An Evaluation of a Supermarket Bagging Task Using a Wrist Motion Monitor

by

Cheryl Fairfield Estill

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APPROVED:

K.H.E. Kroemer, Chairperson

J.C. Woldstad

H.L. Snyder

Blacksburg, Virginia

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Committee Chairman: K.H.E. Kroemer, Dr. Ing.

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(ABSTRACT)

Cumulative trauma disorders have become common among workers in industry. Grocery stores are an industry with one of the highest number of repeated trauma illnesses. Checkout departments have a rate of musculoskeletal injuries two to three times higher than other supermarket departments.

The primary objective of this study was to quantify the wrist motions required to bag groceries. Subjects participated in the laboratory or in the supermarket. The wrist motions included wrist deviations, velocities, and accelerations for flexion-extension, radial-ulnar, and pronation-supination deviations. The dependent variables were handle type and object location. A wrist motion monitor designed at Ohio State University was used to quantify wrist posture and movement.

Objects with finger-thumb handle couplings required more extreme ulnar deviations, more extreme pronations, greater

wrist velocities for pronation-supination deviations, and greater wrist accelerations for pronation-supination deviations than did other objects. When comparing soft and solid objects, or round and square objects, there were few differences in wrist positions, velocities, or accelerations. Objects with 10-cm wide hand couplings required more extreme flexion, larger ranges of movement for radial-ulnar deviations and pronation-supination deviations, and greater wrist velocities in the radial, ulnar, and pronation directions than did 5-cm wide objects. The right and front locations required more extreme positions than did the left and back locations. Subjects participating at the supermarket site picked up objects with greater wrist velocities and accelerations than those in the laboratory; conversely, wrist positions were not affected by site. Because finger-thumb and 10-cm wide hand couplings required larger wrist deviations and greater velocities, these objects may pose a greater risk to the bagger of developing cumulative trauma disorders.

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INTRODUCTION

Rationale

Cumulative Trauma Disorders (CTDs) have become very common among workers in industry. The Bureau of Labor Statistics reports that of the 331,600 occupational illness cases in 1990, 185,400 cases were associated with repeated trauma (conditions due to repeated pressure, vibration, or motion). Supermarkets are among the industries with the highest number of illness cases for disorders associated with repeated trauma. Supermarkets accounted for 2,300 repeated trauma cases in 1990. Other industries with a high incidence of repeated trauma were manufacturing industries, including meat products and motor vehicles (U.S. Department of Labor, 1991).

Many supermarket workers who are afflicted with cumulative trauma disorders are those working in the checkout department, including cashiers and baggers. Ryan (1989) determined that the checkout departments had rates of musculoskeletal injuries two to three times higher than the other departments of seven supermarkets.

Only one study has been conducted that determined the extent to which the bagging task affects a person's risk of developing a cumulative trauma disorder. This study (NIOSH, 1991) reported that cashiers who bagged groceries had a higher prevalence of upper extremity musculoskeletal problems than did those who did not bag groceries. Additionally, the study determined that the bagging task required the bagger to maneuver many "awkward" wrist postures.

There are no studies known which quantify the bagger's wrist movements to determine the extent of the awkward postures. Therefore, the primary objective of this study was to observe a laboratory-simulated bagging operation. The purpose was to provide quantitative information about the wrist motions occurring during a bagging job, specifically wrist deviations, velocities, and accelerations for flexion-extension (F/E), radial-ulnar (R/U), and pronation-supination (P/S) deviations. The wrist motions are associated with different handle types and locations of the manipulation areas with respect to the body.

The apparatus used for this study was a wrist motion monitor which was designed and built at the Biodynamics Laboratory at Ohio State University. In its use, it was decided to analyze its accuracy to determine the error associated with an incorrectly placed monitor.

Experimental Objectives

The primary objectives of this study are:

1) to quantify the wrist motions necessary to complete a bagging operation in terms of wrist deviation, velocity, and acceleration;

2) to determine if wrist deviation, velocity, and acceleration are influenced by different handle types or distance of the item from the body; and

3) to characterize the accuracy required for attaching a wrist motion monitor to a subject.

LITERATURE REVIEW

Overview

This literature search begins with a review of research conducted to determine the cause, extent, and control of musculoskeletal injuries among cashiers and baggers. This topic is covered to review the research that has already been conducted and to determine research needs. The following two sections of the literature review provide a detailed description of the anatomy and cumulative trauma disorders of the forearm, wrist, and hand. The last section reviews goniometers.

Checkout Personnel

Cashiers. Cashiers experienced ergonomic problems even before the introduction of scanners or electronic cash registers. In 1976, Japanese researchers documented health problems mainly on an operator's right side while using conventional cash registers (Ohara, Aoyama, and Itani, 1976). The researchers suggested electronic cash registers should be used to alleviate the force needed to activate the registers. However, the faster rate of checking items with the electronic cash registers increased the shoulder and neck pain of the cashiers. An Australian researcher also reported ergonomic problems among cashiers who did not use laser scanners (Ryan, 1989). Ryan believed that many of the cashiers' problems were caused by their static standing position. Ryan compared the musculoskeletal problems of cashiers with other supermarket employees. Cashiers showed the highest prevalence of symptoms in the lower back, lower legs, ankles, and feet.

Other research on cashiers concentrated on the ergonomic problems associated with laser scanners. Margolis and Kraus (1987) found a slightly higher incidence of carpal tunnel syndrome (CTS) among cashiers who used scanners than those who used conventional cash registers. Ayoub (1990) surveyed 30 cashiers and reported that all experienced some pain associated with the use of a laser scanner checkout. Wilson and Grey (1984) found a greater prevalence of neck and arm discomfort of seated cashiers using scanners than in those using conventional cash registers. Wilson and Grey proposed workstation changes to improve the seated posture of the cashier. Lannersten and Harms-Ringdahl (1990) used EMG recordings to determine that scanning items caused higher muscle activity in the shoulder and neck than using a pen reader or a conventional cash register. NIOSH researchers Baron, Milliron, Habes, and Fidler (1991) found that cashiers using laser scanners had higher rates of CTDs than those who did not use laser scanners. Higher rates of neck and shoulder CTD and CTS were associated with cashiers who used a left takeoff cash register configuration. They also found that checkers had a higher rate of cumulative trauma disorders than non-checkers and a dose-response relationship between checking and the disorders.

Checkstand configurations were also compared. Lannersten and Harms-Ringdahl (1990) reported higher EMG activity in the neck and shoulder muscles of cashiers using vertical scanners than in those using horizontal scanners. Marras, Greenspan, and Schoenmarklin reported lower wrist accelerations for cashiers who used checkstands which required the use of both hands to scan items compared to those which required the use of only one hand (Bureau of National Affairs, 1991).

Other research was confined to a specific cash register configuration. NIOSH (1990) researchers reported reduced symptoms (based on self-administered questionnaires) in the neck, back, and shoulder and low back, buttock, and leg areas after incorporating ergonomic interventions into an express checkout station. The interventions included reducing the area in which the cashier was required to reach and installing a telescoping keyboard. Arm, forearm, and wrist symptoms were not reduced.

Other research on cashiers concentrated on the cashier's motions as related to grocery (food) item type. Harper, Bloswick, Peña, Beck, Lee, and Baker (1992) videotaped a cashier scanning objects. They developed a consistent, systematic way to record items being scanned, the deviation of the cashier's wrist, the type of grip, and the type of motion (lift or drag). The researchers divided all scanned items into the following eight categories: Small Box, Heavy (detergent); Small Box, Light (cereal); Gallon Bottle (of milk); Very Small Object (candy bar); Single Can (of soup); Plastic Bag, Light (bread); Liter Bottle (of soda); and Six-Pack (of Coke). The researchers concluded that "Plastic Bag, Light" items might be most problematic for the cashiers because of the high frequency of use and the type of grip used.

Baggers. Bagging groceries is often an integral part of the cashier's job (although, some supermarkets employ individuals whose main job is bagging groceries). There is only one known study which attempted to determine the musculoskeletal problems associated with the bagging of groceries. NIOSH (1991) researchers defined bagging as a task of the cashiers. The epidemiologic evaluation in the study did not reveal a difference in the musculoskeletal problems of cashiers who bagged groceries and those who did not. However, the ergonomic evaluation established that cashiers who did not bag groceries had 67% and 57% less repetitive movements for their right and left hands, respectively, than those who did bag groceries. The study reported that trunk flexion and shoulder flexion and abduction are common awkward postures associated with the bagging operation. The authors believed that large bagging areas contributed to the ergonomic problems of the bagger. The placing of plastic bags onto the metal frames and the opening of paper bags also resulted in extreme wrist postures. The authors suggested further research to compare plastic versus paper bags and to quantify the musculoskeletal problems associated with bagging groceries.

Anatomy of the Forearm, Wrist, and Hand

Skeletal System. The forearm has two bones: the ulna (medial) and the radius (lateral). The olecranon process is located at the proximal end of the ulna. The proximal end of the radius can move at the elbow joint while the distal portion articulates with the proximal portion of the wrist. The ulna and radius bones have the ability to twist over one another to allow the hand and wrist to be turned anteriorly (supination) or posteriorly (pronation). Figures 1A and 1B show the skeletal system of the forearm.

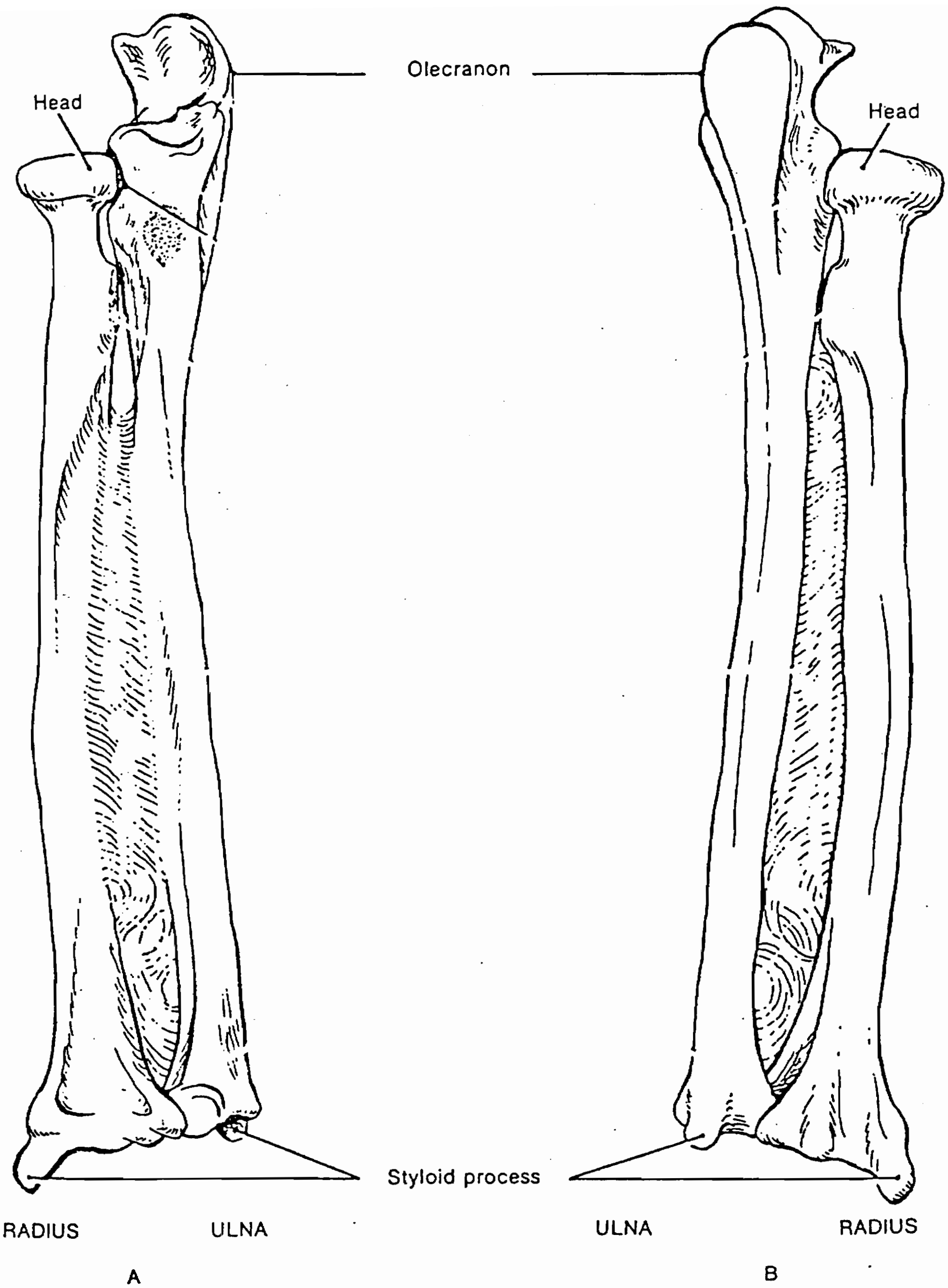


Figure 1A Right ulna and radius anterior view
Figure 1B Posterior view (Wilson and Wilson, 1978).

The wrist is composed of eight carpal bones in two rows. The first row, located distal to the radius and the articular disc (distal to the ulna), consists of the scaphoid, lunate, triquetrum, and pisiform. The second row consists of the trapezium, trapezoid, capitate, and hamate. Distal to the wrist bones are the five metacarpal bones of the hand.

The wrist joint has two degrees of freedom in flexion and extension, and in abduction (radial) and adduction (ulnar). Flexion and extension occur primarily at the midcarpal joint which is between the two rows of carpal bones. Additionally, some flexion and extension occur at the radiocarpal joint. Radial and ulnar movement of the wrist joint takes place at the radiocarpal joint, which consists of the articulation between the distal radius and articular disc and the first three carpal bones. Figure 2 shows the skeletal system of the wrist and hand.

Nerves. Three nerves innervate the hand and fingers: the median, ulnar, and radial nerves. The median nerve extends along the flexor tendons through the carpal tunnel in the wrist. The carpal tunnel is surrounded anteriorly by the carpal bones and posteriorly by the flexor reticulum. The ulnar nerve lies along the ulnar artery through the canal of

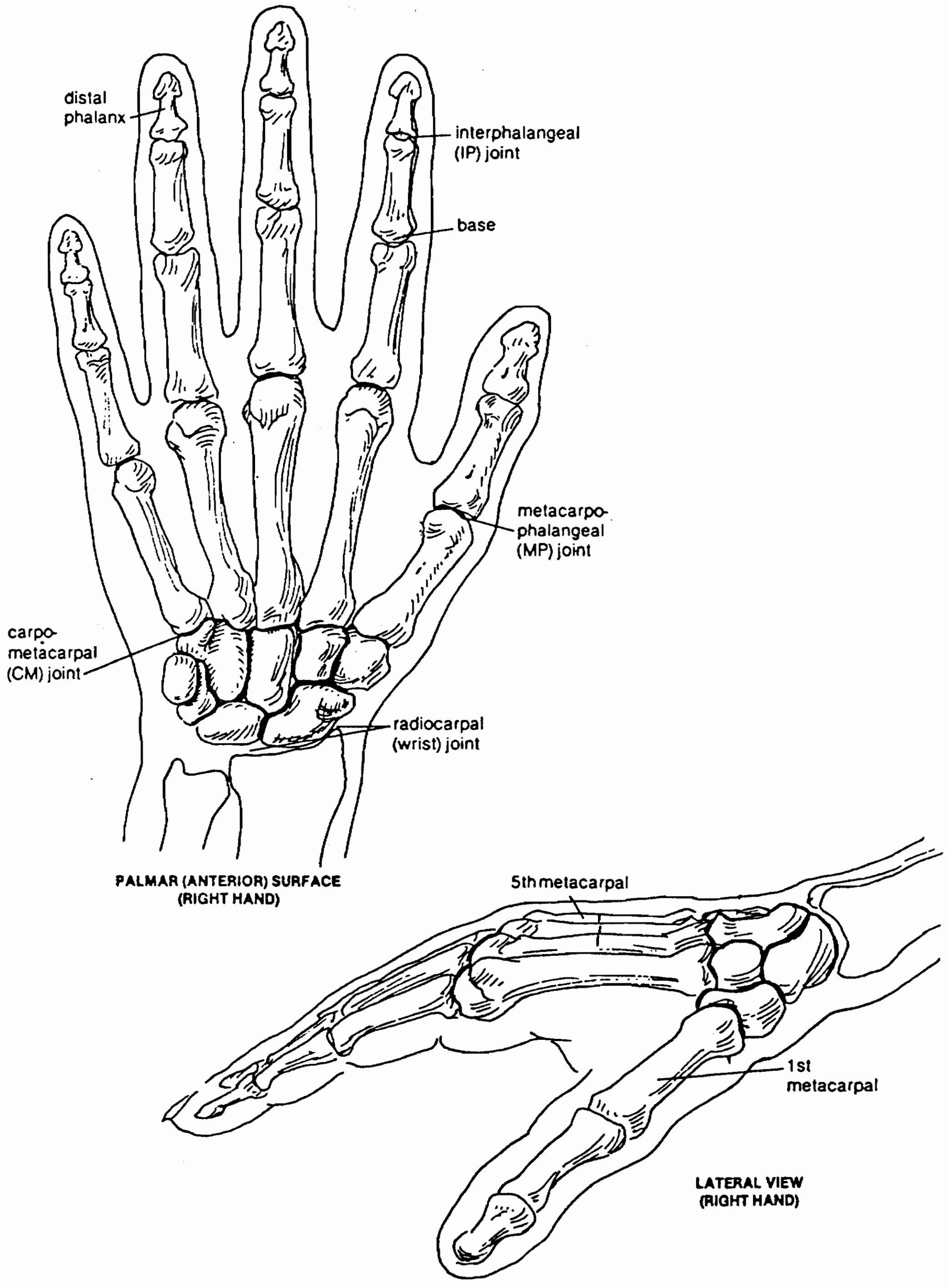


Figure 2 Bones of the hand and wrist (Kapit and Elson, 1977).

Guyon. The canal of Guyon is formed proximally and medially by the pisiform bone, laterally and distally by the hook of the hamate, posteriorly by the transverse carpal ligament, and anteriorly by the aponeurosis of the palm. The radial nerve passes through the wrist on the dorsal side near the radius (Streib and Sun, 1984).

The median nerve supplies the thumb, second, third, and part of the fourth digits and the thenar compartment (Office of Technology Assessment, 1985). The ulnar nerve supplies the other half of the fourth digit, the fifth digit, the interossei muscles (located in each metacarpal space), and the third and forth lumbrical muscles. The radial nerve supplies the dorsum of the hand and the back of the proximal phalanges of the thumb, index, and part of the middle finger. Figure 3 shows the nerves of the forearm, wrist, and hand.

Muscles and Tendons. The primary muscles which move the wrist and rotate the forearm are the pronator teres, flexor carpi radialis, palmaris longus, flexor carpi radialis, pronator quadratus, extensor carpi radialis longus and brevis, extensor carpi ulnaris, supinator, extensor carpi radialis longus, and brevis. Figure 4 shows the muscles of the forearm, wrist, and hand. Flexion of the wrist is

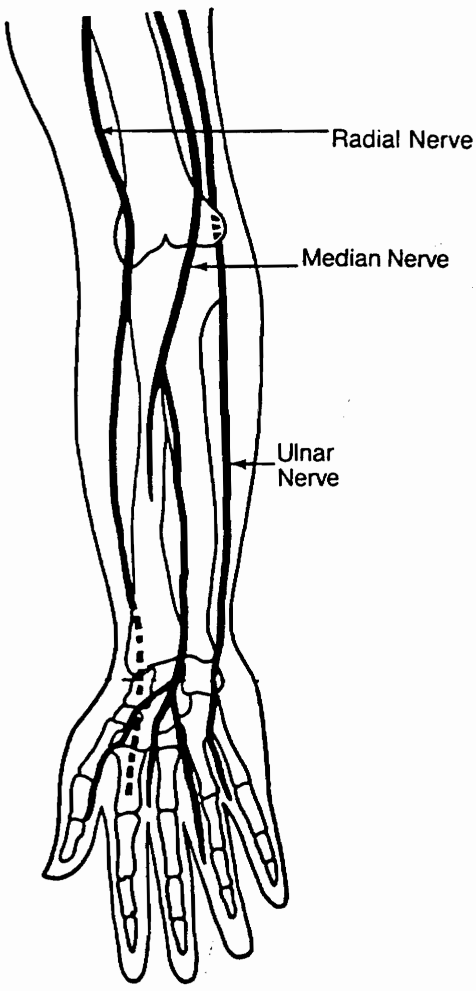


Figure 3 Nerves of the upper limb (Dionne, 1984).

