MEASURING INTENTION TREMOR IN MULTIPLE SCLEROSIS USING INERTIAL MEASUREMENT UNIT (IMU) DEVICES

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Abstract: This paper describes research to create a sensor based measurement system in order to provide detailed and accurate data on the movement disorder known as intention tremor, a condition that affects a significant proportion of individuals with multiple sclerosis. Intention tremor is a complex movement disorder that worsens during goal directed movements and can therefore be extremely disabling. Multiple inertial measurement unit devices were used to measure the upper limb of subjects with multiple sclerosis and intention tremor during standard clinical finger-to-nose tests and reach-retrieve tasks, which were designed to mimic activities of daily living. Analyses allowed information on tremor characteristics to be ascertained during these movements. The equipment and software provide a useful tool for clinical assessment of tremor, displaying a variety of relevant information at differing levels of detail, obtainable at several points over the torso, shoulder, upper arm, lower arm and hand. Examples of this data are discussed. The system allows tremor assessment in more detail than is possible with clinical tests that rely on visual assessments, and provides a tool that can accurately assess the benefits of future tremor reduction devices, or other interventions.

1 INTRODUCTION

MS is the most common disabling neurological condition affecting young adults (Calabresi, 2004). The onset of symptoms is typically between 20 and 45 years of age. More than 2.5 million individuals worldwide have MS. MS leads to substantial disability in more that 50% of patients (Prat, et al., 2002).

Though currently incurable, several treatments are available which may slow the appearance of new symptoms and reduce the severity of existing ones.

Movement disorders, including tremor, often occur as a result of MS. Tremor is estimated to affect 75% of people diagnosed with MS; it can be severely disabling and extremely difficult to treat (Alusi, et al., 1999). A form of tremor called intention tremor (sometimes described as, or as a sub-category of, kinetic tremor) is especially common in MS. This tremor exhibits itself during purposeful movement, such as reaching out or picking up an object, rather than at rest. It is often accompanied by slower, uncoordinated movements and a tendency to overshoot or undershoot targets, referred to as ataxia and dysmetria, respectively (Alusi, et al., 1999). Muscle weakness and sensory impairments are also found (Alusi, et al., 2000); these are likely to further complicate the movement disorder. Wrist, elbow and shoulder tremors were found to be particularly disabling when they occurred during activities of daily living (ADL) (Alusi, et al., 2001).

Initial work in this area discussed the use of miniature accelerometer and gyroscope micro-electromechanical systems (MEMS) sensors for measuring positions and movement (Hyde, et al., 2008). Such sensors have been combined into devices that provide three orthogonal axes each of accelerometer, gyroscope and magnetometer measurements, together with microprocessors that convert these readings into 3D orientations in space. The early development of these sensors is detailed in Luinge, et al., 2004 Luinge, et al., 2005. These have since been developed into commercial devices and

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several publications discuss their use in human measurement, monitoring and rehabilitation applications (e.g., Heinz, et al., 2006, Beauregard, 2007, Moore, et al., 2007 and Zhou, et al., 2006).

2 MOVEMENT MEASUREMENT

Several commercial systems that can provide 3D orientations in this manner are discussed in Ketteringham, 2010. The sensors used in this work were chosen for their ability to provide 3D orientation measurements in real-time, in an easily applied, unobtrusive system. These data can be used to give the position and movement of body segments in space.

This research used a set of 5 MTx sensors (in an Xbus kit, Xsens Technologies, The Netherlands). The computed 3D orientation from each of the 5 sensors was recorded over time during each run. The MTx sensors communicated with a battery powered Xbus Master unit that was worn on the body and communicated wirelessly with a PC.

The five sensors were positioned over the body surfaces at the torso, shoulder, upper arm, lower arm and hand, allowing the orientation of each body segment to be found at each point in time. The base of the torso was assumed to be static. Applying the measured body segment orientations to the known body segment dimensions allowed calculation of the body segment displacements, along with the displacements of points in space that move in relation to the body segments (e.g. a held object).

