position in work was related mainly to the job itself. It could be argued that the absolute value of wrist position in this study was fairly small. If the wrist angle required in the task is large, people will finally yield to the restriction of wearing wrist splint orthoses and alternate their behaviors and gestures to accomplish their normal work. Chan and Chapparo (1999) compared the amount of shoulder movement used by elderly men in a set of tests, which included writing, turning over cards, picking-up small objects, simulated feeding, stacking checkers, picking-up light cans and picking-up heavy cans, between splinted and un-splinted hands. They found that
participants used significantly more total degrees of shoulder movement when splinted as compared to free handed (83.44º vs. 78.99º, p<0.05). Similar results were also found by King et al. (2003). These authors studied the immediate and short term (1 week later) effects of a wrist splint on range of shoulder motion in two special designed tasks. One task consisted of picking-up a 16-ounce can, emptying its contents of water and setting the can back down to a destination spot. The other task consisted of reaching from the edge of a table retrieving three 1-inch wooden cubes, one at a time, and stacking them on a marked spot on the table. The subject was seated in these two tasks. They found the mean of shoulder abduction was significantly greater (18.94º vs. 13.75º in pretest, 16.62º vs. 12.31º in posttest) when wearing the splint than freehanded. The approximately constant difference between splinted hand and bare hand in pretest and posttest also showed that the adaptation of wearing wrist splint orthoses will not overcome the negative effect of the wrist splint on increasing shoulder abduction angles. Some kinematics effects of a wrist splint on working performance were also evaluated in this study. The movements of splinted hand tended to be slower, less smooth initially in the experiment tasks.

**EMG**

Surface EMG is an assessment tool that is used to evaluate the neuromuscular activation associated with a contracting muscle and several studies have used this tool to assess the effect of wrist splint orthoses on muscle activities generated during work tasks. Stegink Jansen et al. (1997) recorded the root mean square of surface EMG of the extensor carpi radialis brevis (ECRB), one of the main wrist extension muscles, in three different lifting tasks. The results showed that the EMG of the ECRB in all the three lifting tasks was significantly reduced by wearing wrist splint orthoses. Opposite results were found by Perez (2000), when she measured the EMG of extrinsic flexor muscles and
the anterior deltoid muscle on three subjects who self-reported symptoms of wrist MSDs. The two specific jobs that were chosen for analysis involved the repetitive grasping and positioning of containers and sprouts. The results showed that the use of the wrist splint increased the activity of both of the studied muscles. Bulthaup (1999) conducted a similar experiment. Seventeen subjects were asked to perform several specified movements with a 1-lb can, including picking the can up, turning and setting it back down. The EMG activity of five proximal joint muscle groups, wrist extensor carpi radialis brevis (ECRB) and wrist flexors measured in this study was significantly increased with the wrist splint orthoses. The EMG of ECRB in long orthoses (108.4 microvolts) and in short orthoses (99.8 microvolts) was significantly greater than that for bare hand (90.8 microvolts).

These results revealed that wearing wrist splint orthoses placed additional stress on the proximal joint musculature and elevated the EMG of the studied muscles. While these previous studies have found contrasting results on the effect of wrist splint orthoses on muscle activity, close attention needs to be paid to the specific tasks being performed. Most of the studies compared the response of the subjects with and without wrist splint orthoses in one, or a series of, simple wrist/hand motion(s), such as lifting, picking-up objects, turning the wrist, and stacking, etc. To date, no specific analysis has been done on the relationship between the required wrist angle and the job/task content, and these important EMG and kinematics response variables.

1.3. Specific aims

The specific aims of the current study are to 1) evaluate the impact of specific wrist angles and the effects of wrist splint orthoses on the activation of the forearm muscles and 2) investigate the impact of work surface angle and the effects of wrist splint orthoses on proximal upper extremity postures. It is hypothesized that wearing wrist splint orthoses will not increase the EMG activity of forearm muscles at neutral wrist
postures (as compared with the bare hand)(Hypothesis 1), but at deviated wrist postures
the wrist splint orthoses will generate higher forearm muscle activities (Hypothesis 2). It
is also hypothesized that if an individual is wearing a wrist splint orthoses during a task
requiring wrist deviations, other joints in the upper extremity must deviate from their
neutral posture in order to perform the task (Hypothesis 3).

2. Experimental method

2.1. Subjects

Ten healthy college students, all right-handed, age from 22 to 28 years (standard
deviation 1.4), with no current or previous upper extremity disorders, participated in this
study. At the beginning of each experiment, the subject read and signed the consent form
approved by Institutional Review Board for the Protection of Human Subjects in
Research of North Carolina State University. Other anthropometric data are listed below
in Table 1.

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<th>STD</th>
</tr>
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<td>Wrist Circum. (cm)</td>
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<td>17.15</td>
<td>13.97</td>
<td>1.20</td>
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</table>
2.2. Apparatus

2.2.1. Wrist splint orthoses

Two kinds of commercial wrist splints were selected based on advice from several therapists: 1) the “Motion Manager” wrist support from Medical Specialties, model number: 223901 to 223905 (x-small to large) and 2) the “Comfort Cool” D-ring Wrist Splint from North Coast Medical, Inc, model number NC52961 to NC52967(x-small to large). Each was fitted to the subject based on the directions included with the orthoses.

