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Quantitative measurement of Upper limb motion pre- and post-treatment with Botulinum Toxin

Lu Bai[1*], Matthew G Pepper[2,3], Yong Yan[2], Malcolm Phillips[4] and Mohamed Sakel[3]

Abstract

Background: Muscle spasticity is a common motor complication after stroke and brain injury, and Botulinum Toxin is considered effective treatment for upper limb spasticity. However, clinical assessments are not possible to provide the quantitative measurement of changes happening on different upper limb segments.

Methods: We aim to develop a multi-sensor system for quantitatively measurement of movement in all segments of upper limb. Five patients under neurorehabilitation were recruited to attend two-session rehabilitation assessment program to evaluate the changes before and one week after the Botulinum Toxin treatment.

Results: Clinical assessments are all improved in general (Disability Assessment Scale: $p<0.01$). Analysis of Kinematic parameters and smoothness quantification parameters showed that number of movement units ($p<0.05$ for elbow and wrist), normalised jerk score are improved for all upper limb segments.

Conclusions: This study demonstrate that our multi-sensor inertial sensing system can provide additional insights for motion quantification pre and post the Botulinum Toxin treatment.

Keywords: Botulinum Toxin; Kinematics; Upper limb function, Quantitative measures

Background

Upper limb spasticity could occur to patients who had stroke and brain injury [1]. The spasticity had been defined by Lance [2] as the velocity-dependent increase in the muscle tone which is due to the excitability of the stretch reflex. The spasticity affects the patients daily activities and mobility and also leads to pain and risk of falls [3]. Currently, Botulinum Toxin (BTX) treatment which is an injectable pharmacological agent has been proved an effective treatment for reducing the spasticity [4–6]. It improves patients upper limb dexterity in daily activities and increase the range of motion [7,8].

Traditionally, clinical scales are used to measure quality of life or the assessment of the motor function e.g. Fugl-Meyer [9] and Motor Assessment Scale [10]. The Modified Ashworth Scale (MAS) [11] widely used in clinical practice for evaluating upper limb muscle spasticity [12–14]. MAS measure relies on the expertise of the clinicians and it is very subjective. A device - NeuroFlexor [15] was proposed to quantitatively measure the spasticity of the wrist and fingers muscles. Though NeuroFlexor can capture some quantitative measures but similar as the traditional MAS, it only focuses on the passive motion rather than the active motion.

Functional recovery of the upper limb motion is extremely important in stroke rehabilitation, and it has been noted that the voluntary motion relates to the spasticity [1]. Though the above mentioned assessment methods are widely used, they are not able to capture the dynamic performance of the limb and the voluntary motion which is thought to be especially essential when assessing upper limb motor recovery.

The Vicon system which is seen as a gold standard in motion monitoring and has been used to capture kinematic information changes [16] after the BTX treatment. However, the Vicon

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system is complex in system set-up and is very expensive. With the emerging of the sensing technology, miniature wearable sensors for human movement tracking are becoming commercially available [17]. Studies have been done in measuring Range of Motion (ROM) [18] and movement coordination in neurological rehabilitation [19]. Additionally low cost sensors e.g. Microsoft Kinect has been used in human motion monitoring [20]. The analysis of the kinematics has shown the changes in the movement during the rehabilitation [21]. Especially, the movement smoothness calculated based on the kinematic measures has been used as an important indication of the performance evaluation of the upper limb motor function [22]. A number of parameters have been proposed for the quantification of the upper limb movement smoothness, for example, Number of Movement Units (NMU) [23], Normalised Jerk Score (NJS) [24].

More recently, several studies have been carried out to explore the quantitative measures on muscle spasticity using wearable devices [25] and robot assisted tools [26], which are mainly focused on evaluation of upper limb spasticity after BTX treatment. More specifically, one study is focusing on quantitative spasticity of calf muscle [27]. Voluntary movement is considered important to the upper limb functioning in the daily lives of patients [28] and facilitating the optimal recovery of upper limb volunteer movement is a major concern in rehabilitation [29]. However, to our knowledge there is no study quantitatively assesses voluntary upper limb functions for the BTX efficacy using inertial sensors based systems.