The relative orientations between segments (joint rotations) can also be found, and these can each be converted into a set of three rotations (Euler angles) that represent the rotation of each the joint around three orthogonal axes. These angles could prove useful in clinical practice if there was a requirement to study a specific joint angle, or set of joint angles.

The displacement and angle data can also be differentiated with respect to time to produce velocities and accelerations, and angular rates and angular accelerations. Further analyses can reveal the frequency content of the movements. The joint angles, angular rates and angular accelerations have also been used in inverse dynamics models, created in the Matlab® SimMechanics™ toolbox, for estimating joint torques during the movements, as described in Ketteringham, 2010 and Ketteringham, et al., 2008.

The movement measurement system therefore provides a useful tool for measuring tremor levels and movement capabilities in individuals during clinical assessments. It allows quantitative assessment of the efficacy of other treatments in a less subjective manner and in far more detail than is possible with visual assessment alone.

3 EQUIPMENT AND EXPERIMENTAL DESIGN

The Xbus Master was wirelessly interfaced via Bluetooth® to a portable PC running code written in Matlab, to obtain orientation and sensor data from the MTx sensors. Data were obtained at 50 Hz for each of the 5 MTx sensors.

3.1 Initial and Clinical Measurements

Ethical approval was obtained before carrying out these studies, and all subjects completed consent forms at or prior to the time of testing.

The subjects were initially tested to determine their symptom characteristics, before attachment of sensors. The initial clinical tests consisted of:

- A check for pain-free range of joint movement;
- An evaluation of eyesight;
- Muscle strength evaluation assessed on a Motricity scale;
- A Fahn test for upper limb tremor and ataxia.

These joint range of movement, eyesight and muscle strength tests were carried out to ensure that the subjects could comfortably carry out the tasks required during the recorded movements. Further details are given in Ketteringham, 2010.

The Fahn test consisted of a tremor assessment by observation while the subject held a pose, to assess postural tremor, and performed a finger-to-nose test, to assess kinetic and intention tremor. The subject was asked to hold a pose and perform these actions while a clinician observed the resulting movements.

Resting tremor was assessed with the subject sitting upright and fully supported by a high-backed chair, with arms fully supported against gravity on the chair's armrests. Postural tremor was assessed while the subject sat upright, with their arms held out in front of them (elevated to 90° flexion) so that the upper arm, lower arm and hand were horizontal, and pointed directly forwards, with the hands shoulder width apart and palms faced downwards. Kinetic and intention tremor were assessed during a finger-to-nose test, described below. The movement towards the nose in the finger-to-nose test was used to assess kinetic tremor, while the part of the finger-to-nose test where the finger approached and briefly remained at the nose was used to assess intention (goal oriented) tremor. Feys et al., 2003 discuss the reliability of the observed finger-to-nose test for rating tremor.

Body segment dimensions were measured before attachment of the sensors, as described in Ketteringham, 2010.

3.2 Sensor Positioning

The MTx sensors were placed as follows, locating as flat an attachment position under each sensor as possible:

1. On the midline of on the torso, over the upper part of the body of the sternum, pointing superiorly (upwards);
2. On the superior aspect (top) of the shoulder, on a flat region (where one could be found), medial to the acromion process, pointing laterally (to the side, along the shoulder);
3. On the distal end of the upper arm (the end of that segment that is closest to the hand), proximal to the lateral epicondyle, pointing distally (towards the hand end of the arm);
4. On the distal end of the lower arm, proximal to the wrist, on the dorsal surface (at the position that a watch would normally be worn), pointing distally;
5. On the dorsal surface (back) of the hand, pointing medially (inwards, towards a plane that divides the left and right sides of the body).

These sensor locations were chosen, in consultation with medical professionals, as being positions on the body where minimal skin movement artefacts would occur, due to movement of the flexible and compressible soft tissues that cover the more rigid skeletal structures beneath.