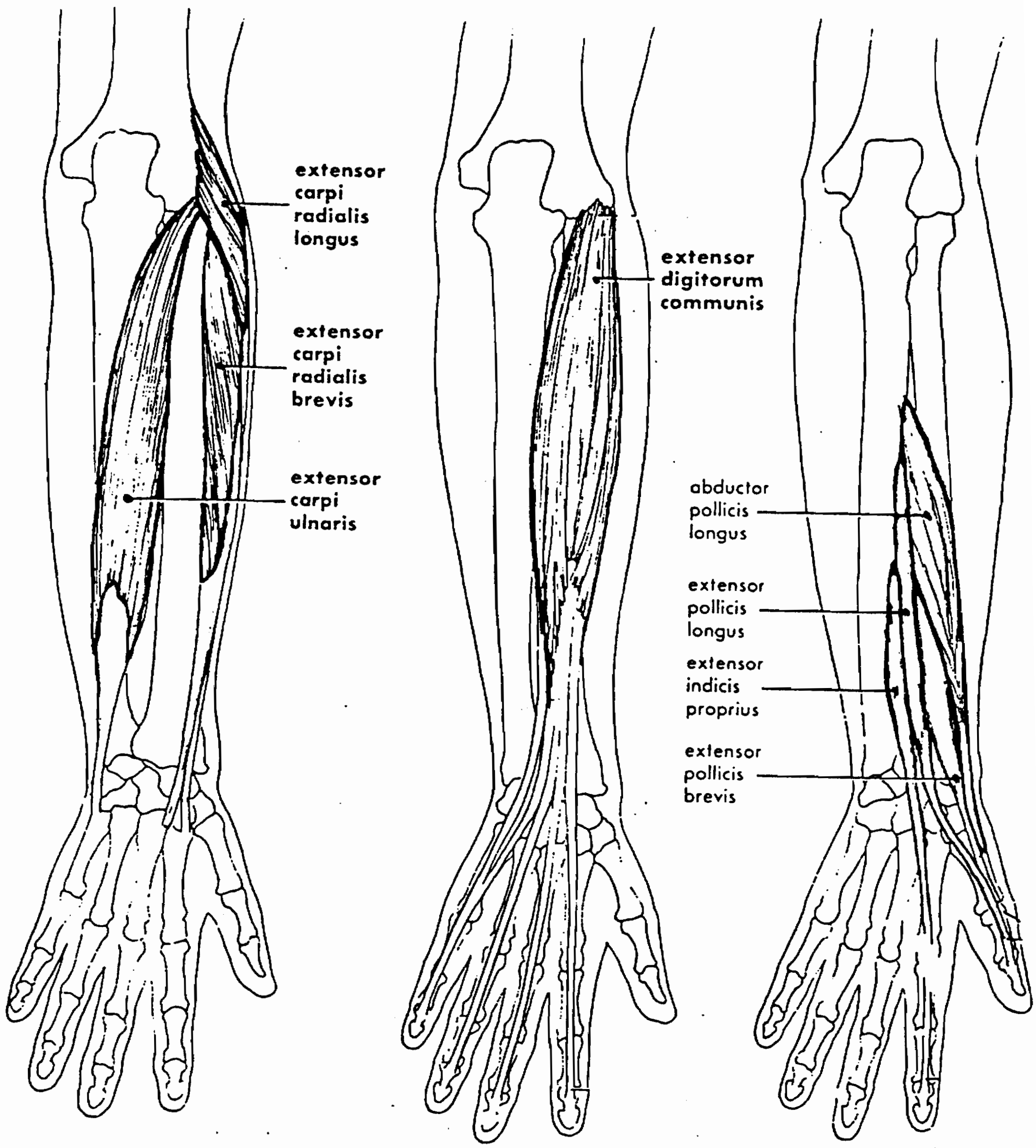


Figure 4 Posterior aspects of the muscles of the upper limb, Crouch 1978).

performed by the pronator teres, the flexor carpi ulnaris, the palmaris longus, and the flexor carpi radialis. Extension of the wrist is performed by the extensor carpi radialis longus and brevis and the extensor carpi ulnaris. Ulnar deviation of the wrist is performed by the extensor carpi ulnaris and flexor carpi ulnaris. Radial deviation of the wrist is performed by flexor carpi radialis, and extensor carpi radialis longus and brevis. Pronation of the forearm is performed by the pronator teres and the pronator quadratus. Supination of the forearm is performed by the supinator.

Tendons connect muscles to the bones. Some tendons of interest are located in the distal portion of the forearm and travel through the wrist to move the hand, fingers, and thumb. Figures 5A and 5B show the tendon sheaths in the hand and wrist. The flexor tendons pass through the wrist in the carpal tunnel with the median nerve. The tendons which pass through the carpal tunnel are connected to the following muscles: the flexor carpi radialis, the flexor digitorum superficialis, the flexor digitorum profundus, and the flexor pollicis longus. The flexor carpi ulnaris does not pass through the carpal tunnel. This muscle tendon connects to the pisiform and then passes to the thumb. The extension tendons pass the wrist on the posterior of the

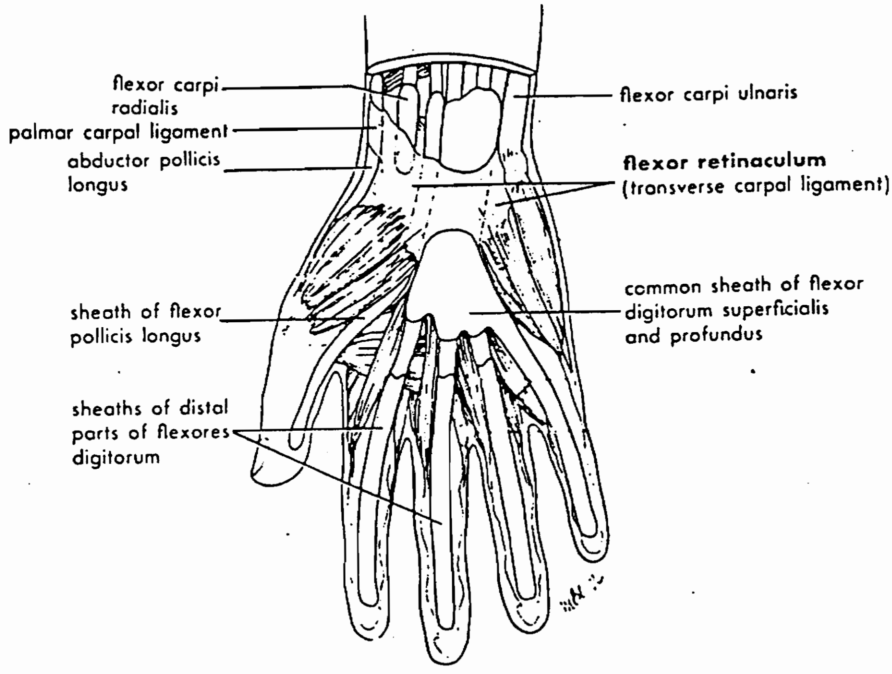


Figure 5 Tendon sheaths of the right hand, anterior view (Crouch, 1978).

hand. These tendons are contained in six compartments formed by the extensor reticulum. Nine tendons are contained in these six synovial membranes. Following are the muscle tendons located in each compartment: 1) the abductor pollicis longus and the extensor pollicis brevis; 2) the extensor carpi radialis longus and brevis; 3) the extensor pollicis longus; 4) the extensor indicis and extensor digitorum; 5) the extensor digiti minimi; and 6) the extensor carpi ulnaris.

The deep layer of fascia thickens at the wrist and forms the flexor retinaculum. The purpose of the flexor retinaculum is to keep the flexor tendons from bulging outward during a flexion of the wrist. Other ligaments at the carpus are the palmar radiocarpal, dorsal radiocarpal, ulnar collateral, and radial collateral. These ligaments keep the carpal bones closely fit together.

Arteries. The radial and ulnar arteries pass through the wrist into the hand. The radial artery is located superficially on the lateral side of the distal forearm. The radial artery then winds dorsally around the lateral side of the carpus and into the hand. The ulnar artery passes through the wrist adjacent to the ulnar nerve.

Injuries of the Forearm, Wrist, and Hand

Repetitive motion injuries of the hand and wrist include carpal tunnel syndrome, tendinitis, tenosynovitis, De Quervain's syndrome, trigger finger, ganglionic cysts, pronator syndrome, and Guyon tunnel syndrome (Kroemer, 1989; Putz-Anderson, 1988).

Carpal Tunnel Syndrome. Carpal tunnel syndrome is a disorder resulting from the compression of the median nerve. The median nerve may become compressed because of an inflammation of the flexor tendons. Tendons may become inflamed from repeated, awkward, or forceful wrist movements. Other causes may include vibration and cold temperatures (Office of Technology Assessment, 1985). CTS can lead to extreme discomfort, impaired hand function, and disability (Centers for Disease Control, 1989).

The first symptoms of CTS include tingling in one or both hands at night and numbness in the fingers. Increased symptoms include attacks of painful tingling during the day and changes in the squeezing power of the hand. In severe cases, the thenar muscle, located at the base of the thumb, atrophies and strength is lost (Office of Technology Assessment, 1985).

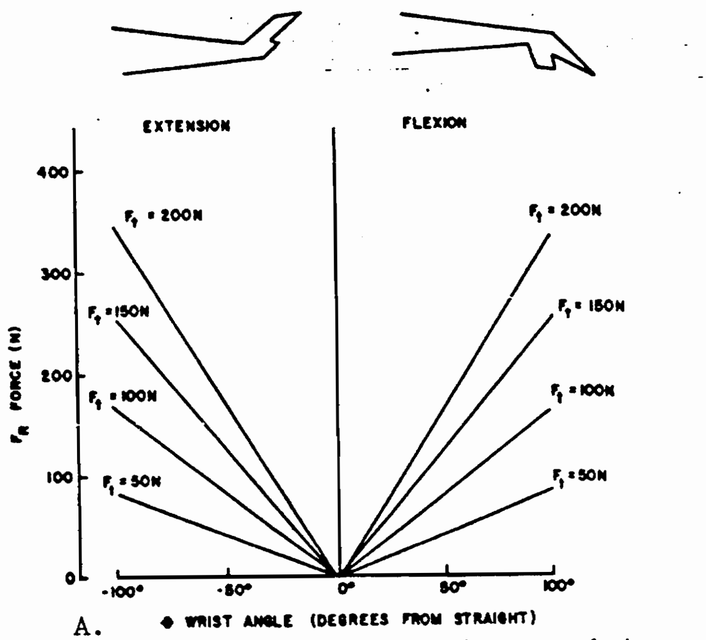
Non-occupational risk factors include systemic diseases, acute trauma, congenital defects, wrist size, pregnancy, oral contraceptive use, and gynecological surgery (Office of Technology Assessment, 1985). Women have a higher incidence of CTS; however, it is not known if this fact is a result of women having more risk factors or of their job assignment (Dionne, 1984; Office of Technology Assessment, 1985). Ergonomic risk factors may include frequent deviation from neutral wrist position, frequent use of the "pinch" grasping hand position, repetitive wrist and hand movements, and extreme and forceful wrist positions (Armstrong, 1983; Dionne, 1984). Compression of the median nerve can also result from prolonged pressure on the palm of the hand as in using a screwdriver (Armstrong, 1983).

A wrist which is extremely flexed or extended, especially with strong finger exertion, results in more pressure in the carpal tunnel (Schenck, 1988). The relation of flexion and extension to pressure in the carpal tunnel was studied by Armstrong and Chaffin (1979) who showed that the force within the wrist can be directly related to the angle of the wrist. The force of the flexor tendons within the carpal tunnel was computed assuming that the sliding of flexor tendons over curved bone surface was analogous to a belt wrapped around a pulley. Assuming friction as negligible, the force of the tendon upon the curved surface (either the carpal bones during extension or the flexor reticulum during flexion) was determined. The force of the tendon was increased by greater flexion or extension of the wrist and greater force exerted by the wrist as shown in Figures 6A and 6B.

Tendinitis. Tendinitis (also called tendonitis) is an inflammation of a tendon caused by repeated movement, contact with hard surfaces, or vibration (Kroemer, 1989). Repeated exertion can tear or fray tendon fibers (Putz-Anderson, 1988). Tendonitis is characterized by a tendon which has become thickened, bumpy, and irregular (Putz-Anderson, 1988).

Tenosynovitis. Tenosynovitis refers to a disorder of tendons when extra fluid is produced within the synovial sheath, causing it to swell. Hence, movement of the tendon within the sheath becomes painful (Kroemer, 1989). The symptoms are pain, swelling, and feelings of burning or numbness of the finger tips (Hammer, 1934).

De Quervain's syndrome. De Quervain's syndrome is a stenosing (narrowing of a passage) tenosynovitis occurring in the single sheath of the abductor (abductor pollicis



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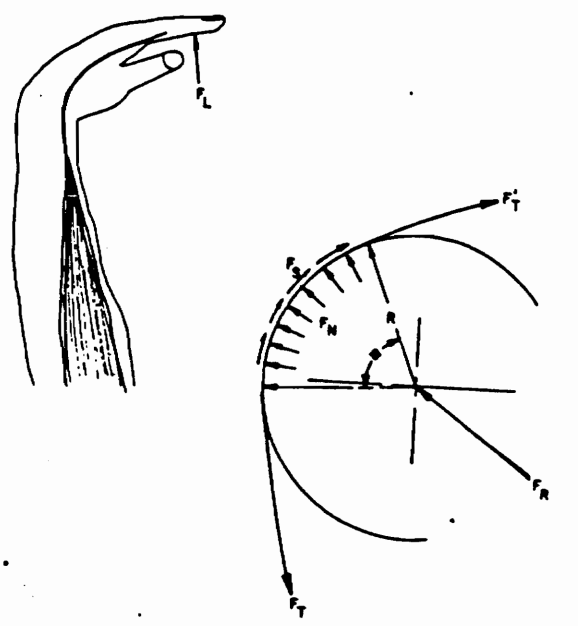


B.

Figure 6A Tendon position during flexion and extension
Figure 6B Force exerted by tendons on wrist structures as a function of wrist angle and tendon load (Armstrong and Chaffin, 1979).

longus) and extensor (extensor pollicis brevis) tendons of the thumb (Kroemer, 1989). Combined, forceful gripping and hand twisting often causes this condition (Kroemer, 1989). The symptoms of De Quervain's syndrome are pain, tenderness, and swelling over the radial styloid (Pick, 1979). When having this condition, the patient often cannot or will not move the thumb in an effort to avoid pain (Kelly and Jacobson, 1964).

Trigger Finger. Another special case of tenosynovitis occurs within the finger, causing it to become locked and then move in snapping or jerking movements; this condition is known as trigger finger. A cause of this condition is the use of hand tools that have sharp edges or require the last joint of the finger to be flexed (Kroemer, 1989).

Ganglionic Cyst. A ganglionic cyst is another form of tenosynovitis. This disorder is one type of cystic tumor which appears at the back of the wrist (Dao, 1964). It is characterized by the swelling of a tendon sheath which is filled with synovial fluid causing a bump under the skin (Putz-Anderson, 1988).

Pronator syndrome. Repeated pronation coupled with force can cause hypertrophy of the pronator muscle which compresses the median nerve. Symptoms of pronator syndrome include numbness of the proximal forearm, the radial side of the palm, and the palmar sides of the first three digits and half of the fourth. This condition can be caused by performing tasks which require pronation, abduction of the forearm, and forceful finger flexion or hand force (Feldman, Goldman, Keyserling, 1983).

Guyon tunnel syndrome. Guyon tunnel syndrome is a disorder resulting from entrapment of the ulnar nerve which can be caused by prolonged pressure on the base of the palm or repeated flexion and extension (Kroemer, 1989). This condition can result from tasks which involve using the palm of the hand as a tool such as activating palm operated buttons or using staplers or drills (Feldman, et. al., 1983). This condition is characterized by painless weakness at the location of the interossei muscle resulting in a weak handgrip, claw position of the fourth and fifth fingers, and abduction of the fifth finger. The hypothenar muscles and the proximal part of the forearm may also be affected (Strieb and Sun, 1984).

Quantification of Joint Movements

Combining a potentiometer or electrical transducer with a goniometer results in an electrogoniometer or elgon (Chaffin and Andersson, 1991). Electrogoniometers have been used since 1959 for the measurement of joint motions (Chao, 1980). An electrogoniometer can be connected to a recording device or computer to measure joint angles over time. Most goniometers require the addition of a lightweight exoskeleton to a subject's body. The goniometer must be designed to keep the potentiometer at the joint center of rotation and only ball-and-socket type joints can be used. Electrogoniometers are limited to the measurement of joint action in one plane (Roebuck, Kroemer, and Thomson, 1975). Most human joints require two or three orthogonally placed goniometers to record the movement at all axes (Chaffin and Andersson, 1991). Some error is inevitable when using electrogoniometers because they are attached to soft tissue (Chao, 1978).

Chao, An, Askew, and Morrey (1980) devised an electrogoniometer for the elbow joint. The monitor records flexion and extension of the elbow and pronation and supination of the forearm. Adduction and abduction of the elbow was recorded although the elbow joint does not move in these directions. If an adduction and abduction movement of the elbow was recorded this movement corresponded to an error in measuring flexion and extension or pronation and supination. The study found that placement of the flexion and extension axes of the goniometer caused greater error in measurement than the placement of the elbow centers of rotation.

Brumfield and Champoux (1984) used an electrogoniometer to record flexion and extension of the wrist joint during daily activities. Landmarks for the attachment of the goniometer were the lateral epicondyle, radial styloid, and center of the second metacarpal head. The researchers reported that the daily activities required a maximum flexion of 19° and a maximum extension of 64°.

A wrist motion monitor was designed and constructed by the Biodynamics Laboratory at the Ohio State University (Marras and Schoenmarklin, 1991). The monitor is comprised of three measurement devices which collect data in six directions of motion: flexion and extension (F/E), radial and ulnar (R/U) deviation, and pronation and supination (P/S). The wrist motion monitor apparatus weighs approximately 50 gm. Both measurement devices for radial and ulnar deviation, and for flexion and extension consist of a rotary potentiometer which is attached to two thin strips of metal. The strips are joined in a one-degree-of-freedom joint where a small potentiometer records electrical signals analogous to the angle between the metal strips. The potentiometer, mounted on the metal strips, is 4.0 cm high, 3.0 cm long, and 1.3 cm wide. One metal strip is 16 cm long and 1.3 cm wide; the other metal strip is 9.0 cm long and 1.3 cm wide. The longer metal strips are positioned on the forearm, while the shorter metal strips move through sliders (2.3 cm long by 2.8 cm wide) which are positioned on the hand. This device can be positioned on the hand with adhesive tape (Marras and Schoenmarklin, 1991). For this study, however, the device was positioned with Velcro® tape (Velcro USA, Inc., Manchester, NH) for easy readjustment for each experimental trial.

The measurement device for pronation and supination is attached to the distal and proximal ends of the forearm. The potentiometer is placed at the distal end of the forearm and a stationary cuff is positioned at the proximal end. The two ends are connected by a metal rod (diameter of 1.6 mm). The potentiometer measures the rotation of the distal end of the forearm with respect to the proximal end. The pronation and supination device is mounted on the ulnar side, parallel to the forearm.

Fitts' Law

Fitts Law states that when movement amplitude and target width are manipulated, the effect is summarized by an equation:

$$Movement\,Time\,(MT) = a + b\log_2(\frac{2A}{W})$$

Where a and b are constants, A is the distance moved, and W is the target width. The quantity $\log_2(2A/W)$ is the *index of difficulty* of the movement. Fitts found a linear relationship between movement time and index of difficulty; therefore, movements with the same index of difficulty will take the same amount of movement time. This equation also demonstrates the trade-off between speed and accuracy (Wickens, 1992).

Summary

This literature review revealed several points which can be summarized as follows:

- Cashiers experienced cumulative trauma disorders before the introduction of laser scanners.
- Checkstands which incorporate laser scanners have been associated with a higher incidence of cumulative trauma disorders than conventional checkstands.

- Cashiers who did not bag groceries had 67% and 57% less awkward movements for their right and left hands, respectively, than did those who did bag groceries.
- There is a lack of quantitative information on supermarket bagging. Although bagging requires awkward postures, most research has been done on cashiers.
- The basic anatomy of the forearm, wrist, and hand must be known to determine skeletal landmarks for the location of a wrist motion monitor.
- Knowledge of the location of the nerves, muscles, and tendons in the forearm, wrist, and hand can aid in determining possible causes of cumulative trauma disorders.
- Repeated awkward postures, forceful movements, or extreme flexion or extension of the wrist can cause carpal tunnel syndrome.
- Repeated movement of the wrist can cause tendinitis, tenosynovitis, or Guyon Tunnel Syndrome.
- Forceful gripping and hand twisting can cause De Quervain's syndrome or pronator syndrome.
- Electrogoniometers provide a direct measurement of body positions, can be used for measurement of

multiple joints, and can record postures which cannot be seen directly.

- To use electrogoniometers one must assume that human joints are of the ball-and-socket type. Soft tissue movement may induce error in the electrogoniometer and attachment of the device may alter normal motion patterns.
- Fitts' law can be used to show a relationship between movement time and the index of difficulty.

