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Elbow motion patterns during daily activity

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Background: This in vivo kinematic study was developed to ascertain (1) elbow posture and motion during daily activities and (2) to compare motions of the dominant and nondominant elbows.
Methods: Forty-six subjects wore a custom instrumented shirt to continuously measure elbow posture and motion for the waking hours of 1 day. The 3D orientations of each of the forearm and humerus sensors enabled calculation of elbow flexion-extension and pronation-supination angles.
Results: The elbow flexion-extension postures that were most common ranged from 60°-100° for both the dominant and nondominant extremities averaging 44% ± 4% and 35% ± 4% of the day, respectively. When elbow flexion motions were calculated, there were a large number of motions over a wide distribution of flexion angles, with the dominant side exhibiting significantly more motions per hour than the nondominant side.
Conclusion: Both flexion-extension and pronation-supination motions occur more commonly in the dominant arm, and the dominant arm is more commonly in pronation. These data provide a baseline for assessing treatment outcomes, ergonomic studies, and elbow arthroplasty wear testing.
Level of Evidence: Basic Science Study; Kinesiology
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Keywords: Elbow motion; elbow and activities of daily living; elbow kinematics; upper extremity motion

Elbow motion during activities of daily living (ADL) has been the focus of several laboratory studies. Morrey et al[6] laid a foundation for our understanding of the functional necessities of the elbow. The authors were able to characterize the essential motions for performing ADL. Using an electro-goniometer, elbow flexion and extension and forearm pronation and supination were quantified while 33 subjects performed a set series of common tasks. The majority of activities could be accomplished with 30°-130° of flexion-extension and 50° of pronation-supination. Sardelli et al[7] repeated a study similar to Morrey's original experiment, using an optical tracking system with a few added contemporary tasks, and concluded that more elbow range of motion (ROM) may be necessary for ADL and that increased pronation is required for keyboarding and computer use. Aizawa et al[1] were able to accurately define the position of each upper extremity joint for ADL, but this was done for just one limb.

To understand the motion and posture of the elbow joint during the routines of daily life, we developed a wearable kinematic shirt. By characterizing these typical motions, we hope to inform biomechanical testing and create a baseline by which pathologic conditions and surgical treatments can be studied. Our purpose, therefore, was to ascertain (1) the posture and cumulative elbow motion during activities of human subjects during the waking hours of 1 day and (2) to

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Institutional review board approval was received from Western University HS REB (#105934).

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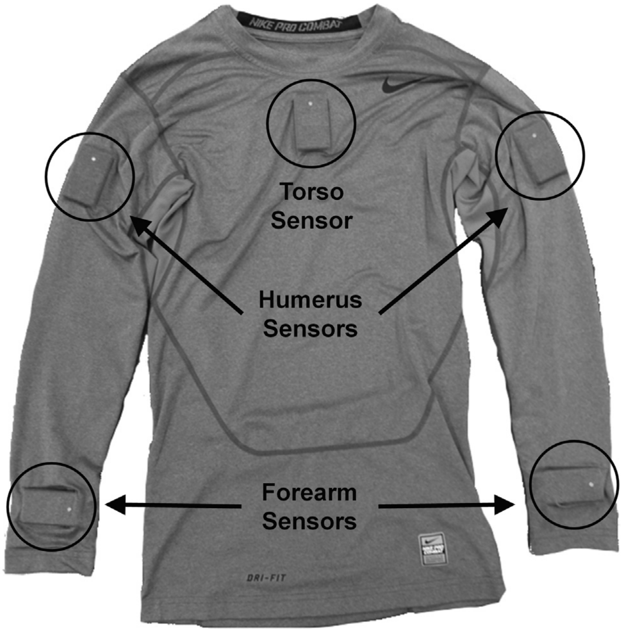

Figure 1 Testing shirt with inertial measurement units. The shirt fits very tightly against the skin, compressing the inertial measurement units (in custom-sewn pockets) against the skin. To further secure the sensors at the wrists, 3M Coban wrap was used to ensure a tight fit without extraneous motion.

compare motions of the dominant and nondominant elbows.

