International Journal of Industrial Ergonomics, 11 (1993) 207–224
Elsevier

Dynamic capabilities of the wrist joint in industrial workers

Richard W. Schoenmarklin * and William S. Marras

Biodynamics Laboratory, Department of Industrial and Systems Engineering, The Ohio State University, 1971 Neil Avenue, Columbus, OH 43210, USA

(Received April 24, 1991; accepted in revised form March 8, 1992)

Abstract

The objective of this study was to measure the maximal static and dynamic capability of the wrist joint in industrial workers. Estimates of the wrist's dynamic capability could aid ergonomists in assessing whether an industrial job can be physically executed by a worker and also in evaluating the risk of cumulative trauma disorders (CTDs) from highly repetitive, hand-intensive jobs.

Range of motion and peak velocity and acceleration were measured in the radial/ulnar, flexion/extension, and pronation/supination planes. Peak velocity and acceleration in the radial/ulnar plane were approximately 450 deg/sec and 7500 deg/sec^2. Flexion/extension peak velocity and acceleration were approximately twice that of radial/ulnar (approximately 1000 deg/sec and 16,000 deg/sec^2). Pronation/supination peak velocity and acceleration were greater than twice that of flexion/extension (2200 deg/sec and 45,000 deg/sec^2). The differences in dynamic capabilities between planes are probably due to biomechanical components of musculature (size and moment arm) and maximal range of motion.

Dynamic capabilities did depend on the direction of movement within a plane. Maximal flexion movements were faster than extension, and supination motions were swifter than pronation. Overall, there were no significant differences in dynamic capabilities between the dominant and nondominant wrists. Generally, anthropometric dimensions of the hand and forearm correlated poorly with static and dynamic measures.

Relevance to industry

Cumulative trauma disorders are a common set of problems in industry where manual repetitive work is done. Quantitative measurements of hand/wrist motions are the key to understanding the relationship between CTD and wrist angles.

Keywords

Carpal tunnel syndrome; ergonomic(s); wrist; biomechanic(s); velocity; acceleration; capabilit(y); performance.

Introduction

Cumulative trauma disorders (CTDs) are disorders of the body's soft tissues – most frequently the tendons and nerves – due to repeated exertions and excessive movements of the body (Armstrong, 1986; Kroemer, 1989). Carpal tunnel syndrome (CTS) is probably the most publicized CTD of the hand and wrist. The incidence of CTDs is growing precipitously, as evinced by data from the U.S. Bureau of Labor Statistics (1990). According to the Bureau, the percentage of reported injuries due to repeated trauma in the U.S. rose from approximately 18% in 1981 to over 50% in 1989. The actual number of reported injuries in the U.S. in 1988 was 115,000.

Based on epidemiological studies, Silverstein, Fine, and Armstrong (1986, 1987) established repetition as a risk factor for CTS and CTDs overall, and they found that the risk of CTS and CTD injury in high repetition jobs was 1.9 and 3.6 times greater than low repetition jobs. Kinemati-

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* Now at Marquette University, Department of Mechanical and Industrial Engineering, Milwaukee, WI.

cally, repetition can be considered cyclic wrist movements comprising angular acceleration, peak velocity, and deceleration of the wrist. Based on Silverstein et al.'s (1986, 1987) crude dose–response relationship between repetition and CTD risk, Marras and Schoenmarklin (1991, 1993) and Schoenmarklin, Marras, and Leurgans (1993) conducted a micro-motion study of industrial workers to determine quantitatively which specific kinematic components of wrist motion were associated with high risk of CTDs. In this micro-motion study, these authors demonstrated that dynamic components of wrist motion were important factors in the etiology of occupational CTDs.

In order to effectively prevent occupational CTDs, quantitative analysis of dynamic wrist motion should be integrated into ergonomic programs so that staff can a priori design jobs, evaluate existing work layouts, and test alternative job designs. With respect to wrist motion, ergonomists first need to know the dynamic capabilities of the wrist joint – maximum position, velocity, and acceleration in all three planes of movement. A database consisting of empirical knowledge of wrist dynamics needs to be established for three reasons. First, from a practical viewpoint, ergonomists need to know the biomechanical capabilities of the wrist to determine whether it is physically possible for workers to perform jobs that require swift wrist motions. Second, once it is determined that a worker can perform the task, then the required wrist motion can be compared to maximal capability and calculated as a percentage of maximal performance. This calculation could possibly be used to compare the injurious effects of competing job designs on CTDs. Third, dynamic capabilities of the wrist joint can be utilized as upper limits for input into biomechanical models that estimate the impact of cumulative repetition and force on anatomical structures in the wrist. The purpose of these models is to develop a biomechanical mechanism for the occupational etiology of CTDs.

Methodology

Approach

The objective of this study was to establish a preliminary database on maximal dynamic capability of the wrist joint in all three planes of movement. Maximal wrist motion was measured on industrial workers who performed highly repetitive, hand-intensive jobs.

Subjects

A total of 39 industrial workers (22 men and 17 women) volunteered to participate in this study. Although eleven of the subjects had previous CTD injuries, all of the subjects were healthy and free of injury at the time their wrist motion was monitored. All of these workers performed highly repetitive, hand-intensive work. The mean number of fundamental wrist motions (Barnes, 1981) was 25,435 (*sd* = 12,921) per eight-hour shift. The subjects' average age was 41.73 years (*sd* = 10.48), and the mean seniority was 15.43 years (*sd* = 8.21). 38 of all the subjects were right-handed.

Apparatus

Goniometric instrumentation was used to collect maximal wrist motion data in the radial/ulnar (R/U), flexion/extension (F/E), and pronation/supination (P/S) planes. Figure 1 illustrates the three planes of movement. R/U and F/E

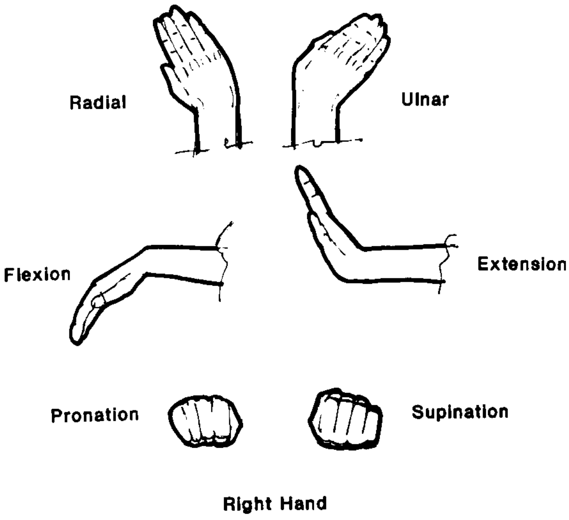

Fig. 1. Three planes of movement of the hand. Radial/ulnar deviation and flexion/extension occur in the wrist joint, and pronation/supination is a function of the radius rotating around the ulna in the forearm.

movements are generated in the wrist joint itself, while P/S actually occurs in the forearm when the radius bone crosses over the ulna bone.

