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Characterization of Postural Tremor in Essential Tremor Using a Seven-Degree-of-Freedom Model

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Using a Seven-Degree-of-Freedom Model

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ABSTRACT

Characterization of Postural Tremor in Essential Tremor Using a Seven-Degree-of-Freedom Model

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Essential Tremor (ET), a condition characterized by postural and kinetic tremor in the upper limbs, is one of the most prevalent movement disorders. While pharmaceutical and surgical treatment options exist, they are not ideal. Assistive devices have the potential to provide relief to patients but are largely unexplored for ET. Furthermore, prior characterizations of essential tremor have focused on endpoint tremor and provide insufficient detail for designing such a device. We propose and demonstrate a novel method for characterizing essential tremor in the 7 proximal degrees of freedom (DOF) of the upper limb in various postures. In addition, we provide a preliminary characterization in a small number of patients with mild ET.

We collected data from 10 patients with ET. Subjects were instrumented with four electromagnetic sensors that recorded orientation of upper limb segments. After a calibration, each subject positioned his/her upper limb in 16 different postures for 15 seconds each. This procedure was repeated 4 times for each subject, with each repetition being considered a run. Sensor data were converted to angular kinematic data for each DOF using inverse kinematics, a practice unique to this study. These data were then analyzed in the frequency domain to calculate the power associated with the tremor in each DOF and posture. More specifically, we computed the area of the periodogram over the 4-12 Hz frequency band typically associated with ET [narrow-band area (NBA)] and over the wider frequency band from 2 Hz to the Nyquist frequency [wide-band area (WBA)]. If significant peaks were found in the 4-12 Hz band, their frequency and amplitude were reported. Mixed-model ANOVA tests were used to investigate effects of DOF, posture, run, gravity, and patient characteristics on reported measures.

NBA and WBA varied significantly between DOF, being lowest in the wrist, intermediate in the shoulder, and greatest in the elbow and forearm (pronation-supination). NBA and WBA also varied significantly with posture. Only 5% of observations had significant peaks, with 49% of peaks occurring in wrist flexion-extension and 39% occurring in wrist radial-ulnar deviation. Peak frequency was quite stereotyped (5.7 Hz ± 1.3Hz). Run had no significant effects, indicating that tremor measures were consistent over the duration of the experiment. Effects of gravity and demographic factors on measures were mixed and did not present a discernible pattern. This preliminary characterization suggests that tremor may be focused in a subset of upper limb DOF, being greatest (in terms of power) in elbow flexion-extension and forearm pronation-supination, and most concentrated (with peaks at a stereotyped frequency) in wrist flexion-extension and radial-ulnar deviation. Our method of 7 DOF characterization through inverse kinematics, in conjunction with future research (isolation studies, EMG, and finger DOF) may allow for optimal tremor suppression by an orthosis.

Keywords: essential tremor, upper limb, motor control, inverse kinematics

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ACRONYMS

ANOVA ......Analysis of Variance
CM ....Center of Mass
DBS............Deep Brain Stimulation
DOF............Degree(s) of Freedom
EFE ....Elbow Flexion/Extension
EMG...........Electromyography
ET...............Essential Tremor
FFT.............Fast Fourier Transform
FPS.............Forearm Pronation/Supination
FTM ....Fahn-Tolosa-Marin (Tremor Rating Scale)
HMV ....Half-Max Value
ISB ....International Society of Biomechanics
NBA ....Narrow-Band Area
RMS ....Root Mean Square
SAA............Shoulder Abduction/Adduction
SFE.............Shoulder Flexion/Extension
SHUR..........Shoulder Humeral Rotation
STA ....Soft Tissue Artifact
WBA ....Wide Band Area
WFE ....Wrist Flexion/Extension
WRUD ....Wrist Radial/Ulnar Deviation

1 INTRODUCTION

1.1 Motivation

Essential Tremor (ET) is one of the most common movement disorders [1], with an estimated worldwide prevalence of 0.7-2.2% in the general population and up to 4.6% of the global population aged 65 and older [2]. ET is estimated to affect between 1 and 12 million people in the U.S. alone [3]. It is described as a visible and persistent bilateral postural and kinetic tremor (i.e., it is present during maintenance of posture and while attempting intentional movements) involving the hands and forearms and is largely symmetric [4]. ET is progressive, with amplitude worsening over time and adversely affects or limits patients' ability to perform many common activities of daily living (eating, writing, grooming, etc.) [5]. ET is often hereditary and believed to involve cerebello-thalamic pathways, but its cause is unknown [6]. While many have benefitted from various treatments, options are limited. Medications (see Chapter 2) are only effective in 50% of patients and lose their effectiveness over time [7]. Surgical procedures, such as deep brain stimulation, are both costly and invasive. Few assistive devices have been investigated and produced. Those devices that do exist are either limited to specific tasks (writing, eating, etc.) [8] or are impractical due to size and weight [9]. There is potential for an improved assistive device but its design would rely heavily on a more detailed and thorough characterization of ET than currently exists.

Many studies have investigated the nature of ET. ET is most commonly characterized and described through clinical rating scales which are also used in diagnosis [10, 11]. While useful, these scales are subjective, have low resolution, and only provide a qualitative assessment of tremor. Other studies report the amplitude, frequency or power of sensor data such as accelerometers [12, 13], EMG [14, 15], lasers [16], and gyroscopes [17]. Quantitative studies report ET to have an amplitude of 192±305 cm/s^2 [18] and 120 cm/s^2 with and a frequency between 4-12 Hz [19]. However these studies generally use a single sensor, usually attached to the hand or a finger. While such a configuration can measure the linear acceleration of the endpoint of the upper limb, the upper limb is a complicated linkage with many degrees of freedom (DOF). The distribution of ET throughout the DOF of the upper limb is unknown and cannot be measured from a single endpoint sensor. Additionally, previous studies usually only measure tremor in a single posture. It is unknown how changing the orientation of the upper limb might affect ET. No characterization of ET that considers these two factors (DOF and limb orientation) exists. A more comprehensive method is necessary to provide such a characterization and may lead to both improved diagnosis and improved assistive devices. The purpose of this study was to create and demonstrate such a method and to provide a preliminary characterization of ET in a small number of patients.

1.2 Thesis Objective

We characterized tremor in 10 patients with mild ET in the 7 proximal DOF of the upper limb (3 at the shoulder, 1 at the elbow, 1 in the forearm, and 2 in the wrist). Using orientation sensors and inverse kinematics, we estimated the tremor in each DOF and calculated measures relating to the amount and frequency of the tremor. We showed that this new method which includes the application of inverse kinematics to tremor to provide 7 DOF of measurement, the use of soft tissue artifact compensation, and the calculation of gravitational contributions to tremor, is capable of recording tremor throughout all 7 DOF in any posture. Furthermore, this method has comparable quality to accelerometer data but avoids common accelerometer issues and limitations such as drift and confounding effects of gravity. Using this method, we investigated how tremor varied between DOF, postures, levels of gravitational torque, and various patient characteristics (age, age of onset, gender, and medication status) to provide a preliminary characterization of ET throughout the upper limb.

2 BACKGROUND

2.1 Prevalence

The estimated prevalence of ET varies widely. The International Essential Tremor Foundation states that 10 million US citizens (~3%) have ET. Worldwide estimates vary from 0.08 to 220 per 1000 (0.008-22%). This large variability in estimates is attributed to various causes; nevertheless, it is widely agreed that ET is one of the most prevalent movement disorders [20].

2.2 Symptoms

ET is an involuntary, oscillatory movement characterized by a frequency of 4-12 Hz. In 90% of patients, ET occurs in the upper limbs [21]. It manifests most often in a static posture opposing gravity (postural tremor) and/or during movement (kinetic tremor). The tremor is most commonly found with an endpoint oscillation magnitude (at the finger tips) of less than 1cm. For a given individual, the magnitude and the frequency of the tremor vary over small time scales (throughout the day) as well as large time scales (years) [22]. Over a period of years, the frequency of the tremor will decrease while its magnitude will increase [5, 23].

2.3 Diagnosis

The diagnosis of tremor can be difficult and is often imprecise. Tremor is usually classified by location in the body, severity, and the times and tasks during which it is most prevalent. These criteria are neither universal nor exact [21, 22]. Most rating scales are qualitative, allowing for individual bias, and have a low resolution. Quantitative measures are being investigated with promising results [21]. Essential Tremor is difficult to diagnose because it is a diagnosis based almost entirely on exclusion of other tremor disorders, such as Parkinson's disease [24]. It has been suggested that ET may actually consist of a number of distinctive subtypes, but there is no conclusive evidence to date [7, 21].

2.4 Treatment

Currently, patients' treatment options are limited to pharmaceutical treatments and surgery. Two common pharmaceutical treatments involve Propranolol, a non-selective beta-blocker, and Primidone, an anti-convulsant. Propranolol has been shown to reduce tremor amplitude by up to 50%. However, either drug taken separately or combined is effective in only 50% of patients and the effectiveness decreases with time [7].

The most common surgical treatment for ET is deep brain stimulation (DBS). DBS involves implanting electrodes into the thalamus. These electrodes are connected to a programmed power source implanted in the chest cavity and provide electrical stimulation which, in many cases, tend to reduce the symptoms of ET [21]. However, DBS is usually not preferred as a treatment due to its invasive nature and possible side effects.

2.5 Devices

Efforts have been made to create various mechanical devices to assist patients with ET. A number of fixed-frame, energy-dissipation devices have been built. However, being grounded to a frame of reference external to the user (ground, table, or wheelchair) severely limits their practicality[25, 26]. Several wearable devices have been developed to impede tremor using various methods, including active approaches (motors) and passive approaches (fluid viscosity). However, to date, these devices have been impractical due to their weight, size, and constriction of motion in other degrees of freedom [25].

2.6 Implications of this Study

ET adversely effects the quality of life for millions of people. While various medical and surgical treatments can aid patients, their effectiveness is often limited or comes at great cost. Some orthoses have been investigated, but this area remains largely unexplored. By establishing a method that can provide a more detailed characterization of ET, we hope to lay the groundwork for the development of an orthosis designed to optimally suppress tremor for ET patients. This characterization may also prove useful in creating improved differential diagnosis.

3 METHODS

3.1 Subjects

Ten subjects participated in this study. All subjects were 18 years old or older and reported that they had been diagnosed with ET by a neurologist. Subjects all exhibited tremor in the upper limbs that was not limited to writing tremor. Subjects with an age of onset before 20 or after 65 were excluded as early- and late-onset cases [27, 28]. Subjects reported that they were free of any other conditions affecting upper limb movement or motor control. Following procedures approved by Brigham Young University's Institutional Review Board, informed consent was obtained from all subjects. Several sources were used in the recruitment of subjects. Advertising on campus, through local clinicians, and by word of mouth all proved ineffective. Our best resource for subject recruitment proved to be the International Essential Tremor Foundation. Advertising through their website and newsletter resulted in many interested responses, although the majority lived too far away to participate in this study. A summary of subject data is presented in Table 3-1. Subject 5 exhibited much higher tremor than any other patient. This data set was omitted as an outlier in both the analysis and Table 3-1. While ten subjects did not provide enough significant power for a thorough characterization, it was enough for a preliminary analysis.

Table 3-1. Patient Data (subject 5 omitted)

Subject	Age	Height (in)	Weight (lbs)	BMI	Age of Onset	Gender	FTM Score	Medication
1	82	65.5	170	27.9	55	M	25.0%	Y
2	58	68	150	22.8	25	M	11.1%	Y
3	31	76	245	29.8	25	M	13.2%	N
4	75	69	188	27.8	62	M	19.4%	Y
6	74	62	118	21.6	60	F	11.1%	N
7	78	64	151	25.9	55	F	31.3%	Y
8	50	64	142	24.4	22	F	17.7%	N
9	53	63	160	28.3	20	F	24.0%	Y
10	62	66	272	43.9	59	F	28.8%	Y
Mean	62.6	66.4	177.3	28.0	42.6	-	20.2%	-
St. Dev.	16.5	4.3	50.3	6.5	18.7	-	7.5%	-

3.2 Experimental Setup

Each subject was first evaluated using the Fahn-Tolosa-Marin (FTM) tremor rating scale (see Appendix A) [29]. Subjects were then seated in a stool (~19” in height) with no back and fitted with four sensors from an electromagnetic motion capture system [*trakSTAR by Ascension Technologies, Burlington, VT*]. The system recorded orientation through three Euler angles from each sensor simultaneously using a varying sample rate (either 333Hz or 500Hz) with a static accuracy of 0.5° RMS over the entire tracking volume (sphere of 4 ft. radius) and a resolution of 0.007°. Each sensor’s mass was approximately 5 grams and was assumed to interfere minimally with natural movement (on average for our subjects, this weight represents 1.1% of hand mass, 0.39% of forearm mass, 0.23% upper arm mass). The arm that exhibited more severe tremor was tested. If tremor was reported to be the same in both arms, the subject’s dominant arm was tested. Sensors were placed on the dorsum of the hand over the third and fourth metacarpals, the posterior aspect of the forearm just proximal to the wrist, the posterior aspect of the upper arm just proximal to the elbow over the triceps tendon, and over the acromion, straddling the acromial angle for stability. Each sensor was placed in a small plastic holder with a wide base to minimize roll over the skin and was then taped in place. The three distal sensors were wrapped with Coban tape for extra stability.

The arm's neutral position was the anatomical position. Eight dots were placed on the subject's arm to mark anatomical landmarks. These dots were then used in conjunction with three orthogonal laser levels to orient the arm in a calibration position. This calibration was reached from the neutral position by flexing the elbow 90° and pronating the forearm 90° (Figure 3-1). In this position, the long axis of the upper arm was vertical. Some overweight patients could not position their arms in this orientation and were instructed to hold the upper arm as close to vertical as possible.