Materials and methods

Institutional ethics approval was obtained. Forty-six subjects (24 men, 22 women) comprised a convenience sample of volunteers ($n = 13$, 30 ± 17 years, range 19-81 years) and volunteers with shoulder arthroplasties ($n = 33$, 74 ± 8 years, range 56-86 years). The maximum elbow extension angle of the dominant and nondominant side of all subjects was 5° ± 10° and 4° ± 6°, respectively, and the maximum elbow flexion angle was, respectively, 138° ± 25° and 138° ± 26°. The mean duration of wear for all subjects was 10.8 ± 2.5 hours. Subjects were screened for elbow pathology by history and physical examination, and each subject demonstrated full elbow ROM. Once informed consent was obtained, subjects presented to our clinic for the first appointment of the morning (7-8 AM) for sizing and fitting of the wearable kinematic shirt.

The wearable kinematic shirt (Fig. 1) included 5 inertial measurement units (YEI Technology; Portsmouth, OH, USA), which incorporated a triaxial gyroscope, accelerometer, and compass sensors to allow for accurate tracking of 3D sensor orientation. The sensors are self-enclosed devices in sealed housings with dimensions of 6×3.5×1.5 cm. The sensors were secured in custom pouches inside a tight-fitting long-sleeved spandex shirt (Nike, Beaverton, OR, USA) and connected to a portable battery (Royal Consumer Information Products, Bridgewater, NJ, USA). One sensor was placed against the sternum in a custom shirt pocket to determine the position of the torso, 1 sensor was secured in a custom pocket on each upper arm, and another sensor was further secured and stabilized on the dorsum of the distal forearm of both the left and right arms using Coban (3M, St Paul, MN, USA) self-adherent wrap. The sensors collected position data in a continuous fashion and recorded their positions at an accuracy of ±1° for dynamic conditions and all orientations.

The accuracy of the shirt construct was confirmed experimentally by having 3 subjects wear the kinematic shirt while being instrumented with a passive reflective marker–based motion capture system in a motion capture lab. Each subject was then instructed to perform a standard set of elbow motions while both motion capture systems recorded the resulting elbow angles. The resulting accuracy of the kinematic shirt was determined to be 4° ± 3° compared with the simultaneous passive optical tracking recording. According to the study outcome parameters, this level of accuracy indicated that the system was an acceptable mobile method of measuring patient kinematic data.

After donning the shirt and securely positioning the sensors, the devices were turned on, having each subject stand with arms at the side and elbows fully extended. The sensors were then automatically calibrated to the "tin soldier" position as a standard means of calibrating the wearable kinematic shirt. Any error in positioning of the sensors was automatically corrected by this calibration.

Subjects were instructed to wear the shirt and sensors for the waking hours of a full day and to continue with all routine activities. At the end of the day, the shirt and sensors were removed and returned for data collection and analysis.

The 3D orientations of each of the sensors allowed for the calculation of elbow joint angles including flexion-extension and forearm pronation-supination angles. These were tabulated to provide data regarding the distribution of elbow and forearm posture throughout the ADL, which allowed for the calculation of the elbow posture for the entire period the shirt was worn.

To provide data regarding discrete elbow motions, the joint angles for each subject were then calculated to identify the peaks and valleys of elbow flexion-extension and pronation-supination. To filter out the minute motions that occurred, a motion threshold of 10° was set such that once a discrete elbow posture was identified, the next elbow posture that would be used to constitute the end point of a discrete motion would have to be at least 10° away from the last position. This removed the small motions that were observed to occur at very high frequency throughout the duration of wearing of the motion shirt. The angular position of the humerus and forearm (start and stop positions) were then calculated as a function of joint angles, and the magnitudes of motions were determined and the occurrences per hour noted.

The resulting motion data set was then normalized to the number of hours each subject wore the shirt. The dominant and nondominant elbows were compared, and the volunteer and TSA volunteer groups were compared using a 3-way analysis of variance (dominant or nondominant side, joint angle range) with a significance level of $\alpha = 0.05$. To ascertain if there were significant differences in the overall effect between the volunteers and shoulder arthroplasty volunteers, a separate 1-way analysis of variance was performed. No significant difference was detected between these groups ($P > .99$), and as a result, the data from both groups were pooled.