Wrist monitor

A wrist monitor was developed in the Biodynamics Laboratory to collect on-line data on wrist angle in R/U and F/E planes simultaneously, and further analysis of wrist angle data yielded velocity and acceleration in both planes of motion. The design of the wrist monitor is still proprietary, so its description will be brief. This wrist monitor was composed of two segments of thin metal that were joined by a rotary potentiometer. The potentiometer measured the angle between the two segments of thin metal. The potentiometers were placed on the center of the wrist in the R/U and F/E planes. This wrist monitor was small, light (approximately 0.05 kg), recorded R/U and F/E angles independently, and did not have to be calibrated extensively for each subject.

The monitor was calibrated to each subject by recording the voltages of the R/U and F/E potentiometers while the subject's wrist was in neutral position on a calibration table. The bony landmarks shown in figure 2 were used as reference points to align the wrist in the R/U and F/E planes. In both the R/U and F/E planes, the wrist is in a neutral position when the longitudinal axis of the radius is parallel to the third metacarpal bone (Taleisnik, 1985; Palmer et al., 1985). Neutral position in the R/U plane was accomplished by aligning marks placed on the third metacarpophalangeal joint (middle finger knuckle), the center of the wrist, and lateral epicondyle of the elbow (Taylor and Blaschke, 1951; Knowlton and Gilbert, 1983). The center of the wrist on the dorsal side is the "palpable groove between the lunate and capitate bones, on a line with the third metacarpal bone" (Webb Associates, 1978, p. IV–61). The wrist was aligned in a neutral position in the F/E plane when the center of the second metacarpal head, radial styloid, and lateral epicondyle were collinear (Brumfield and Champoux, 1984).

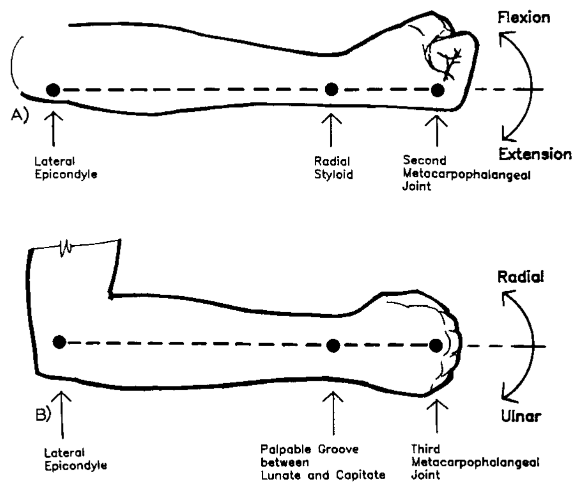

Fig. 2. Bony landmarks on the elbow, wrist, and hand that were used to align the wrist in a neutral position in the radial/ulnar and flexion/extension planes. Adapted from Schoenmarklin and Marras (1989).

The angular deviation of the wrist in the R/U and F/E planes was calculated according to regression equations. The sign convention for angles in the R/U and F/E planes was as follows:

R/U:
Pos = radial deviation Neg = ulnar deviation
F/E:
Pos = flexion Neg = extension

Pronation / supination device

The P/S device recorded the P/S angle of the forearm. The P/S device consisted of a rod that remained parallel to the forearm during rotation. The rod was attached to a bracket affixed to the proximal end of the forearm with a velcro cuff. The rod did not rotate with respect to the proximal cuff. On the distal end of the forearm, the rod was connected to a potentiometer that was attached to a bracket. As the forearm rotated, the potentiometer rotated with respect to the fixed rod, and voltages from the potentiometer recorded the angular displacement of the forearm.

The ratio between angular excursion and change in voltages was not constant for subjects in the P/S plane, so this ratio had to be calculated for each subject. The P/S device was calibrated by the use of a P/S dial. The subject grasped the handle on the dial while he held his elbow at 90 degrees next to his side and his forearm parallel to the ground. When the handle was aligned vertically, this position was defined as the neutral P/S angle. Voltages were collected from the P/S potentiometers in both arms when the forearms were aligned in a neutral position. Then, the subject was asked to maximally pronate his forearms within comfortable limits. Voltages were recorded while his forearms were maximally pronated. Maximal supination was recorded in a manner similar to pronation.

Based on the three pairs of angular and voltage data, a best-fitting regression equation was calculated for each subject's forearm. The relationship between P/S angle and voltage was highly linear, as evinced by r-squared values that averaged about 0.98. The P/S angle was calculated according to each subject's best-fitting regression equation. The sign convention for angles in the P/S plane was as follows:

P/S: Pos = pronation Neg = supination

Sampling frequency

The R/U, F/E, and P/S voltages were monitored at 300 Hz. This frequency was selected on the basis of computations of the minimum frequency needed to ensure an upper limit of 10% change in displacement between consecutive data points during maximal wrist movements. Refer to Marras and Schoenmarklin (1991) for a detailed description of the sampling rate process.

Calculation of velocity and acceleration

Angular velocity and acceleration were computed by a filter. This filter was structurally different from the conventional finite difference method used to compute velocity and acceleration. With the finite difference method, the position of each point in time is computed, and then the velocity is calculated as the derivative of position. Subsequently, acceleration is computed as the derivative of velocity. However, the filter in this study calculated position, velocity, and acceleration simultaneously. In addition to the computation of three kinematic measures, the filter conditioned the data by sifting out a certain amount of noise. Refer to Marras and Schoenmarklin (1991) for a detailed description of the filter and its validation.

Integrated data collection system

The goniometers were combined with customized data collection software into a portable, self-contained system. Figure 3 shows a schematic of the flow of data. Six channels of wrist motion were monitored directly on the factory floor, and these voltages were transmitted to a 12-bit analog-to-digital (A/D) converter board (Labmaster). The six channels comprised R/U, F/E, and P/S motion of both upper extremities.

The data from all six channels were stored on a portable 386 micro-computer and analyzed later in the laboratory. In the laboratory, the wrist motion voltages were converted into R/U, F/E, and P/S angles by regression equations, and the position, velocity, and acceleration were calculated according to the filter described earlier. The summary statistics (mean, maximum, minimum) of the position, velocity, and acceleration were computed for each trial and were transmitted to a mainframe computer for analysis.

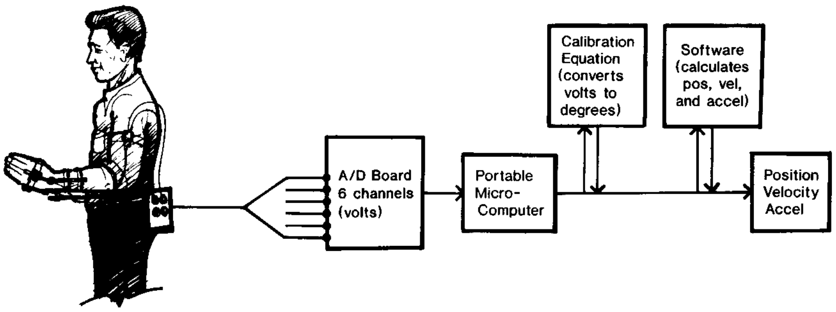

Fig. 3. Integrated data collection system consisting of hardware and software that monitor wrist motion on the factory floor and process the data in the laboratory.