Because of the lack of information on wrist deviations, velocities, and accelerations required to bag groceries, a study was developed to quantify these wrist indices. The study was designed to determine if handle type or location of the object from the body influenced wrist deviation, velocity, or acceleration. Quantification of wrist positions and movements may determine if a bagger is at risk of any of the repetitive motion injuries of the hand or wrist mentioned previously. The bony landmarks that are required for attaching the wrist motion monitor are sometimes difficult to identify; hence, a secondary part of the study was designed to determine the accuracy required when attaching the monitor to the subject.

METHOD

Subjects

Bagging Experiment. Sixteen subjects performed the experiment in the laboratory. An additional three subjects performed the study in a nearby supermarket. The subjects were right handed. To assure that each subject had sufficient wrist and forearm mobility, the subject's range of motion for flexion and extension was measured and found to be within the 5th and 95th percentile values as reported by Kroemer, Kroemer, and Kroemer-Elbert (1990). Attaching and calibrating the wrist motion monitor to the right hand and performing the task took approximately one hour for each subject. The subject was paid at a rate of $5.00 per hour.

Apparatus. The apparatus for this study included a wrist motion monitor and a data acquisition system.

Wrist Motion Monitor. The wrist motion monitor was attached to the subject's right wrist. This monitor was described previously in Section 2.5.

Data Acquisition System. The wrist motion monitor was attached to a MacADIOS ADPO (GW Instruments, Inc., Somerville, MA) interface which converted the analog signals to digital signals. The digital signals were then converted into voltage signals and processed by the experiment specific software, Superscope (GW Instruments, Inc., Somerville, MA). The microcomputer system consisted of a MacIntosh IIci (Apple Computers, Inc., Cupertino, CA) with a MacADIOS II Analog-to-Digital (A to D) board, Superscope data acquisition software, and a color monitor. The MacADIOS II board contained eight 12-bit analog-to-digital converters which were capable of receiving analog input voltages within the range of 0 to +10V (unipolar) or -10 to +10V (bipolar). The analog-to-digital conversion resolution for this board was 12 bits (4096 counts). Superscope data acquisition software was capable of collecting data from eight channels simultaneously and could emulate oscilloscope, chart recorder, spectrum analyzer, and XY recorder modes. Three channels were read by the data acquisition system at 25 Hz: right hand flexion and extension, right hand radial and ulnar deviation, and right hand pronation and supination.

Bagging Station. The bagging station at the laboratory was designed to simulate a bagging station at a nearby supermarket; therefore, dimensions mentioned here correspond to those at the nearby grocery store. Figure 7 shows a diagram of the simulated bagging area. The bagging station consisted of the takeoff chute (96 cm high) and the bagging table (56 cm high). The takeoff chute was 120 cm wide and 100 cm deep. The bagging table was 67 cm wide and 35 cm deep. The bagging table was located in front of the takeoff chute. The subject stood directly in front of the bagging table. The subject picked up objects from the takeoff chute and placed them one at a time into a paper bag on the bagging table. The subject picked items up from four locations on the takeoff chute. The distances were measured from the front middle of the takeoff chute: 1) "right front" 30 cm to the right and 25 cm forward; 2) "left front" 30 cm to the left and 25 cm forward; 3) "right back" 30 cm to the right and 75 cm forward; and 4) "left back" 30 cm to the left and 75 cm forward.

Grocery objects required different hand couplings. Six types were chosen to exemplify objects handled at grocery stores. The objects initially considered were those used by Harper et al, (1992). Harper's categories were altered so that 5-cm objects could be compared to 10-cm objects, round objects could be compared to square objects, soft objects could be compared to solid objects, and objects with a

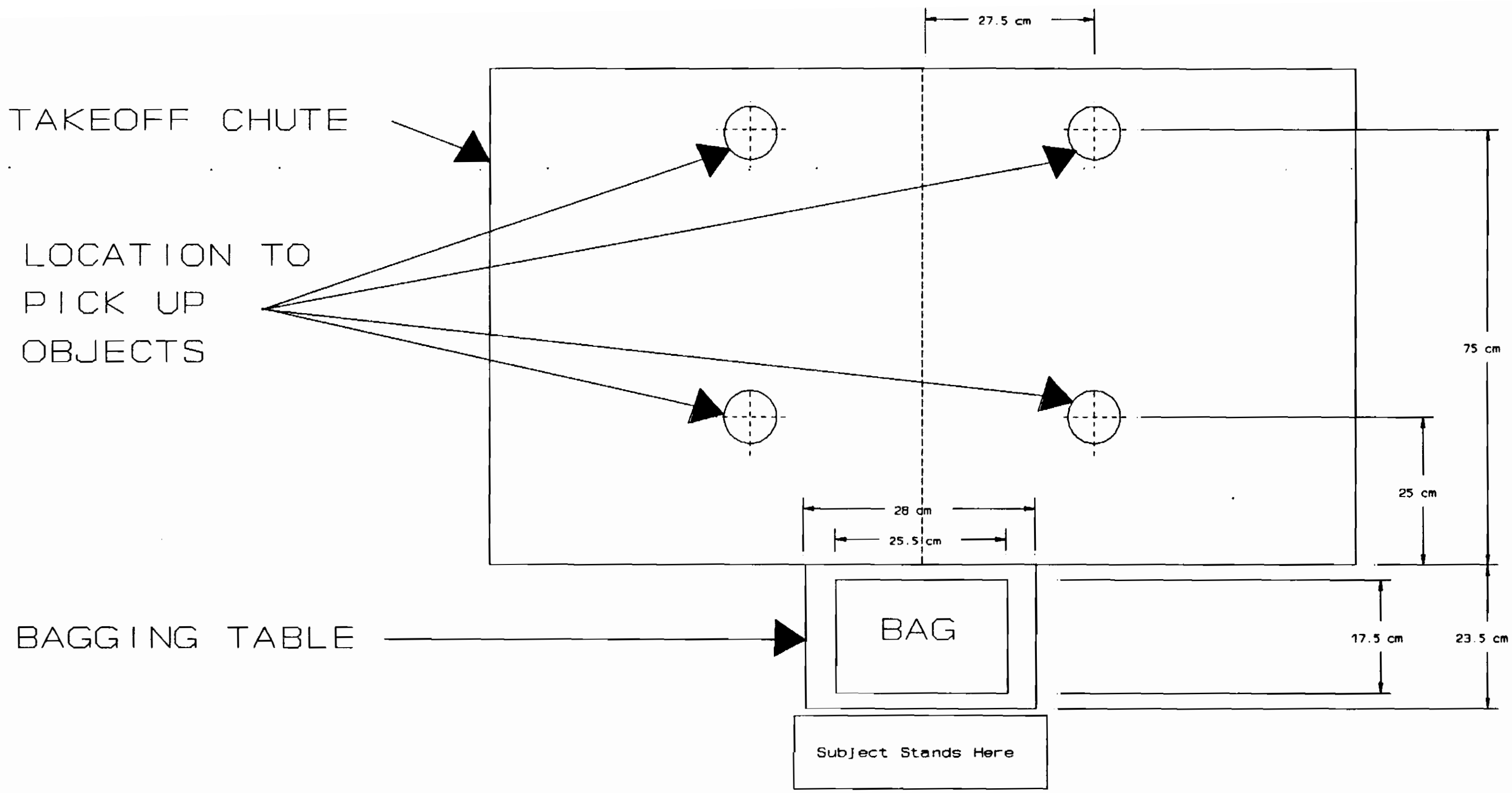


Figure 7 Diagram of the bagging table.

finger-and-thumb hand coupling could be compared to those grasped at the side. The weight of all the objects was the same so that comparisons could be made. The six objects had the following characteristics: 5-cm diameter "solid" round, 10-cm diameter "solid" round, 5-cm "solid" square, 10-cm "solid" square, 10-cm "soft" square, and 5-cm finger-and-thumb handle. The "solid" objects were made of wood or sturdy cardboard. The "soft" objects were pliable with a deformation constant of 0.025 N/mm. The four solid objects and the soft object were each 18 cm high. The portion from 7.5-cm to 16.5-cm, measured vertically, was painted blue; this highlighted area was where the object should be grasped. The object with a 5-cm finger-and-thumb handle was a six-pack. The location of the finger-and-thumb handle was 12 cm from the base of the cans. All items were filled with weights, clay, or water to make them weigh 1 kg.

Digital filtering. A finite impulse response (FIR) filter was used to filter the data before velocity and acceleration could be computed. A finite impulse response filter, a non-recursive filter, has an impulse response sequence $\{h(k)\}$ of finite support, that is $h(k)=0$ for $k>N_1$ and $k<N_2$ with $N_1 \geq N_2$, for some finite integers N_1, N_2. A non-recursive filter is inherently stable and it can be designed to have an exactly linear phase characteristic in the passband. Conversely,

non-recursive FIR filters require a high order to meet sharp cutoff specifications and are determined by trial and error (Bose, 1985).

The window-function is the simplest and most obvious way to design an FIR filter. It truncates the response outside a chosen interval and inside the interval a window is designed for the response. Some window choices are Rectangular, Hanning, Hamming, Blackman, and Kaiser. The Rectangular window simply truncates the response at the bandpass edges. This truncation is an unacceptable choice because a truncation of the Fourier Series will produce Gibbs Phenomenon, an increased attenuation of about 9% at the band edges. The attenuation associated with maximum stopband ripple for the Rectangular filter is only about 21 dB. The Hanning, Hamming, and Blackman windows all overcome the abrupt truncation of the Rectangular window by gradually sloping to zero at the band edges. The three windows use a simple raised cosine equation but with different weights for the constant and cosine terms. The Hanning window has a maximum stopband ripple of approximately 44 dB from the passband gain, while the Hamming window is approximately 53 dB. The transition widths for the Hanning and Hamming windows are about the same. The Blackman filter has a greater maximum stopband ripple (74 dB); however, the transition width is about 50 percent larger than either the Hanning or Hamming windows. The Kaiser window requires an additional parameter, β, which can be chosen to provide the desired maximum stopband ripple and transition width. All of the these windows have the incompatible objectives of minimizing the transition width while maximizing the stopband ripple (Jackson, 1989).

For the current application, the Hamming window was chosen. The Hamming window provides a compromise between the maximum stopband ripple and the transition bandwidth. The following is the equation for the Hamming window:

$$\omega_M(n) = 0.54 - 0.46\cos\frac{2\pi n}{M}$$

Where M is the sampling length and n = 0,1,2...M.

Procedures

Experimental Design. The experimental design for the bagging study was a two-factor, within-subject design. The factors were handle types and pick up location of object. The between-subject factors were site of study and subjects. The presentation order of the object handles and object locations was randomized.

The dependent variables were the following: maximum, minimum, mean, and range of wrist deviation; maximum velocity in each direction and mean velocity; maximum acceleration in each direction, and mean acceleration in the following directions: flexion and extension, radial and ulnar, and pronation and supination. Table 1 lists the experimental variables.

Table 1 Experimental design - bagging experiment

Constant Parameters		
Height of Center of Handle, painted blue (12-cm)		
Weight of Object (1 kg)		
Hand-Handle Coupling		
Orientation of Object versus Subject		
Right Hand Use		
Independent Variables (Within Subject)		
Handle Type (6)		
	Solid Round 5-cm Diameter	
	Solid Round 10-cm Diameter	
	Solid Square 5-cm Wide	
	Solid Square 10-cm Wide	
	Soft Square 10-cm Wide	
	5-cm Finger-and-Thumb Handle	
Pickup Location of Object (4)		
	Right Front	30-cm right, 25-cm forward
	Right Back	30-cm right, 75-cm forward
	Left Front	30-cm left, 25-cm forward
	Left Back	30-cm left, 75-cm forward
Independent Variables (Between Subject)		
Subjects (19)		
Sites (2)		
	Laboratory	
	Supermarket	
Dependent Variables (31)		
Maximum, Minimum, Mean, & Range		
	Wrist Position for F/E, R/U, & P/S	
Maximum, Minimum, & Mean		
	Angular Velocity for F/E, R/U, & P/S	
	Angular Acceleration for F/E, R/U, & P/S	
Time		

An evaluation of the wrist motion monitor consisted of determining the error associated with 1) positioning the center of the wrist motion monitor in the wrong place by as much as 1-cm in any direction, 2) orienting the long metal strip with the wrong skeletal landmark, and 3) positioning the center of the wrist motion monitor and the long metal strip in the wrong place. The difference between the correct angle and the angle of the wrist motion monitor was determined geometrically. This part of the study did not require any subjects. The results and discussion of the evaluation of the wrist motion monitor is located in Appendix E.

Experimental Tasks. For the bagging experiment, subjects were asked to move objects from the takeoff chute into a paper bag on the bagging table. There were six objects which represented different handles. The object was located in one of four locations during each trial. Each trial began when the experimenter positioned the object on the takeoff chute and said "O.K." The subject then picked up the object and placed it in the bag on the bagging table. The trial ended when the subject set the object down into the bag. The experimenter recorded the beginning and ending of each trial by activating a switch connected to the A to D board. This task was repeated for each of the six objects in each of the four locations. Therefore, there were 24 trials for each subject. The objects were presented to the subject in random order and in the same orientation every time. The subjects were instructed to grasp the blue portion of the objects (except the 6-pack). The objects were grasped on their right sides as seen by the subject. The subjects used their first, second, and third digits to pick up the 6-pack by its finger-and-thumb handle, from the top.

<u>Application Procedure</u>. The components of each wrist monitor were applied to the subject's right wrist in the following order: radial and ulnar device, flexion and extension device, and pronation and supination device. During application of the radial and ulnar device the subject was in the following position for the wrist monitor to be applied: seated upright with the upper arm adjacent to the body, the elbow flexed 90°, and the posterior of the forearm positioned superiorly. The subject's upper arm and forearm rested on a table with the lateral epicondyle, the center of wrist rotation, and the third phalange in line. The device was positioned on the posterior of the forearm with the potentiometer directly on top of the center of wrist rotation. This point was palpated between the hamate and capitate bones. The proximal and distal metal strips of the device were in line with the lateral epicondyle and third metacarpophalangeal joint, respectively. Velcro® tape was put on the subject's forearm and hand, and on the device so that it was easily pressed into place. The subject radially and ulnarly deviated his wrist to help the investigator

ensure that the potentiometer was placed directly on the center of wrist rotation. A slider was positioned on the distal metal strip and the subject was asked to flex and extend his wrist to ensure the slider would not slip off the distal end or bottom out on the proximal end of the device.

During application of the flexion and extension device, the subject was in the following position: seated upright with the upper arm adjacent to the upper body, the elbow flexed 90°, and the posterior of the forearm positioned on the posterior side of the subject. The forearm rested on the table while the wrist and hand were over the end of the table. The olecranon, radial styloid, and fifth metacarpophalangeal joint were in line when viewed from the ulnar side. The potentiometer was placed proximal to the styloid process on the ulnar side of the wrist. The distal strip of the device was in line with the fifth metacarpophalangeal joint. The proximal strip of the device was in line with the subject's olecranon. A slider was positioned on the distal strip of the device so that when the subject deviated his wrist radially or ulnarly, the slider did not bottom out or slide off. The slider was secured with Velcro®. The subject then flexed, extended, radially deviated, and ulnarly deviated to ensure that no sliders would slide off or bottom out.

The pronation and supination device was placed directly in line with the flexion and extension device and the olecranon on the ulnar side of the forearm. The subject ulnarly deviated as much as possible to make sure there was no interference between the pronation and supination and the flexion and extension potentiometers. The pronation and supination device was also held in place with Velcro® on the distal end of the forearm. At the proximal end of the forearm, the pronation and supination device was secured with a cuff which wrapped around the arm. The subject moved his arm and wrist in all directions to ensure all equipment was properly positioned and stable. The wires were then connected to the three potentiometers (radial and ulnar deviation, flexion and extension, and pronation and supination) and kept from interfering with the subject's motion by wrapping Velcro® around the subject's upper arm.

Calibration Procedure. To calibrate the radial and ulnar deviation device, the subject was seated upright with the upper arm adjacent to the upper body, the elbow flexed 90°, and the posterior of the forearm positioned superiorly. The subject's lateral epicondyle, center of wrist rotation, and third metacarpophalangeal joint were in line. This position was considered to be the neutral position (0°) for the radial and ulnar deviation device, and a voltage measurement was taken in this position. Additional voltage measurements were taken when the subject radially deviated the wrist 15° and the maximum, and ulnarly deviated 15°, 30°, and the maximum. A voltage measurement was taken in each position. The degrees of deviation were determined by positioning the subject's forearm, wrist, and hand on a protractor. The subject's hand was moved while keeping the forearm in position. The degree of radial or ulnar deviation was measured by locating the position of the subject's third digit. Radial deviation was recorded as positive and ulnar deviation was negative.

The subject was seated in the same position for the calibration of flexion and extension device as for the radial and ulnar deviation device. Neutral position was recorded when the subject's olecranon, radial styloid, and fifth metacarpophalangeal joint on the ulnar side of the forearm were in line. A voltage measurement was taken in this position. Additional voltage measurements were taken when the subject's wrist were flexed 20°, 45° and the maximum, and extended 20°, 45°, and the maximum. A voltage measurement was taken in each position. The degrees of deviation were determined by aligning a goniometer on the subject's wrist. Flexion was recorded as positive and extension was negative.

For the calibration of the pronation and supination device, the subject was standing with the arms next to the body and elbows flexed 90°. The subject grasped the handle of the calibration device (BTE) so that the center of the handle was in line with the radial and ulnar deviation device (third metacarpophalangeal joint). The neutral position was recorded when the handle was exactly vertical. Additional voltage measurements were taken when the subject's wrist was pronated 20°, 45°, and maximum and supinated 20°, 45°, 75°, and maximum. A voltage measurement was taken in each position. The degrees of deviation were determined by the scale on the BTE device. Pronation was recorded as positive and supination was negative.

Regression analysis was used to determine the relationship between measured degrees and voltages acquired from the calibration procedures. The following model was used: Y=aX+b. This equation was used to determine the angle of the wrist from the wrist motion monitor voltage output.

Experimental Protocol

The study was conducted in one session for each subject. When subjects arrived, they were given written instructions (Appendix A). The experimenter reviewed the procedures and answered any questions. Subjects received an informed consent form which they read and signed (Appendix B). Subjects moved their wrists in all directions for approximately 30 seconds to "warm up" their wrists.

The first measurements to be recorded concerned the maximum movement in each direction without any apparatus attached to the subject's wrist. The subjects were asked to perform these maximum movements: flexion, extension, radial deviation, ulnar deviation, pronation, and supination using the calibration technique described previously. The values were compared with the 5th percentile and 95th percentile populations to assure the subject's range of motion was within those constraints (Kroemer et al., 1990) The subjects were then fitted with the wrist motion monitor and the monitor was calibrated. The subject was then ready to perform the bagging task.

The subject began by practicing the bagging task, performing at least one trial with each of the six objects. This practice period allowed the subject to get accustomed to the procedure and assured that the subject grasped each object correctly. Wrist positions were not recorded during the practice period, but data were collected during the subsequent trials. The subject was instructed to move the items one at a time from the take-off chute into the bag on the bagging table. There were 24 trials for each subject. The subject moved the objects in the order in which they were presented. After the subject completed all trials, the wrist monitor was removed.

DATA ANALYSIS

Data Compilation

The data were converted from voltage to position in degrees using the calibration data for each subject. First-order regression models were computed for flexion-extension, radial-ulnar, and pronation-supination directions. The flexion-extension equations had 7 data points: maximum flexion, 45° flexion, 20° flexion, 0°, 20° extension, 45° extension, and maximum extension. The radial-ulnar equations had 6 data points: maximum radial deviation, 15° radial deviation, 0°, 15° ulnar deviation, 30° ulnar deviation, and maximum ulnar deviation. The pronation-supination equations had 8 data points: maximum pronation, 45° pronation, 20° pronation, 0°, 20° supination, 45° supination, 75° supination, and maximum supination. Linear models were good estimators of the relationship between degrees and voltage as shown by the coefficient of determination, r^2. For the subjects, it ranged from 0.970 to 1.000 in flexion-extension; from 0.949 to 0.999 in radial-ulnar deviation; and from 0.914 to 0.996 in pronation-supination (the regression analysis for the first subject is shown in Appendix D). The regression equations were used to convert the data from voltage to position in degrees.

Upon examination of the graphs of the flexion and extension data, it became apparent that some of the data had abnormal peaks. A wire on the flexion and extension device was found to be loose during the study, which caused large peaks in the data (the peaks were approximately 130° while the rest of the data ranged between 45° and -45°). The peaks lasted from 0.04 to 0.52 s, consisting of 1 to 13 data points. Of the 456 runs, there were 23 with a peak. Each peak was removed and new data points interpolated. No abnormal peaks were found for the other two directions of movement.

Position

Position data of interest consisted of the average, maximum, minimum, and range (maximum minus minimum) for each experimental trial in the flexion-extension, radial-ulnar, and pronation-supination directions. These data were the dependent variables for the statistical analysis. A repeated measures analysis of variance (ANOVA) was conducted upon the wrist position data using SAS® (SAS Institute, Inc., Cary, N.C.) statistical software release 6.08. Separate analyses were computed for each dependent variable for each direction of movement. Geisser-Greenhouse corrected values for p were used to correct for the bias associated with repeated measurements. A two-tailed t-test was used for the planned comparison.