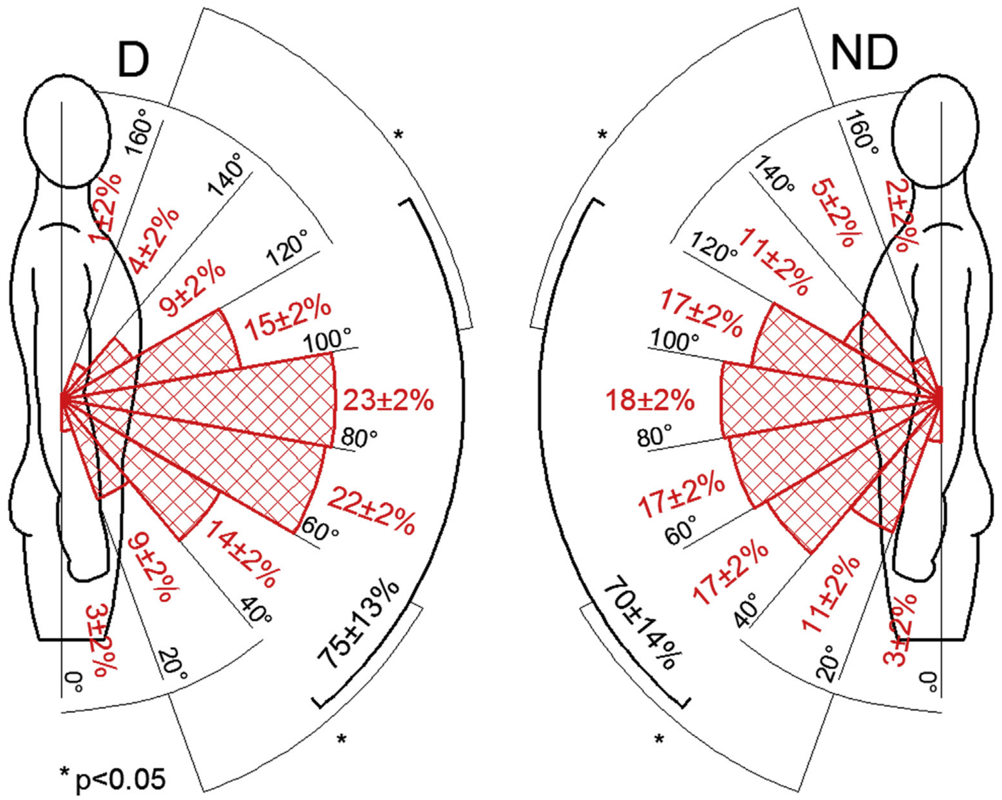

Figure 2 Elbow flexion posture (percentage of total time spent in each flexion angle range). * Statistically significant difference between flexion ranges of 40°-120°, and both lower and higher flexion angles. *D*, dominant; *ND*, nondominant.

Results

Elbow posture

When elbow posture was discretized as a function of the percentage of time spent in each flexion-extension range (Fig. 2), it was found that the elbow was most commonly at an angle of flexion between 60°-100° for both the dominant and nondominant side, occupying 44% ± 4% ($P < .001$) and 35% ± 4% ($P < .001$) of the day. The flexion range of 40°-120° occupied 75% ± 13% ($P < .001$) and 70% ± 14% ($P < .001$) of the day for the dominant and nondominant sides, respectively. No significant differences in elbow flexion-extension posture were detected between the dominant and nondominant side ($P > .99$).

Forearm posture was centered about neutral rotation (Fig. 3), falling within 30° of supination to 30° of pronation for 65% ± 15% ($P < .001$) and 60% ± 13% ($P < .001$) of the day for the dominant and nondominant sides, respectively. If we examine the pronation-supination range beyond the neutral 20° arc, the forearms were more often in greater than 10° of pronation (42% of the day compared with 35% for supination angles greater than 10°), although this was not statistically significant ($P > .3$ for both sides).

Elbow motion

Elbow motion was quantified in terms of 2 characteristics: where in the flexion-extension arc these motions began, and the angular magnitude of the motions. When elbow flexion-extension motions were discretized in terms of where they occurred, there were a large number of motions occurring over a wide range of flexion angles; most commonly between 20°-120° of flexion (Fig. 4). On average for all study participants, the dominant side exhibited more flexion motions vs. the nondominant side with 1517 ± 26 and 1396 ± 25 motions per hour, respectively ($P = .031$).