Experimental protocol

Subjects filled out a consent form and a background survey form. The background survey form included age, health status, history of CTDs, work experience, number of years worked on current job, job. satisfaction, etc. The wrist monitor and pronation/supination device were strapped on the subject's right and left forearms and hands, and neutral calibration voltages were recorded, as described earlier in the Apparatus section. Holding his/her hands in a vertical midprone position and elbows at 90 deg, the subject moved his/her hands from one extreme angle to another as quickly as he/she could in the R/U, F/E, and P/S planes. No physical constraints were placed on the subject to keep each movement monoplanar. However, the subject was instructed to keep each excursion within one plane and minimize simultaneous movement in the other two planes. There were two trials within each plane. The first trial started at a positive angle and ended at a negative angle (i.e. R to U, F to E, P to S), and the second trial was in the opposite direction (i.e. U to R, E to F, S to P). The data from these dynamic trials were later analyzed in the laboratory to compute the maximum range of motion, velocity, and acceleration in each plane. After the data collection period, the wrist monitor and P/S device were removed, and anthropometric recordings of the subject's gross and upper extremity dimensions were measured. Upper extremity dimensions were recorded on only the dominant arm, forearm, and hand. The subject was then thanked for his/her time and efforts and was given a Biodynamics Lab T-shirt in exchange for his/her participation.

Results

Wrist performance of dominant and nondominant hands

Figures 4 through 6 and table 2 show the peak angles, velocities, and accelerations of the dominant and nondominant hands. (Refer to table 1 for key to coding of variable names.) The difference between dominant and nondominant performance was analyzed with a paired t-test (within subject). Table 3 shows the results of the paired t-test, which reveals overall a lack of significant differences between the performance measures of the dominant and nondominant hands.

As illustrated in figure 4 and indicated in table 2, the mean maximal radial and ulnar deviation angles were approximately 20 and 28 degrees, respectively. The average peak velocity and accel-

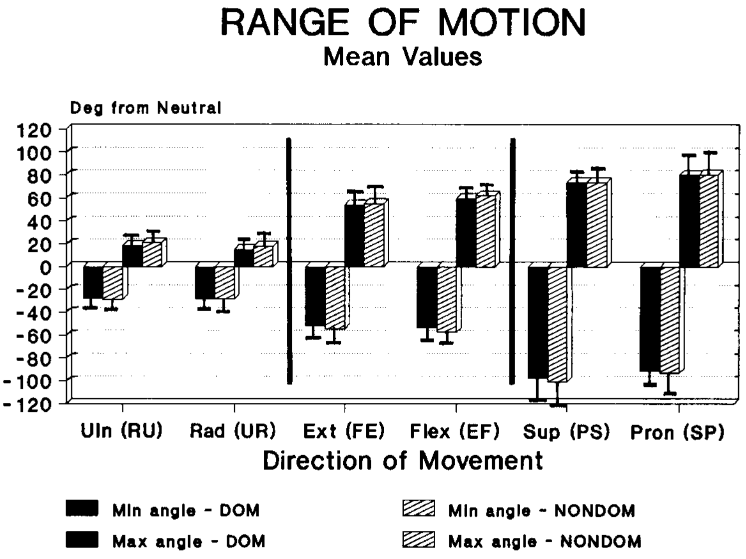

Fig. 4. Mean maximal wrist angles from neutral position as a function of direction of movement and hand (DOMinant vs. NONDOMinant). Each bar represents the respective standard deviation. Refer to table 1 for coding of direction of movement.

eration in ulnar movements were 436 deg/sec and 7640 deg/sec^2, respectively.

The mean maximal flexion and extension angles were approximately 62 and 57 degrees, respectively, as shown in figure 5 and table 2. The average peak velocity and acceleration in flexion movements were 1049 deg/sec and 16,092 deg/sec^2, respectively.

Figure 6 and table 2 reveal that the mean maximal pronation and supination angles were approximately 80 and 100 degrees, respectively. The average peak velocity and acceleration in supination movements were 2,202 deg/sec and 45,034 deg/sec^2.

Table 1

Key to coding of variable names

1st and
2nd char.: Plane and direction of motion
RU = radial dev.: rad. ang. (+) to uln. ang. (−);
UR = ulnar dev.: uln. ang. (−) to rad. ang. (+);
FE = extension: flex. ang. (+) to exten. ang. (−);
EF = flexion: exten. ang. (−) to flex. ang. (+);
PS = supination: pron. ang. (+) to supin. ang. (−);
SP = pronation: supin. ang. (−) to pron. ang. (+);

3rd through
5th char.: MIN = minimum angle (negative)
MAX = maximum angle (positive)
PEK = peak velocity or acceleration

6th char: P = position (deg);
V = vel (deg/sec);
A = accel (deg/sec^2)

e.g.

UR-MIN-*P* = mean value of the minimum position (max ulnar angle) of all trials in which subjects moved their wrist from an extreme ulnar to radial angle.

FE-PEK-*V* = mean value of the peak velocity of trials in which subjects moved their wrist from an extreme flexion to extension angle.

SP-PEK-*A* = mean value of the peak acceleration of trials in which subjects moved their wrist from an extreme supination to pronation angle.

Wrist performance and direction of movement

The magnitude of dynamic wrist performance depended on the direction of movement in each plane, as shown in figures 5 and 6 and table 2. Ulnar, flexion, and supination movements generated greater peak velocity and acceleration than radial, extension, and pronation, respectively. A paired *t*-test (within subject) was executed to determine whether there was a significant difference in static and dynamic performance measures between opposing movements. Table 4 displays results of this paired *t*-test, which reveals significant differences between peak velocity and acceleration within each plane.

As illustrated in figures 5 and 6 and indicated in table 2, the average peak velocity and acceleration in ulnar movements were 22% and 51% larger in magnitude than radial movements (436 vs. 356 deg/sec and 7640 vs. 5055 deg/sec^2, respectively).

The average peak velocity and acceleration in flexion movements were 15% and 34% larger than extension movements (1049 vs. 914 deg/sec and 16,092 vs. 12,007 deg/sec^2, respectively) (refer to figures 5 and 6 and table 2).

The average peak velocity and acceleration in supination movements were 16% and 24% larger in magnitude than pronation movements (2202 vs. 1898 deg/sec and 45,034 vs. 36,336 deg/sec^2, respectively) (refer to figures 5 and 6 and table 2).

Anthropometry

Table 5 shows the summary statistics of the gross and upper extremity dimensions of all the subjects. The correlations among the hand and forearm dimensions are revealed in table 6. Overall, the correlations are approximately 0.50 or less. The highest correlations, ranging from 0.72 to 0.89, are between one dimension, wrist circumference, and a cluster of variables – wrist thickness and breadth and hand breadth.