The DOF of the upper limb were defined using ISB standards [30], except for the shoulder joint. ISB defines the shoulder DOF using a Y-X'-Y'' rotation sequence. Not only does this rotation order have little anatomical meaning, but it also places the gimbal lock position at a location used frequently in the experiment. To avoid these issues, we used a Z-X'-Y'' rotation sequence that uses the same coordinate frame defined by the ISB. Thus the 7 DOF measured in this study listed in order from proximal to distal are shoulder flexion/extension (SFE), shoulder abduction/adduction (SAA), shoulder humeral rotation (SHUR), elbow flexion/extension (EFE), forearm pronation/supination (FPS), wrist flexion/extension (WFE), and wrist radial/ulnar deviation(WRUD).

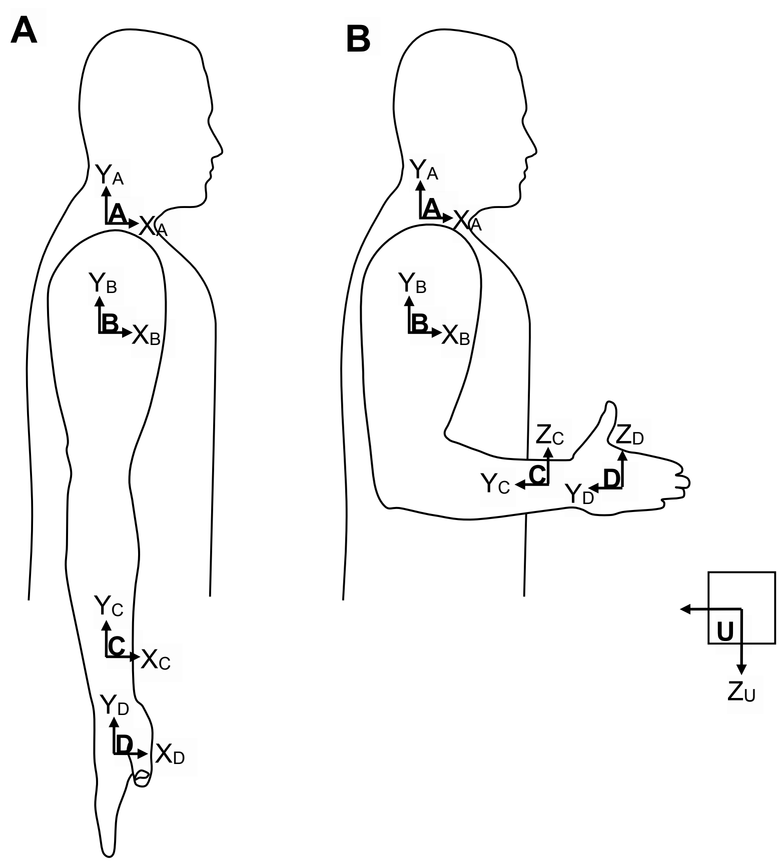

Figure 3-1. Limb Orientations. A: Neutral position with body fixed axes. B: Calibration position with body fixed axes.

3.3 Experimental Procedure

Each subject placed their upper limb in sixteen different postures of various combinations of the seven arm DOF. Each posture was held for 15 seconds before assuming the next posture. Once tremor had been measured in all 16 postures (Figure 3-2), we repeated the process for a total of four runs. Each run was a set of one trial from each of the 16 postures performed consecutively. The sequence of postures was not varied between runs. Postures were assumed in numerical order. Special instructions were given for several postures as follows.

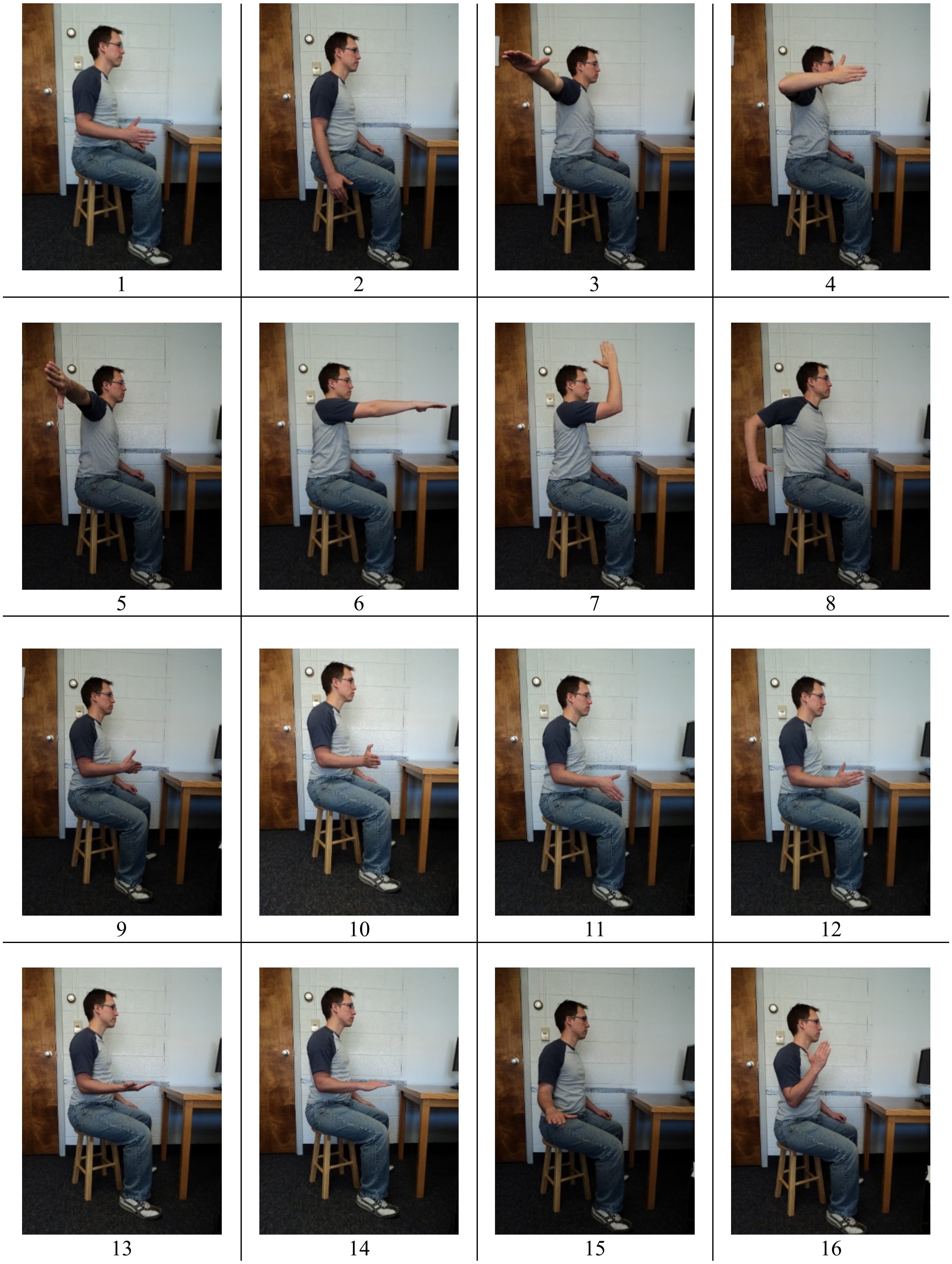

Figure 3-2. Postures Used in Study.

For postures 8, 15 and 16 subjects were instructed to move in a specific DOF to the limit of comfortable range of motion (shoulder extension, external humeral rotation, and elbow flexion respectively). For postures 9-14 subjects were instructed to move in a specific DOF to the limit of comfortable range of motion starting in the calibration position and then chose a position that felt halfway between the limit and the starting position (wrist flexion, wrist extension, ulnar deviation, radial deviation, forearm pronation, and forearm supination respectively).

3.4 Data Processing

Because the sensor system used in this study samples with a varying sample rate, we first interpolated all sensor data to create a constant time step (500Hz). The joint angles for each DOF of the arm were derived from the interpolated sensor data (azimuth, elevation, and roll Euler angles) using rotation matrices and inverse kinematics for the upper limb. We derived the inverse kinematics and a description can be found in APPENDIX B. Soft tissue artifact was overcome using a compensation method developed by Dr. Steven Charles that uses the orientation of the forearm to determine SHUR and the orientation of the hand to determine FPS. This method also set both the elbow carry angle and wrist pronation/supination angle to zero (See APPENDIX C). The method is similar to Schmidt et al, but is adapted for our electromagnetic motion capture system [31].

Welch's power spectrum was calculated from the time series data for all joint angles for all patients, postures, and runs. The area of each spectrum was calculated over the 4-12Hz band commonly associated with Essential Tremor (this area was called narrow-band area) (Figure

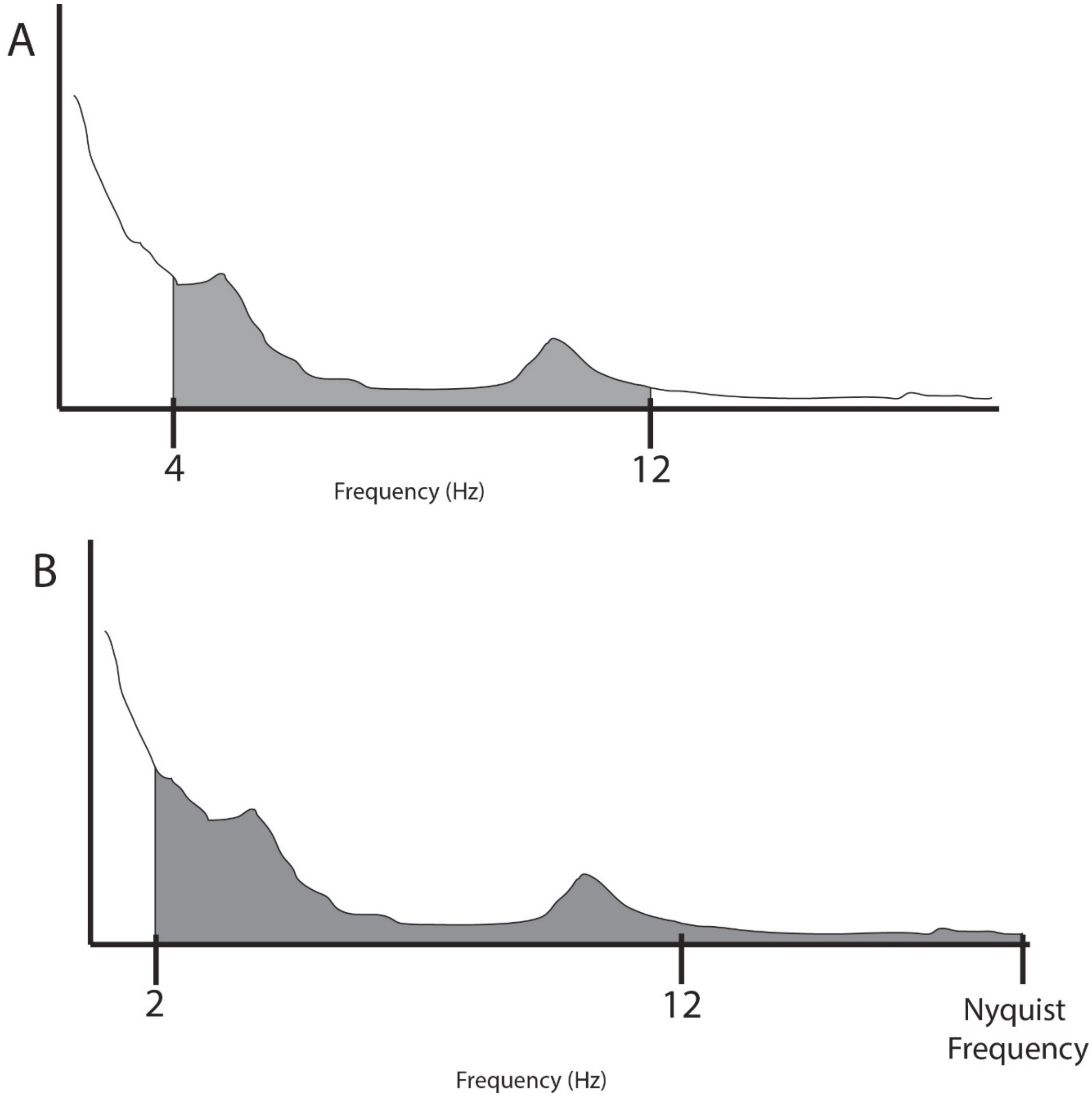

Figure 3-3. Area Calculations. A: Narrow-band area (NBA). B: Wide-band area (WBA).

3-3.A) and for the wide frequency band from 2Hz to the Nyquist frequency (wide-band area) (Figure 3-3.B).