Comparing the elbow motion of the volunteer and the TSA volunteer groups, the latter had significantly less elbow motion for the 0°-20° and 20°-40° elbow flexion ranges, with the TSA patients having on average 72.6 ± 36 ($P < .001$) and 66.0 ± 36 ($P < .001$) fewer motions per hour than the healthy volunteer group. For all other flexion angle groups, no significant differences were detected ($P > .588$).

When the magnitudes of elbow flexion-extension motion were examined, the majority of motions were less than 40°, representing 77% ± 13% and 76% ± 14% motion of the dominant and nondominant sides, respectively (Fig. 5). Flexion motions with a magnitude of greater than 100°

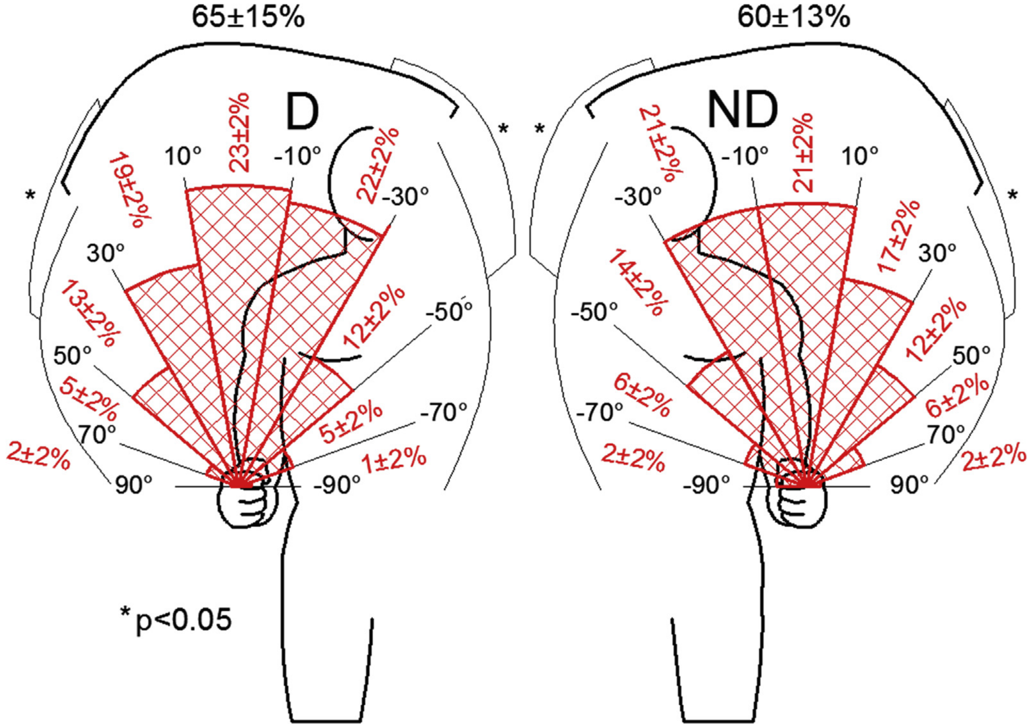

Figure 3 Forearm pronation and supination posture (percentage of total time spent in each pronation-supination angle range). *Statistically significant difference between the range of 30° of pronation and supination posture and increasing angles of prosupination. *D*, dominant; *ND*, nondominant.