Correlations among the static and dynamic measures and hand and forearm dimensions are shown in table 7. Overall, these dimensions and wrist performance measures were poorly correlated. The highest correlation coefficients were in the order of 0.40. Wrist breadth, thickness, and circumference were negatively correlated with

Table 2

Summary statistics of wrist performance of dominant and nondominant hands (iN = 39 subjects). The units for position (*P*), velocity (*V*), and acceleration (*A*) are deg, deg/sec, and deg/sec^2, respectively. Refer to table 1 for key to coding of variables.

Dependent variable	Dominant hand		Nondominant hand	
	Mean	*sd*	Mean	*sd*
RU-MIN-*P*	−27.83	(6.75)	−28.80	(7.51)
RU-MAX-*P*	18.59	(7.22)	20.88	(7.98)
RU-PEK-*V*	−436	(130)	−447	(143)
RU-PEK-*A*	−7640	(2679)	−7473	(3009)
UR-MIN-*P*	−28.09	(6.23)	−28.34	(7.16)
UR-MAX-*P*	15.19	(8.13)	17.98	(9.32)
UR-PEK-*V*	356	(109)	378	(124)
UR-PEK-*A*	5055	(1796)	5393	(2169)
FE-MIN-*P*	−52.00	(9.49)	−54.25	(10.74)
FE-MAX-*P*	54.15	(12.15)	55.30	(13.14)
FE-PEK-*V*	−914	(195)	−926	(213)
FE-PEK-*A*	−12007	(3552)	−12051	(3640)
EF-MIN-*P*	−53.44	(8.73)	−57.44	(10.06)
EF-MAX-*P*	59.89	(10.08)	62.46	(11.94)
EF-PEK-*V*	1049	(155)	1069	(201)
EF-PEK-*A*	16092	(3343)	16020	(4321)
PS-MIN-*P*	−97.77	(15.47)	−100.9	(20.86)
PS-MAX-*P*	73.96	(18.31)	74.01	(18.06)
PS-PEK-*V*	−2202	(401)	−2072	(548)
PS-PEK-*A*	−45034	(12140)	−39367	(16363)
SP-MIN-*P*	−91.52	(11.59)	−93.26	(18.99)
SP-MAX-*P*	80.38	(20.25)	80.74	(19.38)
SP-PEK-*V*	1898	(469)	1784	(517)
SP-PEK-*A*	36336	(14069)	33217	(13487)
Max grip strength [a] (kgf)	38.04	(14.63)		

[a] Measured on dominant hand only.

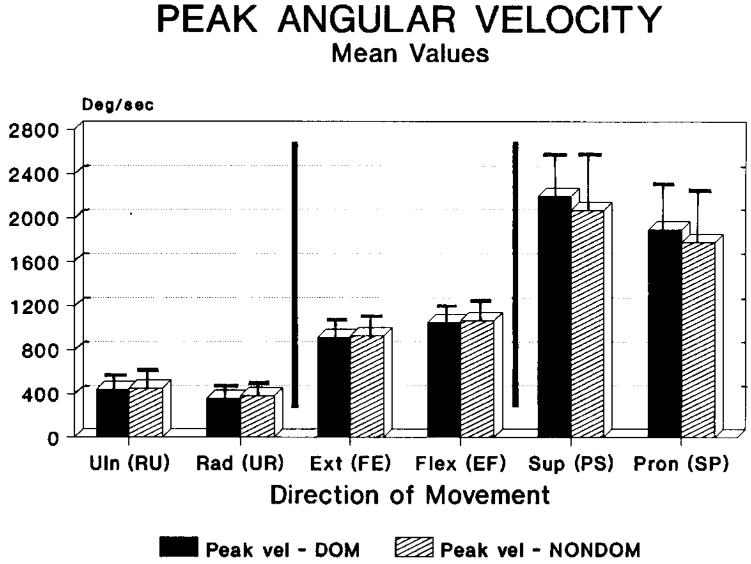

Fig. 5. Mean peak angular velocities as a function of direction of movement and hand (DOMinant vs. NONDOMinant). Each bar represents the respective standard deviation. Refer to table 1 for coding of direction of movement.

Table 3

Results of paired *t*-test on differences between *dominant and nondominant* biomechanical capabilities within subjects. Refer to table 1 for key to coding of variables.

Dependent variable	*t* Statistic	Prob > |*t*|
RU-MIN-*P*	0.95	0.3479
RU-MAX-*P*	−1.85	0.0714
RU-PEK-*V*	0.60	0.5537
RU-PEK-*A*	−0.45	0.6541
UR-MIN-*P*	0.28	0.7820
UR-MAX-*P*	−1.95	0.0586
UR-PEK-*V*	−1.55	0.1298
UR-PEK-*A*	−1.29	0.2050
FE-MIN-*P*	1.60	0.1173
FE-MAX-*P*	−0.99	0.3279
FE-PEK-*V*	0.49	0.6263
FE-PEK-*A*	0.10	0.9197
EF-MIN-*P*	3.17	0.0030
EF-MAX-*P*	−1.91	0.0641
EF-PEK-*V*	−0.87	0.3919
EF-PEK-*A*	0.15	0.8831
PS-MIN-*P*	0.78	0.4398
PS-MAX-*P*	−0.01	0.9902
PS-PEK-*V*	−1.60	0.1190
PS-PEK-*A*	−2.52	0.0160 [a]
SP-MIN-*P*	0.47	0.6430
SP-MAX-*P*	−0.11	0.9165
SP-PEK-*V*	1.66	0.1052
SP-PEK-*A*	1.80	0.0799

[a] Significant at the 0.05 level.

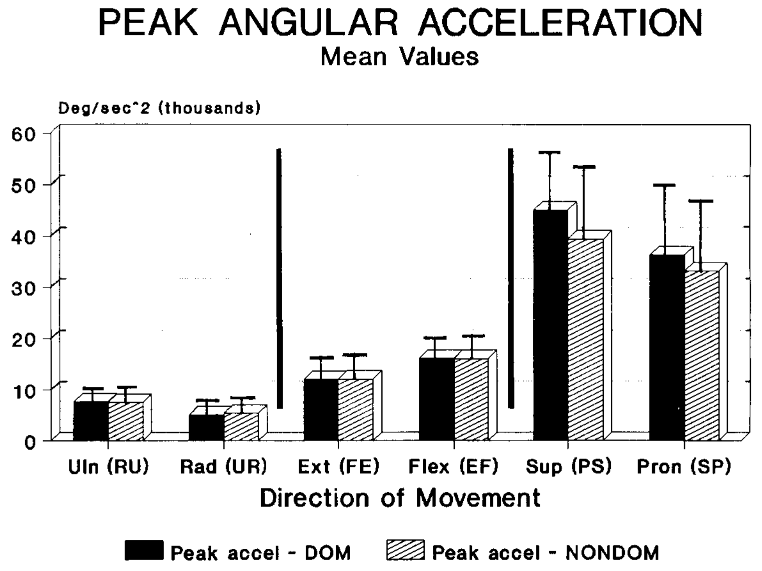

Fig. 6. Mean peak angular accelerations as a function of direction of movement and hand (DOMinant vs. NONDOMinant). Each bar represents the respective standard deviation. Refer to table 1 for coding of direction of movement.