Sensor positions can be seen in Fig. 1 (with the exception of the sensor on top of the shoulder). Sensors on the top of the shoulder, arm and hand were all positioned so that they were as horizontal as possible when the arm was in the starting position (described below).

The MTx sensors were adhered to the skin surface using PALstickies™ hydrogel adhesive pads (PAL Technologies Ltd, UK) in order to prevent the sensors moving relative to the skin surfaces. MaxWrap™ silicone elastic straps (La Pointique Int'l Ltd., USA) were wrapped around the upper arm, lower arm and hand over the sensors to ensure minimal movement between the sensors and the underlying rigid body structures. The straps are not shown in Fig. 1, for clarity of the sensor positioning.

Figure 1: MTx sensor positions on the torso, shoulder (at the top of the image, under clothing), upper arm, lower arm and hand.

The Xbus Master data transmitter, which the sensors were attached to, is shown as the white box at the bottom of Fig. 1, attached to the subject with the supplied waistband.

3.3 Sensor Calibration and Starting Position

At the beginning of each movement test, which consisted of three replicates of each type of movement, the torso, shoulder, arm and hand were stabilised in the starting position (described below) for six seconds to allow the sensor readings to stabilise and to obtain the initial sensor orientations. The physiotherapist stabilised the arm in the starting position by grasping the hand and the elbow, and maintained as steady and stable a position as was possible. The pose was held as steadily as possible during this time, despite some subjects finding it difficult to maintain a completely relaxed, steady pose, even when fully supported and stabilised by the physiotherapist.

The starting pose was defined as:

- The torso held as upright as possible facing forwards;
- The shoulder and upper arm longitudinal axes pointed laterally (to the side);
- The lower arm and hand longitudinal axes pointed to the front;
- The fingers pointed forwards, with the hand held flat, palm faced downwards.

All body segments were held as horizontal as possible (except the torso, which was held vertical), with orientations as close to the world X-, Y- and Z-axes as possible, as shown in Fig. 2. It was the central axis of each segment (considered to be the line that directly linked the joints between the body segments) that was held aligned to the world X-, Y- and Z-axes when in this starting pose.

This starting pose was easy for the physiotherapist to maintain and had the additional advantage of starting each axis of rotation, of each joint, at a position that was close to the centre of its range of movement. This meant that the joint angles would be much less likely to vary by as much as ±90° from this position during these movement tests, which is a great advantage when working with Euler angles, as discontinuities can be achieved if the middle angle of a set of Euler angles reaches ±90°.

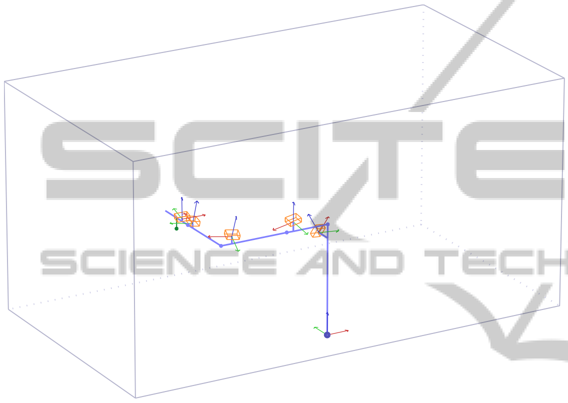

Figure 2: Representation of the body segments for the left arm (thick, purple lines), in the starting position, viewed from behind and to the left. Sensors are shown as orange wireframe boxes, in their average orientations during this period, and in the approximate positions relative to each body segment. World axes are shown as red, green and blue arrows (X-, Y- and Z-axes, respectively) at the base of the torso. Local axes of each sensor are shown in the same colours, emanating from the centre of each sensor's base. The thin green line connects the point of interest (green dot, described below) with the hand.