Maximum Flexion. The ANOVA of the maximum flexion data revealed that the main effect *site* (laboratory or supermarket) was not significant. The ANOVA of the maximum flexion data revealed that the main effect *object* (p=0.0049) and *location* (p=0.0019) were significant (Table D.1). The planned comparisons showed that the maximum flexion for round objects (11.3°) was statistically less than for square objects (16.2°) (p=0.0342), the maximum flexion for 5-cm objects (11.7°) was statistically less than for 10-cm objects (15.8°) (p=0.0126), the maximum flexion for right locations (18.5°) was significantly greater than for left locations (10.8°) (p=0.0003), and the maximum flexion for back locations (16.1°) was significantly greater than for front locations (13.3°) (p=0.0498).

Maximum Extension. The ANOVA of the maximum extension data revealed that the main effect *site* was not significant. The ANOVA of the maximum extension data revealed that the main effect *object* (p=0.0455) was significant (Table D.2). The planned comparisons showed that the maximum extension for 5-cm objects (30.8°) was statistically greater than for 10-cm objects (28.7°) (p=0.0480) and the maximum extension for soft objects (30.4°) was statistically greater than for solid objects (26.1°) (p=0.0412).

Average Flexion and Extension. The ANOVA of the average flexion and extension data revealed that the main effect *site* was not significant. The ANOVA of the average flexion and extension data revealed that the main effect *object* (p=0.0149) and *location* (p=0.0425) were significant (Table D.3). The planned comparisons showed that the average flexion and extension for 5-cm objects (9.2°) was statistically greater than for 10-cm objects (7.0°) (p=0.0048) and the average flexion and extension for right locations (6.4°) was significantly less than for left locations (8.9°) (p=0.0094).

Range of Flexion and Extension. The ANOVA of the range of flexion and extension data revealed that the main effect *site* was not significant. The ANOVA of the range of flexion and extension data revealed that the main effect *location* (p=0.0015) was significant (Table D.4). The planned comparisons showed that the range of flexion and extension for six-pack objects (46.9°) was statistically greater than for all other objects (44.7°) (p=0.0455) and the range of flexion and extension for right locations (49.5°) was significantly greater than for left locations (40.6°) (p=0.0003).

Maximum Radial. The ANOVA of the maximum radial deviation data revealed that the main effect *site* was not significant. The ANOVA of the maximum radial deviation data revealed that the main effect *object* (p=0.0307) was significant (Table D.5). The planned comparisons showed that the maximum radial deviation for six-pack objects (17.5°) was statistically less than for all other objects (30.0°) (p=0.0019).

Maximum Ulnar Deviation. The ANOVA of the maximum ulnar deviation data revealed that the main effect *site* was not significant. The ANOVA of the maximum ulnar deviation data revealed that neither the main effect *object* or *location* were significant (Table D.6). The planned comparisons showed that the maximum ulnar deviation for six-pack objects (15.1°) was statistically greater than for all other objects (9.8°) (p=0.0025).

Average Radial and Ulnar Deviation. The ANOVA of the average radial and ulnar deviation data revealed that the main effect *site* was not significant. The ANOVA of the average radial and ulnar deviation data revealed that the neither the main effect *object* or *location* were significant (Table D.7). The planned comparisons showed that the average radial and ulnar deviation for six-pack objects

(2.8°) was statistically less than for all other objects (10.9°) (p=0.0007).

Range of Radial and Ulnar Deviation. The ANOVA of the range of radial and ulnar deviation data revealed that the main effect *site* was not significant. The ANOVA of the range of radial and ulnar deviation data revealed that the main effect *object* (p=0.0079) was significant (Table D.8). The planned comparisons showed that the range of radial and ulnar deviation for 5-cm objects (35.5°) was statistically less than for all 10-cm objects (43.4°) (p=0.0059).

Maximum Pronation. The ANOVA of the maximum pronation data revealed that the main effect *site* was not significant. The ANOVA of the maximum radial deviation data revealed that the main effect *object* (p=0.0001) was significant (Table D.9). The planned comparisons showed that the maximum pronation for six-pack objects (119.8°) was statistically greater than for all other objects (48.8°) (p=0.00003) and the maximum pronation for 5-cm objects (41.7°) was statistically less than for all 10-cm objects (55.9°) (p=0.0321).

Maximum Supination. The ANOVA of the maximum supination data revealed that the main effect *site* was not significant. The ANOVA of the maximum supination data revealed that the main effect *object* (p=0.0008) and *location* (p=0.0019) were significant (Table D.10). The planned comparisons showed that the maximum supination for six-pack objects (22.5°) was statistically less than for all other objects (44.7°) (p=0.0006), and the maximum supination for back locations (46.3°) was statistically greater than for front locations (35.7°) (p=0.0001).

Average Pronation and Supination. The ANOVA of the average pronation and supination data revealed that the main effect *site* was not significant. The ANOVA of the average pronation and supination data revealed that the main effect *object* (p=0.00001) was significant (Table D.11). The planned comparisons showed that the average pronation and supination for six-pack objects (35.0°) was statistically greater than for all other objects (2.3°) (p=0.0000009) and the average pronation and supination for back locations (0.9°, pronation) was statistically less than for front locations (6.9°, pronation) (p=0.0255).

Range of Pronation and Supination. The ANOVA of the range of pronation and supination data revealed that the main effect *site* was not significant. The ANOVA of the range of pronation and supination data revealed that the main effect *object* (p=0.0005) and *location* (p=0.0231) were significant

(Table D.12). The planned comparisons showed that the range of pronation and supination for six-pack objects (142.3°) was statistically greater than for all other objects (93.5°) (p=0.0002), the range of pronation and supination for 5-cm objects (83.2°) was statistically less than for 10-cm objects (102.6°) (p=0.0022), and the range of pronation and supination for back locations (107.9°) was statistically greater than for front locations (95.4°) (p=0.0012).

Velocity

Before velocity was computed, the position data was filtered using a finite impulse response filter, the Hamming window-function. The sampling frequency of the position data was 25 Hz; therefore, the Nyquist frequency was 12.5 Hz or one-half the sampling frequency. Filtering the position data required two parameters: M, the sampling length, and ω_c, the cutoff frequency. The longer the sampling length, the sharper the cutoff tends to be; however, long sampling lengths require more computation time. The cutoff frequency must be at or below the Nyquist frequency. This filtering method required some trial and error to determine the best combination of sampling length and cutoff frequency to use. A sampling length of 101 and a cutoff frequency of 7.5 Hz was able to smooth the position data and minimize the loss of acceleration data.

Velocity was computed by differentiating the filtered position data using a variation of Ridder's method as computed using Mathcad software (Mathsoft, Inc., Cambridge, MA). The average and maximum in each direction were computed for the velocity of each experimental trial. Average velocity was determined by averaging the absolute values of the directional velocities.

Maximum Velocity - Flexion Direction. The ANOVA of the maximum velocity in the flexion direction revealed that the main effect *site* was significant (p=0.0478). The mean maximum velocity in the flexion direction for those subjects who performed the tasks at the laboratory was 45°/s and for those who performed the tasks at the supermarket was 63°/s. The ANOVA of the maximum velocity in the flexion direction revealed that the main effect *object* and *location* were not significant (Table D.13). The planned comparison showed that the maximum velocity in the flexion direction for six-pack objects (43°/s) was statistically less than for all other objects (49°/s) (p=0.0392), the maximum velocity in the flexion direction for round objects (46°/s) was statistically less than for square objects (49°/s) (p=0.0325), and the maximum velocity in the flexion direction for right location (52°/s) was statistically greater than for left locations (43°/s) (p=0.0158).

Maximum Velocity - Extension Direction. The ANOVA of the maximum velocity in the extension direction revealed that the main effect *site* was not significant. The ANOVA of the maximum velocity in the extension direction revealed that the main effect *location* (p=0.0212) was significant (Table D.14). The planned comparison showed that the maximum velocity in the extension direction for right locations (61°/s) was statistically greater than for left locations (52°/s) (p=0.0064).

Average Velocity for Flexion and Extension. The ANOVA of the average velocity for flexion and extension revealed that the main effect *site* was significant (p=0.0396). The average velocity for flexion and extension for those subjects who performed the tasks at the laboratory was 21°/s and for those who performed the tasks at the supermarket was 29°/s. The ANOVA of the average velocity for flexion and extension revealed that neither the main effect *object* or *location* were significant (Table D.15). The planned comparison showed that the average velocity in the flexion and extension direction for right locations (25°/s) was statistically greater than for left locations (20°/s) (p=0.0021).

Maximum Velocity - Radial Direction. The ANOVA of the maximum velocity in the radial deviation direction revealed that the main effect *site* was not significant. The ANOVA of the maximum velocity in the radial deviation direction revealed that the main effect *object* (p=0.0036) was significant (Table D.16). The planned comparison showed that the maximum velocity in the radial direction for six-pack objects (43°/s) was statistically less than for all other objects (55°/s) (p=0.0035) and the maximum velocity in the radial direction for 5-cm objects (50°/s) was statistically less than for 10-cm objects (58°/s) (p=0.0165).

Maximum Velocity - Ulnar Direction. The ANOVA of the maximum velocity in the ulnar deviation direction revealed that the main effect *site* was not significant. The ANOVA of the maximum velocity in the ulnar deviation direction revealed that the main effect *object* (p=0.0033) was significant (Table D.17). The planned comparison showed that the maximum velocity in the ulnar direction for 5-cm objects (48°/s) was statistically less than for 10-cm objects (63°/s) (p=0.0015).

Average Velocity for Radial and Ulnar Deviation. The ANOVA of the average velocity for radial and ulnar deviation revealed that the main effect *site* was significant (p=0.0202). The average velocity for radial and ulnar deviation for those subjects who performed the tasks at the laboratory was 21°/s and for those who performed the tasks at the supermarket was 32°/s. The ANOVA of the average velocity for radial and ulnar deviation revealed that the main effect *object* (p=0.0099) was significant (Table D.18). The planned comparison showed that the average velocity in the radial and ulnar direction for 5-cm objects (22°/s) was statistically less than for 10-cm objects (25°/s) (p=0.0302) and the average velocity in the radial and ulnar direction for back locations (22°/s) was statistically less than for front locations (24°/s) (p=0.0485).

<u>Maximum Velocity - Pronation Direction</u>. The ANOVA of the maximum velocity in the pronation direction revealed that the main effect *site* was not significant. The ANOVA of the maximum velocity in the pronation direction revealed that the main effect *object* (p=0.0142) was significant (Table D.19). The planned comparison showed that the maximum velocity in the pronation direction for six-pack objects (199°/s) was statistically greater than for all other objects (138°/s) (p=0.0281), the maximum velocity in the pronation direction for 5-cm objects (122°/s) was statistically less than for 10-cm objects (154°/s)

(p=0.0077) and the maximum velocity in the pronation direction for back locations (153°/s) was statistically greater than for front locations (143°/s) (p=0.0141).

Maximum Velocity - Supination Direction. The ANOVA of the maximum velocity in the supination direction revealed that the main effect *site* was not significant. The ANOVA of the maximum velocity in the supination direction revealed that the main effect *object* (p=0.0431) was significant (Table D.20). The planned comparison showed that the maximum velocity in the supination direction for six-pack objects (141°/s) was statistically greater than for all other objects (115°/s) (p=0.0084).

Average Velocity for Pronation and Supination. The ANOVA of the average velocity for pronation and supination revealed that the main effect *site* was not significant. The ANOVA of the average velocity for pronation and supination revealed that the main effect *object* (p=0.0119) was significant (Table D.21). The planned comparison showed that the average velocity in the pronation and supination direction for six-pack objects (73°/s) was statistically greater than for all other objects (59°/s) (p=0.0016) and the average velocity in the pronation and supination direction for 5-cm objects (55°/s) was statistically less than for 10-cm objects (61°/s) (p=0.0469).

Acceleration

Acceleration was computed by differentiating the velocity data using a variation of Ridder's method as computed using by Mathcad software (Mathsoft, Inc., Cambridge, MA). The average and maximum in each direction were computed for the acceleration of each experimental trial. Average acceleration was determined by averaging the absolute values of the directional velocities.

Maximum Acceleration - Flexion Direction. The ANOVA of the maximum acceleration in the flexion direction revealed that the main effect *site* was not significant. The ANOVA of the maximum acceleration in the flexion direction revealed that neither the main effect *object* or *location* were significant (Table D.22).

Maximum Acceleration - Extension Direction. The ANOVA of the maximum acceleration in the extension direction revealed that the main effect *site* was not significant. The ANOVA of the maximum acceleration in the extension direction revealed that neither the main effect *object* or *location* were significant (Table D.23). The planned comparison showed that the maximum acceleration in the extension direction for 5-cm ($331°/s^2$) was statistically less than for 10-cm objects ($402°/s^2$) (p=0.0214).

Average Acceleration for Flexion and Extension. The ANOVA of the average acceleration for flexion and extension revealed that the main effect *site* was significant (p=0.0029). The average acceleration for flexion and extension for those subjects who performed the tasks at the laboratory was $82°/s^2$ and for those who performed the tasks at the supermarket was $150°/s^2$. The ANOVA of the average acceleration for flexion and extension revealed that neither main effect *object* or *location* were significant (Table D.24). The planned comparison showed that the average acceleration in the flexion and extension direction for round objects ($91°/s^2$) was statistically less than for square objects ($95°/s^2$) (p=0.0174) and for right locations ($100°/s^2$) was statistically greater than for left locations ($87°/s^2$) (p=0.0068).

Maximum Acceleration - Radial Deviation Direction. The ANOVA of the maximum acceleration in the radial deviation direction revealed that the main effect *site* was not significant. The ANOVA of the maximum acceleration in the radial deviation direction revealed that neither the main effect *object* or *location* were significant (Table D.25). The planned comparison showed that no comparisons of interest were significantly different.

Maximum Acceleration - Ulnar Deviation Direction. The ANOVA of the maximum acceleration in the ulnar deviation direction revealed that the main effect *site* was significant (p=0.0448). The maximum acceleration in the ulnar deviation direction for those subjects who performed the tasks at the laboratory was 669°/s^2 and for those who performed the tasks at the supermarket was 1199°/s^2. The ANOVA of the maximum acceleration in the ulnar deviation direction revealed that the main effect *object* (p=0.0128) was significant (Table D.26). The planned comparison showed that the maximum acceleration in the ulnar direction for six-pack objects (478°/s^2) was statistically less than for all other objects (807°/s^2) (p=0.00004).

Average Acceleration for Radial and Ulnar Deviation . The ANOVA of the average acceleration for radial and ulnar deviation revealed that the main effect *site* was significant (p=0.0101). The average acceleration for radial and ulnar deviation for those subjects who performed the tasks at the laboratory was 83°/s^2 and for those who performed the tasks at the supermarket was 145°/s^2. The ANOVA of the average acceleration for radial and ulnar deviation revealed that the main effect *object* (p=0.0091) was significant (Table D.27). The planned comparison showed that the average acceleration in the radial and ulnar direction for six-pack objects (70°/s^2) was statistically less than for all other objects (98°/s^2) (p=0.0037).

Maximum Acceleration - Pronation Direction. The ANOVA of the maximum acceleration in the pronation direction revealed that the main effect *site*, *object*, and *location* were not significant (Table D.28).

Maximum Acceleration - Supination Direction. The ANOVA of the maximum acceleration in the supination direction revealed that the main effect *site* was not significant. The ANOVA of the maximum acceleration in the supination direction revealed that the main effect *object* (p=0.0012) was significant (Table D.29). The planned comparison showed that the maximum acceleration in the supination direction for six-pack objects (3770°/s^2) was statistically greater than for all other objects (1965°/s^2) (p=0.0001) and the maximum acceleration in the supination direction for back locations (2303°/s^2) was statistically greater than for front locations (2287°/s^2) (p=0.000004).

Average Acceleration for Pronation and Supination. The ANOVA of the average acceleration for pronation and supination revealed that the main effect *site* was significant (p=0.0484). The average acceleration for pronation and supination for those subjects who performed the tasks at the laboratory was 231°/s^2 and for those who performed the tasks at the supermarket was 369°/s^2. The ANOVA of the average acceleration for pronation and supination revealed that neither the main effect *object* or *location* were significant (Table D.30). The planned comparison showed that the average acceleration in the pronation and supination direction for six-pack objects (286°/s^2) was statistically greater than for all other objects (246°/s^2) (p=0.0204).

Time

The ANOVA of the time of the run revealed that the main effect *site* was significant (p=0.0278). The average time for the task to be performed by subjects at the laboratory was 4.8 s and for those who performed the tasks at the supermarket was 3.2 s. The time was measured from when the object was presented to the subject until the object was placed in the bag. The ANOVA of the time revealed that the main effect *object* (p=0.0005) and *location* (p=0.0057) were significant (Table D.31). The planned comparison showed that the time for picking up six-pack objects (5.0 s) was statistically greater than for all other objects (4.4 s) (p=0.0003), the time for picking up 5-cm objects (4.2 s) was statistically less than for 10-cm objects (4.6 s) (p=0.0015), and the time for picking up back locations (4.8 s) was statistically greater than for front locations (4.3 s) (p=0.0054).

Since back locations required statistically greater bagging times than front locations, it appears that Fitts Law applies in the this circumstance. The data was compared to see if the Fitts' Law Index of Difficulty was linearly related to the bagging time. The movement amplitude (A) was the distance from where the object was picked up to the bag (39-cm for front locations and 80-cm for back locations). The target width (W) was the size of the object's handle (10-cm or 5-cm). The movement amplitude and target width were used to determine the index of difficulty. A linear regression analysis of index of difficulty with bagging time resulted in a r^2 of 0.0139; therefore, index of difficulty and bagging time, in this case, are not linearly related. The bagging time consists of reaction time, time to grab the object, movement time, and time to place the object in the bag. Only movement time is considered in Fitts' Law. The time to place the object in the bag varied depending upon object; the wrist motion monitor sometimes interfered with the bag which also increased bagging time. Therefore, Fitts' Law does not apply to bagging time.

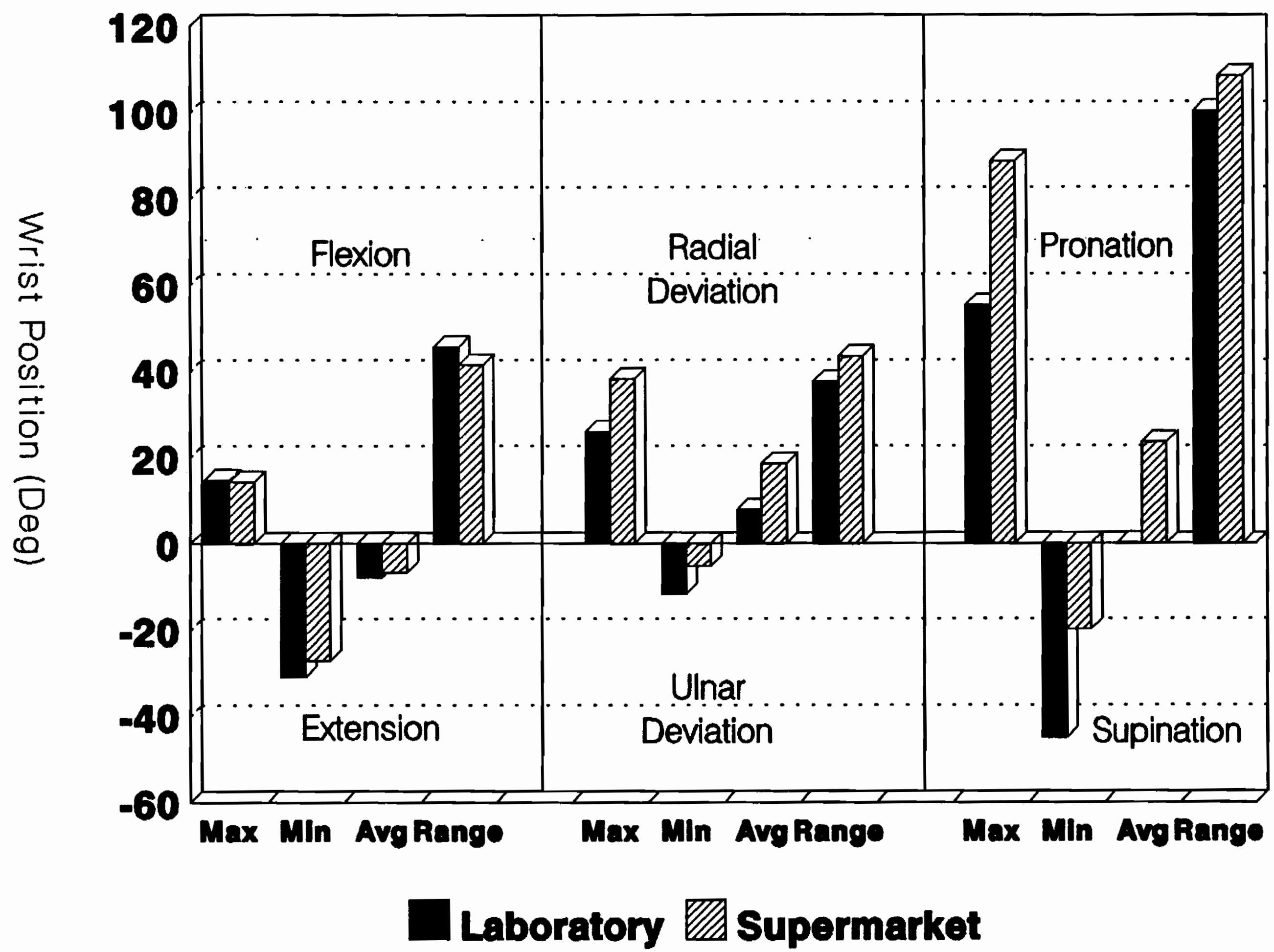
DISCUSSION

Site

Although all subjects picked up the objects as the experimenter requested, the professional baggers tended to pick up the objects much more quickly, possibly because of their on-the-job training and familiarity with the task. The supermarket baggers (mean of 3.2 s) picked up the objects in significantly less time than the laboratory baggers (mean of 4.8 s).