In our previous work, we proposed two sensing systems including a gold standard inertial sensing system and a gaming controller based system for upper limb rehabilitation assessment [30]. The system validation results demonstrated that both these systems were able to track the position within 0.5 cm over a 10 cm movement and orientation within 2.5 deg. In this study, we combine the traditional clinical assessments with kinematic and quantitative movement smoothness measures were calculated using the recorded data from inertial sensors attached on all four segments of the upper limb. First, in order to evaluate the usefulness of the kinematic and movement smoothness measures, each of the participants have been asked to perform a range of different tests including different range of motion tests and task-oriented test. Second, in order to understand the upper limb motion in a comprehensive way, the system captures the motion from all the upper limb segments by exploring the nature of the collected time series sensor data. Finally, the correlation between the clinical assessment, the kinematic measure and the quantitative smoothness measures has been explored. Furthermore, this multi-sensor system makes it feasible to the understanding of the coordination between different upper limb segments which are still a challenge for researchers [31,32].

Furthermore, this system aims to bridge the gap between the research and clinical practice for the upper limb motion assessment. In comparison with the traditional clinical scores carried out by clinicians using different standard clinical assessment scales, the proposed multi-sensor system provides an in-depth and comprehensive understanding of patients performance pre- and post the BTX treatment. It can also help clinicians with the therapeutic planning to improve patients' upper limb function restore and provide the opportunity to automate the process of upper limb motion assessment in clinical setting. In addition, with the emerging of the low cost wearable inertial sensors, it is possible to build a system for patients to use remotely.

Methods

Participants recruitment

Five patients have been recruited in this study and the patients information are listed in Table 1. Patients consented for this study and they were consecutive clinic patients in Kent Canterbury Hospital. We included patients who had confirmed focal spasticity. A clinical decision was taken by Neurorehabilitation Specialist to try Botulinum toxin intramuscular injection as part of treatment, and patients agreed to that treatment as per usual clinical care. They were all outpatients with no specific therapy following the BTX treatment. The BTX treatment was treated based on the spasticity of each patient and the details of the BTX dose and muscle injected are presented in Table I. This study had been carried out in a quiet room at University of Kent by a researcher. The patients were accompanied with their carers if needed. Before the study, all the patients signed an informed consent document which had been reviewed and approved by the UK NHS National Research Ethics Committee and the Hospital

Patient	Age	Gender	Handedness prior to stroke	Time since stroke (yrs)	Brain Lesion	BTX Dose	Muscle Injected
1	52	Male	Right	3	Stroke	200 units (Dilution with 4ml normal saline)	brachioradialis, FDP, FDS, bioep and pectoralis major
2	72	Male	Right	2	Right MCA	300 units (Dilution with 4ml normal saline)	Bicep, FDP, FDS
3	76	Male	Right	4	Right thalamic infarct	300 units (Dilution with 3ml normal saline)	Pectoralis Major, FDP, FDS, FCR, FCU
4	75	Female	Right	4	Right MCA infarction infarct	200 units (Dilution with 4ml normal saline)	FDP, FDS, Bicep, and Brachioradialis
5	69	Male	Right	2	Right MCA infarction infarct	200 units (Dilution with 4ml normal saline)	FDP, FDS, Bicep

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

Table 1 Patient Information and BTX treatment Information

Institutional Review Board (IRB) prior to the study.

Clinical measurements

The clinical tests include Disability Assessment Scale (DAS) [33], MAS and Motor Assessment Scale. All the patients were assessed using clinical assessment scales i.e (DAS, MAS and Motor Assessment Scale) and were asked to perform all the upper limb function experiment tests. A range of clinical tests have been carried out prior to the experimental tests using proposed sensing system. These assessment tests are widely accepted for rehabilitation assessment. The patients may not be able to complete all the assessment items in Motor Assessment Scale due to the upper limb disability.

Measurement system and kinematic model

Two monitoring system has been proposed in this study. One is gold standard four sensor Xsens [34] MTx sensing system and the other is low cost two sensor gaming sensing system. A system set-up of two systems has been shown in Fig. 1. In this paper, only the kinematic data recorded from MTx four sensor system are analysed and reported. This study aims to understand the upper limb functional performance before and after BTX treatment using inertial sensor-based system. The experiment tests are focusing on the active range of motion of the upper limb and upper limb functionality. 3D acceleration and 3D angular velocity were captured using the four wearable sensors from Xsens. Two kinematic models used to obtain the position tracking during all the experimental tests can be found in the previous study [21].