F/E parameters – as the wrist size increased, the maximum flexion angle and peak velocity decreased.

Discussion

Range of motion

As shown in figure 7 and table 8 the ranges of motion recorded in this study are consistent with general estimates of normal wrist angles in the literature. Suggested normal maximal wrist angles from the American Academy of Orthopaedic Surgeons (1965), American Medical Association (1958), and Thurber (1960) are similar to those found in this study. However, the maximal R/U and F/E wrist angles reported by Barter et al. (1957) and Bonebrake et al. (1990) are much higher than those reported in this study. Barter et al.'s (1957) maximal angles in the ulnar direction and F/E plane are approximately 19 and 30

Table 4

Summary statistics and results of paired *t*-test on differences between *opposing movements* within subjects (i.e. RU vs. UR, FE vs. EF, and PS vs. SP). The units for position (*P*), velocity (*V*), and acceleration (*A*) are deg, deg/sec, and deg/sec^2, respectively. Refer to table 1 for key to coding of variables.

Dependent variable	Mean diff.	*sd* of diff.	*t* Statistic	Prob > |t|
Dominant hand				
Rad/uln plane (RU minus UR)				
MIN-*P*	0.26	(4.45)	0.36	0.7224
MAX-*P*	3.41	(3.49)	6.09	0.0001 [a]
PEK-*V*	79.4	(100)	4.96	0.0001 [a]
PEK-*A*	2584	(2634)	6.13	0.0001 [a]
Flex/ext plane (EF minus FE)				
MIN-*P*	1.44	(5.45)	1.65	0.1071
MAX-*P*	−5.74	(8.33)	−4.30	0.0001 [a]
PEK-*V*	134	(182)	4.61	0.0001 [a]
PEK-*A*	4084	(4088)	6.24	0.0001 [a]
Pron/sup plane (PS minus SP)				
MIN-*P*	−6.25	(8.03)	−4.86	0.0001 [a]
MAX-*P*	−6.42	(8.47)	−4.73	0.0001 [a]
PEK-*V*	303	(623)	3.04	0.0043 [a]
PEK-*A*	8698	(12491)	4.35	0.0001 [a]
Nondominant hand				
Rad/uln plane (RU minus UR)				
MIN-*P*	−0.46	(4.91)	−0.58	0.5622
MAX-*P*	2.89	(4.96)	3.64	0.0008 [a]
PEK-*V*	68.7	(95.9)	4.47	0.0001 [a]
PEK-*A*	2079	(2598)	5.00	0.0001 [a]
Flex/ext plane (EF minus FE)				
MIN-*P*	3.19	(6.21)	3.20	0.0028 [a]
MAX-*P*	−7.16	(9.13)	−4.90	0.0001 [a]
PEK-*V*	143	(166)	5.38	0.0001 [a]
PEK-*A*	3969	(4850)	5.11	0.0001 [a]
Pron/sup plane (PS minus SP)				
MIN-*P*	−6.25	(8.03)	−5.21	0.0001 [a]
MAX-*P*	−6.42	(8.47)	−4.96	0.0001 [a]
PEK-*V*	303	(623)	2.88	0.0065 [a]
PEK-*A*	8698	(12491)	3.44	0.0001 [a]

[a] Significant at the 0.05 level

degrees, respectively, greater than those measured in this study.

The ranges of motion in this study could be underestimates of the true range because of the experimental protocol. In this study, the subject held his unsupported forearms parallel to the floor, and maximal angles were recorded at the beginning and end of maximal dynamic movements. The subjects might have focused more on the dynamic exertion and less on maximal range, resulting in a reduced range of motion.

The discrepancy in R/U and F/E range of motion between this study and Barter et al.'s (1957) could possibly be explained by differences in how the data were collected relative to a fixed position. The anthropometric data that Barter et al. (1957) analyzed were measured by Dempster (1955). In Dempster's (1955) study, the subject's hand was strapped to a table, and the subject rotated his forearm with respect to the table. It appears from Barter et al.'s (1957) illustrations that the subject could have used his large arm and shoulder muscles to forcibly rotate the forearm with respect to the hand. If this were the case, then the maximal wrist angles would expectedly be greater than if the subject relied on his forearm muscles solely to rotate an unsupported wrist, as was the protocol in this study.

Maximal pronation/supination angles from this study and Barter et al. (1957) agree reasonably well. Subjects generated about 20 degrees more supination than pronation (101 vs. 81 deg) while the elbow was flexed 90 deg. However, pronation/supination maximal angles change as a function of elbow angle, so the angles reported here should not be generalized to elbow angles other than approximately 90 deg.

Wrist performance of dominant and nondominant hands

The lack of differences in range of motion and movement capabilities between dominant and nondominant wrists are consistent with the literature (refer figures 4 through 6 and table 3). In an investigation into the anthropometric dimensions of males' left and right sides, Laubach and McConville (1967) found that the difference was less

Table 5

Summary statistics of gross and upper extremity anthropometric dimensions ($N = 39$ subjects). Upper extremity dimensions are of *dominant* arm, forearm, and hand. The gross and upper extremity dimensions were measured and numerically titled according to Webb Associates (1978) and Garrett (1970), respectively.

		Mean	*sd*
Gross dimensions (kg and cm) (Webb Associates, 1978)			
#957	Weight	81.11	(15.69)
#805	Stature	172.3	(10.21)
#23	Shoulder height	143.0	(9.07)
#32	Arm length	76.02	(5.37)
#896	Trunk depth	25.89	(5.50)
#751	Shoulder–elbow length	36.55	(2.72)
#324	Elbow–wrist length	28.51	(2.20)
#381	Elbow–hand length	46.48	(3.12)
Dominant hand dimensions (cm) (Garrett, 1970)			
#1	Hand length	18.35	(1.27)
#47	Digit 1 length (thumbtip to crotch)	5.85	(0.65)
#49	Digit 3 length (middle finger)	7.86	(0.81)
#2	Hand breadth at metacarpal	8.18	(1.09)
#8	Hand thickness at metacarpal 3	3.00	(0.84)
#37	Wrist breadth	5.92	(0.76)
	Wrist thickness	4.08	(0.47)
#7	Wrist circumference	17.14	(1.74)
	Forearm circumference	26.71	(4.00)
	Wrist thickness/ breadth ratio	0.70	(0.13)

than one mm in twelve of 21 recorded measurements. Furthermore, these authors questioned whether the statistical significance found in eight of the 21 measurements had any practical value. The results from Laubach and McConville (1967) and this study indicate that anthropometric measurements and maximal movements of the wrist joint are functionally similar for both the dominant and nondominant upper extremities. However, there are significant differences in wrist strength between dominant and nondominant hands, as demonstrated by Van Swearingen (1981). Using a Cybex isokinetic dynamometer, Van Swearingen (1981) found significant differences between extremities in extension and radial torque exerted under isometric and isokinetic (60 deg/sec) conditions.