There were no significant differences between the two sites when comparing the dependent variables for wrist position. A comparison between the sites for position is shown in Figure 8. The position data from the subjects in the laboratory is a good representation of the wrist positions required to bag groceries.

The average wrist velocity for flexion and extension and for radial and ulnar deviation showed significant differences between the study sites. In both circumstances the subjects at the supermarket had greater wrist velocities. All other average and maximum velocities were greater for the subjects participating in the supermarket than for those in the laboratory, although not significantly different. The



No Comparisons are Significant ($p \leq 0.05$)

Figure 8 Comparison of dependent variable velocity outcomes at the two experimental sites greater velocities at the supermarket are understandable because of the shorter time it took the subjects in the supermarket to pick up each object. A comparison of the wrist velocities for the subjects at the two study sites is shown Figure 9.

The average wrist acceleration for all three directions of movement and the maximum acceleration in the ulnar direction were statistically greater for the subjects in the supermarket than for those in the laboratory as shown in Figure 10. Maximum acceleration in the flexion, extension, and supination directions were greater for subjects in the supermarket than in the laboratory, although not statistically significant. These greater accelerations are due to the shorter times to pick up objects associated with the professional baggers in the supermarket. The subjects participating in the supermarket were bagging groceries for this study at a slower pace than usual. They had to bag slower because the wrist motion monitor would interfere with placing the objects in the bag, they could only use one hand, and they had to use the hand-object coupling that

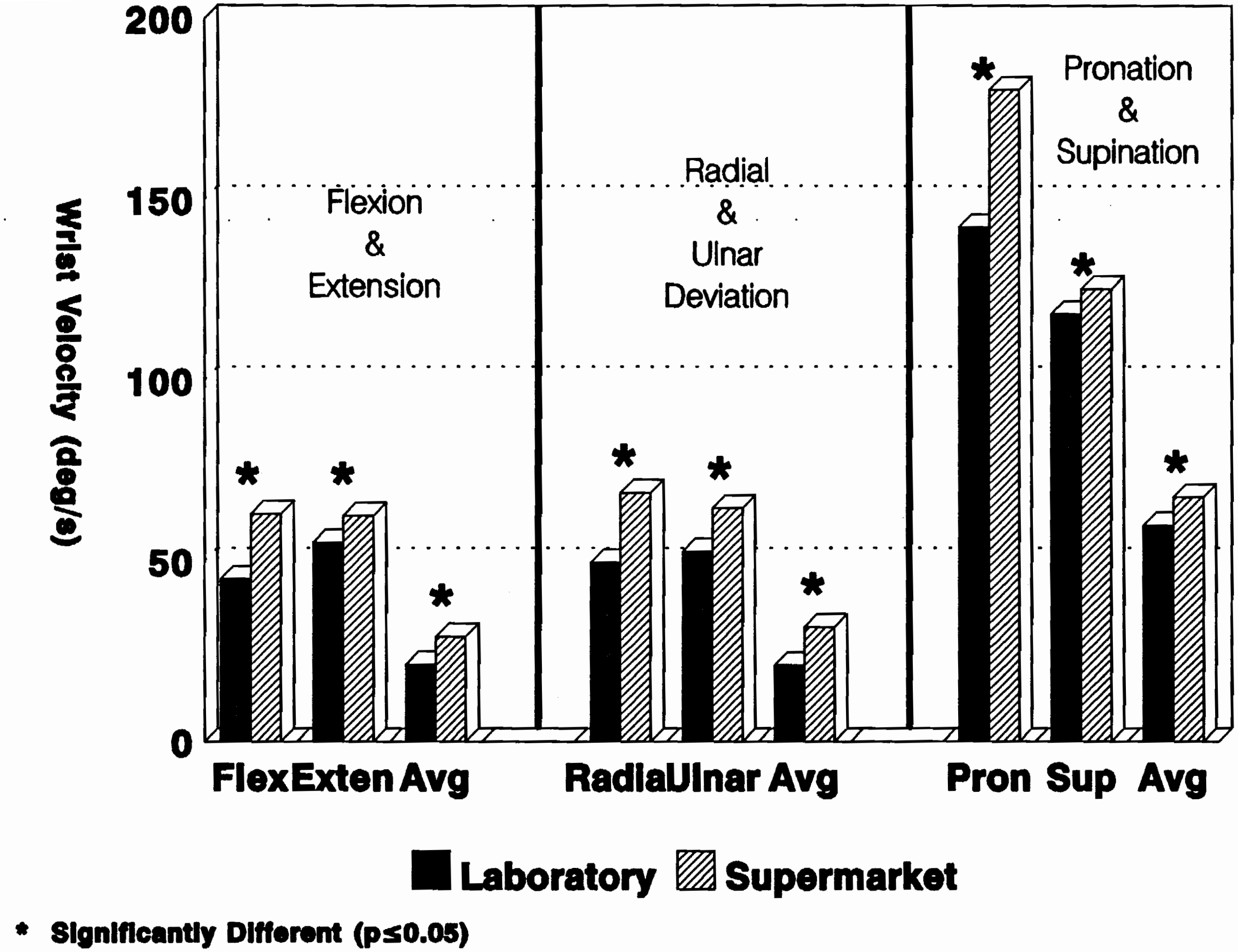


Figure 9 Comparison of dependent variable velocity outcomes at the two experimental sites

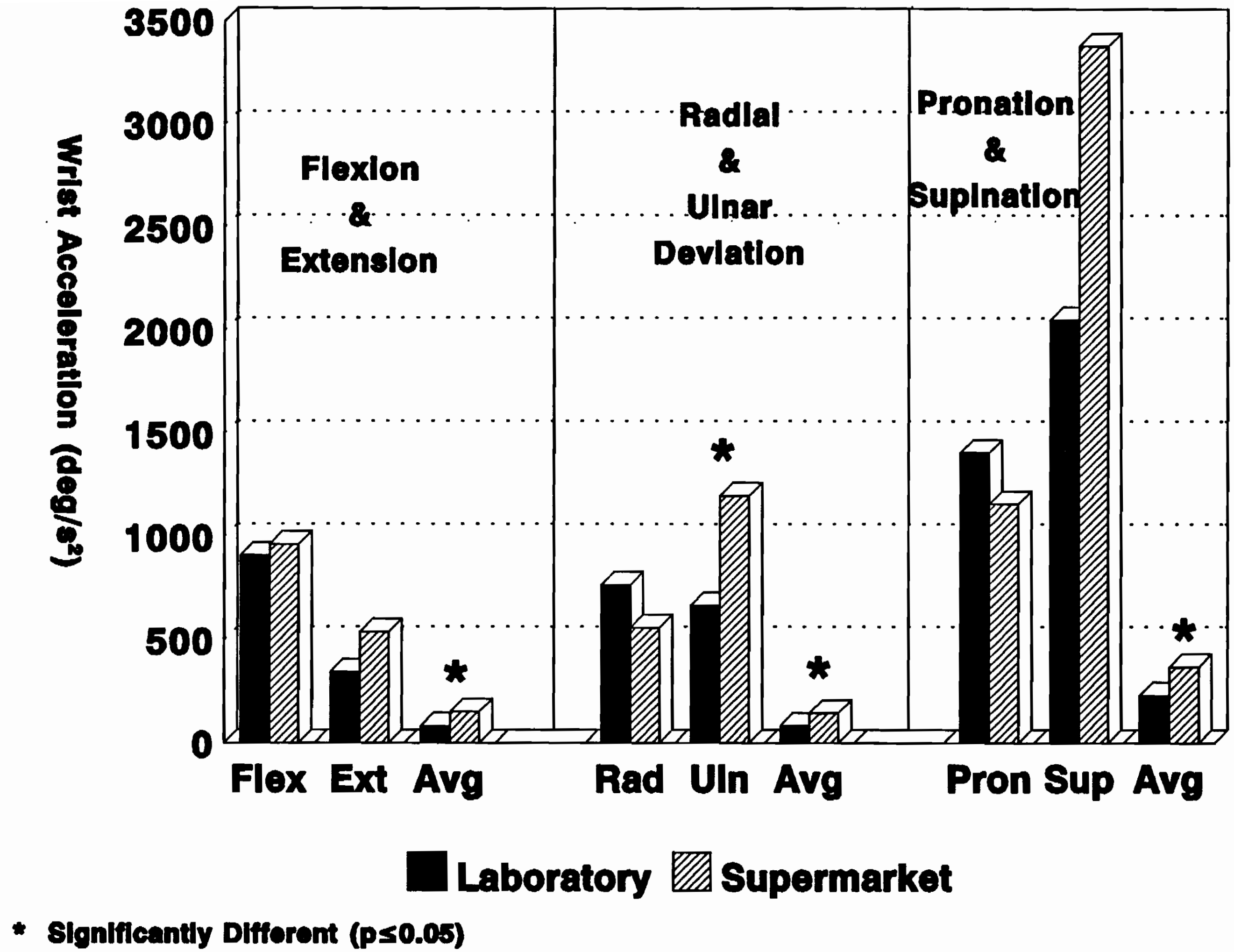


Figure 10 Comparison of dependent variable acceleration outcomes at the two experimental sites

the study designated. Therefore, velocity and acceleration measurement may be artificially low.

Object

Six-Pack versus All Other Objects. There were significant differences for wrist position between six-pack objects (with a 5-cm finger-and-thumb handle) and all other object handle types (Figure 11). The greatest differences are found for pronation and supination. The range of pronation for six-pack objects was 142° and for all other objects was 94°. Six-pack objects required more pronation and less supination than all other objects.

Six-pack objects also required more ulnar deviation which can be seen when comparing the average deviation for radial and ulnar directions; six-pack objects required an average of only 3° deviation in the radial direction while other objects required 11°. Also, the maximum radial deviation was less for six-pack objects while the maximum ulnar deviation was greater for six-pack objects than all other objects.

Six-pack objects required a slightly larger range of movement in the flexion and extension direction than any other object. The range of flexion and extension for six-pack objects was 47° while other objects required 45°. However, the average flexion and extension and maximum in each direction were not significantly different.

For the pronation and supination directions, all dependent variables showed significantly greater wrist velocities for six-pack objects than for other objects. Since six-pack objects required much greater range of motion for the pronation and supination directions than all other objects, six-pack objects also required greater velocities in the pronation and supination directions than did all other objects. The average velocity for six-pack objects was 73°/s while the other objects required 59°/s. Maximum velocities for pronation and supination were also greater for six-pack objects than for all other objects (Figure 12).

When considering wrist acceleration, there are significant differences between six-pack objects and other objects. The maximum acceleration in the ulnar direction and the average acceleration in the radial and ulnar direction were significantly less for six-pack objects than for any other objects. For the pronation and supination directions, maximum acceleration in the supination direction and average acceleration were significantly greater for six-pack objects than for all other objects (Figure 13). Wrist acceleration

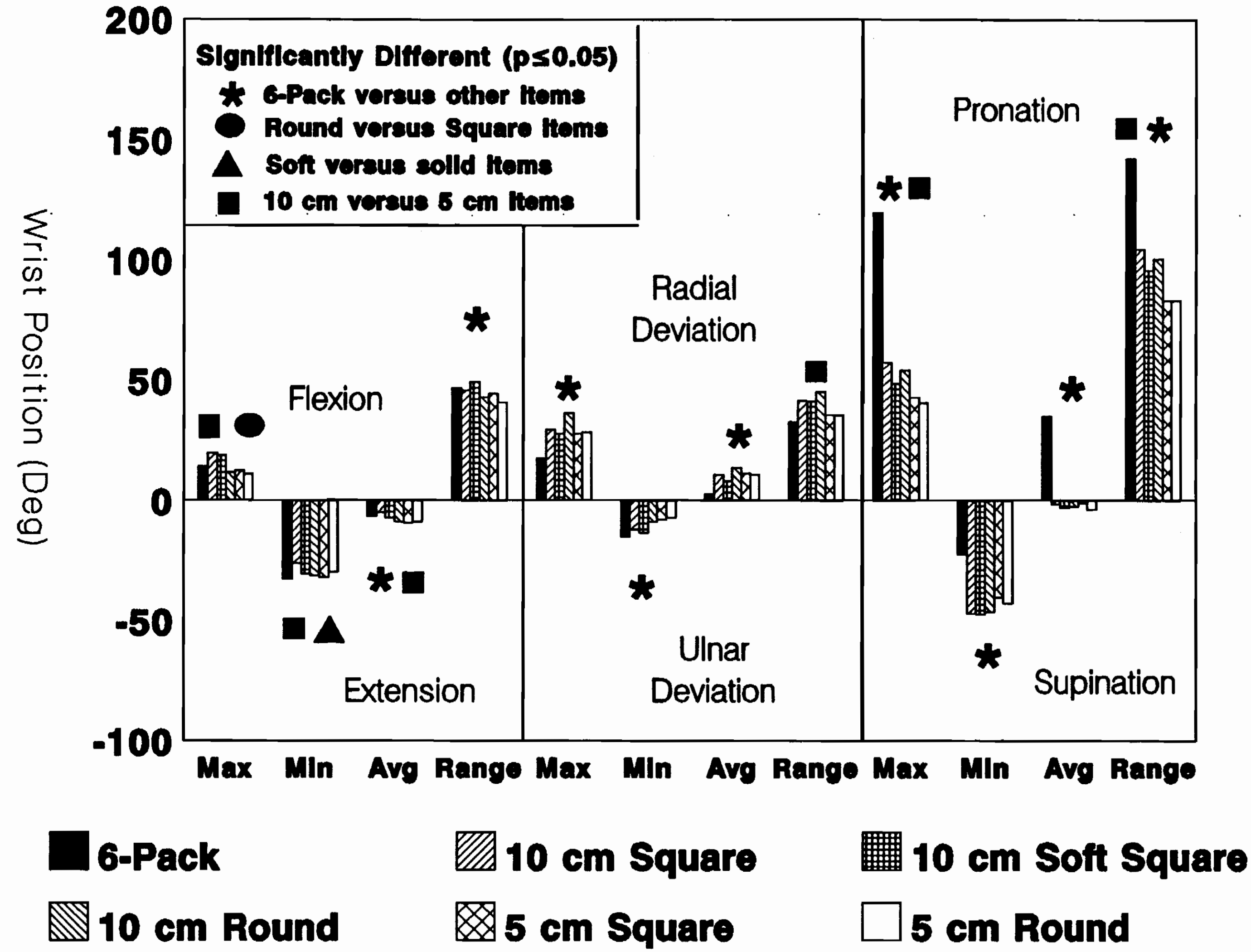


Figure 11 Comparison of dependent variable position outcomes for the objects.

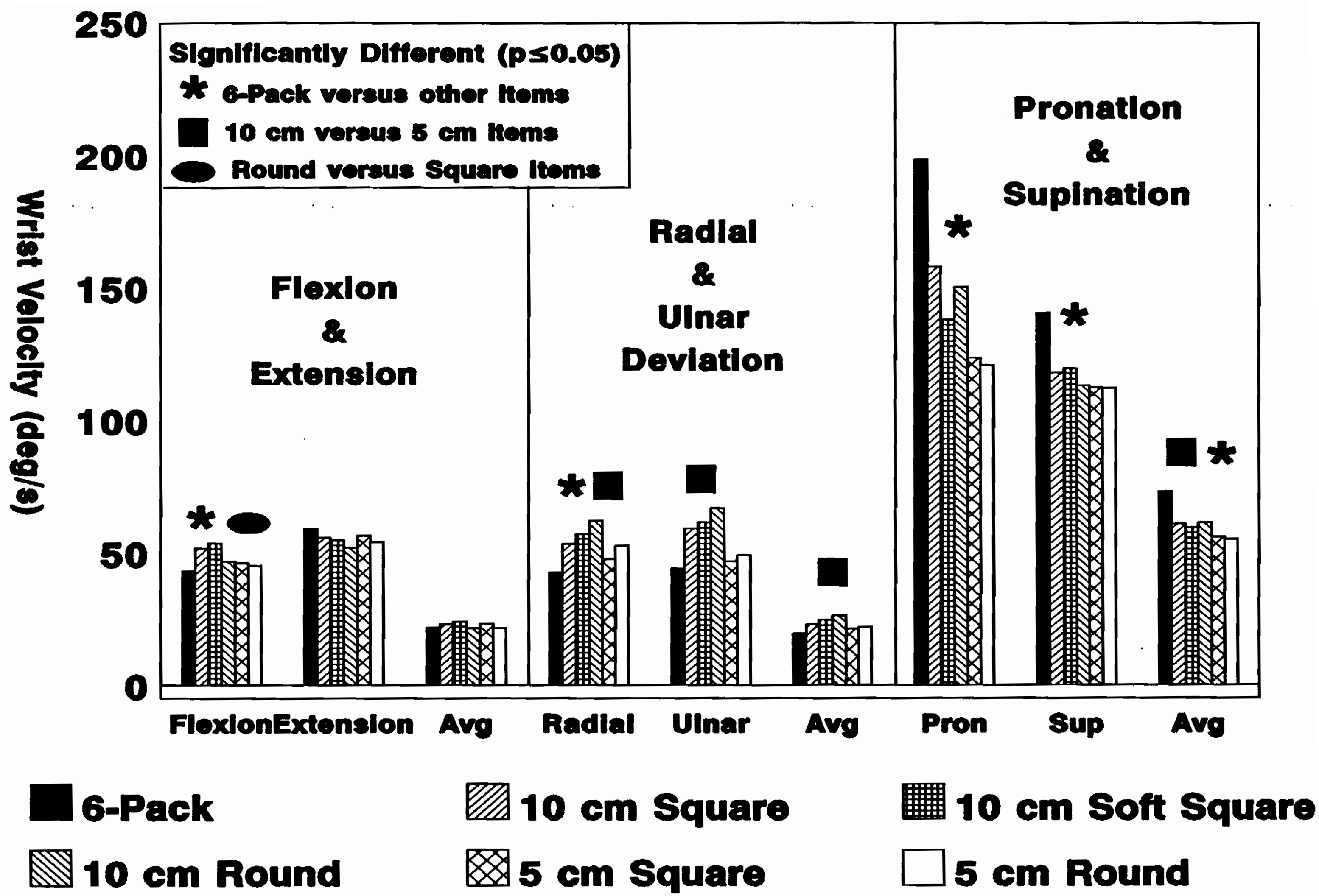


Figure 12 Comparison of dependent variable velocity outcomes for objects.

for pronation and supination was significantly greater for six-pack objects than for other objects especially in the supination direction. The maximum supination for six-pack objects was 3770°/s² and for all other objects was 1965°/s². The average acceleration for pronation and supination for six-pack objects was 286°/s² compared to 246°/s² for all other objects. The six-pack objects required significantly less average acceleration for radial and ulnar deviation than all other objects. Maximum acceleration in the ulnar direction was also significantly less for six-pack objects compared to other objects.

There was a difference in the total time. It took significantly longer to pick up 6-pack objects than to pick up any other object.

The greatest differences between six-pack objects and other objects are found when comparing pronation and supination. The six-pack object required more extreme pronation, greater wrist velocity for pronation and supination, and greater acceleration for pronation and supination than all of the other objects. Velocity and acceleration in the supination direction account for the largest differences; this fast supination movement is probably in response to the large deviation in the pronation direction required to pick up a six-pack object. The finger-and-thumb handle is the only object which has a top coupling; the other objects were picked up from the side. Extreme pronations, together with higher velocities and accelerations required to pick up a six-pack, may be responsible for any cases of pronator syndrome which can be caused by repeated pronation coupled with force. Also, the faster movements required to pick up a six-pack could result in De Quervain's syndrome which is caused by forceful coupled along with hand twisting. Ulnar deviation is performed by the flexor carpi radialis and extensor carpi radialis longus and brevis. The tendon of the flexor carpi radialis passes through the carpal tunnel; therefore, repeated and forceful use of this muscle may be a cause of carpal tunnel syndrome.