After the timer-series data (Figure 3-4.A) was converted to the frequency domain and the power spectrum was detrended with a fitted decaying exponential (Figure 3-4.B), we used a sliding window constant false alarm rate peak detection algorithm using a 1Hz window and

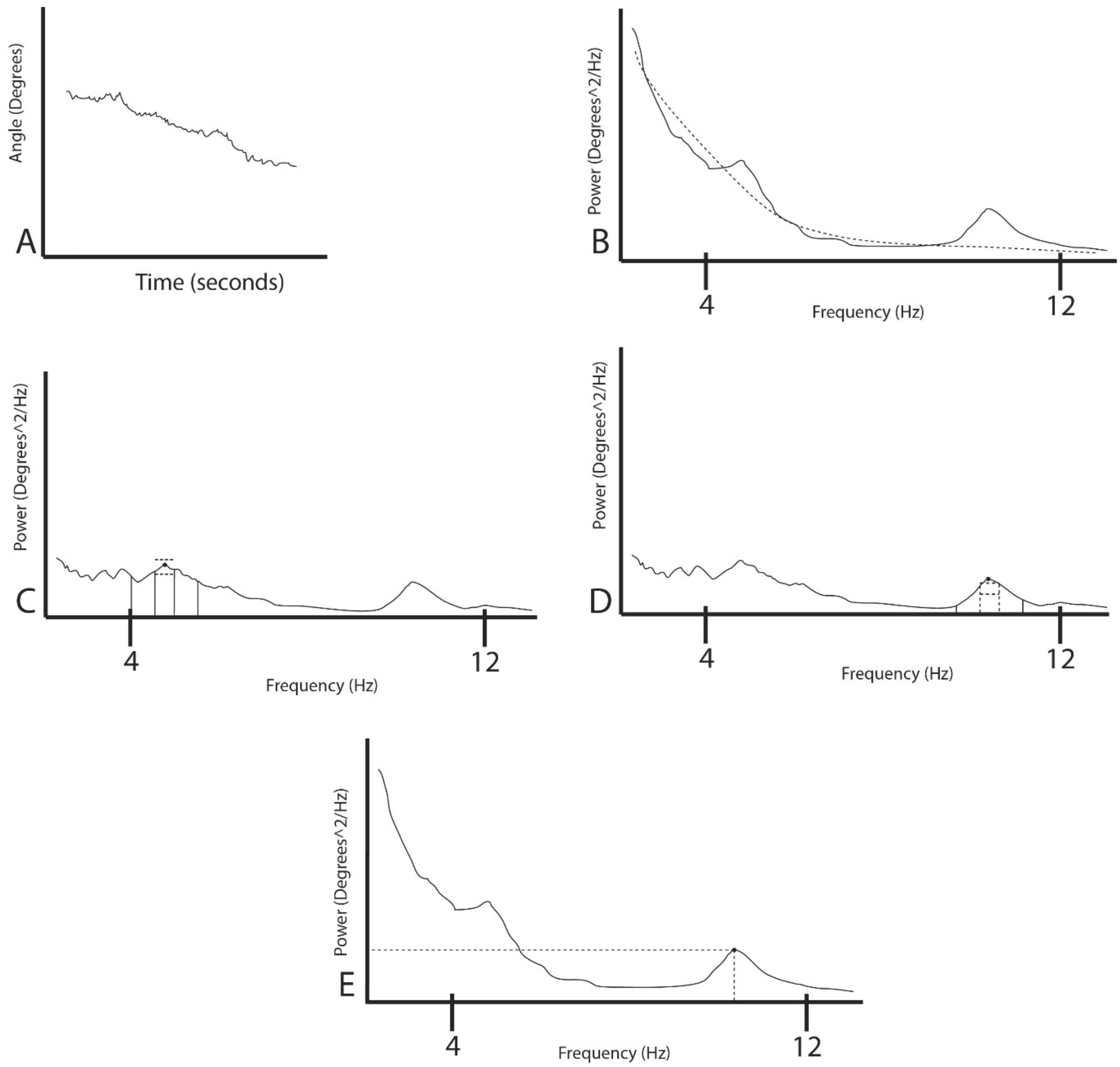

Figure 3-4. Peak Detection. A: Time-series data. B: Power Spectrum with decaying exponential curve fit. C: Detrended data with peak that is not significant. D: Detrended data with peak that is significant. E: Reporting significant peak frequency and power.

1.5Hz sidebands to determine the existence of any significant peaks over the 4-12 Hz frequency band [32]. The mean of the data in the sidebands was calculated. If the peak was less than 3 standard deviations above the mean, it was not considered significant (Figure 3-4.C) and the algorithm moved onto the next peak. If the peak was greater than 3 standard deviations above the mean it was considered significant (Figure 3-4.D). If any significant peaks existed, the

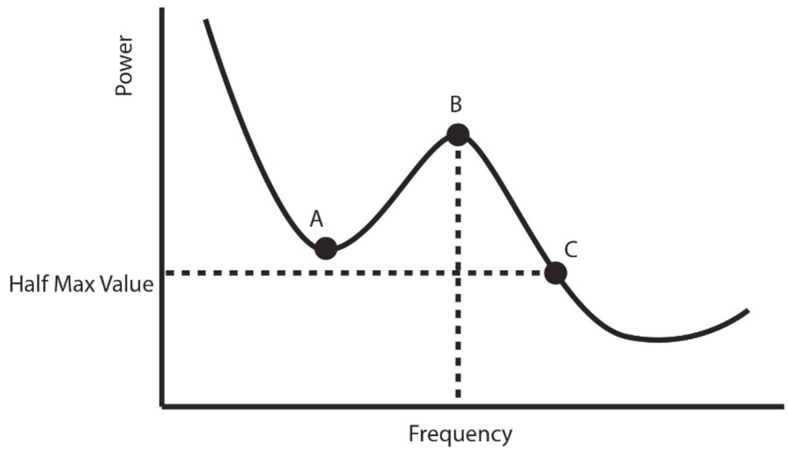

Figure 3-5. Peak Categorized as MIN-HMV. A: Local min. B: Peak. C: Half-max intersect.

amplitude and frequency of the largest peak from the original periodogram was reported (Figure 3-4.E). Peaks were categorized based on whether a local min or the half-max value (HMV) occurred closer to the peak along the frequency axis both to the left and the right (see Figure 3-5).

3.4.1 Calculation of Gravity Moment

Using subjects' self-reported weight and height along with anthropometry tables [33], the moment exerted by gravity about each DOF axis was calculated. This was done by first finding the position vector from each joint center (shoulder, elbow, and wrist) to each distal upper arm link's center of mass (CM) for each posture in the universal coordinate frame. The equations for the shoulder joint are given below.

$$^{U}\vec{r}_{1,1} = {}^{U}_{S}R \cdot {}^{S}\vec{L}_{CM1} \tag{3-1}$$

$$^{U}\vec{r}_{1,2} = {}^{U}_{S}R \cdot {}^{S}\vec{L}_{1} + {}^{U}_{F}R \cdot {}^{F}\vec{L}_{CM2} \tag{3-2}$$

$$^{U}\vec{r}_{1,3} = {}^{U}_{S}R \cdot {}^{S}\vec{L}_{1} + {}^{U}_{E}R \cdot {}^{E}\vec{L}_{2} + {}^{U}_{W}R \cdot {}^{W}\vec{L}_{CM3} \tag{3-3}$$

Where,

${}^{U}\vec{r}_{1,1} = \ position\ vector\ from\ shoulder\ joint(1)\ to\ shoulder\ CM\ (1)\ in\ universal\ frame$

${}^{U}\vec{r}_{1,2} = position\ vector\ from\ shoulder\ joint(1)\ to\ forearm\ CM\ (2)\ in\ universal\ frame$

${}^{U}\vec{r}_{1,3} = position\ vector\ from\ shoulder\ joint(1)\ to\ hand\ CM(3)\ in\ universal\ frame$

${}^{U}_{S}R = rotation\ matrix\ from\ shoulder\ frame\ to\ universal\ frame$

${}^{U}_{E}R = rotation\ matrix\ from\ elbow\ frame\ to\ universal\ frame$

${}^{U}_{W}R = rotation\ matrix\ from\ wrist\ frame\ to\ universal\ frame$

${}^{S}\vec{L}_{CM1} = position\ vector\ from\ shoulder\ joint\ to\ shoulder\ CM\ in\ shoulder\ frame$

${}^{E}\vec{L}_{CM2} = position\ vector\ from\ elbow\ joint\ to\ forearm\ CM\ in\ elbow\ frame$

${}^{W}\vec{L}_{CM3} = position\ vector\ from\ wrist\ joint\ to\ hand\ CM\ in\ wrist\ frame$

The torque vector produced at each joint center (shoulder, elbow, and wrist) from the gravitational force acting on all distal masses was then calculated. This was done by summing the cross products of each previously calculated position vector from the given joint center to the distal segment CM ($\vec{r}_n$) with the force vector($\vec{F}_n$) acting on the respective arm segment.

$${}^{U}\vec{\tau}_i = \sum_{n=i}^{3}(\vec{r}_{i,n} \times \vec{F}_n) \quad for\ i = 1:3 \tag{3-4}$$

Where,

$\vec{F}_n = gravitation\ force\ acting\ on\ the\ nth\ link's\ CM\ in\ universal\ frame$

$i = index\ referring\ to\ joint\ number\ (1 = shoulder, 2 = elbow, 3 = wrist)$

${}^{U}\vec{\tau}_i = \ torque\ at\ the\ ith\ joint$

$\vec{r}_{i,n} = position\ vector\ from\ the\ ith\ joint\ center\ to\ the\ nth\ link's\ CM$

Finally, the moment due to gravity about each DOF axis was calculated by first transforming a unit vector along the DOF axis from the DOF frame into a universal frame and then taking the dot product of the that vector with the torque vector ($\vec{\tau}_i$) at the respective joint center.

$$M_x = ({}_X^U R \cdot {}^X\vec{u}) \cdot \vec{\tau}_i \;\; for\; x = 1{:}9, \quad (3\text{-}5)$$

Where,

${}_X^U R = rotation\ matrix\ from\ Xth\ DOF\ frame\ to\ universal\ frame$

${}^X\vec{u} = unit\ vector\ along\ the\ Xth\ DOF\ \ axis$

The moments about the elbow carry axis and the wrist pronation/supination axis were calculated but the output was ignored.

3.5 Data Analysis

To determine the effect of DOF, posture, and run on each measure (narrow-band and wide-band areas and peak existence, frequency, amplitude, and width) we performed separately for each measure a mixed-model ANOVA with factors DOF, posture, run, and patient (patient was a random factor). Likewise, the effect of gravity and demographic factors on each measure was determined by an ANOVA with factors gravitational torque, age, age of onset, gender, medication, and FTM score. The effect of gravitational torque was analyzed for each DOF separately.

4 RESULTS

Mean and standard deviations for DOF angles in all 16 postures are given in Table 4-1. All angles were close to expected values, with several exceptions (see Discussion). Due to the nature of the data the means and standard deviations were calculated using circular statistics [34]. Standard deviations calculated using this method are less intuitive with a range of 0 to √2 but avoid miscalculations due to quadrant changes. Typical results for collected data are illustrated in Figure 4-1.

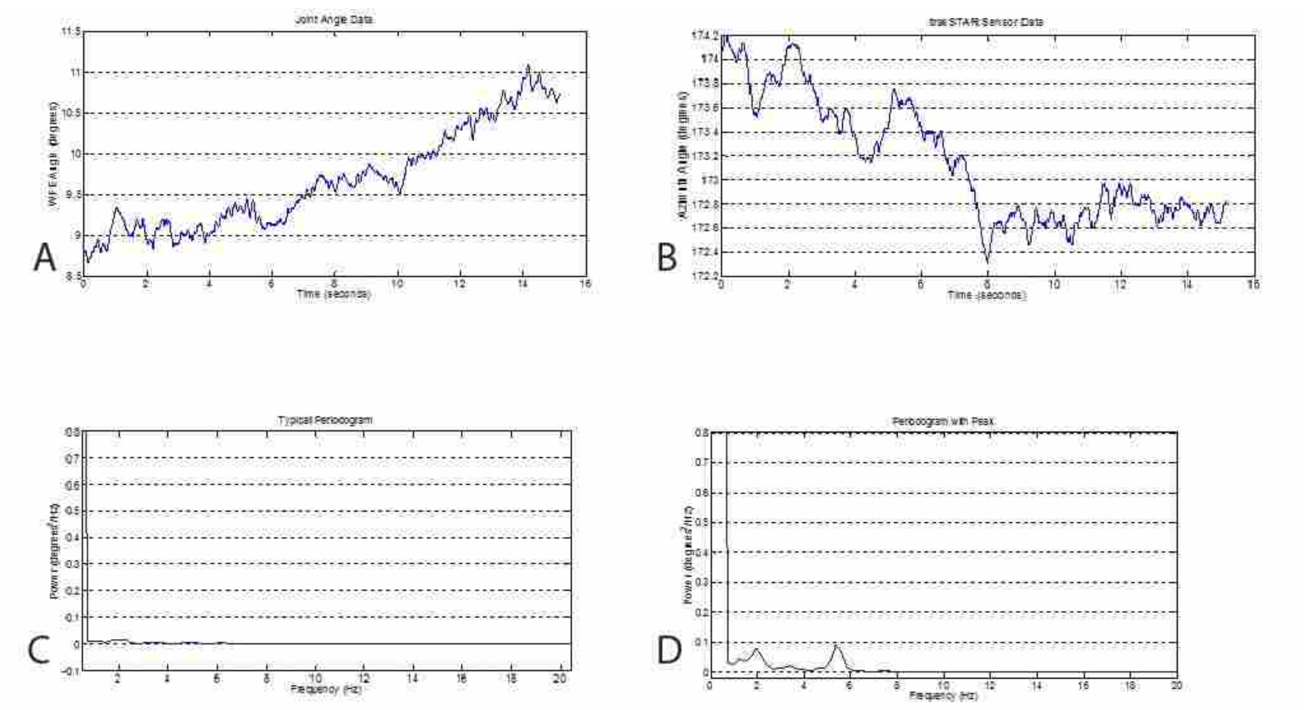

Figure 4-1. Typical Plots. A: trakSTAR data. B: Joint angles. C: Periodogram with no peak. D: Periodogram with peak.