2.2.2. Goniometer

Penny & Giles Goniometer (X-series #180) (Biometrics Ltd, Cwmfelinfach, Gwent NP1 7HZ, UK) was used to measure flexion/extension and radial/ulnar deviation angles of the wrist in this study. The goniometer was connected to Thought Technology goniometer adapters (SA9545PD) (Thought Technology Ltd., 2180 Belgrave Ave. Motreal, (Qc) Canada, H4A 2L8). The signal was processed and recorded by the FlexComp 1.52 Ergonomic Suite (Thought Technology Ltd) at a frequency of 60Hz. The output could be simultaneously displayed to the subject via the computer screen.

2.2.3. Apparatus for muscle activity experiment

Maximum voluntary contraction (MVC) apparatus

An apparatus was constructed to precisely define and control three-dimensional wrist postures for the collection of maximum voluntary contraction data on the forearm muscles. The apparatus consisted of a base board with guiding lines, a flat wood board to support and guide the forearm, and two fork-shaped frames with cushions on the side and bottom. The two frames were used to provide single plane isometric resistance during the measurement of the MVCs. One configuration of the apparatus allowed for precise
flexion/extension positioning (maintaining 0 degrees ulnar deviation) and the other configuration allowed for precise ulnar deviation positioning (maintaining 0 degrees flexion/extension, Figure 1) One frame consisted of two vertical bars with cushions 1.5 inches away from each other and a horizontal base with cushions, which allowed the subject’s palm to be inserted vertically and perform maximum voluntary flexion/extension and ulnar deviation exertions at preset wrist angles. The other frame consisted of two vertical bars 3.4 inches away from each other with cushions on right side, a horizontal base with cushions, and a belt over the base. The subject’s palm could be inserted between the base and belt horizontally and perform maximum voluntary flexion/extension and ulnar deviation exertions at preset wrist angles.

![Figure 1 Frames used to perform MVC for flexion/extension exertions](image)

**EMG**

Three pairs of bipolar surface electrodes (model: E220X-LP, 20”, IN VIVO METRIC) were used to collect the activities of three forearm muscles: flexor carpi radialis (FCR), flexor carpi ulnaris (FCU) and extensor carpi ulnaris (ECU). The signals were recorded at a frequency of 1024Hz, converted to digital and stored on a COMPAQ pentium computer.
2.2.4. Apparatus for upper extremity kinematics study

Magnetic motion tracking system

The three-dimensional shoulder and back posture data (measured as arm elevation from the vertical and back sagittal/lateral bending) were captured by the Ascension MotionStar position and orientation measurement system (“Flock of Birds Motionstar Model” with the extended range transmitter, Ascension Technology, VT, USA), and were recorded at the frequency of 100Hz with the Innovative Sports Training Motion Monitor software (version 4.10).

The magnetic source was placed 2 feet away on the left side of the subject, and the surface of the source was parallel to the sagittal plane of the subject. The transmitter is the origin (0,0,0) of the three-dimensional space in this system. The x-axis is parallel to the transverse and coronal planes, the y-axis is parallel to transverse and sagittal planes, and the z-axis is vertical. Upper extremity sensor locations are shown in Figure 2. The torso sensors were placed on the midline of the spine at T9 and L5.

Figure 2 Configuration of sensors and goniometer
**Pliers**

Conventional straight-handle pliers (Swanstrom model s325E) were used in this experiment, see Figure 3.

![Pliers](image)

**Figure 3 A conventional straight-handle pliers**

Characteristics of the pliers:

- Serrated jaw
- Jaw length=27mm
- Tip width=1.50mm
- Tip thickness=1.50mm

The overall length of the pliers was 15.8cm.

**Jumpers and motherboard**

The jumpers were insulated gold contacts enclosed in a plastic housing, described as standard 0.1”x 0.3” jumpers. The connectors were two standard IED connectors on a used IBM “Venus Pass 3” (2001) mother board. The connectors are vertically parallel to each other. The distance from the center lines of the connectors is 1.1 cm, see Figure 4.
Figure 4 IED connectors on mother board with jumpers

**Video record system**

A Panasonic video recorder (model: pv-d209) was positioned at 2 feet on the right side of the mother board. It was at the same height and parallel to the working surface. This camera recorded the angle between the pliers and the mother board surface as well as the whole working process.

**2.3. Experimental design**

**2.3.1. EMG experiment**

**Independent variables**

There were two independent variables in this study: wrist splint orthoses and wrist angle. There were three conditions for wrist splint orthoses: none (bare hand), wrist splint 1 (“Comfort cool”) and wrist splint 2 (“Motion manager”). There were different number of levels for wrist angle in three wrist motion directions – four levels of wrist angle in flexion, 0º, 12º, 24º and 36º; four levels in extension, 12º, 24º, 36º and 48º; and three levels in ulnar deviation, 0º, 12º and 24º. The different responses of three wrist motion directions were not analysis because of the nature difference of the motions.
Dependent variables

Normalized (to maximum) EMG activities for three forearm muscles: ECU, FCU and FCR were the dependent variables.