Average sensor orientations were obtained during the sixth second of measurement. Since the orientation of each body segment was known during this time, the orientation offset between each sensor and the body segment that it was attached to could be found. Each of these orientation offsets was removed from the orientations measured at each sensor over the entire data recording period, providing the orientations of the body segments themselves.

Once the orientations of the body segments were calculated, the displacements of the body segments in space, relative to the origin at the base of the torso, were found by multiplying the rotation matrices representing the body segment orientations with vectors representing the dimensions of the body segments, then attaching the rotated body segment vectors end-to-end, to provide a model of the body segments like that in Fig. 2.

3.4 Movements Measured using Sensors

Both clinical finger-to-nose and reach-retrieve tests were measured using the sensors. The reach-retrieve tests were designed to measure movement and tremor during task-oriented ("functional") everyday-type movements. The movements were unconstrained to make them as representative as possible of movements in ADL.

The clinically assessed, and sensor-measured, finger-to-nose tests used in these tests were similar to those tested in Feys, et al., 2003 (which compared a variety of methods). The movement sequence is described below:

1. Starting at a holding position, with the arm outstretched, and all limb segments pointing laterally (to the side), with the elbow fully extended, all arm segments held as horizontally as possible;
2. Flexing the elbow to move the finger to the nose;
3. Arriving at the nose and holding the finger at the nose (or as close to it as possible) for a short time;
4. Extending the elbow, and returning the arm to the outstretched position.

The physiotherapist stood in front of the subject and demonstrated the required movement before the tests began. The clinical finger-to-nose test was observed from in front of the subject.

The reach-retrieve movement required the subject to move a ball between a near and a far cup, in the sequence described below:

1. Starting at a resting position moving the hand forwards to pick up the ball, initially situated at the far cup;
2. Carrying the ball from the far cup to the near cup and depositing it;
3. Moving back to the rest position after depositing the ball, and resting briefly at the rest position;
4. Moving forwards, from the rest position to pick up the ball, now situated at the near cup;
5. Carrying the ball from the near cup to the far cup and depositing it;
6. Moving back to the rest position after depositing the ball.

The subject rested their arm before, between and after each reach-retrieve part in a position where it was completely supported by the armrest of the chair in which they were seated. This allowed their tremor to subside between movements, which gave visual pointers to the duration of the movements in the resulting data and provided a relatively static period in which the sensors could reset the drift that can occur in the readings during higher frequency movements.

The balls in the reach-retrieve tests were moved forwards and backwards between shallow cups, which stabilised their position when being picked up and deposited and provided a clear goal of where the ball should be deposited, fixing the positions that the ball was moved between. The far cup was positioned at a distance in front of the subject that provided a comfortable full reach, while the near cup was positioned 5 cm from the edge of the table. Both cups were positioned directly in front of each subject's shoulder joint. The distance between cups depended on the subject's stature, and varied from 14 to 20 cm.

3.5 Selecting a Point of Interest

A "point of interest" (POI) was chosen in order to simplify study of the measured movements. This was considered to be the part of the body, or a position relative to a body part, that the subject was concentrating on during the tests. For this reason, the POI was considered to be in a different position depending on the test being carried out. The POI was considered to be the tip of the middle finger if a finger-to-nose test was being carried out, or below the palm of the hand (as shown in Fig. 2.), at the position that the centre of the ball would be when the ball was being carried in the hand. This POI rotated with the rotation of the hand, and so it was always in the same position relative to the hand.

Some example data, showing the displacement of the POI in space, are discussed below.

3.6 Data Analysis and Filtering

In order to study the tremor in the movements, the displacements of the POI in space were filtered to leave only the high frequency components. A high-pass fifth order Butterworth filter with a cutoff frequency of 2 Hz was applied to the data in forwards and reverse directions, to provide acausal filtering. This filter gave a sharp separation between the high and low frequencies, with minimal ripple in the passband, and 50% attenuation of the data at frequencies of 2 Hz (as it was applied to the data twice).