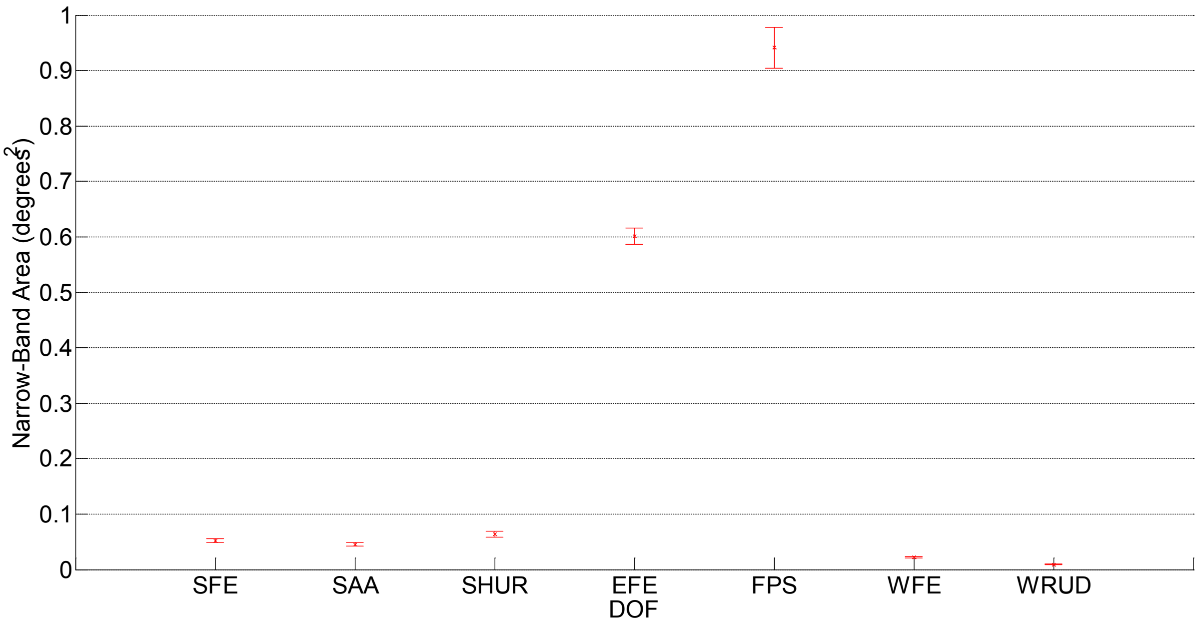

Figure 4-2. Narrow Band Area by DOF.

Narrow-band area (NBA) varied significantly ($p < 0.001$) by DOF (Figure 4-1). The NBA was lowest for WFE and WRUD, intermediate for SFE, SAA and SHUR, and greatest for EFE and FPS, with FPS being the highest. We found statistically significant differences between postures for NBA ($p < 0.0001$), although there were no observable trends or meaningful patterns (Figure 4-2). Gravitational torque had a statistically significant correlation with NBA when analyzed by joint (see Table 4-2). Effects were mixed and there were no clearly discernable patterns. We did not find any significant differences between runs for NBA nor any significant correlation with demographic factors (age, age of onset, gender, medication, and FTM score). These trends described for NBA were identical to those observed for WBA.

Table 4-1. Joint Angle Means (degrees) and Standard Deviations.

	SFE		SAA		SHUR		EFE		FPS		WFE		WRUD	
Posture	mean	st. dev.	mean	st. dev.	mean	st. dev.	mean	st. dev.	mean	st. dev.	mean	st. dev.	mean	st. dev.
1	-3.9	0.1	-2.7	0.1	-2.4	0.2	95.2	0.1	85.4	0.1	2.9	0.2	-3.0	0.1
2	-13.5	0.1	-3.8	0.1	-15.6	0.3	39.7	0.1	110.1	0.4	4.8	0.2	-0.5	0.1
3	3.8	0.3	-49.9	0.1	-71.3	0.4	32.8	0.2	163.6	0.5	6.3	0.2	0.7	0.1
4	-4.0	0.4	-50.5	0.2	2.4	0.4	94.3	0.1	27.3	0.2	8.9	0.2	-1.5	0.1
5	-13.7	0.4	-50.0	0.2	-38.6	0.6	37.5	0.2	-173.0	0.4	11.0	0.2	2.6	0.1
6	48.8	0.2	-20.1	0.2	-8.1	0.3	32.0	0.2	165.4	0.4	7.2	0.1	-1.2	0.1
7	55.2	0.2	-11.1	0.2	-8.9	0.2	99.0	0.1	81.6	0.3	1.8	0.2	-4.3	0.1
8	-46.5	0.2	-6.4	0.2	2.8	0.2	96.4	0.1	83.2	0.2	8.0	0.2	-1.0	0.2
9	-4.9	0.1	-2.3	0.1	0.0	0.2	97.0	0.1	80.9	0.2	30.7	0.2	5.3	0.1
10	-4.8	0.1	-1.2	0.1	-3.3	0.2	96.2	0.1	84.8	0.2	-26.6	0.2	-7.3	0.1
11	-6.7	0.1	-0.8	0.1	1.6	0.2	95.2	0.1	83.3	0.2	0.5	0.2	17.0	0.2
12	-4.7	0.1	-3.7	0.1	-1.2	0.2	100.0	0.1	86.7	0.2	-5.3	0.2	-13.8	0.1
13	-3.6	0.1	2.3	0.1	1.0	0.2	92.9	0.1	12.6	0.2	4.7	0.2	-3.6	0.1
14	-3.9	0.1	-6.7	0.1	-6.2	0.2	99.1	0.1	159.1	0.2	6.6	0.1	-0.3	0.1
15	-2.7	0.1	-3.8	0.1	-48.3	0.3	94.0	0.1	155.1	0.2	4.8	0.2	1.9	0.1
16	5.7	0.2	-5.9	0.1	-2.6	0.2	132.5	0.2	78.2	0.2	0.6	0.2	-10.2	0.1

Only 5% of observations had significant peaks (defined in the methods chapter) in the frequency domain. Therefore, while we fully analyzed differences in peak existence (whether a given observation exhibited a peak or not) between factors, differences in peak frequency and peak amplitude were only analyzed if there were sufficient samples for each factor. WFE and WRUD had the most peaks (49% and 39% respectively), while the other DOF had very few peaks (SFE, SAA, SHUR, FPS) or even no peaks (EFE). Posture significantly affected peak

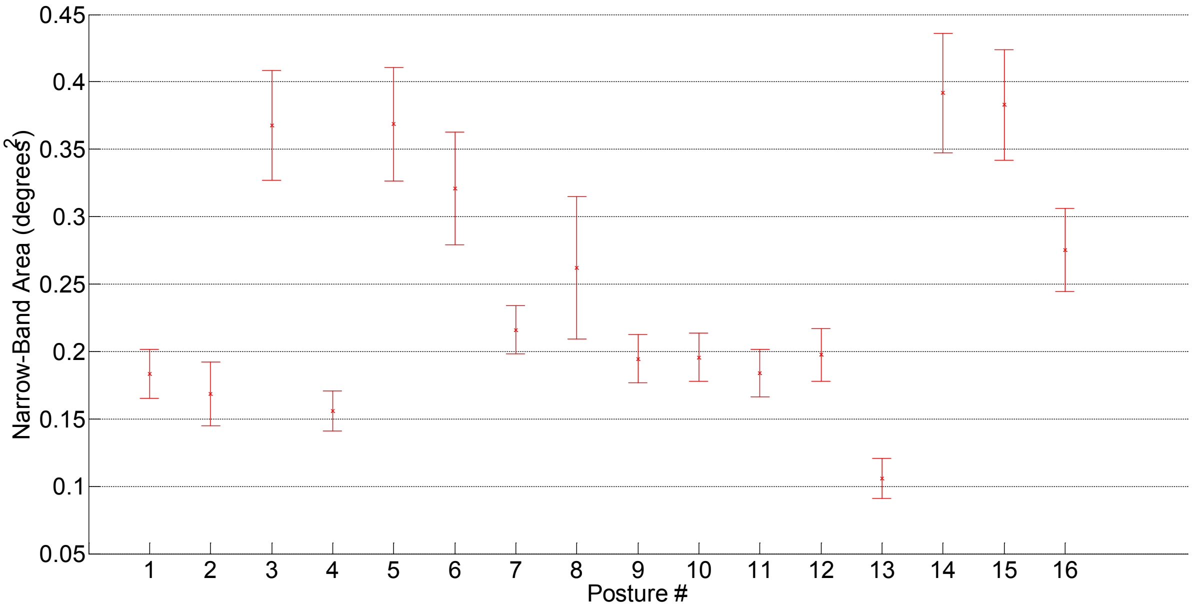

Figure 4-3. Narrow-Band Area by Posture.

existence, but there was no observable trend or pattern (p ranged from <0.001 to 0.469 for significant pairwise comparison). Gravitational torque had no significant effect on peak existence. Age of onset was found to be positively correlated with number of peaks ($p = 0.0032$) and men were found to have a significantly higher number of peaks than women ($p = 0.0262$). The remaining demographic factors had no effect on peaks. A summary of relevant p-values can be found in Table 4-2.

Peak frequencies were quite stereotyped (5.7Hz ± 1.3Hz) (see Figure 4-3). There were statistically significant changes in peak frequency by DOF ($p < 0.0001$), but the effect size was negligibly small (Figure 4-4). On average, the peaks of WFE were greater in amplitude than the peaks of WRUD (0.0528 ± 0.0948 degrees^2/Hz and 0.0114 ± 0.0198 degrees^2/Hz, respectively). Other effects on peak frequency and amplitude (e.g., those due to demographic factors) were ignored because of the insufficient number of peaks.

Table 4-5. Summary of Statistical Analysis with p-values. (Some cells are blank due to an insufficient number of data points for analysis).

	NBA	WBA	Existence	Peak Freq.	Peak Amp.
DOF	**<.0001**	**<0.0001**	-	**<.0001**	**<.0001**
Posture	**<.0001**	**<0.0001**	-	**<.0001**	**0.0034**
Run	0.6055	0.9457	-	0.7862	0.3273
Gravity-DOF 1	**<.0001**	**<.0001**	0.3005	0.8268	0.9234
Gravity-DOF 2	**<.0001**	**<.0001**	0.8851	0.6476	**0.0165**
Gravity-DOF 3	**<.0001**	**<.0001**	0.4403	0.8128	0.9129
Gravity-DOF 4	**0.0066**	**0.0083**	-	-	-
Gravity-DOF 5	**0.0054**	**<.0001**	-	0.6839	0.7896
Gravity-DOF 6	**0.0002**	**<.0001**	0.8524	**0.0006**	0.8078
Gravity-DOF 7	**0.0005**	**0.0005**	0.3224	0.848	0.1504
Age	0.9844	0.4993	0.5846	**0.0034**	0.583
Age of Onset	0.6853	0.2402	**0.0032**	**<.0001**	0.2801
FTM score	0.5397	0.944	0.0637	0.5248	0.1388
Gender	0.4809	0.2029	**0.0262**	0.2732	0.1913
Medication	0.533	0.8606	0.0675	**<.0001**	0.4183

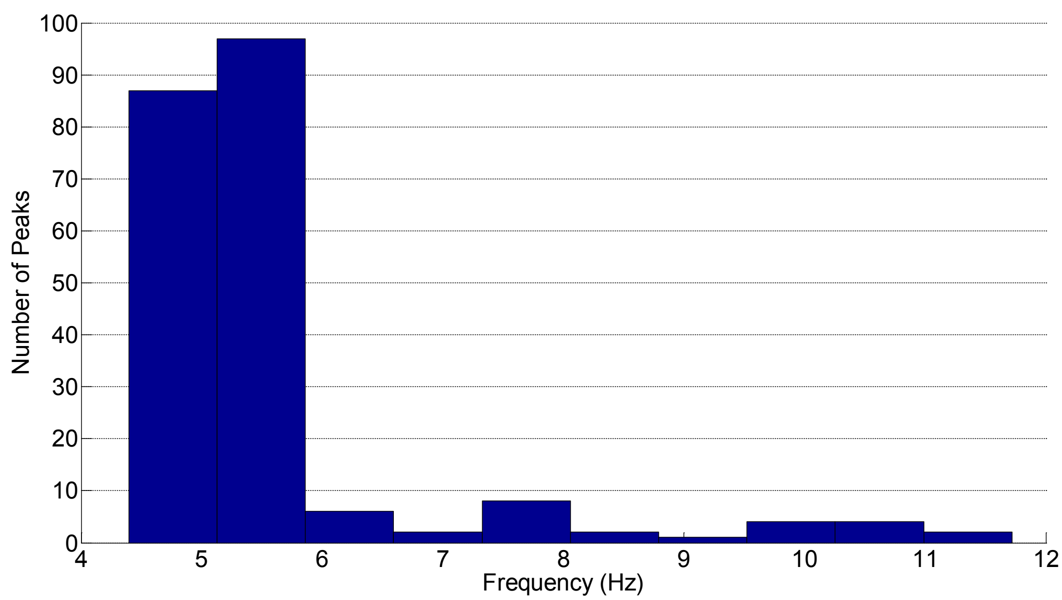

Figure 4-4. Frequency of Peaks.

