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(RESEARCH ARTICLE)

Inertial sensor based quantitative assessment of upper limb range of motion and functionality before and after botulinum toxin: a pilot study

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Abstract

Botulinum toxin (BTX) treatment of upper limb is considered effective for upper limb spasticity following stroke and brain injury. Traditional method - Modified Ashworth Scale (MAS) is widely used for assessment of spasticity, however, it suffers from limitations including the lack of objective outcome measures and ignorance of the active movements. This pilot study is to develop a quantitative assessment utilizing inertial sensors tool for upper limb movement measurement and to investigate an objective measure of upper limb function for neurological patients before and after BTX treatment of spasticity. The system we proposed provides kinematic measurements of upper limb segment and joint motion data. In this study, four stroke patients were assessed by an inertial sensing system immediately before and one week after BTX injection. In addition, patients were assessed using clinical assessment scales e.g. MAS, Disability Assessment Scale (DAS) and Motor Assessment Scale. The results showed that elbow Active Range of Motion (AROM) increased by 19 degrees on average and MAS and Motor Assessment Scale scores did not show significant change. The changes of the kinematic measures for patients 1-3 e.g. AROM, Rate of change of elbow joint angle, NJS, MUN and S-ratio all show that the inertial system is able to identify improvement in performance. This inertial sensing system provides additional and novel dynamic motion data for a sensitive and quantitative assessment of response to treatment and the efficacy of post-injection physiotherapy.

Keywords: Muscle Spasticity; Botulinum Toxin; Upper Limb; Inertial Sensing

1. Introduction

Spasticity is a late complication after an injury to the Central Nervous System (CNS) e.g. multiple sclerosis, spinal cord injury and brain injury. It is characterized by a velocity-dependent increase in the muscle tone and resistance to passive stretch, which is caused by hyperactive stretch reflexes as first described by Lance in 1980 [1]. In addition, the presence of spasticity causes muscle stiffness and in some patients, muscle pain [2-4].

Therefore, untreated spasticity can limit the amount of exercise that a patient will tolerate and hence reduce the effectiveness of therapy and the rate of recovery. Current methods used to treat spasticity include oral anti-spasticity medications (e.g. baclofen) [5] and physiotherapy. More recently, Botulinum Toxin has proved an effective treatment for spasticity [6-8].

Traditionally the Ashworth Scale (AS) [9], MAS [10], DAS [11] and Goal Attainment Score (GAS) [12] are used to measure the spasticity of the upper limb and to assess response to treatment [13]. These spasticity scales measure resistance to passive movement of limb segments about a joint [14] or provide a measure of the patient's ability to perform selected tasks. However, the administration and scoring of spasticity using these assessment methods is thought to be very

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subjective. As a result, they are considered to have questionable validity and reliability [15,16] even though they are the standard spasticity and functional assessments.

Measures such as MAS assess passive, rather than active movement, however active motion may have a closer relationship with function and be a better measure of patient response to treatment. Therefore, there has been a growing demand for a more objective and active assessment of upper limb spasticity and function. In response to this need methods for the objective assessment of spasticity and function have been developed. These include the use of Isokinetic dynamometers [17-18], electro-goniometers [19], electromyography (EMG) [20] and the analysis of data from these techniques using biomechanical models [21]. Most isokinetic dynamometers can only measure passive motion and that motion in one plane only. EMG measurements also have limitations because of the administrative requirements and the impact of subject dependent factors on interpretation of the data, such as electrode placement and muscle atrophy [22-24]. However, due to the lack of a Gold Standard to measure impairment level, major multi-national clinical re-search still relies on AS or MAS to assess the efficacy of rehabilitation protocols, including anti-spastic agents like BTX [25, 26].

Therefore, a measurement system utilizing inertial sensors was developed to measure the kinematics (time dependent movement) of the upper limb segments in order to investigate whether upper limb spasticity, changes in spasticity and changes in function could be assessed in a more objective fashion. This system presents the time dependent 3D position and orientation of segment and joints throughout an assessment. The accuracy of position tracking utilizing this inertial measurement system has been shown to be within 0.1 cm over a movement distance of 10 cm and that of orientation to be within 1° [27]. The system was previously evaluated on five healthy volunteers and two patients with neurological disorders to obtain base line data [28].