Soft objects versus solid objects. There was no statistical difference between the 10-cm wide soft square objects and the 10-cm wide solid square objects when considering wrist position in the directions of movement with one exception – the mean maximum extension when picking up a 10-cm wide soft square object was significantly larger than when picking up a 10-cm wide square object. Although it required more extension to pick up soft objects, the total range of movement and average deviation in the flexion and extension

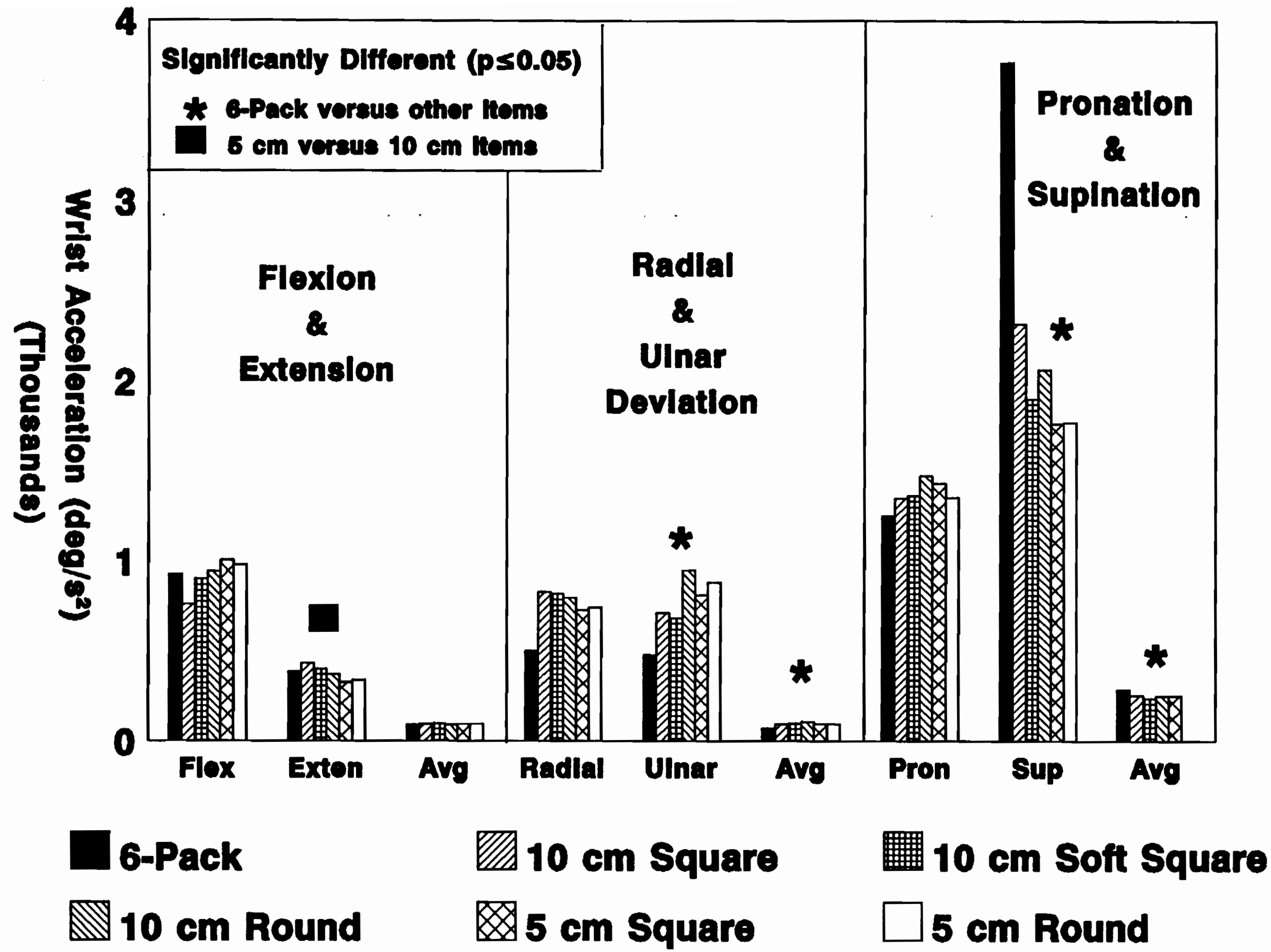


Figure 13 Comparison of dependent variable acceleration outcomes for objects.

direction showed no difference. No velocity or acceleration comparisons showed significant differences.

<u>10-cm objects versus 5-cm objects</u>. There were significant differences when comparing 10-cm objects with 5-cm objects. Maximum extension and average extension were significantly greater when picking up a 5-cm object than when picking up a 10-cm object. Maximum flexion, maximum pronation, range of radial and ulnar deviation, and range of pronation and supination were significantly less when picking up a 5-cm object than when picking up a 10-cm object.

The maximum velocity in the radial direction, maximum velocity in the ulnar direction, and average velocity in the radial and ulnar direction, maximum velocity in the pronation direction, average velocity in the pronation and supination direction, maximum acceleration in the extension direction were significantly less for 5-cm objects than for 10-cm objects. There were no significant differences in the time required for picking up the objects when comparing 10-cm objects with 5-cm objects.

The 10-cm objects as compared to the 5-cm objects required more extreme wrist positions and greater wrist velocities. Therefore, the larger objects may be more likely to cause De

Quervain's syndrome because they required a larger range of pronation and supination. Additionally, more extreme positions and greater velocities may be more likely to cause cumulative trauma disorders, such as carpal tunnel syndrome, tendinitis, and tenosynovitis.

Round objects versus square objects. The maximum velocity in the flexion direction and the average acceleration in the flexion and extension direction was greater for square objects than for round objects. All other comparisons of round and square objects showed no difference. In the flexion direction, square objects resulted in faster movements than round objects.

Location

Right location versus left location. The right and left locations were significantly different; the differences existed only in the flexion and extension direction. Maximum flexion, range of flexion and extension, velocity in the flexion direction, velocity in the extension direction, average velocity, and average acceleration were statistically greater for right locations than for left locations. A comparison of right and left locations is shown in Figures 14, 15, and 16. The times required to pick

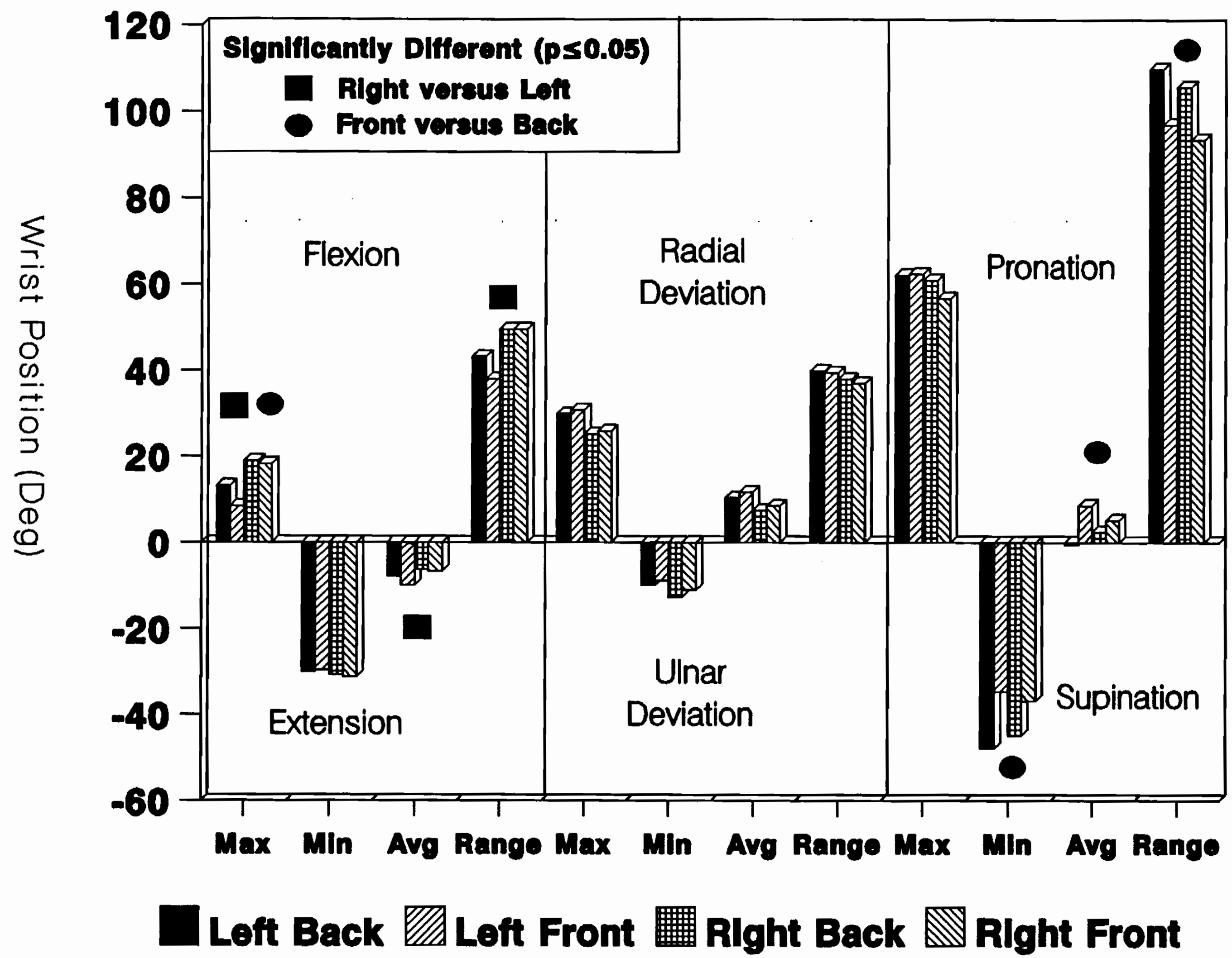


Figure 14 Comparison of dependent variable position outcomes for the four locations.

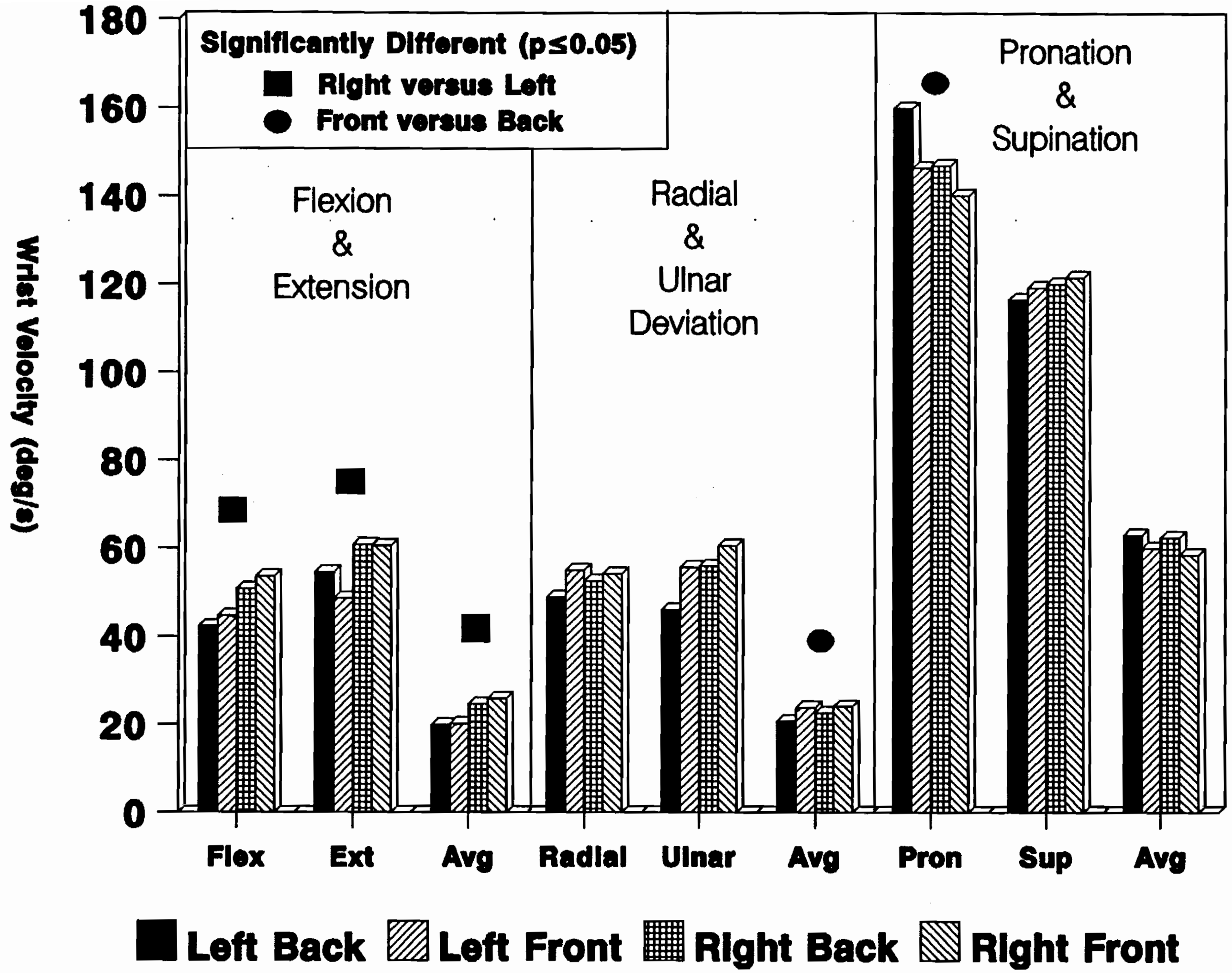


Figure 15 Comparison of dependent variable velocity outcomes for the four locations.

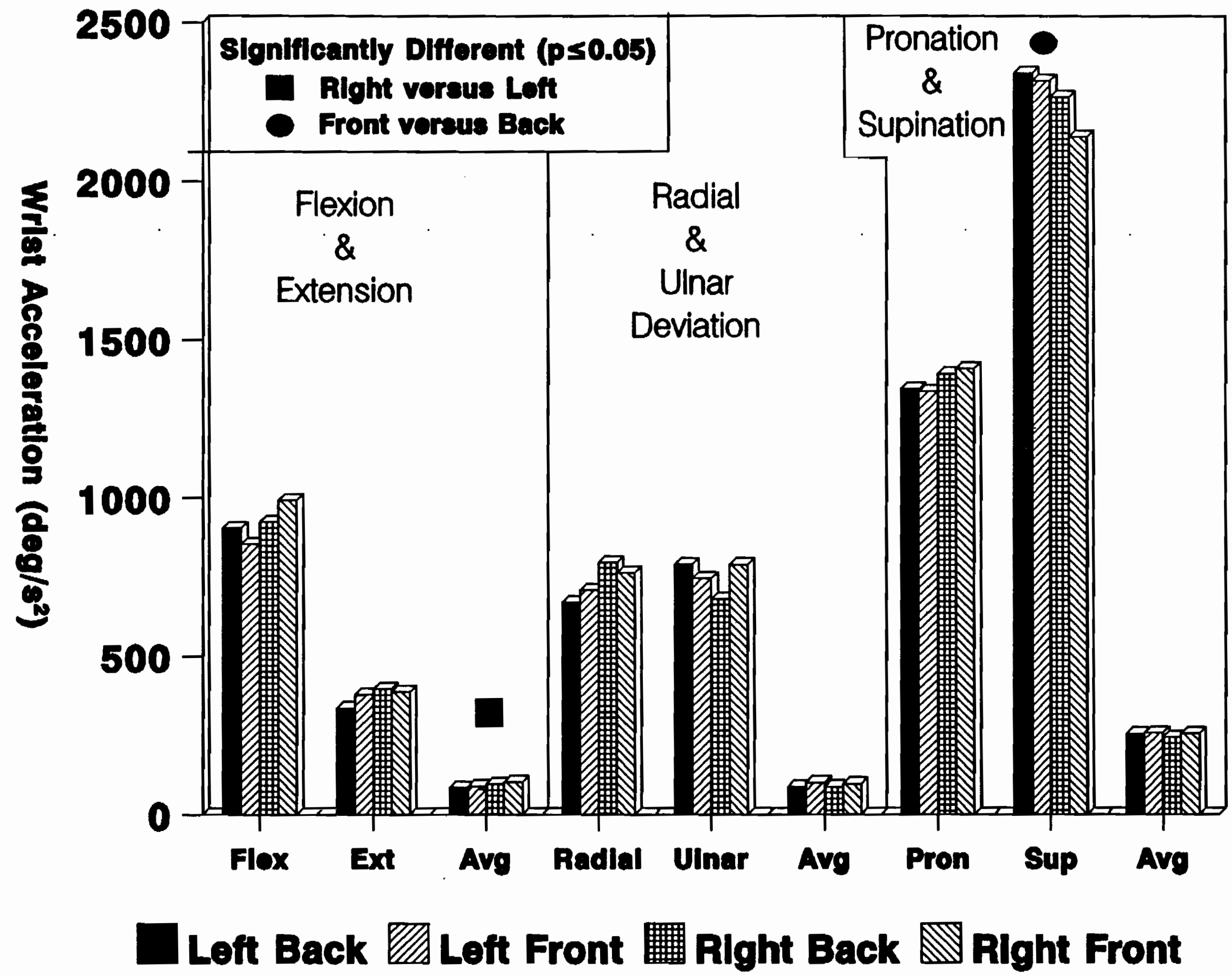


Figure 16 Comparison of dependent variable acceleration outcomes for the four locations.

up objects from the right and left sides were not significantly different.

The differences in flexion and extension for right and left locations were dependent upon all subjects being right-handed and, therefore, the subjects were closer to the right locations. The subjects moved their wrists over a larger range when picking up an object from the right side during the same amount of time; therefore, the velocity and acceleration for this task increased. More extreme movements, movements over a larger range, greater velocities and accelerations as found for right locations may exacerbate conditions caused by repetition and force.

Front location versus back location. Maximum flexion, maximum supination, range of pronation and supination, maximum velocity in pronation direction, and maximum acceleration in the supination direction were statistically greater for back locations than for front locations. Average position in the pronation and supination direction and average velocity in the radial and ulnar direction were less for back locations than for front locations. The time required to pick up objects was significantly greater when picking up objects from back locations than from front locations.

Front locations required greater pronation, possibly because they were closer to the subject. Back locations required a larger range of pronation and supination. Therefore, either a greater velocity or a longer time was needed to complete the task; in this instance, both the velocity and time were greater.

Picking up objects from back locations required statistically more movement time than did picking up objects from front locations. However, Fitts' Law could not be proven for this case because the time included more tasks than just movement of objects.

For the wrist, close locations required either more extreme flexion or more extreme pronation. Therefore, the ideal location may be farther away than that used in this study. However, extreme positions may require more bending which may lead to back problems.

Comparison to Previous Research

Marras and Schoenmarklin (1991) used the same wrist motion monitor to quantify wrist position, velocity, and acceleration of highly repetitive, hand-intensive industrial tasks. Their results for position data are similar to the results obtained in this study.

However, Marras and Schoenmarklin found higher maximum velocities for industrial workers as compared to the supermarket baggers for this study. The average velocity in the flexion and extension direction was 22.6°/s in this study. Marras and Schoenmarklin found 28.7°/s for industrial workers who had a low risk of CTDs and 42.2°/s for those who had a high risk of CTDs. Conversely, the average maximum velocity in the flexion direction was 48°/s for this study, 120°/s for the low risk industrial workers, and 174°/s for the high risk industrial workers. The average maximum velocity in the extension direction was 56°/s for this study, 121°/s for low risk industrial workers, and 183°/s for high risk industrial workers. The subjects in this study had lower maximum velocities than the industrial workers.

Marras and Schoenmarklin found much higher accelerations for the industrial workers than found in this study. The average acceleration in the flexion and extension direction was $94°/s^2$ for this study, $494°/s^2$ for low risk industrial workers, and $824°/s^2$ for high risk industrial workers. Maximum accelerations are also much higher for the industrial workers than those found in this study.

The high risk industrial workers performed an average of 24,738 wrist movements during an eight-hour shift and low risk industrial workers performed an average of 26,132 wrist movement during an eight-hour shift (Marras and Schoenmarklin, 1991). For comparison, supermarket cashiers required 11,452 wrist movements for an eight-hour shift (NIOSH, 1990). No information could be found on the number of wrist movements required for bagging groceries. The higher velocities and accelerations required for the industrial workers compared to the supermarket baggers was due to the inherently higher repetitive demands for the industrial jobs.

Summary of Results

The following statements can be made regarding 1) experimental site, 2) the object type, 3) location.

1) Subjects participating in the study at the supermarket site picked up the objects significantly faster than those participating at the laboratory. Those participating at the supermarket also had significantly greater wrist velocities and accelerations. Therefore, the site of the study did make a difference in the speed of the wrist movements. There were no differences between the sites for position data; therefore, all position data from the laboratory may be a good representation of supermarket wrist positions.

2) Objects with finger-and-thumb handle couplings (6-pack) required more extreme ulnar deviations, more extreme pronations, lower wrist velocities for radial and ulnar deviation, greater wrist velocities for the pronation direction and the supination direction, greater accelerations in the supination direction, and lower accelerations in the ulnar direction. Extreme pronation and high wrist velocities in the pronation and supination directions may increase the likelihood of a bagger developing pronator's syndrome or DeQuervain's syndrome.