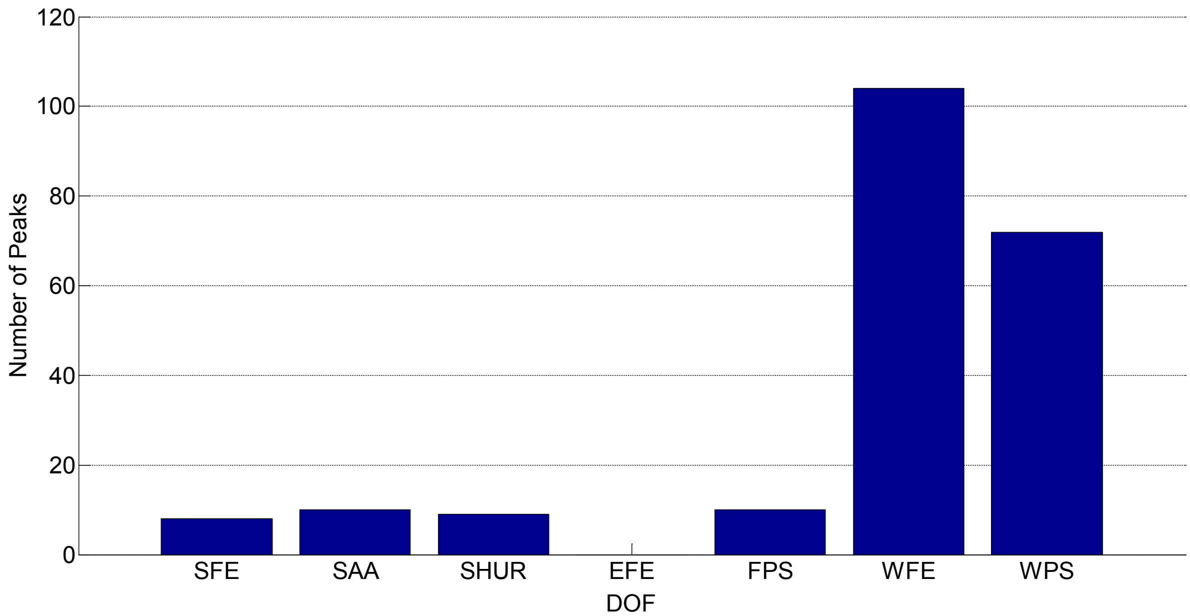

Figure 4-5. Number of Peaks by DOF

5 DISCUSSION

In all known previous studies, tremor has been measured in one or several DOF and recorded from linear motion of the sensor. While these studies have provided useful data and insight into the nature of ET they do not provide enough information to investigate its origin, propagation, and possible suppression strategies. Endpoint translation is an insufficient measure for these goals due to the kinematic redundancies of the upper limb. It is more appropriate measure rotation instead of translation and in all DOF rather than one. We have presented and implemented a method for characterizing the tremor in each DOF. More specifically, we measured angular displacements due to tremor throughout the upper limb, used inverse kinematics to express the displacements in terms of the 7 main DOF of the shoulder, elbow, forearm, and wrist, and computed measures of tremor severity in of these DOF. Using a combination of inverse kinematics and soft tissue compensation we successfully computed joint angle values over time in all 7 DOF. While the primary purpose of this study is to present a method for characterizing tremor in the different DOF of the upper limb, we present preliminary data from a small number of subjects with mild ET.

5.1 Discussion of Method

Accelerometers are the most common way of measuring tremor in prior research studies. They are inexpensive, more readily available than other sensors, and useful for measuring the linear acceleration of the endpoint of the upper limb. However, characterizing each DOF requires inverse kinematics which are more easily performed with orientation measurements available through optoelectronic or electromagnetic motion captures systems while providing data quality comparable to accelerometry. Inverse kinematics result in rotation matrices, Euler angles, or quaternions. For characterizing each DOF, Euler angles are the appropriate measure because they more readily correspond to actual joint motion. Rotations are inherently more complex than translation and Euler angles are sometimes difficult to interpret. ISB standards work well for the distal DOF of the upper limb [30]. The axes and order of rotation corresponds to anatomical axes and the natural hierarchy of DOF in the limb. However, ISB standards do not work well for inverse kinematics involving the shoulder. The gimbal lock position is the same as the neutral position and the calibration position used in this study.

These standards also use a Y-X'-Y'' rotation order for the shoulder. The use of a repeated axis produces Euler angles that are difficult to interpret due to the fact that the rotation axes have no correlation with anatomical movements. In this study we used a Z-X'-Y'' rotation order (the same as the other two joints) with Euler angles corresponding to SFE, SAA, and SHUR respectively.

Previous studies have noted that soft tissue artifact (STA) can negatively affect the quality of data in upper limb inverse kinematics [35]. We chose to include a soft tissue artifact correction algorithm in our analysis to improve our results. STA more commonly affects data when large displacements are being measured. Because we measured postural tremor and the amplitude of tremor is small, STA may not have required a correction to accurately measure tremor (change in DOF angle). However, soft tissue artifact correction was required in order to accurately measure the DOF angles and verify that our methods measured angles correctly.

The large majority of joint angle averages matched the true joint angle values in their respective postures. This is a strong evidence that while providing data of similar quality to accelerometry, our method accurately measures arm position in 7 DOF. No other method has used inverse kinematics to measure tremor or reported tremor in the 7 DOF of the upper limb.

Some studies use the fast Fourier transform (FFT) to analyze data in the frequency domain. However, we chose to analyze the power spectrum instead of the FFT. This was due to the fact that the FFT amplifies noise whereas the power spectrum does not.

While some studies have investigated how adding weight to the subject's upper limb affects tremor, none have considered how the limb's own weight might affect tremor or how that effect might change with the orientation of the limb. The algorithm we developed allows us to find the torques exerted about each DOF axis due to each distal limb segment's mass in any orientation. It does this using the same sensor data used in the inverse kinematics so no additional measurements are required.

We limited our study to only include patients with an age of onset between the ages of 20 and 65. This was done to avoid the inclusion of possible early- and late-onset subtypes of ET. However, the distribution of age of onset among our patients is clearly bimodal, suggesting that our study may still include subtypes [36].

5.2 Discussion of Results

Several joint angle averages did not match the true joint angle values in their respective postures. The first situation in which this occurred was when the elbow was fully extended. The EFE angle should be zero but reads close to 40 degrees. This is likely due to soft tissue artifact, which is expected to be greatest when the joint is at the limit of its range of motion. Another possible cause is that anytime the elbow is fully extended, the SHUR and FPS axes align and subjects can choose how much of each DOF to contribute to the overall posture. The second situation in which joint angle averages were unexpected was in SFE. This likely due to the shoulder angles being complicated by soft tissue artifact and scapular movement.

Both NBA and WBA varied significantly by DOF, being the lowest in the wrist and the highest in the forearm (FPS and EFE). In some ways area may be considered the most robust measure of tremor. It includes all power in a certain band and is independent of the parameters required for peak detection which are often arbitrary. Area is also easier to interpret. It is the square of the RMS tremor (in this case without low-frequency components). Because inertia of limb segments decreases from proximal to distal, we expected to see an increase in tremor in the same direction. However, we found the greatest power in the elbow and forearm.

Posture significantly influenced NBA, WBA, and peak existence, but no meaningful pattern was discernable, so there is currently no reasonable explanation for the differences between postures. The 16 postures used in this study were chosen to explore the wide range of possible arm orientations. A study with postures chosen with small progressive changes may better establish if a pattern exists. While there were several statistically significant effects due to gravitational torque, the size of these effects was generally small, suggesting that tremor is relatively unaffected by gravity.

While the values of WBA were higher than the values of NBA, these two metrics exhibited similar patterns when analyzed over runs, postures, and DOF. ET is often reported to exist in the 4-12 Hz frequency band, although at least one recent paper reported ET components below 4 Hz [37]. The nearly identical trends shown by NBA and WBA indicate that tremor outside of the 4-12 Hz band is small compared with tremor within this band and/or that the effect of factors such as DOF, posture and run on tremor is the same outside the 4-12 Hz band as it is inside. We also found that all tremor metrics were consistent over runs. Subjects' tremor was measured over a period of 30 minutes or more. No aspect of tremor that we measured changed over that time scale. This is a strong indication that a passive orthosis could be effective.

In our analysis peaks occurred rarely. Peaks may have been infrequent due to the mild nature of the subjects' tremor. It is interesting to note that peaks were found much more abundantly and consistently in the data of the omitted subject, whose tremor was significantly more severe. When they were detected, almost all peaks were located in the two wrist DOF and centered at ~ 6 Hz (5.7Hz ± 1.3Hz). The consistency of peak distribution throughout the arm DOF, particularly in WFE and WPS, are strong indicators that while tremor has its largest amplitude in FPS it is much more concentrated in frequency in the wrist DOF. While the lack of peak frequency in FPS would make suppression by targeting a specific frequency of tremor unfeasible, a device that acts as a high-pass filter with an appropriate cut-off frequency could still suppress tremor in this DOF. 98% of peaks were categorized by a half-max value on both sides indicating that these peaks stand out substantially from surrounding data. As with any peak detection algorithm, our algorithm was not perfect and occasionally identified a peak at a high frequency (~11 Hz) whose amplitude was very small compared to the mean amplitude at lower frequencies. FPS had the largest values of peak amplitude, but overall had few peaks. While WFE and WRUD exhibited the highest values of peak amplitudes, elbow FE and PS had much greater values of NBA and WBA than WFE and WRUD. To compare the amplitude of the peaks in WFE and WRUD to the amplitude of the tremor in elbow FE and PS, we divided the NBA in elbow FE by the width of the frequency band over which NBA was integrated, (8Hz). The average amplitude for FPS was much higher than the amplitudes of peaks found in WFE and WRUD (9.4 and 44 times greater, respectively), indicating that the tremor is greater in FPS, but tremor is more concentrated (in terms of frequency) in the wrist DOF. It is important to note that the existence of a significant peak for specific combinations of patient, posture and DOF was not consistent across runs.

There was surprisingly little correlation between our tremor measures and subjects' demographic factors. The few correlations that were significant had small effect sizes. It is likely that our sample size of nine subjects was too small. This was especially true for binary demographics. For example, seven subjects were taking medication and only three were not. This is an insufficient number to properly investigate this demographic. Likewise, our measures were not correlated with subjects' FTM score. It is not uncommon to find poor agreement between clinical scales and quantitative measures. For example, comparing clinical scales to quantitative measurements made by rehabilitation robots in stroke patients often does not match. In our case, there are several possible explanations. First, all of our subjects had mild tremor and therefore occupied a narrow range of FTM scores. Second, our study measured tremor differently than the FTM. The FTM, while focusing on the upper limbs, measures tremor throughout the body. Our study focused exclusively on the upper limbs. Even where FTM focuses on the upper limbs, it combines tremor throughout the limb whereas our study investigated individual DOF. The FTM is also bilateral, while our study was not.

5.3 Other Limitations

This study had several limitations. First, all subjects exhibited mild tremor. This affected our ability to correlate our measures with the FTM score (see above) as well as the accuracy of our measures. To clarify, our motion capture system had a static accuracy of 0.5° RMS over the entire tracking volume (sphere of 4 ft. radius), which is larger than some of our tremor measures. However, because tremor consists of small changes over time, what is important is the motion capture system's ability to detect relative changes, not the accuracy of the system. Normal physiological tremor has been shown to have a magnitude of 0.1° [38]. The resolution of our motion capture system was 0.007°, which is sufficiently small to measure both physiological and larger pathological tremor. Note that the values of our measures were not integer multiples of the resolution because we interpolated and transformed the raw data (to obtain a constant sampling frequency and perform the inverse kinematics, respectively).

5.4 Conclusion

Using position sensors to measure tremor allows for characterization by DOF in most postures, with measurements becoming inaccurate only for postures that have severe STA. This method provides a characterization with a level of detail both sufficient for orthosis design and undocumented elsewhere. Preliminary data showed that tremor is focused in a subset of upper limb DOF, being greatest (in terms of power) in elbow flexion-extension and forearm pronation-supination, and most concentrated (with peaks at a stereotyped frequency) in wrist flexion-extension and radial-ulnar deviation. Run had no significant effects, suggesting that tremor was consistent over the duration of the experiment. Both the distribution of tremor throughout the DOF of the upper limb and the consistency over runs indicate that a suppressive orthosis may be possible. While this study only analyzes preliminary data, using this technique on a larger number of patients with a wider range of tremor severity will provide a thorough characterization of ET. Isolation studies that restrict specific DOF and include EMG instrumentation will help is determining both the origin of the tremor and how it propagates through the limb. Many patients in our study exhibited tremor in the fingers, so additional instrumentation to measure these DOF may be beneficial. Our method combined with suggested future work will allow for optimal tremor suppression through an orthosis and may allow an improved differential diagnosis.

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APPENDIX A: FAHN-TOLOSA-MARIN TREMOR RATING SCALE

The word *tremor* is derived from the Latin *tremere*, meaning "to tremble." Tremor can be defined as involuntary oscillations of any part of the body around any plane, such oscillations being either regular or irregular in rate and amplitude and resulting from alternate or synchronous action of groups of muscles and their antagonists (definition slightly modified from Holmes, 1904.)

Tremors are usually classified according to their phenomenology, most commonly "present at rest," "present with postural sustention," "present with action," and "present with intention" (i.e., on approaching the target of a skilled movement) (Fahn, 1972; Jankovic and Fahn, 1980; Findley et al., 1984). Tremor at rest is almost always a sign of parkinsonism, whereas postural tremor is most commonly a sign of essential tremor. The latter condition will usually be even more pronounced with action and often with intention. Intention tremor is typically a feature of a lesion of the cerebellar outflow pathway, but, when severe, usually spreads to become a postural tremor. Enhanced physiological tremor resembles essential tremor, although it often has a faster frequency (Marsden et al., 1983).