This study on four neurological patients, follows on from this evaluation and the system was used to investigate whether it is possible to monitor changes in spasticity and upper limb function immediately before and one week after Botox treatment. The data was analysed to provide the kinematic parameters of elbow extension AROM, rate of change of elbow joint angle, normalized jerk scores (NJS) [29], Movement Unit Number (MUN) [30] and upper limb joint/segment trajectory. This data and changes in the data are then compared with the traditional MAS and Motor Assessment scale measures.

2. Methods

2.1. Instrumentation

In this study, a wearable system is used, which does not require a specialised set-up as required by the video systems of Vicon and Qualisys and can be used in any environment [28]. Xsens MTx [31] inertial sensors are attached to the hand, forearm, upper arm and shoulder of each participant (Figure 1). Each inertial sensor comprises of a 3D accelerometer, gyroscope and magnetometer which enable 3D orientation tracking [27, 32]. Its dimension is 38*53*21 (W*L*H) (mm) and weight is 30 grams. A kinematic model was developed in order to translate the sensor movement from the sensor reference frames to that of the desired reference relative to the patient [27]. In this case the reference frame is usually the patient's shoulder for segment displacement or the elbow AROM measurement (Figure 1).

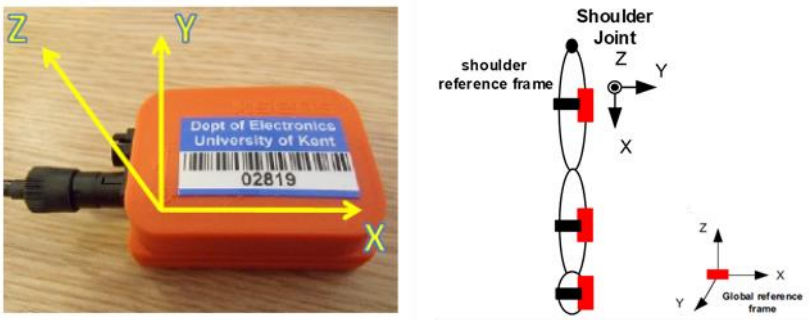


Figure 1 Reference frames for the XSens MTx inertial sensor system.

2.2. Participants

Three men and one woman (69-76y with a mean age of 73y) undergoing BTX treatment were recruited (Table 1) to investigate the effect of that treatment on upper limb spasticity. All participants were right handed, both upper limbs were affected and the left side most affected. Therefore, in this study the left upper limb was assessed.

Table 1 Participant Information**.**

Patient No.	**1**	**2**	**3**	**4**
Gender	Male	Male	Female	Male
Age	72	76	75	69
Handedness	Right	Right	Right	Right
Injected Side	Left	Left	Left	Left
Stroke duration	2 yrs	4 yrs	4 yrs	2 yrs
Brain Lesion	Right MCA infarct (parietal lobe)	Right thalamic infarct	Right MCA infarction infarct	Right MCA infarction infarct
BTX Dose	200 units (Dilution with 4ml normal saline)	300 units (Dilution with 3ml normal saline)	200 units (Dilution with 4ml normal saline)	200 units (Dilution with 4ml normal saline)
Muscle Injected	Bicep, FDP, FDS	Pectoralis Major, FDP FDS, FCR, FCU	FDP, FDS, Bicep and Brachioradialis	FDP, FDS and Bicep

Acronym: FDP: Flexor Digitorum Profundus, FDS; Flexor Digitorum Superficialis, FCU: Flexor Carpi Ulnaris, FCR: Flexor Carpi Radialis

Written informed consent was obtained from each subject before enrolment and participation in this study. Ethics permissions were obtained from the UK NHS National Research Ethics Committee (IRAS 25835) and the Hospital Institutional Review Board (IRB).

2.3. Test procedure

Participants were seated on a chair or their own wheelchair in front of a fixed height test-table and four Xsens MTx inertial sensors were then aligned and attached with Velcro straps.

Spasticity was assessed by use of the MAS, and up-per limb function by using DAS and Motor Assessment Scale. The inertial measurement system was used to monitor elbow active extension and to collect data during the nine-hole peg test, bean bag test and water drinking test. Because of the issue of participant fatigue, each test could only be implemented twice. All four subjects participated in two assessment sessions, one before and the second seven days after BTX treatment.