2.3.2. Jumper experiment

Independent variables

There were two independent variables in this experiment: wrist splint orthoses and working surface angle. There were three conditions for wrist splint orthoses: none (bare hand), wrist splint 1 (“Comfort Cool”) and wrist splint 2 (“Motion Manager”). There were four working surface angles (in the sagittal plane, see Figure 8): 0º (horizontal), 30º, 60º and 90º (vertical). The working surface angle represented the angle between the surface of the motherboard and the horizontal plane.

Dependent variables

There were nine dependent variables in this experiment. Shoulder abduction (rotation relative to the sagittal plane), shoulder flexion (rotation relative to the coronal plane), shoulder joint angle (angle between upper body and upper arm, regardless of plane), back lateral bending angle and back sagittal bending angle were the five variables to represent body kinematics. The time to complete each trial was recorded as a measure of efficiency. Angle of the pliers to the motherboard surface was recorded for testing the assumption that the job itself requires awkward working posture. Wrist flexion/extension and radial/ulnar deviation angles were two variables studied to test the effect of wrist splint orthoses on wrist posture.
2.4. Experimental Procedure

2.4.1. EMG experiment

The subject read and signed the Informed Consent Form. The stature and weight of
the subject were collected, as was the circumference of wrist at the distal wrist crease.
This was used to establish the appropriate size of wrist splint orthoses to be used. Next,
three pairs of surface electrodes were placed on the surface of the skin over the three
studied muscles. The electrode placement followed the instructions of Basmajian (1989).
Before placing electrodes, the surface of the forearm in the location of the electrodes were
shaved (if necessary) and cleaned with alcohol. Once the signal quality was verified, the
subject was asked to perform a series of maximum voluntary contractions with the
muscles of the forearm in the frame system made for this experiment. The subject
performed maximum voluntary wrist flexions, extensions and ulnar deviations against the
resistance provided by the frame system. In total there were 11 exertions in different wrist
postures, 4 trials from 0° to 36° (in 12° increments) in flexion, 4 trials from 12° to 48° in
extension, (radial/ulnar deviation was 0°) and 3 trials from 0° to 24° degrees (in 12°
increments) in ulnar deviation plane (flexion/extension angle was 0°). There was 1
minute rest time after each trial.

After the MVC measurements, the goniometer was placed on the right hand of the
subject following the instructions of the manufacturer. Then the subject was asked to sit
beside a table, put the forearm on the table and let the wrist and hand extend beyond the
edge of the table. The subject then performed a series of simple, single-plane wrist
posture-maintenance tasks at the varied wrist angles, see Figure 5. The plane of motion
was always horizontal to minimize gravitational effects. The FlexComp system provided
real-time feedback on wrist flexion/extension and radial/ulnar deviation values on a
monitor screen. The subject watched the values on the screen and was asked to maintain their wrist angle at the target angle area for 3 seconds. The tolerance was ±1 degree and all subjects successfully accomplished the trials. The order of the three wrist splint treatments: bare hand, “Comfort cool” (wrist splint 1), and “Motion Manager” (wrist splint 2) were randomly selected. There were 11 target angles for each wrist splint condition. (As in the MVC exertions, the off plane angles were held at 0 degrees) Under each wrist splint orthoses condition, the presentation order of all these trials was randomized.

![Figure 5 Single plane wrist exertion trial](image)

**2.4.2. Jumper experiment**

The height of the table and working surface in the jumper experiment was carefully adjusted based on the subject’s elbow height. The apparatus was positioned such that when the subject was standing still, fully relaxing the upper arm, flexing the elbow to 90 degrees and parallel to ground, the tip of the middle finger was at the height of the center of the IDE connectors, see Figure 6.
Before commencing the experiment, the static standing posture data was collected through the magnetic motion tracking system as the reference posture. All subsequent angles of the shoulder and back were measured relative to this upright, neutral posture. The subject was instructed to grasp the pliers in a standard way, see Figure 7. Subsequently he/she was asked to practice the jumper experiment for 10 minutes until his/her performance was stabilized where no obvious improvement in working time was observed in three consecutive trials.

During the experimental trials, the subject used the pliers to unplug five jumpers one by one from the primary IDE port, move horizontally one 1/2 inch and plug it into the
coordinate position of the second IDE port, and then move them back to the original position. (Figure 7 and Figure 8) There were ten horizontal movements in each trial.

Figure 8 Working at 30° work surface angle without wrist splint

The order of the three wrist splint conditions was randomized. There were four different work surface angles, 90 degrees (vertical), 60 degrees, 30 degrees and 0 degrees (horizontal), and they were randomly assigned under each wrist splint orthoses condition. In total, there were twelve trials (4 surface angles x 3 wrist splint levels). During these trials the upper extremity and trunk motions were captured by the magnetic motion sensors. The wrist postures were captured by the goniometer. The angles of the pliers were captured by the video recorder.