Soft objects required the same wrist positions, velocities, and accelerations that similar solid objects required. Square objects required a greater velocity in the flexion direction and a greater mean acceleration in the flexion and extension direction than similar round objects required.

The 10-cm wide objects required more extreme radial deviations, larger ranges of radial and ulnar deviation and pronation and supination, greater wrist velocities in the radial, ulnar and pronation directions, and greater acceleration in the extension direction than did 5-cm wide objects. The larger range of movements and the greater velocities may increase the likelihood of baggers developing

De Quervain's syndrome or repetitive motion disorders such as carpal tunnel syndrome, tendinitis, and tenosynovitis.

3) Picking up an object from a right location required more extreme flexion, greater velocities and greater accelerations for the flexion and extension direction than picking up objects from left locations. Therefore, close locations required more flexion and quicker flexion movements than locations further away.

Picking up objects from front locations required greater average pronation and supination, greater average velocity in the radial and ulnar direction. The right and front locations were closer to the subject as compared to the left and back locations, respectively. Therefore, locations which were too close to the worker may require the worker to use more extreme wrist positions. Conversely, locations which are too far from the bagger may not require extreme wrist positions but may require extreme torso flexion and result in injuries to the worker's back.

Limitations of Experiment

There were some limitations of the wrist motion monitor used in this study. Some of the data for flexion and extension had to be smoothed because of abnormal peaks caused by a loose wire which was not detected by observation. This problem was fixed when the wire finally broke completely off and was repaired. Sometimes the wrist motion monitor interfered with the bagging task. The wrist motion monitor was bulky and the monitor hit against the bag when the subject was placing the object into it. Therefore, the wearing of the wrist motion monitor may have caused subjects to change their movements to avoid hitting the monitor on the bag.

Future Research

This research included different handle-coupling types and different bagging locations, but the weight of each object was held constant. Future research should include a similar study to see if the weight of the object affects the wrist position of the bagger. Additionally, a lumbar motion monitor should be attached to the subject's back to determine if different objects or locations affect the movement of a subject's back.

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Appendix A: Written Instructions for Experiment

Wrist Motions During a Bagging Operation Study

Thank you for participating in this research of the Industrial Ergonomics Laboratory of the Human Factors Engineering Center at Virginia Tech. The experiment is conducted by Cheryl Fairfield as part of her Masters' Thesis work and is supervised by Dr. K.H.E. Kroemer, a professor in Industrial and Systems Engineering.

The purpose of the experiment is to determine the wrist motions associated with a bagging operation. We are interested in determining if the type of grocery or the location of the grocery item will affect wrist motions.

This study will be conducted in one experimental session, lasting approximately one hour. You will be compensated at rate of $5.00 per hour. You will be fitted with a wrist motion monitor on your right hand. The wrist motion monitor will be secured with Velcro® tape. The tape side will be secured to your forearm, hand, and wrist. The wrist motion monitor has the Velcro® fastener attached to it. Therefore, the monitor can be placed on your forearm with the Velcro® fastener. The monitor will then be calibrated. Following calibration, you will be asked to move some objects from one table to another.

The data from this experiment should be analyzed by January 31, 1992 and the results made available should you desire to review them. The research team members for this experiment are:

Cheryl Fairfield, Graduate Student
Dr. K.H.E. Kroemer, Professor, ISE

If you have concerns about the way in which you have been treated or the manner in which the experiment is being conducted and do not wish to express these concerns directly to the experimental team, you may contact the Department's Institutional Review Board Chairperson, Dr. Robert Beaton at (703) 231-5936. Thank you once again for your participation.

Appendix B: Informed Consent Form

Informed Consent Form

This form constitutes informed consent by you to participate in this study. Please read it carefully, as well as the attached sheet, and then sign it below.

Your Rights as a Subject are:

1) It is your right as a subject to withdraw from the study at any time and for any reason.

2) Any of the research team members will answer any questions that you may have, and you should not sign this consent form until you understand fully all of the terms involved.

3) You have a right to see your data and withdraw it from the study if you so desire. Please inform the experimenter immediately of this decision, as the data will be handled anonymously and not possible to track once the session is over.

4) You have the right to be informed of any risks or discomforts in this research. There is minimal risk associated with this experiment. You may experience some discomfort when the Velcro® tape is removed. This discomfort should be short-lived and pose no further complication or discomfort to you.

5) If you wish to receive a synopsis of the study, please include your address under the signature line below and a copy will be sent to you. Once you have read the synopsis, and if you wish for a more detailed report, please contact one of the team members and a full report will be made available to you.

6) Should any further questions arise, please contact one of the team members. If you have any concerns about the way the experiment is being conducted or the way you are being treated, you may contact Dr. Beaton at the phone number on the other page.

7) Your participation is greatly appreciated and we hope that you will find the study a pleasant and interesting experience. Your signature below indicates that you have read this document in its entirety, that your questions have been answered, and that you consent to participate in the study described.

Signature:____
Date

Address:____

____

Appendix C: Voltage to Degree Conversion Regression Analysis

Table C.1 Data and regression output-subject 1-flexion and extension

Position (volts)	Position (°)	Regression Output	
1.465	80	Constant	187.5957
2.041	45	Standard Error of Y Est	2.54689
2.297	20	No. of Observations	7
2.579	0	Degrees of Freedom	5
2.887	-20	X Coefficient	-72.1876
3.211	-45	Standard Error of the Coefficient	1.513297
3.434	-60	R Squared	0.9978

Table C.2 Data and regression output-subject 1-radial and ulnar

Position (volts)	Position (°)	Regression Output	
3.113	33	Constant	-267.147
2.956	15	Standard Error of Y Est	3.200487
2.843	0	No. of Observations	6
2.661	-15	Degrees of Freedom	4
2.494	-30	X Coefficient	95.40158
2.399	-35	Standard Error of the Coefficient	5.196532
		R Squared	0.9883

Table C.3 Data and regression output-subject 1-pronation and supination

Position (volts)	Position (°)	Regression Output	
2.568	78	Constant	-477.199
2.388	45	Standard Error of Y Est	9.5278
2.259	20	No. of Observations	8
2.174	0	Degrees of Freedom	6
2.072	-20	X Coefficient	219.0287
1.938	-45	Standard Error of Coefficient	11.65486
1.787	-75	R Squared	0.9832
1.641	-135		

Table C.4 Voltage to degree conversion regression analysis

Subject	Channel	β_0	β_1	R^2	Significance
1	Right F/E	187.60	-72.19	0.998	p = 0.011
1	Right R/U	-267.15	95.80	0.988	p = 0.010
1	Right P/S	-477.20	219.03	0.983	p = 0.011

Appendix D: ANOVA Summary Tables

Table D.1 Position - maximum flexion ANOVA

Source	df	MS	F	p	G-G p
Site	1	12.85	0.01	0.9426	
Sub(site)	17	2405.4			
Object	5	1105.8	10.45	0.0001	0.0049
Loc	3	2719.7	13.54	0.0001	0.0019
Object*Loc	15	190.82	1.79	0.0368	0.1985
Site*Object	5	126.92	1.20	0.3162	
Site*Loc	3	74.72	0.37	0.8679	
Site*Object*Loc	15	68.62	0.64	0.8384	
Object*Sub(site)	85	105.80			
Loc*Sub(site)	51	200.86			
Object*Loc*Sub(site)	255	106.83			

Table D.2 Position - maximum extension ANOVA

Source	df	MS	F	p	G-G p
Site	1	851.09	0.32	0.5777	
Sub(site)	17	2640.93			
Object	5	416.28	4.66	0.0008	0.0455
Loc	3	63.57	0.67	0.5749	
Object*Loc	15	17.61	0.51	0.9329	
Site*Object	5	49.86	0.56	0.7303	
Site*Loc	3	24.63	0.26	0.8539	
Site*Object*Loc	15	74.41	2.16	0.0079	0.1599
Object*Sub(site)	85	89.24			
Loc*Sub(site)	51	95.00			
Object*Loc*Sub(site)	255	34.37			

Table D.3 Position - average flexion and extension ANOVA

Source	df	MS	F	*p*	G-G *p*
Site	1	78.40	0.03	0.8668	
Sub(site)	17	2703.55			
Object	5	219.28	7.34	0.0001	0.0149
Loc	3	322.34	4.81	0.0050	0.0425
Object*Loc	15	10.36	0.63	0.8449	
Site*Object	5	30.63	1.03	0.4053	
Site*Loc	3	36.16	0.54	0.6571	
Site*Object*Loc	15	25.49	1.56	0.0846	
Object*Sub(site)	85	29.88			
Loc*Sub(site)	51	67.00			
Object*Loc*Sub(site)	255	16.32			

Table D.4 Position - range of flexion and extension ANOVA

Source	df	MS	F	*p*	G-G *p*
Site	1	1073.07	0.34	0.5658	
Sub(site)	17	3128.98			
Object	5	698.67	4.16	0.0020	0.0572
Loc	3	3538.06	14.3	0.0001	0.0015
Object*Loc	15	229.55	1.58	0.0788	
Site*Object	5	138.48	0.82	0.5388	
Site*Loc	3	93.30	0.38	0.7678	
Site*Object*Loc	15	134.20	0.92	0.5370	
Object*Sub(site)	85	167.94			
Loc*Sub(site)	51	247.08			
Object*Loc*Sub(site)	255	145.11			

Table D.5 Position - maximum radial deviation ANOVA

Source	df	MS	F	*p*	G-G *p*
Site	1	9038.44	1.97	0.1789	
Sub(site)	17	4598.06			
Object	5	2803.36	5.55	0.0002	0.0307
Loc	3	883.69	0.98	0.4112	
Object*Loc	15	338.75	1.18	0.2913	
Site*Object	5	75.66	0.15	0.9795	
Site*Loc	3	210.75	0.23	0.8751	
Site*Object*Loc	15	50.43	0.17	0.9998	
Object*Sub(site)	85	504.95			
Loc*Sub(site)	51	905.14			
Object*Loc*Sub(site)	255	288.27			

Table D.6 Position - maximum ulnar deviation ANOVA

Source	df	MS	F	*p*	G-G *p*
Site	1	2427.29	0.57	0.4593	
Sub(site)	17	4312.43			
Object	5	832.52	3.30	0.0089	0.0870
Loc	3	330.88	0.54	0.6561	
Object*Loc	15	347.17	1.71	0.0498	0.2084
Site*Object	5	445.55	1.77	0.1277	
Site*Loc	3	280.50	0.46	0.7114	
Site*Object*Loc	15	130.09	0.64	0.8409	
Object*Sub(site)	85	251.96			
Loc*Sub(site)	51	611.11			
Object*Loc*Sub(site)	255	203.41			

Table D.7 Position-average radial and ulnar deviation ANOVA

Source	df	MS	F	*p*	G-G *p*
Site	1	7013.86	1.80	0.1974	
Sub(site)	17	3897.05			
Object	5	1070.90	3.86	0.0033	0.0660
Loc	3	418.44	0.57	0.6400	
Object*Loc	15	285.56	1.29	0.2093	
Site*Object	5	318.95	1.15	0.3406	
Site*Loc	3	185.68	0.25	0.8610	
Site*Object*Loc	15	48.94	0.22	0.9992	
Object*Sub(site)	85	277.24			
Loc*Sub(site)	51	739.41			
Object*Loc*Sub(site)	255	221.64			

Table D.8 Position-range of radial and ulnar deviation ANOVA

Source	df	MS	F	*p*	G-G *p*
Site	1	2056.50	0.91	0.3526	
Sub(site)	17	2250.93			
Object	5	1724.07	9.05	0.0001	0.0079
Loc	3	200.73	1.40	0.2542	
Object*Loc	15	117.30	1.14	0.4033	
Site*Object	5	233.49	1.23	0.3022	
Site*Loc	3	73.06	0.51	0.6772	
Site*Object*Loc	15	108.06	1.05	0.4033	
Object*Sub(site)	85	190.51			
Loc*Sub(site)	51	143.64			
Object*Loc*Sub(site)	255	102.81			

Table D.9 Position - maximum pronation ANOVA

Source	df	MS	F	*p*	G-G *p*
Site	1	67315.09	1.75	0.2029	
Sub(site)	17	38376.94			
Object	5	67114.11	25.2	0.0001	0.0001
Loc	3	784.41	0.75	0.5259	
Object*Loc	15	782.52	1.13	0.3333	
Site*Object	5	6589.23	2.47	0.0387	0.1345
Site*Loc	3	766.56	0.74	0.5331	
Site*Object*Loc	15	844.14	1.21	0.2607	
Object*Sub(site)	85	2662.77			
Loc*Sub(site)	51	1042.20			
Object*Loc*Sub(site)	255	695.15			

Table D.10 Position - maximum supination ANOVA

Source	df	MS	F	*p*	G-G *p*
Site	1	38298.3	1.26	0.2766	
Sub(site)	17	30315.9			
Object	5	6879.7	16.35	0.0001	0.0008
Loc	3	4525.1	13.42	0.0001	0.0019
Object*Loc	15	79.10	0.50	0.9404	
Site*Object	5	822.10	1.95	0.0945	
Site*Loc	3	158.03	0.47	0.7045	
Site*Object*Loc	15	256.16	1.61	0.0702	
Object*Sub(site)	85	420.88			
Loc*Sub(site)	51	337.12			
Object*Loc*Sub(site)	255	158.70			

Table D.11 Position - average pronation and supination ANOVA

Source	df	MS	F	p	G-G p
Site	1	32986.9	1.06	0.3187	
Sub(site)	17	31262.6			
Object	5	17646.8	38.1	0.0001	0.0001
Loc	3	1752.16	4.42	0.0077	0.0507
Object*Loc	15	66.58	0.53	0.9254	
Site*Object	5	1362.54	2.94	0.0170	0.1046
Site*Loc	3	215.83	0.54	0.6571	
Site*Object*Loc	15	278.67	2.20	0.0069	0.1563
Object*Sub(site)	85	463.11			
Loc*Sub(site)	51	396.49			
Object*Loc*Sub(site)	255	126.73			

Table D.12 Position - range of pronation and supination ANOVA

Source	df	MS	F	p	G-G p
Site	1	4064.3	0.21	0.6513	
Sub(site)	17	19203.			
Object	5	36056.	18.47	0.0001	0.0005
Loc	3	6597.4	6.23	0.0011	0.0231
Object*Loc	15	762.68	1.18	0.2888	
Site*Object	5	3110.1	1.59	0.1716	
Site*Loc	3	746.38	0.70	0.5564	
Site*Object*Loc	15	510.00	0.79	0.6907	
Object*Sub(site)	85	1952.4			
Loc*Sub(site)	51	1059.7			
Object*Loc*Sub(site)	255	647.26			

Table D.13 Velocity - maximum flexion ANOVA

Source	df	MS	F	*p*	G-G *p*
Site	1	19548.3	4.55	0.0478	0.0478
Sub(site)	17	4298.3			
Object	5	1215.4	4.07	0.0023	0.0597
Loc	3	3132.6	4.17	0.0103	0.0570
Object*Loc	15	224.3	0.78	0.7014	
Site*Object	5	650.6	2.18	0.0638	
Site*Loc	3	1101.3	1.46	0.2364	
Site*Object*Loc	15	906.0	3.14	0.0001	0.0943
Object*Sub(site)	85	298.6			
Loc*Sub(site)	51	752.0			
Object*Loc*Sub(site)	255	288.2			

Table D.14 Velocity - maximum extension ANOVA

Source	df	MS	F	*p*	G-G *p*
Site	1	3302.3	0.66	0.4280	
Sub(site)	17	5007.9			
Object	5	681.3	1.66	0.1524	
Loc	3	3893.6	6.44	0.0009	0.0212
Object*Loc	15	302.9	0.90	0.5611	
Site*Object	5	350.0	0.85	0.5183	
Site*Loc	3	489.3	0.81	0.4942	
Site*Object*Loc	15	254.5	0.76	0.7225	
Object*Sub(site)	85	409.7			
Loc*Sub(site)	51	604.9			
Object*Loc*Sub(site)	255	335.4			

Table D.15 Velocity - average flexion and extension ANOVA

Source	df	MS	F	*p*	G-G *p*
Site	1	3600.3	4.97	0.0396	0.0396
Sub(site)	17	724.7			
Object	5	86.5	1.94	0.0954	
Loc	3	1074.4	8.04	0.0002	0.0114
Object*Loc	15	59.1	1.47	0.1177	
Site*Object	5	77.2	1.73	0.1365	
Site*Loc	3	53.6	0.40	0.7376	
Site*Object*Loc	15	111.8	2.78	0.0005	0.1138
Object*Sub(site)	85	44.5			
Loc*Sub(site)	51	133.6			
Object*Loc*Sub(site)	255	40.3			

Table D.16 Velocity - maximum radial deviation ANOVA

Source	df	MS	F	*p*	G-G *p*
Site	1	22331.4	4.22	0.0557	
Sub(site)	17	5293.5			
Object	5	1883.5	11.36	0.0001	0.0036
Loc	3	1079.5	1.31	0.2824	
Object*Loc	15	497.7	2.27	0.0051	0.1503
Site*Object	5	410.4	1.61	0.1661	
Site*Loc	3	772.3	0.99	0.4050	
Site*Object*Loc	15	255.1	0.95	0.5051	
Object*Sub(site)	85	313.4			
Loc*Sub(site)	51	625.3			
Object*Loc*Sub(site)	255	267.5			

Table D.17 Velocity - maximum ulnar deviation ANOVA

Source	df	MS	F	*p*	G-G *p*
Site	1	8503.3	0.99	0.3339	
Sub(site)	17	8598.2			
Object	5	6452.8	11.70	0.0001	0.0033
Loc	3	4272.5	2.45	0.0744	
Object*Loc	15	851.7	1.60	0.0747	
Site*Object	5	907.6	1.65	0.1556	
Site*Loc	3	614.1	0.35	0.7893	
Site*Object*Loc	15	390.1	0.73	0.7519	
Object*Sub(site)	85	551.4			
Loc*Sub(site)	51	1746.5			
Object*Loc*Sub(site)	255	533.5			

Table D.18 Velocity - average radial and ulnar deviation ANOVA

Source	df	MS	F	*p*	G-G *p*
Site	1	7016.7	6.56	0.0202	0.0202
Sub(site)	17	1068.9			
Object	5	448.6	8.43	0.0001	0.0099
Loc	3	262.5	2.05	0.1180	
Object*Loc	15	77.1	1.99	0.0161	0.1764
Site*Object	5	113.9	2.14	0.0684	
Site*Loc	3	35.8	0.28	0.8396	
Site*Object*Loc	15	27.3	0.70	0.7791	
Object*Sub(site)	85	53.2			
Loc*Sub(site)	51	127.8			
Object*Loc*Sub(site)	255	38.7			

Table D.19 Velocity - maximum pronation ANOVA

Source	df	MS	F	*p*	G-G *p*
Site	1	87748.9	1.37	0.2583	
Sub(site)	17	64148.7			
Object	5	61943.0	7.47	0.0001	0.0142
Loc	3	7816.4	2.36	0.0824	
Object*Loc	15	3936.2	1.71	0.0484	0.2084
Site*Object	5	11609.5	1.40	0.2325	
Site*Loc	3	6289.8	1.90	0.1413	
Site*Object*Loc	15	2778.4	1.21	0.2639	
Object*Sub(site)	85	8296.6			
Loc*Sub(site)	51	3312.6			
Object*Loc*Sub(site)	255	2295.9			

Table D.20 Velocity - maximum supination ANOVA

Source	df	MS	F	*p*	G-G *p*
Site	1	3026.3	0.12	0.7346	
Sub(site)	17	25477.5			
Object	5	9028.8	4.78	0.0007	0.0431
Loc	3	518.6	0.19	0.9057	
Object*Loc	15	1351.6	0.97	0.4915	
Site*Object	5	832.4	0.44	0.8194	
Site*Loc	3	2656.5	0.95	0.4235	
Site*Object*Loc	15	2760.8	1.97	0.0175	0.1785
Object*Sub(site)	85	1891.7			
Loc*Sub(site)	51	2794.6			
Object*Loc*Sub(site)	255	1398.8			

Table D.21 Velocity - average pronation and supination ANOVA

Source	df	MS	F	*p*	G-G *p*
Site	1	3764.5	0.41	0.5327	
Sub(site)	17	9279.8			
Object	5	3232.1	7.92	0.0001	0.0119
Loc	3	516.1	1.43	0.2453	
Object*Loc	15	235.1	1.09	0.3684	
Site*Object	5	260.3	0.64	0.6698	
Site*Loc	3	334.9	0.93	0.4330	
Site*Object*Loc	15	304.1	1.41	0.1442	
Object*Sub(site)	85	408.2			
Loc*Sub(site)	51	361.3			
Object*Loc*Sub(site)	255	216.3			