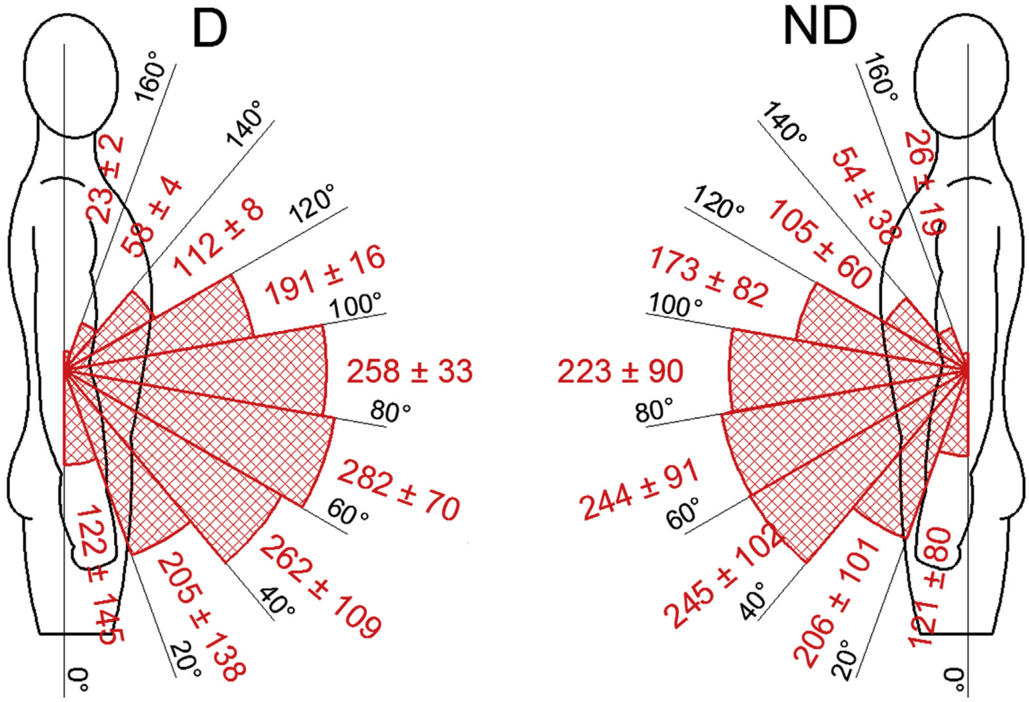

Figure 4 Mean number (±1 standard deviation) of elbow flexion-extension motions per hour defined by starting position. *D*, dominant; *ND*, nondominant.

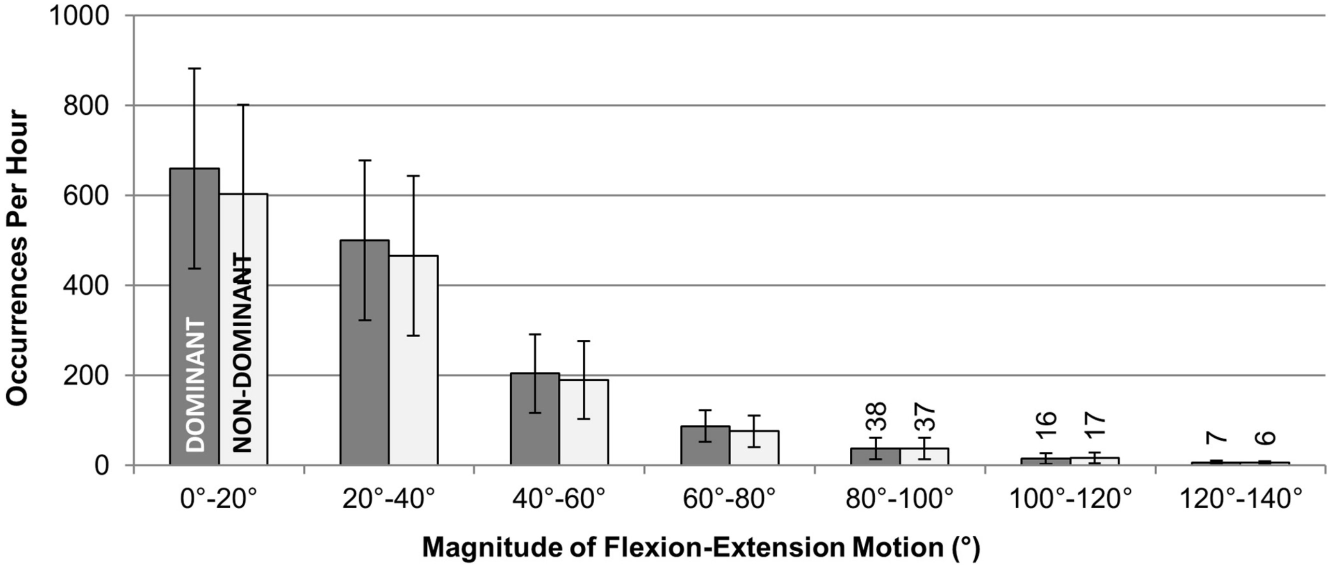

Figure 5 Mean (±1 standard deviation) number of elbow motions per hour by magnitude of motion.

were much less common, at 26 ± 17 and 25 ± 18 occurrences per hour for the dominant and nondominant sides, respectively.