2.5. Data processing

2.5.1. EMG experiment

The EMG data was first processed by applying a 15Hz high-pass filter and a 350Hz low-pass filter. Notch filters at 59Hz-61Hz and 199Hz-201Hz were also applied to eliminate other electrical noise. The EMG data from each of the MVC trials were rectified and then averaged in 1/8 second windows (128 data points). The maximum value of these 1/8 second windows was identified as the maximum EMG value for that muscle.
in that wrist posture and was used as the denominator to calculate normalized EMG for
that wrist posture in the experimental trials. The sub-maximum static bending EMG data
was averaged across the whole 3 seconds of the steady static hold time as the EMG
activity for that muscle in that wrist posture in the experimental trials and used as the
numerator to calculate the normalized EMG for that trial. The normalized EMG data was
calculated as static bending EMG value divided by the maximum EMG value for the
same muscle at the same wrist angle.

2.5.2. Jumper experiment

The three dimensional position data of sensors on the shoulder and trunk were
collected in the jumper experiment. Each sensor provided three 3-D dimension position
variables, which were named by the position of the sensor: shoulder (Xs Ys Zs), elbow
(Xe Ye Ze), hand (Xh Yh Zh), T9 (Xb Yb Zb) and L5/S1 (Xw Yw Zw). Shoulder
abduction angle and shoulder flexion angle were based on absolute reference frames:

Shoulder abduction is calculated as: \( \arctan(\frac{Xe-Xs}{Ze-Zs}) \)

Shoulder flexion is calculated as: \( \arctan(\frac{Ye-Ys}{Ze-Zs}) \)

Shoulder joint angle was calculated as the angle between the z axis of trunk and
upper arm:

\[
p_1 = Xb - Xw \\
q_1 = Yb - Yw \\
r_1 = Zb - Zw \\
p_2 = Xe - Xs \\
q_2 = Ye - Ys \\
r_2 = Ze - Zs
\]

\[
\phi = \arccos\left(\frac{p_1q_2 + q_1r_2 + r_1p_2}{\sqrt{p_1^2 + q_1^2 + r_1^2} \times \sqrt{p_2^2 + q_2^2 + r_2^2}}\right)
\]

\( p,q,r \) were the orientation of upper arm and upper body vector. \( \phi \) is the calculated
shoulder joint angle.
Back lateral bending is calculated as: \(\arctan\left(\frac{X_b - X_w}{Z_b - Z_w}\right)\) (Rotation around Y axis).

Back sagittal bending is calculated as: \(\arctan\left(\frac{Y_b - Y_w}{Z_b - Z_w}\right)\) (Rotation around X axis).

In each jumper experimental trial, the average value of wrist flexion/extension and radial/ulnar deviation angles during that trial was calculated. The pliers working angle was the angle between the center line of the pliers and the working surface relative to the coronal plane. It was measured by using a simple goniometer on the video monitor screen as the video of the experiment was played-back. Working time for the ten movements of the jumpers was collected by watching the video record. The start point was the touch of the first jumper and the end point was the removal of the pliers from the last jumper.

2.6. Statistical analysis

The data was analyzed through the analysis of variance (ANOVA). In the EMG experiment, the dependent variables were the normalized EMG in the wrist motion directions. There are three kinds of motions: flexion, extension and ulnar deviation. There are four angles in flexion, 0, 12, 24 and 36 degrees. There are four angles in extension, 12, 24, 36 and 48 degrees. There are three angles in ulnar deviation, 0, 12 and 24 degrees.

The same model applied in these kinds of motion cases. The model is as follows:

\[ Y_{ijk} = \mu + \alpha_i + \beta_j + \alpha\beta_{ij} + \gamma_k + \alpha\gamma_{ik} + \beta\gamma_{jk} + e_{ijk} \]

The response variable is represented by \(Y\). In each case the overall mean is represented by \(\mu\). The \(\alpha\) term represented the effect of the three wrist splints levels, bare hand, wrist splint 1 and wrist splint 2. The \(\beta\) term represented the effect of subject blocking. The \(\alpha \beta\) term represented the whole plot error. (subject block×wrist splint) The
\( \gamma \) term represented the wrist angle levels. (In flexion case, \( k=4 \); in extension case, \( k=4 \); in ulnar deviation case, \( k=3 \))

Before ANOVA procedure was taken, the normality of residuals and constant variance assumptions were tested first by investigating the normal probability plot of residuals, and the plot of residuals vs. predicted values. The results showed a violation of the assumptions. (Figure 21) Further investigation revealed that the cause of the violation of the constant variance assumption may be the non-linear relationship between the response of EMG of the forearm muscles and the effect of interaction between WSO and angle. (Figure 9 to Figure 11) Because the assumption of normality for ANOVA was not fulfilled, logarithm transforms were applied to the response variables according to the procedures described by Montgomery 2001. After transformation, the normality of the residuals and constant of the variance assumptions were tested again in the same way. No obvious violations were found. Although the statistic results reported below are on the transformed responses, the plots of the normalized EMG of the three forearm muscles were presented in original unites in order to promote ease of interpretation and understanding.

In the upper extremity kinematics experiment, the dependent variables were shoulder abduction angle, shoulder flexion angle, back lateral bending, back sagittal bending angles, wrist flexion/extension, wrist ulnar deviation, pliers angles and working time. The model is as follows:

\[
Y_{ijk} = \mu + \alpha_i + \beta_j + \alpha\beta_{ij} + \tau_k + \alpha\tau_{ik} + \epsilon_{ijk}
\]

The response variable is represented by \( Y \). In each case the overall mean is represented by \( \mu \). The \( \alpha \) term represented the effect of the three wrist splints levels. The \( \beta \) term represented the effect of subject blocking. The \( \alpha\beta \) term represented the whole plot error. (block\( \times \)wrist splint) The \( \tau \) term represented the effect of the four working surface
angles. The $\alpha t$ term represented the effect of the interaction between wrist splint orthoses and working surface angles.