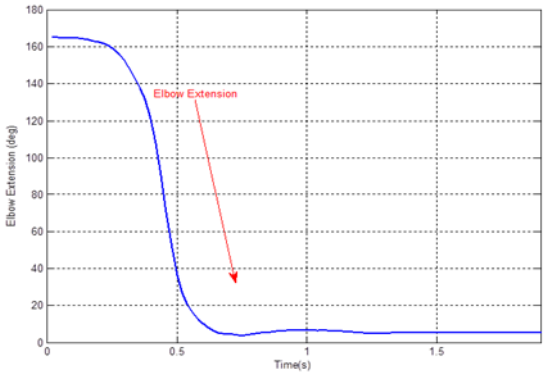
Although the nine-hole peg test and bean-bag tests were carried out, this paper only presents the measurements and analysis for elbow extension and lower arm segment (wrist/hand) movement as these movements are also assessed in the MAS. The analysis of the kinematic data includes presentation of joint angle against time, estimation of the elbow joint extension AROM [27, 32], hand trajectory in 3D space, and the MUN and NJS movement smoothness parameters [33]. The pre and post BTX treatment outcomes for the kinematic parameters and the MAS will be compared.

3. Results

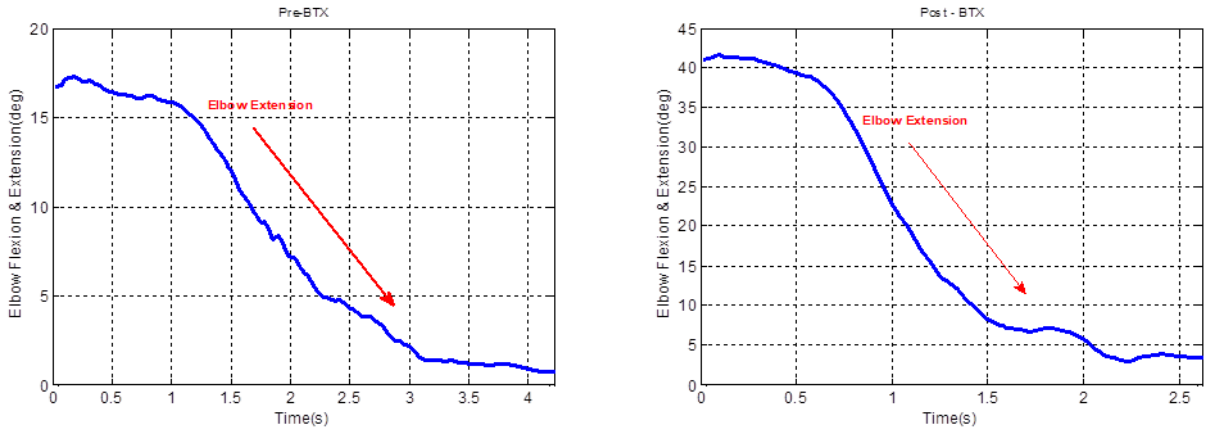
In this paper, only the outcome of the elbow extension analysis and lower arm segment trajectory are presented.

3.1. Active range of motion and elbow extension time dependence

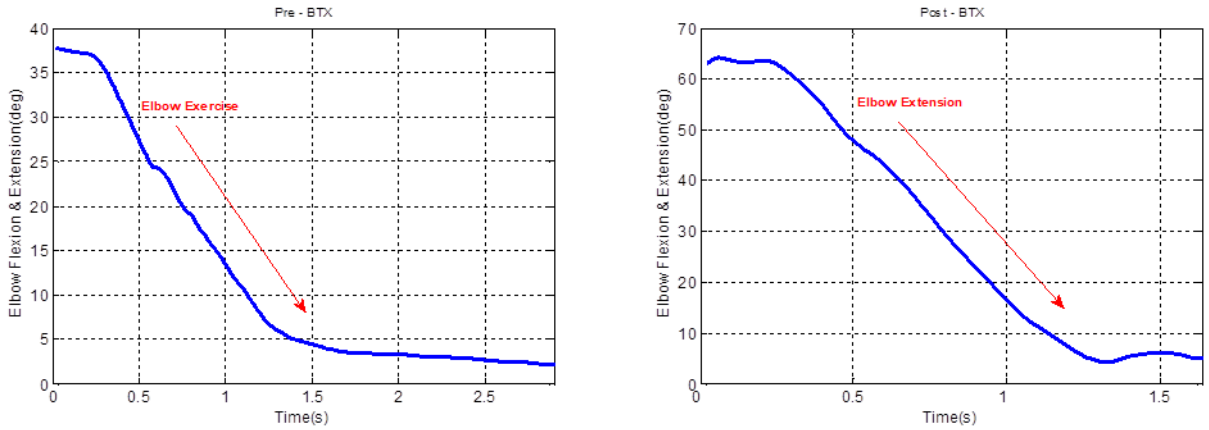
The overall value of the AROM, its time dependence and the completion time are three important parameters which indicate the change of the subject' performance. In Figure 2, the time dependence of the elbow extension angle of a typical healthy participant and for two of the patients are presented.