Although the arms are the part of the body most commonly affected by tremor of all types, other parts of the body are not immune from developing tremor. In parkinsonism, tremor occurs most often in the distal extremities, but can also involve the lips, chin and tongue. Essential tremor, besides appearing in the arms, can also appear in the neck and vocal cords. Cerebellar tremor often involves the head and trunk (titubation). When tremor appears only with writing, it is called primary writing tremor (Rothwell et al., 1979), which many consider to be a form of essential tremor. Tremor can involve the thighs and trunk, only with standing and not with walking, the so-called orthostatic tremor (Heilman, 1984).

Not all rhythmic movements are considered to be tremor (Fahn, 1984). Rhythmic jerking is seen in some forms of myoclonus (Fahn et al., 1986), particularly palatal and ocular myoclonus, and other forms of segmental myoclonus are often rhythmical (Jankovic and Pardo, 1986). Dystonia can appear as a rhythmic pattern; in such cases it is termed dystonic tremor (Jankovic and Fahn, 1980, Fahn et al., 1987). On the other hand essential tremor can be present in patients with dystonia (Yanagisawa et al., 1972; Couch, 1976).

Studies evaluating drug trials for controlling tremor have used a number of methods to estimate tremor severity. Accelerometer recording has been popular with some investigators (Koller, 1984; Findley et al., 1985), but this method ordinarily requires a laboratory setting and specialized instrumentation, which is not feasible for most neurologists. A similar problem exists with methods using the detection or interruption of light, such as a polarized light goniometer (Francis et al., 1986). Clinical assessment by having "blinded" observers rate global severity from randomized videotape sequences (Duquette

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et al., 1985) is not unreasonable, but it does not allow for quantitation of small changes or even qualification of different aspects of tremor. Combinations of accelerometry and clinical assessment from videotape recordings are also utilized (Hallett et al., 1985).

Sweet and his colleagues (Sweet et al., 1974) developed a clinical rating scale for tremor for their study evaluating the effects of propranolol in essential tremor. It was a weighted scale assigning different point values to different affected body areas. For example, this scale gives more points for arm tremor than for tongue tremor, which in turn scored higher than jaw tremor, which scored higher than head tremor. The points for the presence of tremor in each region was then multiplied by a factor (1 to 3) reflecting severity at each site, with 1 being mild, 2 moderate, and 3 marked. To the sum of these products was added a score for functional impairment. For this functional score, a weighted number was assigned to various activities, namely, handling a cup, handling food, use of hands, swallowing, talking, and walking. These points were multiplied by the severity factor used for severity of tremor.

The clinical rating scale developed by Sweet et al. (1974) was designed specifically for essential tremor and not for other tremors, such as resting tremor. Other disadvantages are a 4-point instead of a 5-point scale for severity; the lack of definitions for mild, moderate, and marked severity; and weighing dependent on the involved body site and the type of function that is impaired. Many important functional activities, such as writing and shaving, are not considered individually, but are lumped together as "use of hands." The impact of tremor on the patient's ability to work was not assessed. Moreover, voice tremor was not considered, except subjectively by the patient, as a symptom.

For these reasons the authors decided to develop a new clinical rating scale for tremor, one that could be used for quantitating rest, postural, and action/intention tremors (Table 17-1). This scale would also evaluate voice

Table 17-1. Definitions of Tremor Scale

1–9. **Tremor:** Rate tremor

1) at REST (in repose). For head and trunk, when lying down.
2) with posture holding (UE: arms outstretched, wrists mildly extended, fingers spread apart; LE: legs flexed at hips and knees), foot dorsiflexed; tongue: when protruded; head and trunk: when sitting or standing)
3) with ACTion and INTention (UE: finger to nose and other actions; LE: toe to finger in a flexed posture)

0 = None
1 = Slight (amplitude < 0.5 cm). May be intermittent.
2 = Moderate amplitude (0.5–1 cm). May be intermittent.
3 = Marked amplitude (1–2 cm)
4 = Severe amplitude (> 2 cm)

10. **Handwriting:** Have patient write the standard sentence: "This is a sample of my best handwriting," sign his or her name, and write the date.

0 = Normal
1 = Mildly abnormal. Slightly untidy, tremulous.
2 = Moderately abnormal. Legible, but with considerable tremor.
3 = Markedly abnormal. Illegible.
4 = Severely abnormal. Unable to keep pencil or pen on paper without holding hand down with the other hand.

11–13. **Drawings (A,B,C):** Ask the patient to join both points of the various drawings without crossing the lines. Test each hand, beginning with the lesser involved, *without leaning the hand or arm on the table.*

0 = Normal
1 = Slightly tremulous. May cross lines occasionally.
2 = Moderately tremulous or crosses lines frequently.
3 = Accomplishes the task with great difficulty. Many errors.
4 = Unable to complete drawing.

Table 17-1. *Continued.*

14. **Pouring:** Use firm plastic cups (8 cm tall), filled with water to 1 cm from top. Ask patient to pour water from one cup to another. Test each hand separately.
    - 0 = Normal
    - 1 = More careful than a person without tremor, but no water is spilled.
    - 2 = Spills a small amount of water (up to 10% of total amount).
    - 3 = Spills a considerable amount of water (>10–50%).
    - 4 = Unable to pour without spilling most of the water.
15. **Speaking:** This includes spastic dysphonia if present.
    - 0 = Normal
    - 1 = Mild voice tremulousness when "nervous" only.
    - 2 = Mild voice tremor, constant.
    - 3 = Moderate voice tremor.
    - 4 = Severe voice tremor. Some words difficult to understand.
16. **Feeding (other than liquids):**
    - 0 = Normal
    - 1 = Mildly abnormal. Can bring all solids to mouth, spilling only rarely.
    - 2 = Moderately abnormal. Frequent spills of peas and similar foods. May bring head at least halfway to meet food.
    - 3 = Markedly abnormal. Unable to cut or uses 2 hands to feed.
    - 4 = Severely abnormal. Needs help to feed.
17. **Bringing Liquids to Mouth:**
    - 0 = Normal
    - 1 = Mildly abnormal. Can still use a spoon, but not if it is completely full.
    - 2 = Moderately abnormal. Unable to use a spoon. Uses cup or glass.
    - 3 = Markedly abnormal. Can drink from cup or glass, but needs 2 hands.
    - 4 = Severely abnormal. Must use a straw.
18. **Hygiene:**
    - 0 = Normal
    - 1 = Mildly abnormal. Able to do everything, but is more careful than the average person.
    - 2 = Moderately abnormal. Able to do everything, but with errors; uses electric razor because of tremor.
    - 3 = Markedly abnormal. Unable to do most fine tasks, such as putting on lipstick or shaving (even with electric shaver), unless using two hands.
    - 4 = Severely abnormal. Unable to do any fine-movement tasks.
19. **Dressing:**
    - 0 = Normal
    - 1 = Mildly abnormal. Able to do everything, but is more careful than the average person.
    - 2 = Moderately abnormal. Able to do everything, but with errors.
    - 3 = Markedly abnormal. Needs some assistance with buttoning or other activities, such as tying shoelaces.
    - 4 = Severely abnormal. Requires assistance even for gross motor activities.
20. **Writing:**
    - 0 = Normal
    - 1 = Mildly abnormal. Legible. Continues to write letters.
    - 2 = Moderately abnormal. Legible, but no longer writes letters.
    - 3 = Markedly abnormal. Illegible.
    - 4 = Severely abnormal. Unable to sign checks or other documents requiring signature.
21. **Working:**
    - 0 = Tremor does not interfere with the job.
    - 1 = Able to work, but needs to be more careful than the average person.
    - 2 = Able to do everything, but with errors. Poorer than usual performance because of tremor.
    - 3 = Unable to do regular job. May have changed to a different job because of tremor. Tremor limits housework, such as ironing.
    - 4 = Unable to do any outside job; housework very limited.

tremor, handwriting and other specific tasks of the hands, such as hygienic care and dressing. Functional disability and tremor impact in terms of patient ability to work is also scored. It was decided to use only a uniform, not a weighted score. The larger number of scorings for the upper extremities intrinsically increases weight, however, since the new scale measures many functions dependent on the hands, such as writing, pouring, dressing, and feeding. Definitions are provided to aid the investigator; this should also improve concordance among clinicians. The scale for severity is based on 5 points, rather than 4, providing a more finely tuned assessment.

Description of New Clinical Rating for Tremor

The new rating scale is divided into three parts (A, B, and C), each yielding a subtotal score that can be combined for a total score or can be used for independent analysis (Table 17-1). In addition to the task-specific quantitative scores, a global assessment (by the patient and by the examiner) is also obtained at each visit, with the definitions provided on the scoring form (Fig. 17-1). The scoring form also is used for the execution of the writing and drawing tasks, and it serves as a convenient location for the examiner to record the ratings, list the medications, and make any comments.

Part A

Part A (scores 1 to 9) quantifies the tremor at rest, with posture holding, and with action and intention maneuvers, for nine parts of the body (Fig. 17-1). Naturally, some body parts would not normally have tremor in all three situations. For example, voice tremor is a tremor of action only, so the rating scale does not score voice tremor at rest or with posture. Since face, tongue, head, and trunk tremors are basically present at rest or with posture holding, this new scale eliminates scoring of those tremors in the action/intention category.

Severity of tremor in each of the nine body parts is rated by amplitude. Whether the tremor is intermittent or always present (a phenomenologic characteristic of resting tremor in parkinsonism) is not a factor in the severity score. The definitions for tremor severity (Table 17-1, parts 1 to 9) indicate that 1+ and 2+ tremors could be either intermittent or continuous. Since larger amplitude tremors are less likely to be intermittent, the definitions for 3+ and 4+ severities do not list the choice for intermittency.

Tremor severity in Part A is rated for three situations: rest, maintaining a posture, and performing an activity (Fig. 17-1). Definitions for these three situations are provided for the limbs, tongue, head, and trunk (Table 17-1). Face tremor is scored only as a resting tremor. The lips (orbicularis oris) and chin (mentalis muscle) are the most common sites of face tremor and are affected in parkinsonism particularly, rather than in other types of tremors. The so-called rabbit syndrome in tardive dyskinesia might actually be a type of lip tremor. Tongue tremor at rest is scored with the tongue resting in the mouth; posture tremor is scored with the tongue maintained protruded from the mouth.

Voice tremor can be detected by listening to the patient talk, but it is sometimes difficult to differentiate by sound alone voice tremor and dystonic adductor dysphonia (so-called spastic dysphonia or spasmodic dysphonia). It is much easier to detect voice tremor and to distinguish it from dystonic dysphonia by having the patient utter a single sound, such as "aaahhh . . . " or "eeeehhh . . . " and hold it for as long as possible. Voice tremor is rhythmic, whereas dystonic adductor dysphonia produces irregular interruptions of sound. Occasionally patients have both tremor and dysphonia.

Tremor of the head and of the trunk when the patient is sitting or standing is considered a postural tremor; rest tremor of the head or trunk is measured when the patient is lying down with the head and body supported against gravity.

Tremor of the arms and legs can be distal or proximal. Rest tremor of the limbs is assessed with the limbs in complete repose. Often this

Part A

NAME: ______________________ HOSP. #: ______________

DIAGNOSIS: ______________ AGE: ____ SEX: ____ R/L handed

DATE: ______________

	Rest	Post.	Act./Int.	TOTAL
1. Face tremor			xxxxxx	
2. Tongue tremor			xxxxxx	
3. Voice tremor	xxxx	xxxxx		
4. Head tremor			xxxxxx	
5. RUE tremor				
6. LUE tremor				
7. Trunk tremor			xxxxxx	
8. RLE tremor				
9. LLE tremor				
			SUBTOTAL A:	

List of Medications

Comments:

	TOTAL
10. Handwriting (dominant only)	

	right	left	TOTAL
11. Drawing A:			
12. Drawing B:			
13. Drawing C:			
14. Pouring			

SUBTOTAL B: ______

FUNCTIONAL DISABILITIES DUE TO TREMOR

15. Speaking	
16. Eating	
17. Drinking	
18. Hygiene	
19. Dressing	
20. Writing	
21. Working	

SUBTOTAL C: ______

TOTAL SCORE: ______

Figure 17.1. Tremor rating scale.

Part B

NAME: ______________________________ DATE: ______________

HANDWRITING: This is a sample of my best handwriting.
Signature. Date.