When pronation-supination motions were discretized, the majority were found to occur between 30° of supination and 30° of pronation (Fig. 6), representing 934 ± 96 and 841 ± 120 motions per hour for the dominant and nondominant sides, respectively. On average, the dominant side exhibited more pronation-supination motions per hour than the nondominant side (1732 ± 32 vs. 1615 ± 32 motions per hour); however, this difference was not significant ($P = .099$).

When the magnitudes of pronation-supination motions were discretized, the majority of pronation-supination motions were less than 40° (Fig. 7).

Discussion

The elbow is a highly mobile joint, with 3 articulations that combine to enable elbow flexion and extension and create the proximal linkage to enable forearm pronation and supination. Despite the understanding of elbow ROM required for specific tasks, less is known about elbow posture and motion in our natural environment.

Little documentation of in vivo upper extremity functional ROM and posture has been reported. Van Andel et al[9] completed a lab-based study and suggested some standardized tasks with which to assess upper extremity motion. Coley et al[2] used 3D inertial sensors attached to the humerus to determine the symmetry of humeral motion and suggested an index to quantify asymmetry and shoulder disease. Coley et al[3] also characterized shoulder motion during walking vs. activities while seated or stationary and found that shoulder dominance was evident when periods of walking were eliminated.

With this study, we aimed to describe the posture and motion of healthy elbows, so that pathology and the results of treatment can be assessed within the appropriate context. The most common elbow postures were centered around 90° of flexion, indicating that during most ADL, the elbow is usually positioned within the middle of its ROM. Furthermore, elbow motions were also frequently observed in the same region near the center of elbow flexion ROM. Not surprisingly, the majority of elbow and forearm motions were of small magnitude (<20°), as occur with small changes in posture, with larger flexion and extension motions at a much lower frequency.

Similarly, the most common pronation-supination posture was centered about neutral forearm rotation, with a propensity toward pronation. Interestingly, forearm motions were most commonly observed in slight supination, which suggests that although the forearm is more often in a pronated posture, there are many tasks requiring rotation of the forearm toward supination.

The dominant side exhibited more motion than the nondominant side in terms of both flexion-extension and pronation-supination motions. This suggests that the dominant elbow is used more than the nondominant elbow, likely a result of tasks that are dependent on the dexterity of the dominant hand.

Despite noting no overall effect when comparing the kinematics of the volunteer and TSA volunteer study patients, we did note fewer flexion and extension motions from 0°-40°, compared with the volunteer group. This may be due to age or the presence of a shoulder arthroplasty. We speculate that after shoulder arthroplasty, patients may initiate reaching motions with more elbow flexion and less