Using the above statistical models ANOVA procedures were used to assess the effects of the independent variables. Significant ANOVA results were followed by post-hoc analysis (Tukey’s HSD) to further explore the response ($p<0.05$). Before conducting these analyses, however, the assumptions of the ANOVA procedure (homogeneity of variances, normality of residuals, linearity, and random process) were verified using the procedures described by Montgomery (2001) – examining plots of residuals against the levels of the independent variables, normal probability plots, plot of residuals versus fitted values and plot of residuals versus time of the dependent variables.

3. **Results**

3.1. **Assumptions**

Before performing the ANOVA procedures, the assumptions of the homogeneity of variances, normality of residuals were tested and verified as displayed in appendix and no obvious violations were found.

3.2. **EMG Results**

The response variables of all three studied muscles (FCR, FCU and ECU) showed strong interaction between wrist angle and wrist splint level in flexion ($p<0.001$) and ulnar deviation conditions ($p<0.05$). (Table 2) Because of the significant interaction between wrist splint orthoses and wrist angles, the wrist angle showed different effect on the response of the muscles in the bare hand as compared to the splinted hand. In the bare hand condition, the normalized EMG was comparatively flat in all levels of wrist
deviation. In the splinted hand, the normalized EMG followed a nonlinear trend as a function of wrist angle, increasing rapidly as the wrist angle increased to near maximum.

In flexion condition, the effect of WSO on FCR and FCU was significantly related to wrist flexion angle, see Figure 9 and Figure 10. At the neutral wrist angle, the EMG of FCR and FCU in splinted hand appreciably larger than those in bare hand. But at large flexion angle, such as 36 degrees, the EMG activity of FCU in splinted hand was almost seven times the value in the bare hand. A further post-hoc test revealed no significant difference between the two wrist splint levels.

In extension condition, there was no significant interaction between wrist splint orthoses and wrist angle. (Table 2) ECU was significantly affected by both WSO and wrist angle, but there was no interaction between them. From the post-hoc test, there was significant difference between the response of ECU in bare hand and in splinted hand. But there was no significant difference between two wrist splint levels. There were significant differences among wrist angles. The responses of ECU at 36° and 48° extension angle were significantly different from others, while 48° was significantly higher than 36°.

In ulnar deviation condition, there was significant interaction between WSO and ulnar deviation angles for all three studied muscles. In lower ulnar deviation angles, the wrist splint effect on the EMG for these muscles was small, about 30%. In large ulnar deviation angles, WSO significantly increased the muscles activities around 500%. (Figure 9-Figure 11)
Table 2 ANOVA of EMG data for wrist splint orthoses and angle by motion

<table>
<thead>
<tr>
<th>Motion</th>
<th>Muscle</th>
<th>WSO (df=2)</th>
<th>Wrist angle (df=3)</th>
<th>Interaction (df=6)</th>
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</thead>
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<td>Flexion</td>
<td>FCR</td>
<td>F=42.04, p&lt;0.001</td>
<td>F=81.83, p&lt;0.001</td>
<td>F=13.54, p&lt;0.001</td>
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<td>FCU</td>
<td>F=37.43, p&lt;0.001</td>
<td>F=64.65, p&lt;0.001</td>
<td>F=9.80, p&lt;0.001</td>
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<td>ECU</td>
<td>F=7.12, p&lt;0.01</td>
<td>F=25.66, p&lt;0.001</td>
<td>F=8.14, p&lt;0.001</td>
</tr>
<tr>
<td>Extension</td>
<td>FCR</td>
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<tr>
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<td>FCU</td>
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<td>Ulnar deviation</td>
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<td>FCU</td>
<td>F=42.05, p&lt;0.001</td>
<td>F=59.12, p&lt;0.001</td>
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<td>ECU</td>
<td>F=29.66, p&lt;0.001</td>
<td>F=79.11, p&lt;0.001</td>
<td>F=3.78, p&lt;0.01</td>
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</tbody>
</table>

Figure 9 Plot of EMG of FCR in three wrist splint levels
Figure 10 Plot of EMG of FCU in three wrist splint levels

Figure 11 Plot of EMG of ECU in three wrist splint levels

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3.3. Shoulder and trunk kinematics

There was no significant interaction between wrist splint orthoses and working surface angle for any of the dependent variables in this study. (Table 3)

The working surface angle had significant effects \( (p<0.001) \) on all of these variables indicating that the slope of the working surface is a key characteristic for determining worker posture in this experiment. When the working surface was vertical, the subject stood straight, keeping the upper arm near body, and bending the elbow around 90°. As the slope of the working surface decreased, the subject bent more toward the left and forward (Figure 15 and Figure 16), and raised their arm higher (Figure 12-14).