Wrist performance and direction of movement

As shown in figures 5 and 6 and tables 2 and 4, the peak velocity and acceleration depended on the direction of movement within each respective plane.

Flexion / extension

As illustrated in figures 5 and 6 and tables 2 and 4, the average peak velocity and acceleration in flexion movements were about 10% and 33% larger than extension movements (1049 vs. 914 deg/sec and 16,092 vs. 12,007 deg/sec^2, respectively). Flexion's superiority in peak dynamic measures is probably due to the flexor musculature having greater biomechanical potential than the extensor musculature. According to Basmajian (1982), the primary muscles that flex the wrist are flexor carpi radialis (FCR), flexor carpi ulnaris (FCU), palmaris longus (PL), and abductor pollicis longus (APL). The primary extensor muscles are extensor carpi radialis longus (ECRL) and brevis (ECRB) and extensor carpi ulnaris (ECU). Table 9 shows the physiologic cross-sectional area (PCSA) of these muscles. The PCSA

Table 6

Pearson correlation coefficients of anthropometric data from dominant hand and forearm ($N = 39$ subjects). Anthropometric data were collected and numerically titled according to Garrett's (1970) protocol.

	Anthropometric dimensions									
	A#1	A#47	A#49	A#2	A#8	A#37	Wrst Thck	A#7	Fore circ	ratio
A#1	1.0	0.52 [a]	0.64 [a]	043 [a]	0.22	0 [a]	0.47 [a]	0.48 [a]	0.18	0.04
A# 47		1.0	0.45[a]	0.35 [a]	0.26	0.43 [a]	0.44 [a]	0.37 [a]	0.23	0.02
A#49			1.0	0.22	0.21	0.26	0.35 [a]	0.36 [a]	−0.31 [a]	0.09
A#2				1.0	−0.53 [a]	0.89 [a]	0.33 [a]	0.72 [a]	0.49 [a]	−0.70 [a]
A#8					1.0	−0.35 [a]	0.44 [a]	−0.09	−0.02	0.89 [a]
A#37						1.0	0.51 [a]	0.85 [a]	0.50 [a]	−0.59 [a]
Wrst Thck							1.0	0.79 [a]	0.51 [a]	0.36 [a]
A#7								1.0	0.54 [a]	−0.22
Fore circ									1.0	−0.11
Ratio										1.0

[a] Significant at the 0.05 level

Key to coding of anthropometric dimensions (Garrett, 1970):
A#1 = Hand length
A#47 = Digit 1 length (thumbtip to crotch level)
A#1.49 = Digit 3 length (middle finger)
A#2 = Hand breadth at metacarpal level
A#8 = Hand thickness at metacarpal 3 (middle knuckle)
A#37 = Wrist breadth
Wrst thck = Wrist thickness
A#7 = Wrist circumference
Fore circ = Forearm circumference
Ratio = Wrist thickness/breadth ratio

is a measure of the muscle's maximal force capability – the larger the PCSA, the greater the maximal force. According to Amis et al. (1979), the total PCSA of the four flexor muscles is 11.84 cm^2 whereas the total PCSA of the three extensors is 9.45 cm^2.

In order to estimate the full biomechanical capability of each muscle, the moment arm of each muscle needs to be considered in addition to PCSA. The moment arm of each flexor and extensor muscle's tendon is reported in table 9 (Brand, 1985). The product of each muscle's PCSA and moment arm indicates the full biomechanical potential; these products are also listed

Table 7

Correlation matrix of maximal position, velocity, and acceleration measures and anthropometric dimensions of dominant hand and forearm ($N = 39$ subjects). Refer to table 1 for key to coding of variable names.

	Anthropometric dimensions									
	A#1	A#47	A#49	A#2	A#8	A#37	Wrst thck	A#7	Fore circ	Ratio
RU-MIN-*P*	0.41 [a]	0.16	0.31	0.12	0.05	-0.01	0.03	-0.03	-0.06	0.03
RU-MAX-*P*	-0.09	0.04	-0.14	-0.03	-0.06	0.00	-0.09	-0.09	-0.01	-0.07
RU-PEK-*V*	0.19	0.16	0.07	0.24	0.01	0.24	0.24	0.20	0.23	-0.04
RU-PEK-*A*	0.05	0.08	-0.04	0.13	0.12	0.14	0.24	0.15	0.30	0.07
UR-MIN-*P*	0.30	0.19	0.40 [a]	-0.03	0.22	-0.09	0.02	-0.13	-0.26	0.15
UR-MAX-*P*	-0.06	0.07	-0.18	0.04	-0.03	0.04	-0.01	-0.02	0.16	-0.07
UR-PEK-*V*	0.15	0.22	-0.04	0.18	-0.06	0.14	0.03	0.03	0.13	-0.12
UR-PEK-*A*	0.02	0.12	-0.17	0.19	-0.09	0.11	0.08	0.11	0.24	-0.10
FE-MIN-*P*	0.16	0.22	0.17	-0.05	0.10	-0.09	-0.15	-0.17	-0.17	0.00
FE-MAX-*P*	-0.15	-0.30	-0.11	-0.18	-0.15	-0.22	-0.33 [a]	-0.33 [a]	-0.35 [a]	-0.06
FE-PEK-*V*	0.06	0.14	0.05	-0.13	0.09	-0.19	-0.23	-0.30	-0.24	0.03
FE-PEK-*A*	0.15	0.18	0.13	-0.09	0.14	-0.18	-0.08	-0.19	-0.05	0.12
EF-MIN-*P*	0.32 [a]	0.16	0.30	0.01	0.09	-0.05	-0.03	-0.06	-0.15	0.06
EF-MAX-*P*	-0.25	-0.41 [a]	-0.25	-0.35 [a]	-0.07	-0.46 [a]	-0.48 [a]	-0.54 [a]	-0.28	0.06
EF-PEK-*V*	-0.03	-0.09	-0.02	-0.05	-0.05	-0.13	-0.18	-0.18	0.01	-0.02
EF-PEK-*A*	0.07	-0.05	0.08	0.05	0.03	0.03	-0.06	-0.05	0.04	-0.05
PS-MIN-*P*	-0.19	-0.08	-0.07	-0.06	-0.17	-0.21	-0.08	-0.19	-0.07	0.04
PS-MAX-*P*	0.43 [a]	0.19	0.19	0.45 [a]	-0.12	0.46 [a]	0.19	0.39	0.21	-0.24
PS-PEK-*V*	0.32 [a]	0.33 [a]	0.21	0.46 [a]	-0.09	0.38 [a]	0.23	0.23	0.16	-0.14
PS-PEK-*A*	0.23	0.26	0.20	0.38 [a]	-0.06	0.38 [a]	0.16	0.20	0.12	-0.16
SP-MIN-*P*	-0.30	-0.18	-0.16	-0.24	-0.10	-0.36 [a]	-0.17	-0.31	-0.16	0.11
SP-MAX-*P*	0.41 [a]	0.11	0.19	0.38 [a]	-0.11	0.38 [a]	0.22	0.31	0.14	-0.15
SP-PEK-*V*	0.06	-0.08	0.05	0.06	0.00	-0.11	0.11	0.04	0.12	0.11
SP-PEK-*A*	0.22	0.11	0.03	0.31	-0.05	0.33 [a]	0.09	0.17	0.23	-0.19