The X-, Y- and Z-axis displacement data were filtered separately, to leave only the high frequency components that were superimposed on top of the lower frequency voluntary (intentional) and ataxic movements.

While the alignment of the tremor with the X-, Y- and Z-axes can indicate, to some degree, which joints are involved in the tremor movements, it may be better, from a clinical point of view, to simplify the data by combining the tremor displacements in the three X-, Y- and Z-axes into a single measure of tremor displacement, in an arbitrary direction. These data represent the magnitude of the tremor at any point in time, and can be calculated as a "3D hypotenuse" of individual displacements in the X-, Y- and Z-axes:

$$d_{t,m} = \sqrt{d_{t,X}^2 + d_{t,Y}^2 + d_{t,Z}^2} \tag{1}$$

where $d_{t,m}$ is the tremor displacement magnitude in an arbitrary direction, and $d_{t,X}$, $d_{t,Y}$ and $d_{t,Z}$ are the tremor displacement magnitudes in the individual X-, Y- and Z-axes. This reduces the data set threefold, while maintaining information on the magnitude of tremor, in an arbitrary direction.

Obtaining the tremor magnitude in an arbitrary direction requires squaring the data, however, leading to loss of sign information. This can give inaccurate results when analysing the resulting rectified data for frequency information (as an example, a rectified and non-rectified sine wave contain different frequency components). A method was created to negate portions of the resulting data, in order to return it to being a waveform that represented the tremor movements alternating to "either side" of the lower frequency data, as discussed in Ketteringham, 2010.

Windowed power spectra were calculated at regular intervals through the resulting tremor magnitude data. The power spectra were calculated at time increments of 0.3 s, with a time window size of 1.3 s. This window size was found to be optimal in terms of producing good frequency and time resolution; a shorter window was more responsive to rapid changes in movement while a longer time window gave better differentiation of the frequencies contained in the data. The power spectrum obtained from each analysed window of data was normalised to the maximum power in that time window, as this provided a clearer indication of the dominant frequencies throughout the data. The power spectrum analysis was limited to a maximum of 8 Hz.

4 RESULTS: EXAMPLE DATA FROM FINGER-TO-NOSE AND REACH-RETRIEVE TESTS

The following results are example data from a subject completing the first of three replicates of a finger-to-nose test and a reach-retrieve test, in Fig. 3 and Fig. 4, respectively. The data represent the movements of the POI in space, analysed as described above, shown as a contour plot of the normalised, windowed power spectra, together with a concurrent plot of the displacement data.

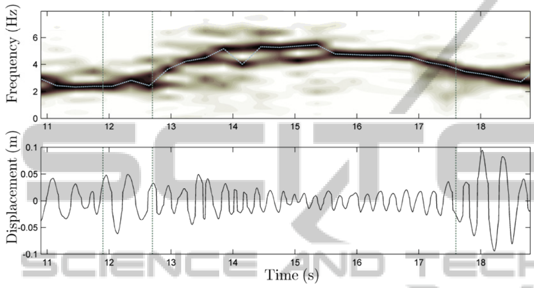

Figure 3: Tremor frequencies and displacements of the POI during a finger-to-nose test.

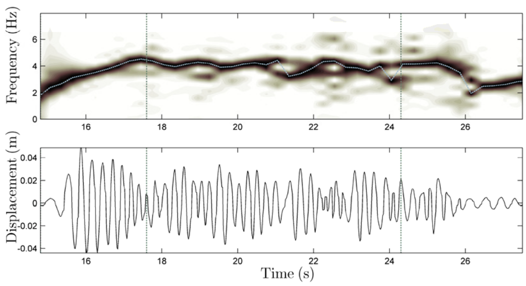

Figure 4: Tremor frequencies and displacements of the POI during parts 1 to 3 of a reach-retrieve test.