Table D.22 Acceleration - maximum flexion ANOVA

Source	df	MS	F	*p*	G-G *p*
Site	1	180439	0.05	0.8311	
Sub(site)	17	3848086			
Object	5	553405	1.54	0.1872	
Loc	3	367796	1.45	0.2378	
Object*Loc	15	157620	0.91	0.5526	
Site*Object	5	212169	0.59	0.7076	
Site*Loc	3	185425	0.73	0.5389	
Site*Object*Loc	15	286548	2.23	0.0059	0.1537
Object*Sub(site)	85	360204			
Loc*Sub(site)	51	252802			
Object*Loc*Sub(site)	255	173051			

Table D.23 Acceleration - maximum extension ANOVA

Source	df	MS	F	*p*	G-G *p*
Site	1	2327260	4.26	0.0546	
Sub(site)	17	546178			
Object	5	124277	2.22	0.0595	
Loc	3	82532	1.08	0.3662	
Object*Loc	15	106104	2.07	0.0116	0.1684
Site*Object	5	126620	2.26	0.0556	
Site*Loc	3	70598	0.92	0.4379	
Site*Object*Loc	15	53306	1.04	0.4129	
Object*Sub(site)	85	55953			
Loc*Sub(site)	51	76473			
Object*Loc*Sub(site)	255	51184			

Table D.24 Acceleration - average flexion and extension ANOVA

Source	df	MS	F	*p*	G-G *p*
Site	1	274410	12.12	0.0029	0.0029
Sub(site)	17	22636			
Object	5	609	1.20	0.3141	
Loc	3	7855	4.31	0.0087	0.0534
Object*Loc	15	599	1.07	0.3896	
Site*Object	5	1539	3.04	0.0142	0.0993
Site*Loc	3	4735	2.60	0.0622	
Site*Object*Loc	15	1447	2.57	0.0013	0.1273
Object*Sub(site)	85	506			
Loc*Sub(site)	51	1823			
Object*Loc*Sub(site)	255	563			

Table D.25 Acceleration - maximum radial deviation ANOVA

Source	df	MS	F	p	G-G p
Site	1	2639673	0.61	0.4446	
Sub(site)	17	4309172			
Object	5	1146139	2.92	0.0177	0.1057
Loc	3	364266	0.77	0.5146	
Object*Loc	15	525657	1.64	0.0630	
Site*Object	5	305438	0.78	0.5669	
Site*Loc	3	190054	0.40	0.7536	
Site*Object*Loc	15	123629	0.39	0.9817	
Object*Sub(site)	85	393094			
Loc*Sub(site)	51	471349			
Object*Loc*Sub(site)	255	319816			

Table D.26 Acceleration - maximum ulnar deviation ANOVA

Source	df	MS	F	p	G-G p
Site	1	17051544	4.69	0.0448	0.0448
Sub(site)	17	3634248			
Object	5	2127861	7.74	0.0001	0.0128
Loc	3	300585	1.43	0.2445	
Object*Loc	15	215484	1.03	0.4277	
Site*Object	5	588851	2.14	0.0684	
Site*Loc	3	1037074	4.94	0.0044	0.0401
Site*Object*Loc	15	392018	1.87	0.0267	0.1893
Object*Sub(site)	85	274907			
Loc*Sub(site)	51	210018			
Object*Loc*Sub(site)	255	209835			

Table D.27 Acceleration - average radial and ulnar deviation ANOVA

Source	df	MS	F	*p*	G-G *p*
Site	1	230994	8.37	0.0101	0.0101
Sub(site)	17	27605			
Object	5	11506	8.66	0.0001	0.0091
Loc	3	5733	1.78	0.1620	
Object*Loc	15	1132	1.47	0.1157	
Site*Object	5	1114	0.84	0.5251	
Site*Loc	3	1952	0.61	0.6116	
Site*Object*Loc	15	1772	2.30	0.0044	0.1477
Object*Sub(site)	85	1329			
Loc*Sub(site)	51	3214			
Object*Loc*Sub(site)	255	769			

Table D.28 Acceleration - maximum pronation ANOVA

Source	df	MS	F	*p*	G-G *p*
Site	1	3835022	0.21	0.6536	
Sub(site)	17	18381774			
Object	5	451326	0.39	0.8513	
Loc	3	143344	0.21	0.8896	
Object*Loc	15	736186	1.20	0.2701	
Site*Object	5	485530	0.42	0.8336	
Site*Loc	3	808741	1.18	0.3266	
Site*Object*Loc	15	111600	0.18	0.9997	
Object*Sub(site)	85	1144030			
Loc*Sub(site)	51	685394			
Object*Loc*Sub(site)	255	612507			

Table D.29 Acceleration - maximum supination ANOVA

Source	df	MS	F	*p*	G-G *p*
Site	1	106829002	2.42	0.1383	
Sub(site)	17	44157531			
Object	5	44497466	15.0	0.0001	0.0012
Loc	3	913132	0.34	0.7933	
Object*Loc	15	992457	0.63	0.8528	
Site*Object	5	1360140	0.46	0.8049	
Site*Loc	3	1635526	0.62	0.6053	
Site*Object*Loc	15	2275491	1.43	0.1311	
Object*Sub(site)	85	2976876			
Loc*Sub(site)	51	2651306			
Object*Loc*Sub(site)	255	1585901			

Table D.30 Acceleration - average pronation and supination ANOVA

Source	df	MS	F	*p*	G-G *p*
Site	1	1161260	4.52	0.0484	0.0484
Sub(site)	17	256764			
Object	5	23751	3.91	0.0031	0.0644
Loc	3	4091	0.34	0.7983	
Object*Loc	15	6860	1.28	0.2170	
Site*Object	5	4181	0.69	0.6323	
Site*Loc	3	34769	2.86	0.0459	0.1091
Site*Object*Loc	15	14556	2.71	0.0007	0.1181
Object*Sub(site)	85	6082			
Loc*Sub(site)	51	12151			
Object*Loc*Sub(site)	255	5374			

Table D.31 Time ANOVA

Source	df	MS	F	*p*	G-G *p*
Site	1	150.85	5.79	0.0278	0.0278
Sub(site)	17	26.05			
Object	5	6.70	18.09	0.0001	0.0005
Loc	3	13.05	9.98	0.0001	0.0057
Object*Loc	15	0.65	1.55	0.0875	
Site*Object	5	1.15	3.11	0.0126	0.0958
Site*Loc	3	1.81	1.38	0.2591	
Site*Object*Loc	15	0.60	1.43	0.1343	
Object*Sub(site)	85	0.37			
Loc*Sub(site)	51	1.31			
Object*Loc*Sub(site)	255	0.42			

Appendix E: Error Associated with Placement of the Wrist Monitor

The amount of error which resulted from incorrect placement of the wrist motion monitor was computed for 1) placing the center of rotation of the wrist motion monitor a distance **a** from the wrist's center of rotation, 2) placing the long metal strip in the wrong position so that the angle is incorrect by an angle of γ, and 3) placing both the center rotation of the wrist motion monitor a distance **a** from the actual center of motion and the long metal strip in the wrong position by an angle of γ.

Case 1 - Center Displacement

The first task was to determine the amount of error associated with placing the center of the wrist motion monitor a distance **a** from the actual center of wrist motion. As shown in Figure 17, α is the true angle, β is the wrist motion monitor angle, **a** is the distance from the center of rotation of the wrist motion monitor to the center of wrist motion, **w** is the distance from the center of wrist motion to the placement on the hand (it is assumed that the placement on the hand will not change). The following equation was used to describe the true angle, α, in terms of the wrist motion monitor angle, β.

$$\alpha = \arcsin\left(\frac{a \sin(\beta)}{w}\right) + \beta \tag{E.1}$$

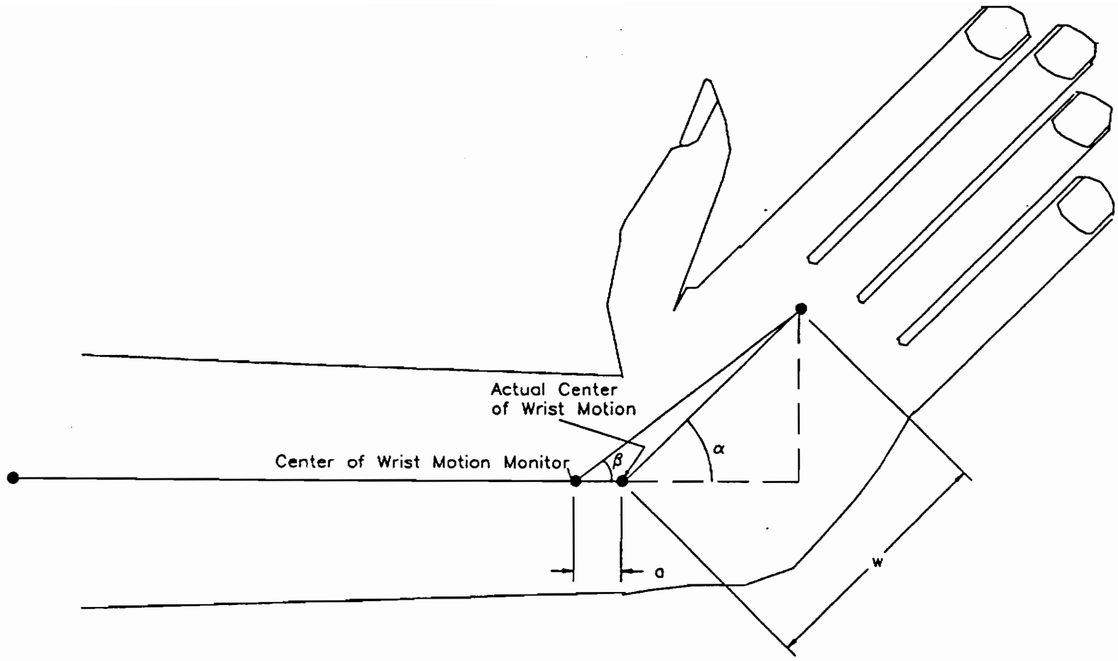

Figure 17 Displacement of center of wrist motion.

After attaching the wrist motion monitor, a calibration procedure was performed in which the true angle of the wrist was measured and the wrist motion monitor, regardless of actual angle, is equated to the true angle. Using equation E.1, the true angle was computed using the wrist motion monitor angle and assuming a distance for **a** and **w** as shown in the table E.1.

Table E.1 True angle given wrist motion monitor angle using Equation E.1

Assuming: **w** = 7, **a** = 2	
Wrist Motion Monitor Angle, (°)	True Angle, α (°)
45	56.65
20	25.61
0	0
-20	-25.61
-45	-56.65

The true angle and the wrist motion monitor angle are linearly related with an R^2 of 0.9999. The equation of the line is: $\alpha = 1.2625\,\beta$. After the calibration was completed, any true angle could be computed using the regression equation. When the wrist motion monitor angle was 30°, the true angle was 37.88° using the regression equation. Using equation E.1 when the wrist motion monitor angle was 30°, the true angle was 38.21°. Therefore, there was an error of 0.33° by using the regression equation as shown in table E.2.

Table E.2 Example of error when comparing the regression equation and Equation E.1

Wrist Motion Monitor Angle, (°)	Angle, α using Regression Equation (°)	True Angle, α (using Equation E.1) (°)	Error (°)
30	37.88	38.21	0.33

* assuming: a = 2, w = 7

As shown in this example, the error associated with having the center of the wrist motion monitor in the wrong position is small. Other combinations os **a** and **w** were tried to see how they affected the error associated with misplacing the wrist motion monitor. Table E.3 shows the error associated with misplacing the wrist motion monitor as computed in the example above.

Table E.3 Error when center of rotation of the wrist monitor is displaced by distance **a**

a	w	Wrist Motion Monitor Angle, (°)	Angle, α (Using Regression Equation) (°)	True Angle, α (Using Equation E.1) (°)	Error (°)
2	7	10	12.63	12.84	0.21
2	7	20	25.25	25.61	0.36
2	7	30	37.88	38.21	0.33
1	10	10	10.91	10.99	0.08
1	10	20	21.83	21.96	0.13
1	10	30	32.74	32.87	0.13
2	10	10	11.83	11.99	0.16
2	10	20	23.66	23.92	0.26
2	10	30	35.50	35.74	0.24
3	10	10	12.76	12.99	0.23
3	10	20	25.52	25.89	0.37
3	10	30	38.28	38.63	0.35
4	10	10	13.70	13.98	0.28
4	10	20	27.39	27.86	0.47
4	10	30	41.09	41.54	0.45
5	10	10	17.70	17.99	0.29

Table E.3 Error when center of rotation of the wrist monitor is displaced by distance **a**

a	w	Wrist Motion Monitor Angle, β (°)	Angle, α (Using Regression Equation) (°)	True Angle, α (Using Equation E.1) (°)	Error (°)
5	10	20	35.41	35.88	0.47
5	10	30	53.11	53.58	0.47

Case 2 - Long Metal Strip Displacement

The second task was to determine the amount of error associated with placing the long metal strip in the wrong position causing the wrist motion monitor to be different from the wrist angle by an amount γ. As shown in Figure 18, α is the true angle and β is the wrist motion monitor angle. The following equation was used to describe the wrist motion monitor angle, β, in terms of the true angle, α:

$$\alpha = \beta - \gamma \tag{E.2}$$

Using equation E.2, the true angle was computed from the wrist motion monitor angle. The same process was followed to compute the error associated with a misplaced long metal strip as that for the error of a misplaced center of the wrist motion monitor. The true angle and the wrist motion monitor angle are linearly related with an R^2 of 1.000. The equation of the line was: $\alpha = \beta - \gamma$. After the calibration was completed, any true angle could be computed using the regression equation with no error because the R^2 was unity.

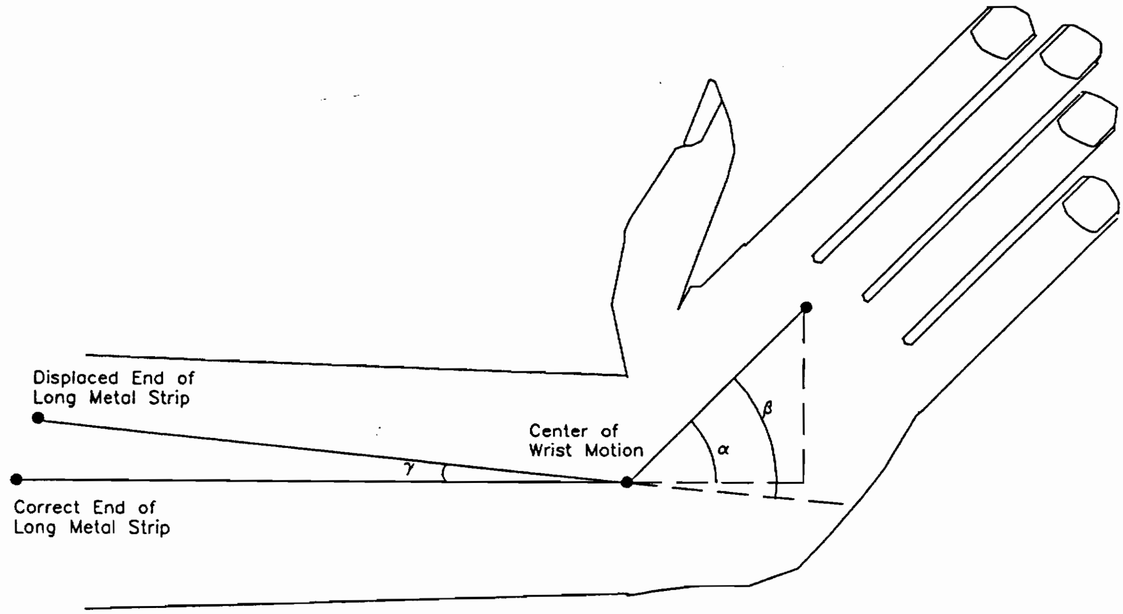

Figure 18 Displacement of long metal strip.

<u>Case 3 - Center and Long Metal Strip Displacement</u>

The third task was to determine the amount of error associated with placing the center of rotation of the wrist motion monitor a distance **a** from the actual center of wrist motion and displacing the long metal strip by an angle γ. As shown in Figure 19, α is the true angle, β is the wrist motion monitor angle, **a** is the distance from the center of rotation of the wrist motion monitor to the center of wrist motion, **w** is the distance from the center of wrist motion to the placement on the hand (it is assumed that the placement on the hand will not change). The following equation which was determined by using geometry was used to describe the wrist motion monitor angle, β, in terms of the true angle, α:

$$\alpha = \arcsin\left(\frac{a \sin(\beta - \gamma)}{w}\right) + \beta - \gamma \qquad \text{(E.3)}$$

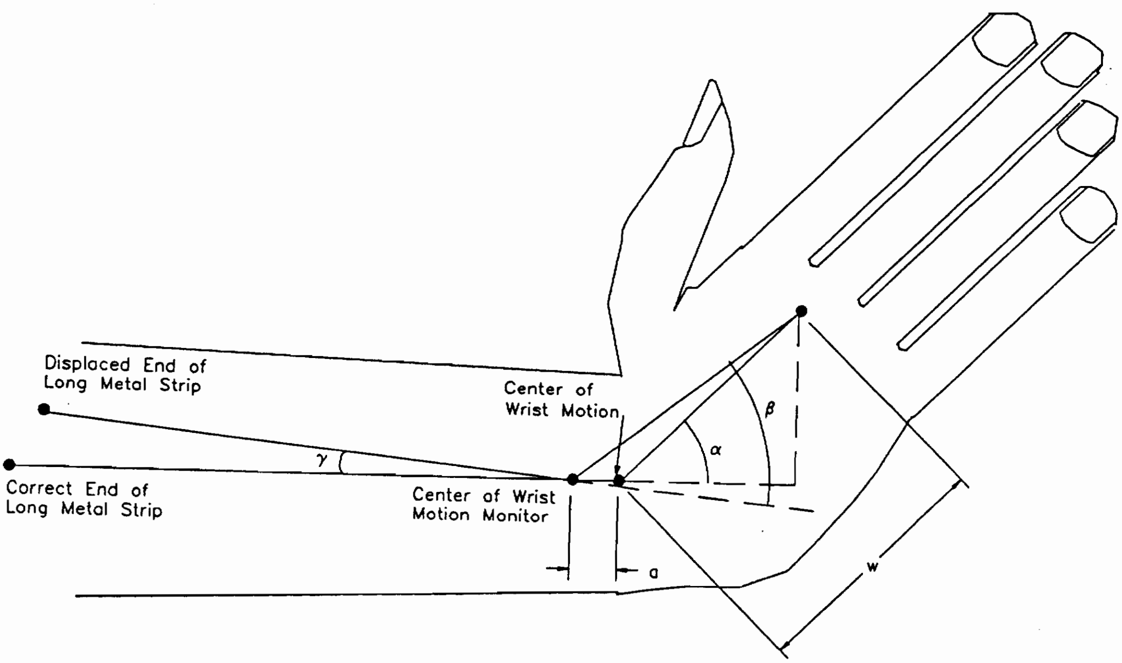

Figure 19 Displacement of center of rotation and long metal strip.

After attaching the wrist motion monitor, a calibration procedure was performed in which the true angle of the wrist was measured and the wrist motion monitor, regardless of actual angle, was equated with the true angle. The true angle and the wrist motion monitor angle are linearly related with an R^2 of 0.9999. The equation of the line is: $\alpha = 1.2586\ \beta - 12.462$. The results when both errors are made is very similar to the results when only the center of the wrist motion monitor is displaced. Therefore, the same logic was followed as in case 1. Table E.4 shows the error associated with an misplacement of the wrist motion monitor.

Table E.4 Error when center of wrist monitor is displaced by distance a and long metal strip is displaced by γ

a	w	γ (°)	Wrist Motion Monitor Angle, β (°)	Angle, α (Using Regression Equation) (°)	True Angle, α (Using Equation E.3) (°)	Error (°)
2	7	10	10	0.12	0	0.12
2	7	10	20	12.71	12.84	0.13
2	7	10	30	25.30	25.61	0.31
3	10	10	10	0.13	0	0.13
3	10	10	20	12.85	12.99	0.14
3	10	10	30	25.57	25.89	0.32

Results

The wrist motion monitor gives an angle accurate within a degree even if it is attached improperly to the subject's wrist. If the center of the wrist motion monitor is attached incorrectly and if the end of the long metal strip is attached at the wrong location, the result is still correct because of the calibration technique used in this study. Less than one degree is considered negligible, because the current measurement technique can only measure to the nearest degree.

Vita

In 1988, Cheryl Fairfield Estill graduated from Purdue University with a Bachelor of Science degree in Industrial Engineering. Since graduation, Ms. Estill has worked at the National Institute for Occupational Safety and Health (NIOSH) as a researcher for the Engineering Control Technology Branch. Although widely varied, her major research at NIOSH has focused primarily on the development of feasible engineering controls for workers exposed to methylene chloride in the furniture stripping industry. In 1991, Ms. Estill was approved to participate in the NIOSH long-term training program, and enrolled in the Human Factors Engineering Program in the Industrial and Systems Engineering Department at the Virginia Polytechnic Institute and State University. In 1992, following completion of her classwork, Ms. Estill returned to NIOSH. This thesis is the final step towards receiving her Master of Science degree, at which point Ms. Estill will concentrate her future research with NIOSH in the area of industrial ergonomics.

Cheryl Fairfield Estill