(a) Elbow extension of a normal participant



(b) Patient No.1 Pre- and post-BTX: Elbow extension



(c) Patient No.2 Pre- and post-BTX elbow extension

Figure 2 Time dependence of elbow extension angle

A typical normal AROM of elbow flexion and ex-tension is 145-160° [34]. However, the elbow extension required for daily activities has been reported to be less than the normal anatomic range and can be as little as 30° [35]. In this case the normal had an AROM of 160° and an average angular velocity of 215°/s. It can be seen from the plots that compared with normal function both participants had restricted AROMs and rate at which the movement is performed. For participant 1 there is improvement in movement with an increase in AROM from 17° to 39°, and a decrease in time from approximately 4 to 2.5 seconds with an increase in rate of 4°/s to 15°/s. Similarly for participant 2, the AROM has increased from 38° to 63°. The time taken to perform the movement has decreased from approximately 3 to 1.5 seconds,

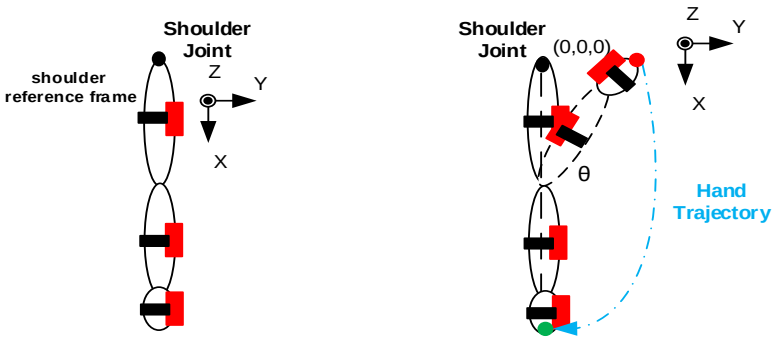
with an improvement in rate of change of angle from approximately 12°/s to 40°/s. Additionally the plot of joint angle against time provides information on the smoothness of the movement. In this case the movement for the normal is visually smother than that of the two patients. Because it is difficult to visually provide a numeric measure of these changes, additional parameters will be added to the automatic analysis - rate of change of joint angle and movement smoothness.

3.2. Joint position trajectory

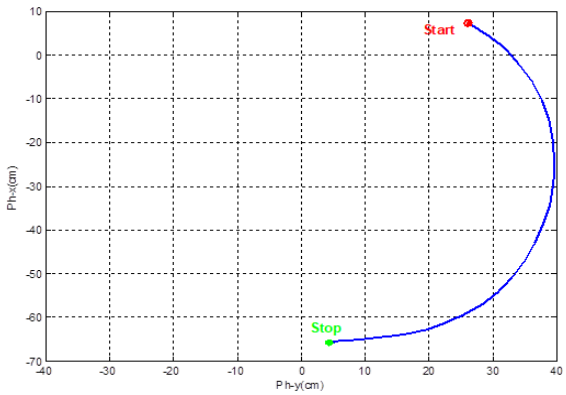
Figure 3 (a) shows the 2D upper limb segment position trajectory in the shoulder reference frame [27]. Figure 3 is that of the hand during the elbow extension test for a typical healthy subject while Figure 3 (c) and (d) show that of patient 1. A knowledge of the AROM and the segment lengths enables an estimate of the expected trajectory to be made.

In Figure 3 (a), it can be seen that the normal volunteer with an elbow hand segment length of approximately 37 cm had a smooth movement, beginning with the hand about 22 cm in front of the shoulder (X displacement). The total displacement of the hand relative to the shoulder in the X axis is approximately 70 cm. The maximum displacement relative to the shoulder is approximately 28 cm in the Y axis, rather than the expected 37 cm. This discrepancy can be accounted for by shoulder joint rotation during the AROM manoeuver. This type of movement is also likely to happen with the patients, who find the manoeuver very difficult and unconsciously compensate by rotating the shoulder joint.