DRAWINGS: with right/left hand

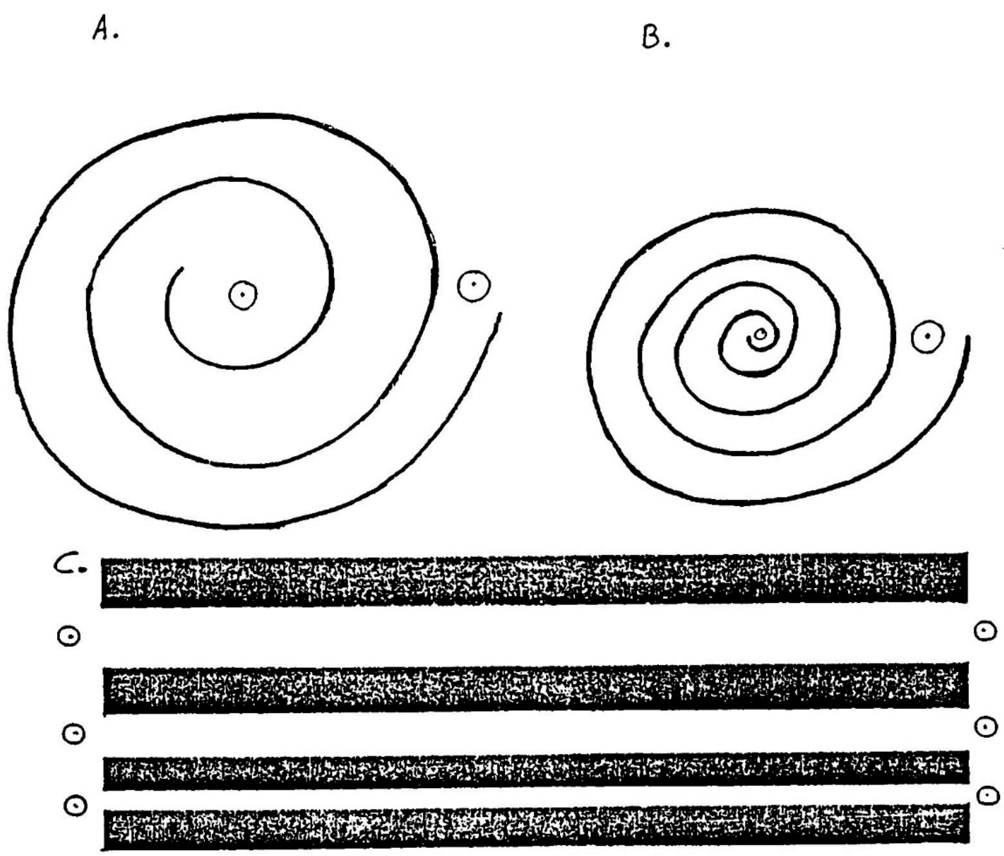

Figure 17.1. *Continued.*

Part C

CALCULATION

Total score/ max. possible score: / % SEVERITY
(The maximum score possible is 144)

GLOBAL ASSESSMENT BY EXAMINER: (Examiner's initials:)

0 = No functional disability.
1 = Mild disability. 1-24% impaired.
2 = Moderate disability. 25-49% impaired.
3 = Marked disability. 50-74% impaired.
4 = Severe disability. 75-100% impaired.

SCORE: ________

GLOBAL ASSESSMENT BY PATIENT:

0 = No functional disability.
1 = Mild disability. 1-24% impaired.
2 = Moderate disability. 25-49% impaired.
3 = Marked disability. 50-74% impaired.
4 = Severe disability. 75-100% impaired.

SCORE: ________

SUBJECTIVE ASSESSMENT BY PATIENT COMPARED TO LAST VISIT:

+3 = Marked improvement (50-100% improved)

+2 = Moderate improvement (25-49% improved)

+1 = Mild improvement (10-24% improved)

0 = Unchanged

-1 = Mild worsening (10-24% worse)

-2 = Moderate to marked worsening (25-49% worse)

-3 = Marked worsening (50-100% worse)

Figure 17.1. *Continued.*

is easily accomplished when the patient is sitting, forearms and hands relaxing on the lap and feet supported by the floor. In individuals who are tense and cannot relax their muscles, one might have to assess for rest tremor of the limbs with the patient supine. Postural tremor of the arms is observed by having the patient stretch the arms in front of the body both with elbows extended and with elbows flexed (winged posture to look for 'wing-beating' tremor). Postural tremor of the legs is observed by having the patient elevate the legs, which is sometimes easiest if done one leg at a time. This can be accomplished with the patient sitting or lying. For ease and consistency in scoring, the sitting position is recommended. The hips and knees are flexed with the legs maintained in the air against gravity.

Action and intention tremor are given a single score. For the arms, the patient carries out the finger-to-nose maneuver as well as such other actions as buttoning, dialing a telephone, writing, and bringing a cup to the mouth. Some of these activities are rated separately in Parts B and C of the rating scale, giving additional weight to this type of tremor in the total tremor score. For the legs, action/intention tremor is assessed by having the patient carry out the toe-to-finger maneuver. Since postural tremor will be superimposed on top of action/intention tremor, it is important to determine if the activity results in a greater tremor amplitude than that seen with posture holding alone. Similarly, rest tremor can superimpose on top of posture tremor after the posture is maintained for several seconds. This resting component should not be misinterpreted as postural tremor.

Part B

Part B (scores 10 to 14) relates to action tremors of the upper extremities, particularly writing and pouring liquids. Severity is determined by watching the patient carry out the aforementioned activities. For handwriting, only the dominant hand used for writing is evaluated; the patient writes a standard sentence, his or her name, and the date (Table 17-1, item 10). Space is provided on the scoring form for this handwriting sample, which will then be part of the patient's record (Fig. 17-1). Drawing is also evaluated by having the patient carry out this activity on the scoring form. Space is available for assessing each hand. To allow consistent evaluation over time, the patient should not rest the drawing hand and forearm on the table or desk. This, of course, makes the task more difficult and the test more sensitive. Tasks A and B are the drawing of an Archimede's spiral. The quantitation of these tasks is defined in Table 17-1 (items 11 to 13) and is based on the crossing of the lines in the figure. There is less space available between the lines in Task B, making the task more difficult. Task C for drawing requires the patient to draw a straight line between narrow confines, three times; each time the confines become narrower, thereby increasing the difficulty. These three drawing tasks, by having different levels of difficulty, give a more precise reflection of tremor severity.

Pouring water from one cup to another is also quantified. Cup size and the amount of water used in the test are specified to ensure consistency between examination events and among clinicians. The amount of water spilled is the basis for the severity grading. The definitions for scoring both pouring and drawing are provided in Table 17-1 (items 10 to 14).

Part C

Part C assesses functional disability. Its items evaluate the severity of tremor with speaking, eating (feeding), bringing liquids to the mouth, hygienic care, dressing, and working, including domestic tasks. These scores, with the exception of speaking, are provided by patients, who are asked to evaluate their ability to carry out these tasks by using the definitions provided in Table 17-1. Speaking can also be evaluated by the examiner. Since patients (and often physicians) cannot distinguish between dystonic adductor dysphonia and voice tremor, and since occasional patients have both disorders, the speaking score encompasses both disabilities. Definitions for all rated functional tasks are provided in Table 17-1. "Working" classifications includes homemaking, as well as other jobs.

Calculations

Space is provided on the scoring form (Fig. 17-1) for calculating subtotal scores, i.e., sums of each separate part (A, B, and C), and an overall score of all three parts. The maximum possible scores are 80 for Part A, 36 for Part B, and 28 for Part C, making the maximum possible total score 144. For patients with amputated or immobile limbs, the maximum possible scores would be reduced appropriately. Page 2 of the scoring form explains how to calculate percent of severity. This is determined by dividing the total score by the maximum score possible and then multiplying by 100.

Global Assessment

In addition to the quantitation of tremor through Parts A, B, and C, the scoring form allows assessment of overall severity by both the patient and the examiner. This subjective global severity is based on the assessment of tremor-related disability, which is calculated according to the percent of impairment in carrying out all activities of daily living and the cosmetic effect of the tremor, which can be psychologically damaging. Subjective global assessments are quick guides for evaluating patients, but they also provide useful comparisons for the quantitative ratings of Parts A, B, and C. The global assessments can serve as the 'gold standard' for validating this clinical rating scale.

Comparison Assessment

This rating scale should be useful for determining the effectiveness of medications or stereotactic surgery on reducing the severity of tremor. The scores obtained on Parts A, B, and C and the global assessments will provide the major input of a comparison before and after starting a new medication or having surgery. However, it is also useful to obtain subjective evaluations by the patient as to the effectiveness of medications or surgery. The scoring form provides definitions for the patient to carry out such a self-evaluation (Fig. 17-1).

Summary

This chapter presents a new clinical rating scale for semiquantitating the severity of tremor in all its forms: at rest, with posture holding, and with action. No special tools are required, other than a pencil, paper, and two cups to hold water. The rating scale can be used to assess tremors of different etiologies. Standard sets of conditions and definitions for tremor severity are provided to help ensure consistency among examiners and also from one date of examination to another. A 5-point scale is used, and the maximum possible (total) score is 144 points. Functional disability and tremor amplitude are both assessed. Furthermore, definitions are provided to allow subjective global assessments of tremor, including subjective comparisons by the patient for evaluating the effectiveness of treatment attempts and variations in tremor severity over time. This rating scale needs to be statistically evaluated for validity and reliability.