The dotted line that passes through the power spectra from left to right indicates the frequency with the maximum power in each of the time windows. The vertical dash-dot lines in Fig. 3 (nominally) separate the four regions of the finger-to-nose test, as described above. Fig. 4 shows only parts 1 to 3 (of parts 1 to 6, described above) of a reach-retrieve test, as the data in parts 4 to 6 were fairly similar to the first three parts, and the duration of parts 1 to 3 was similar to that of one replicate of the finger-to-nose test, giving a better comparison. Again, the parts are separated by vertical dash-dot lines.

The lightness of the regions on the contour plot shows the relative power of the particular frequencies at a particular time, where a darker region indicates the dominant frequencies (those with a higher power). No power magnitude (colour bar) is shown with the contour plot, as the maximum power values in each time window were normalised, so the maximum "elevations" are of value 1.

High frequency Euler angle data (three orthogonal rotations for each joint in the body model) are also shown, in Fig. 5 and Fig. 6. The high frequency angle data were obtained from the Euler angle data by applying the same high-pass, acausal, fifth order Butterworth filter, with a cutoff frequency of 2 Hz, as described above.

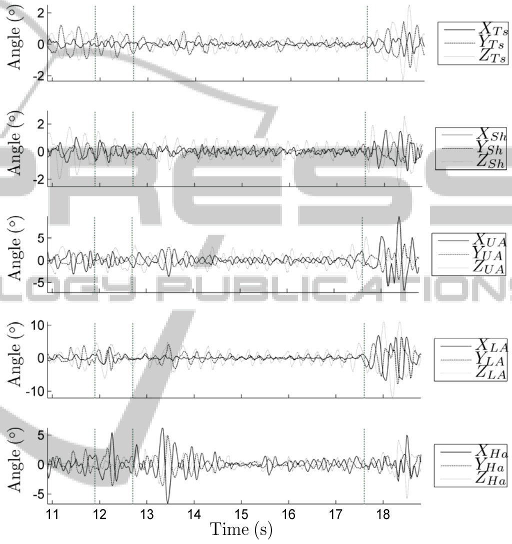

Figure 5: High frequency components of the joint angles during a finger-to-nose test.

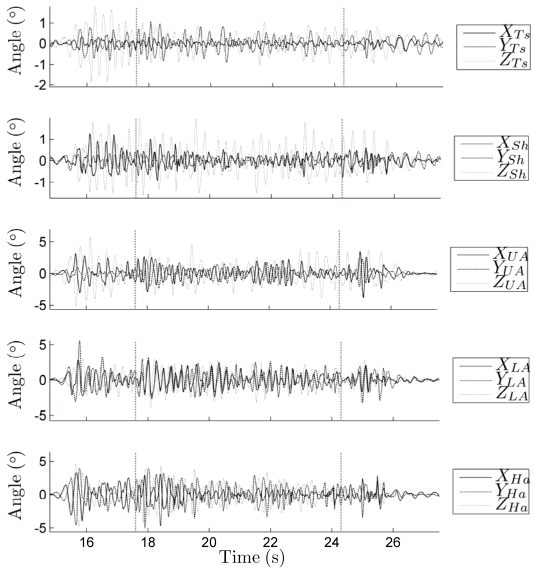

Figure 6: High frequency components of the joint angles during a reach-retrieve test.

The subscripts Ts, Sh, UA, LA and Ha in the legends indicate the particular joint that the torso, shoulder, upper arm, lower arm and hand segments are rotating about. X, Y and Z indicate the axis that the rotation is about. These rotations were aligned with the world X-, Y- or Z-axis, respectively, when the body was held in the starting position. This is discussed in more detail in Ketteringham, 2010.

5 DISCUSSION OF RESULTS

The tremor frequencies found in the data were mainly between 3 and 5 Hz. This agrees with descriptions given in several previous studies (e.g. Alusi, et al., 2001, Gillard, et al., 1999 and Deuschl, et al., 1998). The tremors described in such publications are often reduced to simple values, without reference to changes over time. These data show that the tremor frequencies are by no means constant throughout an unrestricted, full arm movement, but vary due to the configuration of the arm, and may be affected by the stiffness of the joints due to muscle co-contraction. There are also points in the data where the tremor movements are not at a single, dominant frequency, but are distributed over a range of frequencies.