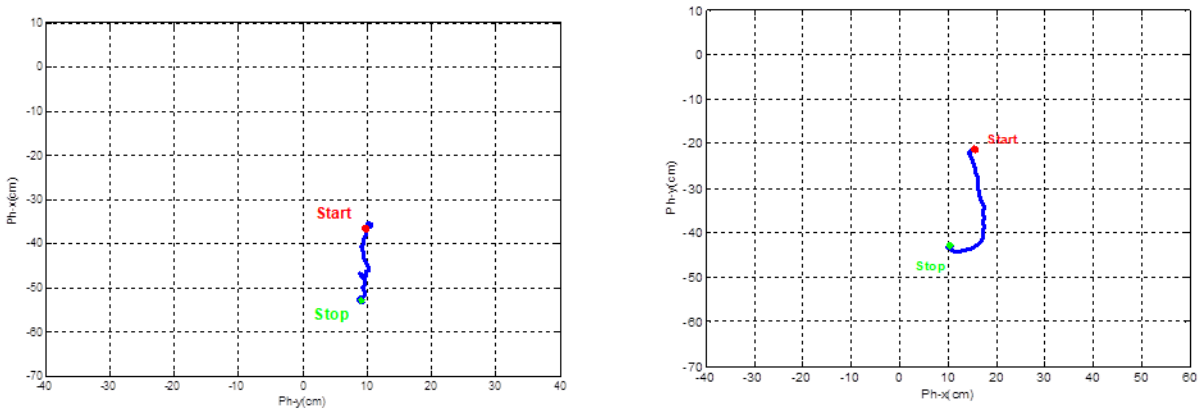
From Figure 3 (b) and Figure 3 (c) it can be seen that the patient, due to the effect of the spasticity, had very limited range of movement (17°). The restricted movement in the Y axis of a few mm and only 14 cm in the X axis indicate that the majority of this manoeuvre was accomplished by compensatory rotation of the shoulder. Additionally, it can be seen that the movements show the presence of tremor. It can be seen that after the BTX injection (Figure 2 (b) and 3(d)), this uncontrolled movement has reduced and the range of the movement has increased (39°), with a 24 cm displacement in the X axis and 5cm in the Y axis. This outcome is typical of the patients assessed in this study.



(a) Elbow extension and hand trajectory in the x-y plane of the shoulder reference frame



(b) Normal: Hand trajectory



(c) Patient No.1 Pre- BTX: Hand trajectory (d) Patient No.1 Post-BTX: Hand trajectory

Figure 3 Hand Trajectory in the X-Y plane during elbow extension for a typical healthy subject and patient 1.

The analysis of this data is time consuming and not straightforward. Therefore additional analysis techniques focusing on the kinematic parameters were investigated.

3.3. Kinematic and standard assessment parameters

In addition to the orientation and trajectory related parameters introduced in the previous section, the following dynamic parameters have been selected to see whether they can indicate early changes in the effect of BTX on upper limb spasticity whilst performing the elbow AROM manoeuvre.

- Active Range of Motion in extension - AROM (°).
- Rate of change of elbow joint angle (°/s) whilst performing the AROM manoeuver.
- Normalised Jerk Score (NJS) - a measure of the smoothness of movement [29] whilst performing the AROM manoeuver - the smaller the score the smoother the movement.
- Movement Unit Number (MUN) - a measure of the smoothness of movement [30] whilst performing the AROM manoeuver - the smaller the MUN the smoother the movement.
- Wrist Trajectory (m) - the measured distance travelled by the wrist (joint) in three dimensions during the AROM manoeuvre.
- Ideal Wrist Trajectory for the measured AROM (m). This should be in two dimensions.
- S-ratio (Actual wrist Trajectory /Ideal wrist Trajectory) - measure of closeness to the ideal for the given trajectory which normalises for changes in trajectory as the participant AROM improves.

These measures are compared with the outcomes from the MAS and Motor Assessment scales in Table 2.