[a] Significant at the 0.05 level

Key to coding of anthropometric dimensions (Garrett, 1970):
A# = Hand length
A#47 = Digit 1 length (thumbtip to crotch level)
A#49 = Digit 3 length (middle finger)
A#2 = Hand breadth at metacarpal level
A#8 = Hand thickness at metacarpal 3 (middle knuckle)
A#37 = Wrist breadth
wrst thck = Wrist thickness
A#7 = Wrist circumference
Fore circ = Forearm circumference
Ratio = Wrist thickness/breadth ratio

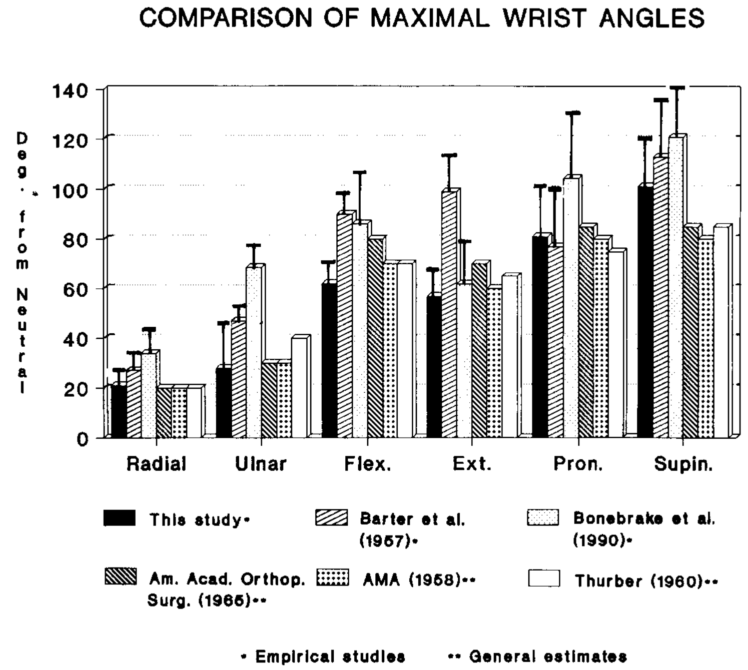

Fig. 7. Comparison of maximal wrist angle data from empirical studies and general estimates. Each bar represents the respective standard deviation.

in table 9. The total biomechanical potential of the four wrist flexors is 19.41, approximately twice as great as the biomechanical potential of the three extensors. The wrist flexor's superior biomechanical potential is corroborated by Van Swearingen (1981), who found that wrist flexor

Table 8

Comparison of maximal wrist angles from this study and other studies reported in the literature. Standard deviations are presented in parentheses

	Maximal wrist angles (deg)					
	Rad.	Uln.	Flex.	Exten.	Pron.	Supin.
This study	21 (8)	28 (18)	62 (12)	57 (10)	81 (19)	101 (21)
Barter et al. (1975)	27 (9)	47 (7)	90 (12)	99 (13)	77 (24)	113 (22)
Bonebrake et al. (1990)	33.9 (10.7)	68.4 (8.65)	86.2 (22.1)	61.8 (18.8)	104.5 (33.8)	120.8 (23.1)
Amer. Acad. Orthop. Surgeons [a] (1965)	20	30	80	70	80–90	80–90
Amer. Med. Assn. [b] (1958)	20	30	70	60	80	80
Thurber [a] (1960)	20	40	70	65	75	85

[a] Wrist angles reported are general estimates for normal range of motion.

[b] Defined as average ranges for people with no permanent impairment of joint.

Table 9

Physiological and biomechanical characteristics of the primary muscles that radially and ulnarly deviate and flex the wrist. The primary movers listed for each direction are according to Basmajian (1982).

Muscle	PCSA [a] (cm²)	Moment arm [b] (cm)	Biomech. potential [c]
Radial deviators			
Flexor carpi radialis	2.73	1.0	2.73
Extensor carpi radialis longus	2.73	2.12	5.79
Extensor carpi radialis brevis	3.47	1.25	4.34
Abductor poll. longus	2.62	2.3	6.03
	Sum = 11.55		18.9
Ulnar deviators			
Flexor carpi ulnaris	5.39	1.62	8.73
Extensor carpi ulnaris	3.25	2.5	8.13
	Sum = 8.64		16.86
Flexors			
Flexor carpi radialis	2.73	1.75	4.78
Flexor carpi ulnaris	5.39	1.9	10.2
Palmaris longus	1.10	2.2	2.42
Abductor poll. longus	2.62	0.75	1.97
	Sum = 11.8		19.41
Extensors			
Extensor carpi radialis longus	2.73	1.0	2.73
Extensor carpi radialis brevis	3.47	1.38	4.77
Extensor carpi ulnaris	3.25	0.55	1.79
	Sum = 9.45		9.29
Pronators			
Pronator quadratus	2.88	–	–
Pronator teres	4.59	–	–
	Sum = 7.47		

Table 9 (continued)

Muscle	PCSA[a] (cm^2)	Moment arm[b] (cm)	Biomech. potential[c]
Supinators			
Biceps short head	2.52	–	–
Biceps long head	3.15	–	–
Supinator	2.66	–	–
Abductor poll. longus	2.62	–	–
Extensor poll. longus	1.04	–	–
	Sum = 12.0		

[a] PCSA = physiologic cross-sectional area of muscle; from Amis et al. (1979).

[b] Moment arm of tendon that passes through the wrist joint while the wrist is in a midprone position; from Brand (1985).

[c] Biomechanical potential is the product of PCSA and moment arm.

torque was almost twice that of extensor torque. The greater muscle mass and longer moment arms of the wrist flexor musculature provide a plausible biomechanical explanation for why the wrist can flex faster than extend. This explanation assumes the flexor and extensor musculature have the same muscle fiber type distribution.

Radial / ulnar

The average peak velocity and acceleration in ulnar movements were about 20% and 45% larger in magnitude than radial movements (436 vs. 356 deg/sec and 7640 vs. 5055 deg/sec^2, respectively) (refer to figures 5 and 6 and tables 2 and 4). The apparent dynamic advantage of ulnar movements over radial movements is not supported by the biomechanical potential of the radial and ulnar deviators. The major radial deviators are ECRL, ECRB, FCR, and APL, and the major ulnar deviators are FCU and ECU (Basmajian, 1982). Table 9 lists the PCSA, moment arms, and biomechanical potential of the primary radial and ulnar deviators. As shown in table 9, the total biomechanical potential of the radial deviators is slightly greater than ulnar deviators' collective potential (18.89 vs. 16.86).