The effect of the wrist splint was significant for shoulder abduction \( (p<0.01) \) and shoulder joint angles \( (p<0.001) \). All variables parallel to sagittal plane (wrist flexion, back sagittal bending) were not significantly affected by wrist splint orthoses. In this experiment, the pliers must be as perpendicular to the motherboard as possible to function properly. With a bare hand, the subject can reach their hand to that orientation with large wrist flexion and ulnar deviation. With the wrist splint, however, the range of motion of the wrist was limited, so the subject must raise their upper arm to get the pliers into the correct position. In general, the shoulder abduction angles were elevated more than 30% on average from bare hand (35.4°) to splinted hand (42.6°).

All the dependent variables in the jumper experiment were significantly affected by the working surface angle. A further post-hoc test found that the shoulder abduction angle, shoulder joint angle and back lateral bending angle were significantly different at all four working surface angles. The shoulder flexion angles were significantly different at 0°, 30° and 60° work surface angles, while there was no significant difference between 60° and 90° work surface angles. It was also found that the back sagittal bending angles
were significantly different at 30°, 60° and 90° work surface angles, and no significant
difference between 0° and 30° work surface angles.

Table 3 ANOVA of upper extremity kinematics in jumper experiment

<table>
<thead>
<tr>
<th>Working surface angle (df=3)</th>
<th>Interaction (df=6)</th>
</tr>
</thead>
<tbody>
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<td>Working surface angle (df=2)</td>
<td></td>
</tr>
<tr>
<td>Shoulder abduction angle</td>
<td>$F=11.46, p&lt;0.001$</td>
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<tr>
<td>Shoulder flexion angle</td>
<td>$F=305.44, p&lt;0.001$</td>
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<tr>
<td>Shoulder joint angle</td>
<td>$F=10.41, p&lt;0.01$</td>
</tr>
<tr>
<td>Back lateral bending</td>
<td>$F=214.20, p&lt;0.001$</td>
</tr>
<tr>
<td>Back sagittal bending</td>
<td>$F=5.54, p&lt;0.05$</td>
</tr>
<tr>
<td></td>
<td>$F=86.72, p&lt;0.001$</td>
</tr>
<tr>
<td></td>
<td>$F=39.38, p&lt;0.001$</td>
</tr>
</tbody>
</table>

Figure 12 Shoulder abduction angles vs. work surface angles and WSO levels
Figure 13 Shoulder flexion angles vs. work surface angles and WSO levels

Figure 14 Shoulder joint angles vs. work surface angles and WSO levels
Figure 15 Body lateral bending angles vs. work surface angles and WSO levels

Figure 16 Body sagittal bending angles vs. work surface angles and WSO levels
3.4. Wrist kinematics, pliers angle and work time

As expected, both wrist flexion and ulnar deviation angles showed a significant effect of the wrist splints (p<0.01), see Table 4. In both splinted hand levels, the wrist flexion angles were limited to around half of those found in the non-splinted hand level, see Figure 17. A further post-hoc test revealed a significant difference between the two different kinds of wrist splints. Wrist splint 2 (“Motion Manager”) was more restricted in controlling wrist flexion than wrist splint 1 (“Comfort Cool”), with an average wrist flexion angle of 13.0º compared to 15.3º. However, there was no significant difference in controlling wrist radial/ulnar deviation angles between the two wrist splints, see Figure 18. The working surface angle significantly affected wrist flexion and ulnar deviation angles, but post-hoc tests found it was only significant at 0º working surface angle.

Finally, the pliers angle was significantly affected by working surface angles, (p<0.001) but wrist splint did not affect pliers angles. A further post-hoc test found the pliers angle was significantly different at all four working surface angles, see Figure 19. Work time for each trial was significantly affected by working surface angles (p<0.001), but only at 90º. No significant difference between other three working surface angles. And no significant effect by wrist splint was found on work time, see Figure 20.

<table>
<thead>
<tr>
<th></th>
<th>WSO (df=2)</th>
<th>Working surface angle (df=3)</th>
<th>Interaction (df=6)</th>
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<tbody>
<tr>
<td>Wrist flexion</td>
<td>F=55.25,p&lt;0.001</td>
<td>F=16.33,p&lt;0.001</td>
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<tr>
<td>Wrist ulnar deviation</td>
<td>F=23.23,p&lt;0.001</td>
<td>F=22.13,p&lt;0.001</td>
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<tr>
<td>Pliers angle</td>
<td>F=1.54,p&lt;0.001</td>
<td></td>
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</tr>
<tr>
<td>Working time</td>
<td>F=25.05,p&lt;0.001</td>
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</tbody>
</table>
Figure 17 Wrist flexion angles vs. work surface angles and WSO levels

Figure 18 Wrist ulnar deviation angles and work surface angles and WSO levels
4. Discussion

The main contribution of the current work is a systematic analysis of the effects of WSOs as a function of forced wrist deviations. Previous work, which included analysis of
wrist angle, treated it as response variable, while in the current work wrist angle was
controlled in the EMG experiment. The results of this experiment showed that the effect
of the wrist angle and wrist splint orthoses interacted. At rest posture (0° wrist angle), the
average normalized EMG activities of all subjects were not significantly elevated by wrist
splint orthoses, which confirmed Hypothesis 1. The slightly higher normalized EMG in
splinted wrist, as shown in Figure 9 and Figure 10 at 0° wrist angle, might come from the
feelings of unfamiliar external pressure around the wrist. The subjects might try to keep
the splinted wrist at neutral position with extra but unnecessary force, while they could
keep wrist position in bare hand with less effort.