Table 2 Clinical measurements and kinematic parameters**.**

Elbow Extension	BTX	Patient No.1	Patient No.2	Patient No.3	Patient No.4	Typical Normal
MAS	Pre-	4	2	5	5	0
	Post- (% diff)	4(0%)	2(0%)	4(-20%)	4 (-20%)	
Motor Assessment Scale	Pre-	9	38	8	49	108
	Post- (% diff)	29(222%)	50(32%)	35(338%)	56(14%)	
AROM (deg)	Pre-	17	38	36	49	160
	Post- (% diff)	39 (129%)	63(65%)	51(42%)	63(29%)	
Rate of change of elbow joint angle (deg/s)	Pre-	3.9	11.1	6.0	14.8	215
	Post- /(% diff)	14.8(279%)	39.2(255%)	14.2(137%)	16.4(11%)	
NJS	Pre-	112	44	168	20	3
	Post-(% diff)	10(-91%)	3(-93%)	36(-79%)	46 (+130%)	
MUN	Pre-	144	94	204	92	12
	Post-(% diff)	60(-58%)	50(-47%)	110(-46%)	116(+26%)	
Wrist Trajectory (m)	Pre-	0.61	0.90	2.04	0.80	0.75
	Post-(% diff)	0.55(-10%)	0.83(-8%)	1.04(-49%)	1.51(+89%)	
Ideal Trajectory for measured AROM (m)	Pre-	0.08	0.18	0.17	0.23	0.78
	Post-(% diff)	0.18(125%)	0.30(67%)	0.24(41%)	0.29(26%)	
S-ratio (Actual Trajectory /Ideal Trajectory)	Pre-	7.9	5	11.9	3.5	1.0
	Post-(% diff)	3.0(-62%)	2.8(-44%)	4.3(-64%)	5.1(+46%)	

4. Discussion

4.1. Active range of motion and elbow extension time dependence

The graphical presentation of this data provides a visual representation in any of the axes, of joint rotation during the AROM. The AROM, time to perform the maneuver, approximate rate of change of angle, initiation, mid and final phases of joint rotation, as well as the smoothness of the movement can be deduced from this plot. Therefore an automated analysis system was developed to provide this information as well as additional kinematic parameters. Whether presenting the data in graphical format is of clinical value requires further investigation.

4.2. Joint position trajectory in the x-y plane relative to the shoulder reference frame

This is an example of one of the options for the presentation of segment movement. A comparison of normal and patient performance shows a significant difference in the way in which the extension of the elbow joint was achieved as well as being more sensitive than the MAS assessment to early improvement in the performance of the participants. However it is recognized that the greater the effect of spasticity on the patient, then the more abnormal the movement, or the greater the use of compensatory movements to perform the manoeuvre.

4.3. Kinematic and standard parameters

The MAS and Motor Assessment Scale show that the patients' performance was far from normal and all the patients have very limited active movement both before and a week after BTX treatment. In Table 2, it can be seen that any

changes in MAS are not significant and those for the Motor Assessment scale, although improving are still significantly subnormal. It should also be noted that the Motor Assessment Scale tests includes activities which are not solely dependent on the use of the elbow joint and lower limb segment. Therefore lack of improvement in elbow joint function may be masked by improvements the mobility of the other joints.

The kinematic analysis for elbow joint function for patients 1-3 shows an improvement in all the parameters, even though the values are still subnormal. The sensitivity of these parameters to change also seems to be better than that for the MAS.

The NJS and MUN values for participants 1-3 show a reduction in jerkiness of movement indicating that although the BTX treatment has not yet had a significant effect on AROM, the muscle function relating to smoothness of movement is significantly improved. The S-ratio, which is a measure of how much compensatory movement the participants are employing to complete the maneuver, indicates that although the AROM and joint angular velocities are still small, the movement of the lower arm segment around the elbow is approaching that of the normal 2D movement. How-ever it can be seen that patient 4 response does not follow the general pattern. Although there are small improvements in MAS (5 to 4), Motor Assessment Scale (49 to 56) and AROM (49° to 63°) outcomes the kinematic measures indicate there is a deterioration in NJS (20 to 46), MUN (92 to 116) and in the ideal limb segment trajectory S ratio (3.5 to 5.1). This indicates that al-though the AROM has improved, control of the movement has not, or that compensatory movements have increased. This patient was also taking Baclofen which in terms of all the measurements presented in Table 2, seems to have reduced the expected effect of Botox.

5. Conclusion

The findings of present study indicate that an inertial measurement system may be able to provide early indication of changes in upper limb mobility and novel information about temporal and spatial characteristics of that movement which may not be evident in the more traditional measures. The measurement of active, rather than passive motion is also thought to be of particular value. This preliminary analysis indicates that an inertial measurement system could be used to detect early changes in upper limb response to Botox treatment for spasticity as well as add value for longer term analysis.

Compliance with ethical standards

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Disclosure of conflict of interest

All the authors would like to declare that there is no conflict of interest relevant to this article.

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