Many previous studies have restricted movement to one joint axis, one joint or a small range of joints. In these cases a more limited range of frequencies may be witnessed. These kinds of studies can not represent the tremor as seen in full, unrestricted movement, though. Measurements of unrestricted movements are arguably more useful when studying movement in ADL, in order to ascertain improvements in tremor due to interventions or other methods for controlling tremor.

Some frequencies below 3 Hz can be seen during the more restful periods at the beginning and end of the reach-retrieve movements. These parts also had low amplitudes in the tremor, as tremor subsided on cessation of movement. At other times during the reaching task, the tremor was relatively stable in terms of frequency and amplitude, though the amplitude varied somewhat over a period of 2-3 cycles, probably due to changes in the configuration of the arm during the task and the interactions between the tremors that arose in the joints. Similar characteristics can be seen in the joint angles in Fig. 6. The tremor took 2-3 cycles to reach full amplitude on beginning the task.

The finger-to-nose test showed quite different characteristics. While the tremor was of a similar, or slightly higher, frequency during the parts where the finger was held at or near the nose, larger, lower frequency tremor occurred at the beginning and end of the movements.

At the beginning of each finger-to-nose movement, the subject held their arm out to the side. A typical stabilisation tactic for subjects with tremor is to “lock” the lower arm and wrist joints at the end of their range of movement while the arm is in this position, with the elbow (Z_{LA} in Fig. 5 and Fig. 6) extended, the lower arm (Y_{LA}) supinated (to turn the palm upwards) and the wrist (X_{Ha}) extended. This was the case during this test.

Little tremor can originate at the elbow, lower arm or wrist when in this position, but it can once the movement to the nose has commenced and the joints can move more freely. The arm is also longer and more rigid in this configuration, making it act like a longer pendulum of larger mass, compared to when the elbow, especially, is more flexed. These factors can lead to lower frequency, larger magnitude tremor displacements at the hand.

Similar features can also be seen in the joint angles in Fig. 5, and the tremor can be seen to originate more from the torso and shoulder at the beginning and end of the test movements, where the distal joints are less free to move.

6 CONCLUSIONS

This kind of coupled measurement and analysis system can be seen to provide detailed and useful data for measuring and investigating movement and tremor.

The system can be used to generate a wide variety of data, including displacements of the body segments in space and joint angles. As discussed earlier, these data can be further analysed to produce kinematic data sets which can be used to drive inverse dynamic models to obtain joint torque estimates.

On their own, however, these displacements can still be a useful measure of the tremor present in an individual's movements, and should prove to be a useful tool in clinical practice, whether used for assessment of tremor progression or for assessment of the effects of an intervention to improve tremor.

The different movements in the two tests measured here result in observable differences in the resulting tremor. The characteristics of the tremor change more during the finger-to-nose test than during the reach-retrieve test. The configuration of the arm when fully extended can be seen to lead to lower frequency, larger amplitude tremors. These are similar to those seen in a typical clinical "postural" tremor test, where tremor is observed while the arms are held out, fully extended in front of the body. The tremor can not occur to such a degree in (especially) the elbow when in this position. The extended arm represents a longer pendulum of larger mass than when the elbow is flexed, so a lower frequency movement results, emanating from the torso and shoulder joints.

It could be argued that the positions held, and movements made, in the finger-to-nose tests are not particularly "functional" (i.e. representative of a typical everyday action, or ADL), and that the tremor seen during a task with the arm held outstretched is somewhat an artefact of the position that the arm is held in.

Movements such as the reach-retrieve task described here could be said to be more representative of ADL. The characteristics of the tremor during those tasks were relatively consistent throughout, and there was no opportunity for joints to be "locked" at the limit of their range of motion.

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