To understand the effect of the wrist splints on forearm muscle activities, the
factor of wrist angle must be included. Hypothesis 2 focused on the interaction between
the wrist splint and the wrist angle. The strong interaction of wrist angle and wrist splint
for flexor muscles in flexion level and ulnar side muscle in ulnar deviation level
confirmed Hypothesis 2. The wrist splints provided restriction force as a function of the
ratio of elongation. So, large forearm muscle force as well as the reaction force from wrist
splint was generated only when the wrist was at extreme angles. For example, when the
wrist was at ulnar deviation 36 degrees, the EMG activities of ECU in splinted wrist were
3 to 4 times larger than it in bare hand.

There were two basic assumptions for Hypothesis 3 which focused on the effects
of the wrist splints on the other joints of the upper extremity. One assumption was that the
wrist splint will limit the motion of wrist. The results with regard to the effects of WSO
on wrist angle confirmed the assumption. The wrist splint orthoses accomplished the goal
of limiting wrist motion. Both the flexion/extension and radial/ulnar deviation angles of
wrist in jumper experiment were smaller in splinted hand, as compared to bare hand. The
other assumption was that wrist splint will not affect pliers working angles. When the job
itself requires awkward posture, the worker must find a way to orient the pliers to the jumpers. The non-significant effect of wrist splint on pliers angle confirmed this assumption.

As the assumptions were confirmed, the significant increase in shoulder abduction by wearing wrist splint in jumper experiment supported Hypothesis 3. Since the pliers had to be oriented in relation to the work, the subject distributed the deviated postural stress from the wrist to the shoulder, thus, increasing the potential risk of shoulder disorders because of these awkward postures.

The time to complete one trial in the jumper experiment was not significantly affected by the wrist splint orthoses, indicating that wearing wrist splint orthoses did not affect subjects’ performance. Interestingly, King et al. (2003) observed slower, less smooth movement in some other tasks, like picking and stacking, but this difference may be a function of the relatively static nature of the tasks in the jumper experiment.

The results of this experiment gave a possible explanation of the contrasting results of Stegink Jasen et al. (1997) (decreased muscle activity of ECRB with WSO) and Bulthaup et al. (1999) (increased muscle activity of ECRB with WSO). In Stegink Jasen’s study, the subjects were asked to perform three lifting tasks “in a standard manner: picking-up a folder weighing 1lb; grasping and holding a paper grocery bag with 6 lb of weight; and grasping and holding a briefcase weighing 10lb.” It was observed that subjects extended the wrist in each task. The force used to lift the objects was mainly from fingers flexors, while some came from wrist extensors as the wrist was extended. After the subject adapted to wearing the wrist splint orthoses, the wrist extension angle could be significantly reduced, resulting in reduced force generated by wrist extensor muscles. In Bulthaup’s study, the subjects were asked to pick up a 1 lb can, turn it clockwise and counterclockwise, and set it back. This task required wrist
flexion/extension and pronation/supination which can not be eliminated by wearing wrist splint orthoses. So the subjects exerted extra force to perform required wrist motions with the resistance of wrist splint orthoses.

The wrist motion angle required in a job/task has a significant effect on the impact of wrist splint orthoses in working environment. In order to reach the required wrist angle to finish a job, the worker must fight against wrist splint orthoses, thus, increasing the exposure to another risk factor – high force wrist exertions. From the results of this experiment, it is reasonable to expect negative effects of splinting for workers in jobs with large amount of wrist exertions. This is consistent with the results of Li et al. (1999), who found that some subjects had increased DUEMSDs symptom severity with splinting treatment, particularly those who worked 12 to 14 hours per day with their hands.