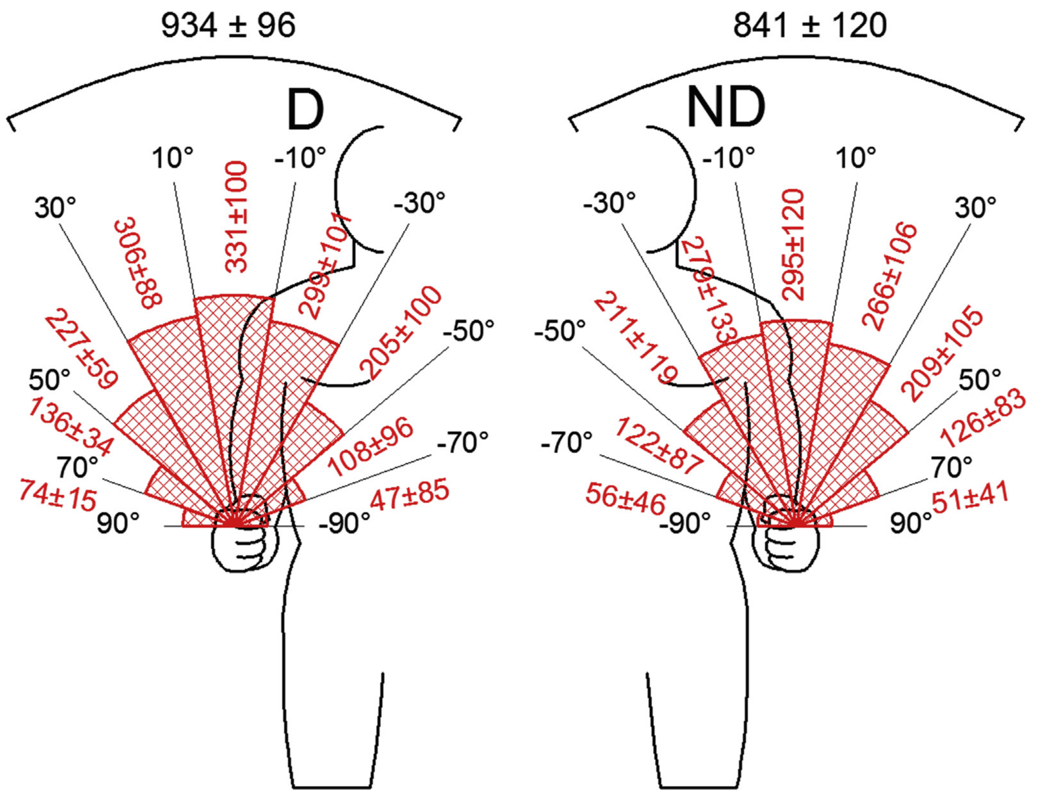

Figure 6 Mean number (±1 standard deviation) of forearm rotation motions per hour by pronation-supination angle of starting position.

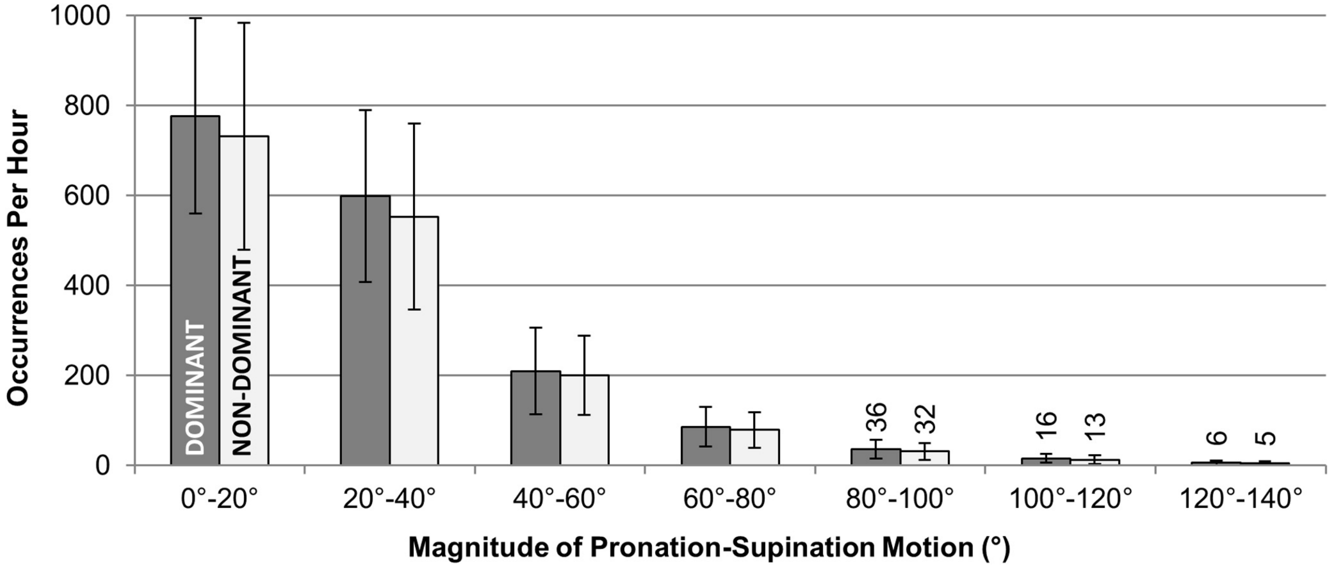

Figure 7 Forearm pronation-supination magnitudes and frequencies of motion.

shoulder elevation. Whereas those with healthy shoulders create a composite reach that includes both shoulder elevation and more elbow extension. Future studies should be considered to better understand reasons for this observation.