APPENDIX B: INVERSE KINEMATICS

Inverse kinematics were used to calculate the joint angles using a function called SensAng2JointAng(). This function first loads all of the sensor data, both at calibration and during data collection. It then calls the function aer2R(), which calculates a rotation matrix between the sensor and the universal frame for each set of sensor data (azimuth, elevation, and roll angles) using the rotation order employed by *trakSTAR* software. SensAng2JointAng() then calculates the rotation matrices between the universal frame and body fixed frames for each arm link at calibration. These matrices are different depending on which arm was tested. Using previously calculate rotation matrices, the matrices between each pair of adjacent arm links is then calculated. These inter-link rotation matrices can then be corrected for soft tissue artifact by calling the STAC() function (see Appendix C). Finally, SensAng2JointAng() calls the function R2abg() which extracts the joint or DOF angles from the inter-link rotation matrices.

```
function [abg_s_mod, abg_s, abg_e, abg_w] =
SensAng2JointAng(Et,Ft,Gt,Ht,E0,F0,G0,H0,approx,side)

% This function calculates upper limb joint angles from electromagnetic
% motion sensor data. More specifically, this function takes as inputs the
% euler angles of four motion sensors (attached to the trunk, upper arm,
% forearm, and hand), and returns euler angles describing rotations at the
% shoulder, elbow/forearm, and wrist joints.
% Depending on the input, this function uses models with 9 or 7 degrees of
% freedom and different levels of correction for soft-tissue artifact.
% Written by Steven K. Charles, Brigham Young University, 2012

% INPUT
% E0 is a 1x3 matrix containing [a,e,r] of sensor E (attached to the trunk)
at calibration (in degrees)
% F0 is a 1x3 matrix containing [a,e,r] of sensor F (attached to the upper
arm) at calibration (in degrees)
% G0 is a 1x3 matrix containing [a,e,r] of sensor G (attached to the distal
forearm) at calibration (in degrees)
% H0 is a 1x3 matrix containing [a,e,r] of sensor H (attached to the dorsal
hand) at calibration (in degrees)
% Et is a nx3 matrix containing [a,e,r] of sensor E over time (in degrees)
% Ft is a nx3 matrix containing [a,e,r] of sensor F over time (in degrees)
% Gt is a nx3 matrix containing [a,e,r] of sensor G over time (in degrees)
% Ht is a nx3 matrix containing [a,e,r] of sensor H over time (in degrees)
```

```
% The input "approx" specifies the level of approximation:
% 0: Full 9-DOF model, i.e. no approximation
% 1: 7-DOF model (be = gw = 0)
% 2: 7-DOF model with gs derived from forearm orientation
% 3: 7-DOF model with ge derived from hand orientation
% 4: Approximations 2 and 3 combined

% The input "side" specifies which arm:
% 'R': right arm
% 'L': left arm

% OUTPUT
% abg_s is an nx3 vector of alpha, beta, and gamma for the shoulder joint (in
degrees)
% abg_e is an nx3 vector of alpha, beta, and gamma for the elbow/forearm
joint (in degrees)
% abg_w is an nx3 vector of alpha, beta, and gamma for the wrist joint (in
degrees)

abg_s = zeros(size(Et));
abg_s_mod = abg_s;
abg_e = abg_s;
abg_w = abg_s;

% CONVERT INPUT FROM DEGREES TO RADIANS
Et = Et*pi/180;
Ft = Ft*pi/180;
Gt = Gt*pi/180;
Ht = Ht*pi/180;
E0 = E0*pi/180;
F0 = F0*pi/180;
G0 = G0*pi/180;
H0 = H0*pi/180;

  for i = 1:size(Et)
    % CREATE ROTATION MATRICES FOR SCS AT CALIBRATION AND TIME t
    % RAB0 and RABt are the rotation matrices of A relative to B (normally
    % written with A as leading subscript and B as leading superscript) at
    % calibration and at time t, respectively.
    if i == 1
        REU0 = aer2R(E0(1), E0(2), E0(3));
        RFU0 = aer2R(F0(1), F0(2), F0(3));
        RGU0 = aer2R(G0(1), G0(2), G0(3));
        RHU0 = aer2R(H0(1), H0(2), H0(3));
    end

    REUt = aer2R(Et(i,1), Et(i,2), Et(i,3));
    RFUt = aer2R(Ft(i,1), Ft(i,2), Ft(i,3));
    RGUt = aer2R(Gt(i,1), Gt(i,2), Gt(i,3));
    RHUt = aer2R(Ht(i,1), Ht(i,2), Ht(i,3));


    if i == 1
        % CREATE ROTATION MATRICES FOR BCS AT CALIBRATION
        if side == 'R'
```

```
            RAU0 = [-1 0 0; 0 0 -1; 0 -1 0];
            RCU0 = [0 1 0; 1 0 0; 0 0 -1];
        elseif side == 'L'
            RAU0 = [1 0 0; 0 0 -1; 0 1 0];
            RCU0 = [0 -1 0; 1 0 0; 0 0 1];
        end
        RBU0 = RAU0;
        RDU0 = RCU0;
    end

    % COMPUTE ROTATION MATRICES FOR JCS
    if approx == 0 || approx == 1
        RBAt = RAU0'*REU0*REUt'*RFUt*RFU0'*RBU0;
        RCBt = RBU0'*RFU0*RFUt'*RGUt*RGU0'*RCU0;
        RDCt = RCU0'*RGU0*RGUt'*RHUt*RHU0'*RDU0;
    else
        [RBAt, RCBt, RDCt] =
STACC(RAU0,RBU0,RCU0,RDU0,REU0,RFU0,RGU0,RHU0,REUt,RFUt,RGUt,RHUt,approx);
    end

    % EXTRACT JOINT ANGLES
    if approx == 0
        [as,bs,gs] = R2abg(RBAt,1,9);
        [asm,bsm,gsm] = R2abg(RBAt,4,9);
        [ae,be,ge] = R2abg(RCBt,2,9);
        [aw,bw,gw] = R2abg(RDCt,3,9);
    else
        [as,bs,gs] = R2abg(RBAt,1,7);
        [asm,bsm,gsm] = R2abg(RBAt,4,7);
        [ae,be,ge] = R2abg(RCBt,2,7);
        [aw,bw,gw] = R2abg(RDCt,3,7);
    end

    % PREPARE FOR OUTPUT IN DEGREES
    abg_s(i,:) = [as,bs,gs]*180/pi;
    abg_s_mod(i,:) = [asm,bsm,gsm]*180/pi;  %modified to return standard
shoulder angle
    abg_e(i,:) = [ae,be,ge]*180/pi;
    abg_w(i,:) = [aw,bw,gw]*180/pi;
 end

end
```

```
function R = aer2R(a,e,r)

% This function takes trakSTAR sensor angles a (azimuth or yaw), e
% (elevation o pitch), and r (roll) and computes the corresponding rotation
% matrix describing the orientaiton of the sensor relative to the
% transmitter.
% Written by Steven K. Charles, Brigham Young University, 2012

% INPUT
% a, e, and r are Euler angles expressed in radians

% OUTPUT
% R is the rotation matrix describing the orientation of the sensor
% relative to the transmitter.
a = a*180/pi;
e = e*180/pi;
r = r*180/pi;

% Rz_a = [cos(a) -sin(a) 0; sin(a) cos(a) 0; 0 0 1];
% Ry_e = [cos(e) 0 sin(e); 0 1 0; -sin(e) 0 cos(e)];
% Rx_r = [1 0 0; 0 cos(r) -sin(r); 0 sin(r) cos(r)];
Rz_a = [cosd(a) -sind(a) 0; sind(a) cosd(a) 0; 0 0 1];
Ry_e = [cosd(e) 0 sind(e); 0 1 0; -sind(e) 0 cosd(e)];
Rx_r = [1 0 0; 0 cosd(r) -sind(r); 0 sind(r) cosd(r)];

R = Rz_a * Ry_e * Rx_r;
end
```

```
function [a,b,g] = R2abg(R,joint,num_dof)
% This function takes the rotation matrix across a joint and extracts the
% corresponding joint angles a (alpha), b (beta), and g (gamma) for the
% shoulder, elbow/forearm, and wrist joints for a 9 or 7 degree-of-freedom
% model of the arm. Joint constraints are specified to determine the
% correct set of joint angles.
% Written by Steven K. Charles, Brigham Young University, 2012

% INPUT
% R is the rotation matrix describing the orientation of the distal segment
% relative to the proximal segment
% joint should be 1 for the shoulder, 2 for the elbow/forearm, and 3 for
% the wrist joints.
% num_dof specifies whether the arm model has 9 or 7 degrees of freedom

% OUTPUT
% a, b, and g are Euler angles expressed in radians
```

```matlab
% Set joint constraints

if joint == 1
    constr = [-90 90; -135 45; -90 90]*pi/180;
elseif joint == 2
    constr = [-15 165; -90 90; -10 170]*pi/180;
elseif joint == 3
    constr = [-90 90; -90 90; -90 90]*pi/180;
elseif joint == 4
    constr = [-45 170; -45 110; -45 90]*pi/180;
end

if joint == 1
    % SHOULDER JOINT
    % Extract both possible sets
    b1 = atan2(sqrt(R(2,1)^2 + R(2,3)^2), R(2,2));
%     d1 = sind(b1*180/pi);
%     a1 = atan2(R(1,2)/d1, R(3,2)/d1);
%     g1 = atan2(R(2,1)/d1, -R(2,3)/d1);
    if (R(1,2) == 0 && sin(b1) == 0)
        t1 = 0;
    else
        t1 = R(1,2)/sin(b1);
    end
    if (R(3,2) == 0 && sin(b1) == 0)
        t2 = 0;
    else
        t2 = R(3,2)/sin(b1);
    end
    a1 = atan2(t1, t2);
    if (R(2,1)==0 && sin(b1) == 0)
        t1 = 0;
    else
        t1 = R(2,1)/sin(b1);
    end
    if (-R(2,3)==0 && sin(b1)==0)
        t2 = 0;
    else
        t2 = -R(2,3)/sin(b1);
    end
    g1 = atan2(t1,t2);

    b2 = atan2(-sqrt(R(2,1)^2 + R(2,3)^2), R(2,2));
%     d2 = sind(b2*180/pi);
%     a2 = atan2(R(1,2)/d2, R(3,2)/d2);
%     g2 = atan2(R(2,1)/d2, -R(2,3)/d2);
    if (R(1,2) == 0 && sin(b2) == 0)
        t1 = 0;
    else
        t1 = R(1,2)/sin(b2);
    end
    if (R(3,2) == 0 && sin(b2) == 0)
        t2 = 0;
    else
        t2 = R(3,2)/sin(b2);
    end
```

```
    a2 = atan2(t1, t2);
    if (R(2,1)==0 && sin(b2) == 0)
        t1 = 0;
    else
        t1 = R(2,1)/sin(b2);
    end
    if (-R(2,3)==0 && sin(b2)==0)
        t2 = 0;
    else
        t2 = -R(2,3)/sin(b2);
    end
    g2 = atan2(t1,t2);


elseif joint == 2
    % ELBOW/FOREARM JOINT
    if num_dof == 9
        % Extract both possible sets
        b1 = atan2(R(3,2), sqrt(R(3,1)^2 + R(3,3)^2));
%          d1 = cosd(b1*180/pi);
%          a1 = atan2(-R(1,2)/d1, R(2,2)/d1);
%          g1 = atan2(-R(3,1)/d1, R(3,3)/d1);
        a1 = atan2(-R(1,2)/cos(b1), R(2,2)/cos(b1));
        g1 = atan2(-R(3,1)/cos(b1), R(3,3)/cos(b1));

        b2 = atan2(R(3,2), -sqrt(R(3,1)^2 + R(3,3)^2));
%          d2 = cosd(b2*180/pi);
%          a2 = atan2(-R(1,2)/d2, R(2,2)/d2);
%          g2 = atan2(-R(3,1)/d2, R(3,3)/d2);
        a2 = atan2(-R(1,2)/cos(b2), R(2,2)/cos(b2));
        g2 = atan2(-R(3,1)/cos(b2), R(3,3)/cos(b2));

    elseif num_dof == 7
        % Extract the only possible set
        b = 0;
        a = atan2(-R(1,2), R(2,2));
        g = atan2(-R(3,1), R(3,3));
    end

elseif joint == 3
    % WRIST JOINT
    if num_dof == 9
        % Extract both possible sets
        b1 = atan2(R(3,2), sqrt(R(3,1)^2 + R(3,3)^2));
%          d1 = cosd(b1*180/pi)
%          a1 = atan2(-R(1,2)/d1, R(2,2)/d1)
%          g1 = atan2(-R(3,1)/d1, R(3,3)/d1)
        a1 = atan2(-R(1,2)/cos(b1), R(2,2)/cos(b1));
        g1 = atan2(-R(3,1)/cos(b1), R(3,3)/cos(b1));

        b2 = atan2(R(3,2), -sqrt(R(3,1)^2 + R(3,3)^2));
%          d2 = cosd(b2*180/pi)
%          a2 = atan2(-R(1,2)/d2, R(2,2)/d2)
%          g2 = atan2(-R(3,1)/d2, R(3,3)/d2)
        a2 = atan2(-R(1,2)/cos(b2), R(2,2)/cos(b2));
        g2 = atan2(-R(3,1)/cos(b2), R(3,3)/cos(b2));
```

```
    elseif num_dof == 7
        % Extract the only possible set
        b = atan2(R(3,2), R(3,3));
        a = atan2(R(2,1), R(1,1));
        g = 0;
    end

elseif joint == 4
    % MODIFIED SHOULDER JOINT
    % Extract both possible sets
        b1 = atan2(R(3,2), sqrt(R(3,1)^2 + R(3,3)^2));
%         d1 = cosd(b1*180/pi);
%         a1 = atan2(-R(1,2)/d1, R(2,2)/d1);
%         g1 = atan2(-R(3,1)/d1, R(3,3)/d1);
        a1 = atan2(-R(1,2)/cos(b1), R(2,2)/cos(b1));
        g1 = atan2(-R(3,1)/cos(b1), R(3,3)/cos(b1));


        b2 = atan2(R(3,2), -sqrt(R(3,1)^2 + R(3,3)^2));
%         d2 = cosd(b2*180/pi);
%         a2 = atan2(-R(1,2)/d2, R(2,2)/d2);
%         g2 = atan2(-R(3,1)/d2, R(3,3)/d2);
        a2 = atan2(-R(1,2)/cos(b2), R(2,2)/cos(b2));
        g2 = atan2(-R(3,1)/cos(b2), R(3,3)/cos(b2));

end

% DETERMINE CORRECT SET OF JOINT ANGLES
if num_dof == 9 || joint == 1 || joint == 4
    if joint == 1
        a = a1;
        b = b1;
        g = g1;
    else
        if (a1 >= constr(1,1) && a1 <= constr(1,2) && b1 >= constr(2,1) && b1
<= constr(2,2) &&...
                g1 >= constr(3,1) && g1 <= constr(3,2))
            a = a1;
            b = b1;
            g = g1;
        elseif (a2 >= constr(1,1) && a2 <= constr(1,2) && b2 >= constr(2,1)
&& b2 <= constr(2,2) &&...
                g2 >= constr(3,1) && g2 <= constr(3,2))
            a = a2;
            b = b2;
            g = g2;
        else
            a = a1;
            b = b1;
            g = g1;
        end
    end
end
```

APPENDIX C: SOFT TISSUE CORRECTION

```
function [RBAt, RCBt, RDCt] =
STACC(RAU0,RBU0,RCU0,RDU0,REU0,RFU0,RGU0,RHU0,REUt,RFUt,RGUt,RHUt,approx)

% This Soft-Tissue Artifact Correction Code calculates joint rotation
% matrices from sensor rotation matrices while correcting for soft-tissue
% artifact in humeral internal/external rotation and in forearm
% pronation-supination.
% Written by Steven K. Charles, Brigham Young University, 2012

% INPUT
% RAU0,RBU0,RCU0, and RDU0 are rotation matrices at calibration of a BCS
% relative to the universal frame U.
% REU0,RFU0,RGU0, and RHU0 are rotation matrices at calibration of an SCS
% relative to the universal frame U.
% REUt,RFUt,RGUt, and RHUt are rotation matrices at time t of an SCS
% relative to the universal frame U.
% The input "approx" specifies the level of approximation:
% 2: 7-DOF model with gs derived from forearm orientation
% 3: 7-DOF model with ge derived from hand orientation
% 4: Approximations 2 and 3 combined

% OUTPUT
% RBAt, RCBt, and RDCt are rotation matrices across joints, describing the
% orientation of the distal segment relative to the proximal segment.

if approx == 2

    BYB = [0 1 0]';
    CYC = BYB;

    UYB = RFUt*RFU0'*RBU0*BYB;
    UYC = RGUt*RGU0'*RCU0*CYC;

    UZB = cross(UYB,UYC) / norm(cross(UYB,UYC));
    UXB = cross(UYB,UZB);

    RBUt = [UXB UYB UZB];

    RBAt = RAU0'*REU0*REUt'*RBUt;
```

```
    RCBt = RBUt'*RGUt*RGU0'*RCU0;

    RDCt = RCU0'*RGU0*RGUt'*RHUt*RHU0'*RDU0;

elseif approx == 3

    CYC = [0 1 0]';
    DXD = [1 0 0]';

    UXD = RHUt*RHU0'*RDU0*DXD;
    UYC = RGUt*RGU0'*RCU0*CYC;

    UZC = cross(UXD,UYC) / norm(cross(UXD,UYC));
    UXC = cross(UYC, UZC);

    RCUt = [UXC UYC UZC];

    RCBt = RBU0'*RFU0*RFUt'*RCUt;
    RDCt = RCUt'*RHUt*RHU0'*RDU0;
    RBAt = RAU0'*REU0*REUt'*RFUt*RFU0'*RBU0;

elseif approx == 4

    BYB = [0 1 0]';
    CYC = BYB;
    DXD = [1 0 0]';
    BXB = DXD;

    % From approx 2
    UYB = RFUt*RFU0'*RBU0*BYB;
    UYC = RGUt*RGU0'*RCU0*CYC;
    UXB = RFUt*RFU0'*RBU0*BXB;

    if cross(UYB,UYC) == 0
        UZB = cross(UXB,UYB)/norm(cross(UXB,UYB));
    else
        UZB = cross(UYB,UYC) / norm(cross(UYB,UYC));
    end

    UXB = cross(UYB,UZB);
    RBUt = [UXB UYB UZB];

    % From approx 3
    UXD = RHUt*RHU0'*RDU0*DXD;
    CXC = [1 0 0]';
    UXC = RGUt*RGU0'*RCU0*CXC;
    %UYC = RGUt*RGU0'*RCU0*CYC; Not needed because calculated above

    if cross(UXD, UYC) == 0
        UZC = cross(UXC,UYC)/norm(cross(UXC,UYC));
    else
        UZC = cross(UXD,UYC) / norm(cross(UXD,UYC));
    end
    UXC = cross(UYC, UZC);
```

```
    RCUt = [UXC UYC UZC];

    RBAt = RAU0'*REU0*REUt'*RBUt;
    RCBt = RBUt'*RCUt;
    RDCt = RCUt'*RHUt*RHU0'*RDU0;

end
```