Numerous studies have evaluated the effects of risk factors that could be associated with DUEMSDs, including force, posture, repetition, etc. (e.g. Chiang et al. 1993, Moore et al. 1994, Silverstein et al. 1987, Stetson et al. 1993, Bovenzi et al. 1991, Luopajärvi et al. 1979, Hagg et al. 1997) Generally, high force, extreme wrist posture, high repetition and vibration are possible reasons of DUEMSDs. Most of these studies also pointed out that the combination of two or more of these risk factors were more dangerous. NIOSH (1997) reviewed most of the papers addressing hand/wrist illness with these risk factors and found there is strong evidence for a positive association between work that requires extreme postures, in combination with other job risk factors. Wrist splint orthoses were only designed to keep wrist at neutral position in order to prevent extreme wrist postures. Wearing wrist splint orthoses could raise the exposure to other risk factors and increase the risk of MSDs to other body regions. So, the use of wrist splint should be considered carefully relative to the demands of the work tasks.
There are a number of limitations to the generalizability of the results of this study. The results in the EMG experiment coincided with Bulthaup’s (1999) study. However, it could be argued that in this experiment, keeping the wrist as some specific angles with empty hand is relatively rare in the work place. The activities of all the muscles studied in this experiment (FCU, FCR and ECU) without wrist splint orthoses are barely over 10 percent. Only at some extreme positions, like extension 48° for ECU or ulnar deviation 24° for FCU and ECU, muscles activities exceeded 10%, but no more than 15%. In a real working environment, the levels of forces are determined by the physical characteristics of the job, from low force requirement, like sewing, to high force requirement, like manual lifting. The forearm muscles activities would be higher in working than in this experiment. However, the effect of increasing muscle force by wearing wrist splint orthoses was expected to be the same, because this effect was mainly related to wrist exertion angles, not force. The second limitation of this experiment is that the EMG of the three studied forearm muscles was measured at static posture in single plane (flexion/extension and radial/ulnar deviation). No analysis was made on dynamic or multi-plane wrist exertions, which need to be studied further. Thirdly, it is also important to remember that when a person is first fitted with a splint, he/she may attempt to perform work activities in the normal manner. This may cause more forceful muscle contraction as he/she attempts to resist the immobilization of the splint. By allowing the worker to learn the limits of the splint, he/she may become more comfortable with resting in the splint and letting the splint position the wrist for function. Perez (2000) found subjects who were accustomed to wear the wrist splint showed a smaller decrease in peak grip strength (-9.5% vs. -13.4%) as a result of wearing the splint as compared to those who were not accustomed to wearing the splint. It was also observed in King’s (2003) research that participants learned to optimize the effect of wrist splint after one week of use. The
average shoulder abduction angle reduced 2.32º after wearing wrist splint orthoses for one
week. This suggested that there was learning and adaptation during the initial week of use.
However, the relatively small effects size of adaptation in this research (5.19º vs. 4.31º)
indicated that differences in range used over time were small. This result showed that
wearing a wrist splint continued to result in poorer hand performance than the free hand
even after the subject was familiar with wearing the wrist splint. Finally, in this study
only healthy subjects were studied. Further study could be focused on patients with CTS
and other wrist disorders to see if the same reactions from the wearing wrist splint result.

5. Conclusions

This study revealed the relationship between the effect of the wrist splint orthoses
and the wrist angle on forearm muscles activities. The additional force required when
wearing the wrist splint was less at the neutral position, but increased rapidly as the wrist
deviation angle increased. If the task requires no deviated wrist postures, then the wrist
splint will not negatively impact the wrist. However, if the task requires large wrist
deviations, then the results of this study indicate that the splinted user will adapt to abduct
their shoulder and/or bend their back to accommodate the limited range of motion of the
wrist, or exert more forearm muscle force to overcome the splint to achieve the required
wrist posture. These results indicated that workplace requirements should be considered
carefully before a wrist splint orthosis is prescribed for a worker.
6. **Reference**


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7. Appendix: Results of the test of the assumptions of ANOVA

7.1. Discussion of log transform for EMG experiment

Before ANOVA procedure was taken in the original EMG data analysis, the normality of residuals and constant variance assumptions were tested first by investigating the normal probability plot of residuals, and the plot of residuals vs. predicted values. The results showed a violation of the assumptions. (Figure 21) This pattern indicated the model was accurate at small numbers, but the accuracy decreased as the predicted number increase. Further investigation revealed that the cause of the violation of the constant variance assumption may be the non-linear relationship between the response of EMG of the forearm muscles and the effect of interaction between WSO and angle. (Figure 9 to Figure 11) The response of EMG of the forearm muscles was more like a quadratic term to angle in splinted hand.

Because the assumption of normality for ANOVA was not fulfilled, the normalized EMG of all the three studied muscles were log transformed. The same test procedure was then performed on the transformed data. No obvious violation was found. (Figure 22)
Figure 21 Plot of residuals vs. predict value of original data for FCR

Figure 22 Plot of residuals vs. predict value of log transformed data for FCR
7.2. Test of assumptions for EMG experiment

The assumptions for ANOVA procedure for log transformed EMG experiment data were evaluated by investigating the normal probability plot of residuals, the plot of residuals vs. subject, and the plot of residuals vs. predicted values (Montgomery, 2001). No serious violation was found in these plots.

Figure 23 Normal probability plots of residuals for FCR

Figure 24 Normal probability plots of residuals for FCU

Figure 25 Normal probability plots of residuals for ECU
Figure 26 Plot of residuals vs. predicted value for FCR

Figure 27 Plot of residuals vs. predicted values for FCU
Figure 28 Plot of residuals vs. predicted values for ECU

Figure 29 Plot of residuals vs. subject for FCR in flexion level
Figure 30 Plot of residuals vs. subject for FCU in extension level

Figure 31 Plot of residuals vs. subject for ECU in ulnar deviation level
7.3. Test of assumptions for jumper experiment

The assumptions for ANOVA procedure for jumper experiment were evaluated by investigating the normal probability plot of residuals, the plot of residuals vs. subject, and the plot of residuals vs. predicted values (Montgomery, 2001). No serious violation was found in these plots.

![Normal Probability Plot](image1)

**Figure 32 Normal probability plots of residuals for shoulder abduction**

![Plot of residuals (wrist flexion) versus subject](image2)

**Figure 33 Plot of residuals (wrist flexion) versus subject**
Figure 34 Plot of residuals versus predicted value (wrist flexion)

Figure 35 Plot of work time versus order