Based on biomechanical information, the ulnar movements should not have a dynamic advantage over radial movements (assuming similar fiber type distributions). The greater peak velocity and acceleration of ulnar movements found in this study are probably attributable to the effect of gravity. In this study, maximal wrist motions were performed when the wrist was in a vertical midprone position. Ulnar motions were exerted downward, assisted by gravity, and radial motions were exerted upward, opposing gravity. Gravity attenuated the maximal velocity and acceleration in the radial direction, thereby probably causing the discrepancy in maximal dynamic performance between radial and ulnar motions.

Pronation / supination

As listed in tables 2 and 4 and illustrated in figures 5 and 6, the average peak velocity and acceleration in supination movements were about 16% and 21% larger in magnitude than pronation movements (2202 vs. 1898 deg/sec and 45,034 vs. 36,336 deg/sec^2, respectively). Similar to flexion's dynamic advantage over extension, supination's superior dynamic performance is probably attributable to its biomechanical advantage. Table 9 reveals the PCSA of the primary supinator muscles – biceps short head and long head, supinator, extensor pollicis longus, and APL. The primary pronators are pronator quadratus and pronator teres (Basmajian, 1982). Unlike the tendons passing through the wrist, the pronator and supinator muscles's lines of action are not perpendicular to the axis of rotation (except the biceps' line of action). The axis of rotation for pronation/supination is the longitudinal axis of the forearm. A true estimate of the biomechanical potential of the pronator and supinator muscles would require calculation of the component of the force vectors that is perpendicular to the axis of rotation.

Comparison of the PCSA of the pronator and supinator muscles can provide insight into why supination movements were faster than pronation movements. As indicated in table 9, the total PCSA of the supinator muscles was 12.0 cm^2, approximately 60% greater than the pronator muscles' total PCSA. The greater PCSA of the supinator muscles, in particular the biceps that act perpendicular to the axis of rotation, provide greater force capability in supination movements. According to Newton's second law, greater force capability translates into greater acceleration (assuming the fiber type distribution is similar in the pronator and supinator muscles).

Peak velocity and acceleration as function of plane

The peak velocity and acceleration of flexion movements were 140% and 111%, respectively, greater than ulnar movements (1049 deg/sec vs. 436; 16,092 deg/sec^2 vs. 7640; refer to figures 5 and 6 and table 2). The faster flexor motions are probably partially due to two biomechanical reasons. First, the 140% greater range of motion in the F/E plane allows the hand more angular excursion to reach peak velocity than in the R/U plane (120 deg of range vs. 50; refer to table 2). Second, as shown in table 9, the summated biomechanical potential of the flexors was 19.41, approximately 15% greater than the ulnar deviators' potential of 16.86. The flexors have greater force capability, which translates into faster accelerations (assuming muscle fiber type distributions are similar for flexors and ulnar deviators).

The peak velocity and acceleration of supination movements were 110% and 180%, respectively, greater than flexion movements (2202 deg/sec vs. 1049; 45,034 deg/sec^2 vs. 16,092; refer to figures 5 and 6 and table 2). Supination's superior dynamic performance is probably due to its additional range of motion. The angular excursion in the P/S plane is approximately 180 deg, about 157% greater range of motion than in the F/E plane.

Anthropometry and correlation with performance measures

Overall, correlations between wrist and hand dimensions were consistent with published correlations among body dimensions (Webb Associates, 1978; refer to table 6). Generally, the correlations were under 0.50, but there were clusters of correlations in ranges of 0.60 to 0.80. The highest correlations occurred in functional relationships, such as the relationship between wrist circumference and wrist breadth and thickness.

Correlations among the static and dynamic measures and hand and forearm dimensions were poor, as shown in table 7. The highest correlation coefficients were in the order of 0.40. The negative correlations between wrist dimensions and flexion range of motion is consistent with the literature. In an analysis of Dempster's (1955) data, Barter et al. (1957) found an inverse relationship between flexibility and size. Thin people tended to have greater flexibility than muscular persons, and muscular people had greater flexibility than rotund persons. In this study, the subjects who had large wrists tended to have less flexion range of motion than those people with small wrists.

Wrist ratio

The ratio between wrist thickness and breadth has been suggested by clinicians as a method to predict those workers who are susceptible to CTDs in an industrial settings. Gordon et al. (1988) and Johnson et al. (1983) found a significant positive correlation between wrist ratio and distal median sensory latency, a clinical EMG test used to diagnose CTS. This positive correlation indicates the squarer the wrist, the longer the latency. Gordon et al. (1988) suggested a ratio of 0.70 (thickness/breadth) as a "critical value at which the median distal sensory latencies reached or exceeded the upper limits of normal" (p. 270).

As indicated in table 5, the mean wrist ratio of the 39 subjects in this study was 0.70 with a standard deviation of 0.13. This mean ratio is similar to Gordon et al.'s (1988) mean ratio of 0.69 from a random sampling of 200 wrists in industry. However, their standard deviation of 0.04 was much smaller than the 0.13 found in this study. According to Gordon et al.'s (1988) and Johnson et al.'s (1983) results and conclusions, a portion of the subjects in this study should be susceptible to CTDs. Although all of the subjects in this study reported that they were healthy and free of injury at the time of testing, some of them may have had higher than normal median sensory latencies.

Applications to ergonomics

The data on maximal wrist kinematics presented in this article can aid ergonomists in three ways. First, ergonomists now have some data on upper limits of dynamic wrist motion that can be used to determine whether some jobs are physically possible for humans to perform. For instance, if a certain job required a part to be moved from one point to another within a prescribed time, then the ergonomist could determine whether a human can physically execute that task. The ergonomist would accomplish this by converting the required linear velocity into angular velocity and comparing the required angular velocity with the maximal angular velocity that a person can generate in the respective plane.

Second, once it is determined that a job can be performed by a worker, then the ergonomist can estimate the required wrist motion as a percentage of maximal dynamic performance. This estimate of maximal motion could be used as a tool to evaluate the biomechanical impact of a job or select the best job design from a pool of competing work layouts. Also, the dynamic motion benchmarks that Marras and Schoenmarklin (1993) and Schoenmarklin et al. (1993) measured in industry can now be calculated as percentages of maximal dynamic capability. These motion benchmarks, which were were developed from data collected in highly repetitive, hand-intensive industrial jobs, indicate the magnitude of F/E acceleration that increases a worker's CTD exposure from low to high risk.

Third, dynamic capabilities of the wrist can be used as physiologic- upper limits in biomechanical models. Heretofore, there was a dearth of information on the dynamic capabilities of the wrist joint. Research is currently being conducted on developing a biomechanical model of the wrist joint that will estimate the impact of dynamic movements on anatomical structures in the wrist, particularly the tendons. Modeling of this nature provides a theoretical explanation for why certain motions expose workers to CTDs and also enhances our general understanding of the wrist joint.

Acknowledgments

This research was supported, in part, by the U.S. National Institute for Occupational Safety and Health, grant #1 R01 OHO2621-01 and 02 and the National Institute on Disability and Rehabilitation Research, grant #H133E00817.

The efforts of Dr. R.A. Miller, Carolyn Sommerich, Larry Wright, and Eric Nelson were truly appreciated throughout this project.

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