We observed that multiple motions occur during both active and passive tasks. An example of an active task is reaching for a glass of water, while passive tasks occur as in holding a glass of water while getting up from a chair. The first is a deliberate task, whereas the second is a series of compensatory motions to accommodate changes in trunk posture and gait. The most striking observation is that simple motions, like reaching for a glass of water, are actually composed of multiple flexion and extension motions as the hand reaches, adjusts posture, and then grasps the target. A reaching motion we had thought might have consisted of 1 extension motion and 1 flexion motion often registers as up to 7 motions with sensitive inertial measurement units.

To understand how many motions occur during the waking hours of 1 day, we extrapolated the hourly motion data to estimate the average number of daily elbow motions. There were 1517 total elbow flexion-extension motions per hour for the dominant arm × 16 waking hours = 24,272 motions per day. The flexion-extension motions for the nondominant arm averaged 22,336 motions per day. Using the same method, the dominant arm pronation-supination motions per day averaged 14,944 and the nondominant motions per day averaged 13,456.

The results of this study support the importance of a mobile elbow joint, as we require a range of postures and frequent motions to position the hand appropriately. The unsatisfactory outcomes associated with elbow fusion are easily understood, considering that ADL require substantial ROM. Koller et al[5] reported that 7 of 14 patients post elbow arthrodesis were disabled; none were able to reach their mouth and that compensatory motion was most lacking in approximating normal supination.

The elbow posture and motion data reported in this study should be used to simulate in vivo elbow activity in wear testing of elbow arthroplasty in biomechanics labs. Component loosening and bushing wear are common clinical failure mechanisms that are likely related to the amount of use and forces across the joint.[8] Arthroplasty wear studies using servo-hydraulic actuators can be calibrated to a natural ROM, magnitude, and frequency to help gauge more natural wear and facilitate improvements in design.[4]

This wearable sensor device, and the accompanying sternal and humeral sensors, will also enable specific ergonomic assessment of repetitive tasks in demanding workplaces. By providing details of frequency and amplitude of motion based on workplace tasks, a reasonable ergonomic design can be assessed and tailored to minimize repetitive strain and workplace injury.

Strengths of the study include the long and consistent duration of testing and capturing a diversity of activities throughout a typical day outside of a laboratory setting. The shirt and sensors were found to be comfortable to our subjects, and we feel this enabled them to pursue the majority of activities without being hindered during the testing procedure. The range (19-86 years) of subject age creates generalizable results that can be compared to a wider population.

Weaknesses include the inherent limitation in activities during which the testing apparatus can be worn. Subjects were unable to wear the shirt during personal bathing activities in the morning prior to donning the shirt, and these activities require a maximal amount of elbow flexion, so we might expect to see a greater number of large-magnitude flexion motions if bathing was recorded.[6] We also did not address the impact of compensatory motion; further study should elucidate the compensatory motions of the shoulder as it relates to elbow and forearm posture. Although these findings provide new kinematic data for the elbow and forearm, postures that are seldom recorded may still be crucial to accomplishing ADL. As an example, elbow flexion angles greater than 120° may be far less common than lower flexion angles, but this posture is necessary to feed oneself, and so we must be cautious to conclude that infrequent postures are less important than the more common elbow and forearm postures.

Conclusion

The results of this study help to understand the natural and essential motion and posture of the elbow and forearm. Activities of daily living require a large number of elbow flexion-extension and forearm pronation-supination motions, the majority of which are less than 40° of magnitude, and occur within the 20°-120° flexion-extension arc. Subjects exhibit significantly more motion on their dominant side for both elbow flexion-extension and pronation-supination. The forearm is predominantly held in neutral posture and pronation; however, supination motions occur frequently.

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Disclaimer

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