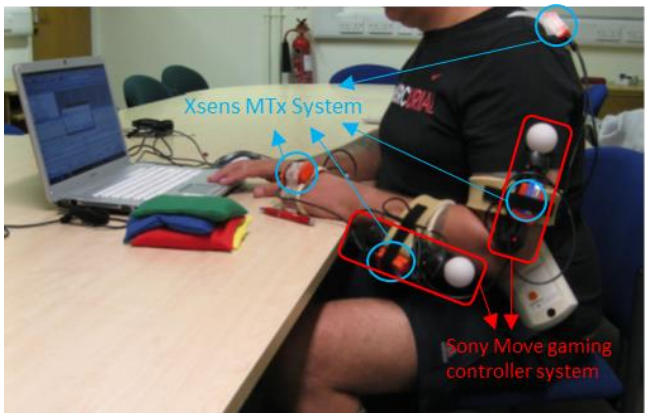


Figure 1. Quantitative Measurement multi-sensor system set-up (Two monitoring systems: Xsens MTx system & Sony Move gaming controller system)

The gold standard Xsens MTx sensing system measures the 3D acceleration, 3D rate of gyro, 3D magnetic field. It can also provide 3D orientation (Roll, Pitch and Yaw) with a built-in sensor fusion algorithm. The upper limb positions and trajectory were calculated by the implementation of a kinematic model developed in our previous study [21]. The low-cost gaming sensing system uses Sony Move gaming controller [35] as it can also measure raw data from a 3D accelerometer, 3D gyroscope and 3D magnetometer. Post-processing is required to calibrate the gaming sensors and applying sensor fusion algorithms e.g. complementary filter and Kalman filter. The detailed calibration of the gaming sensor and implementation of the sensing fusion has been reported in our previous work [30].

Experiment tests

In this study, in order to better understanding of the upper limb functions of the patients, a range of experimental tests have been done (See Fig. 2). A detailed description of the experiments is presented in subsections below. However, due to the patient's upper limb function limitations, some of the tests had not been completed or only partially completed.

Active Range of motion test (AROM)

The range of motion test is shown to be a reliable test for the assessment of the upper limb functions [36]. In clinical assessment, the range of motion is normally measured by a goniometer. Compared with the goniometer, our sensing system can capture the dynamic changes of the upper limb motion during the assessment besides the range of motion value. In this work, a number of active range of motion (Fig. 2 (a)) with regard to different upper limb segments are considered including: shoulder flexion, shoulder abduction, patients were asked to perform the tests using their affected side. If they cannot complete the task with the affected side, they can use their unaffected side to assist. The patients task completion performance is shown in Table 2.

Drinking test

The drinking test (Fig. 2 (b)) in this study is to evaluate the functional performance in daily life, especially the drinking action involves stretching the hand to reach the cup placed in the middle of the table and bring it to the mouth and finally put the cup back on the table [37]. There is no water in the mug and the patient is only asked to mimic the drinking action. Typically, drinking test is composed of 5 stages, reach->grasp->transport->release->return.

Bean bag test (BBT)

In bean bag test (Fig. 2 (c)), 4 Small bean bags were place on the table. The patients asked to pick up one bean bag at a time and release at a pointed location on the table which is 20cm distance from the original location of the bean bag. The completion of the Bean bag test requires the coordination of multiple upper limb segments.

Nine Hole Peg Test (NHPT)

NHPT [38] (Fig. 2 (d)) is considered as the gold standard assessment of the impaired manual dexterity focusing the patients and had been frequently used in the clinical assessment [39]. NHPT requires the finger movements to handle the small pegs which is difficult for the selected participants in this study since the BTX treatment in this study is focusing on the upper arm and forearm muscles (details can be found in Table 1). However, in this study, none of the patients was able to perform the NHPT due to their severe conditions due to lack of the fine movement of the hand.

Data analysis

Statistical analysis

In this work, on the consideration of the small number of samples, the paired t test was applied to both the clinical assessment scales measures and kinematic experimental tests (for kinematics and movement smoothness quantification parameters) to compare from pre- to post-BTX treatment. The statistical tests were conducted using IBM SPSS Version 25, with $p<0.05$ regarded as significant. Tri-axis accelerometer, gyroscope and magnetometer signals were recorded and a multi-segment kinematic model for trajectory monitoring [21] is developed in Matlab (MathWorks).

Kinematic measurement and quantification of movement smoothness

Joint Range of Motion (ROM) and Joint position are the two most important parameters for the kinematic measurement for the upper limb motion monitoring. The visualisation of the range of motion and the position in time series give additional insights for the clinicians and help them understand the upper limb motion in an intuitive manner.

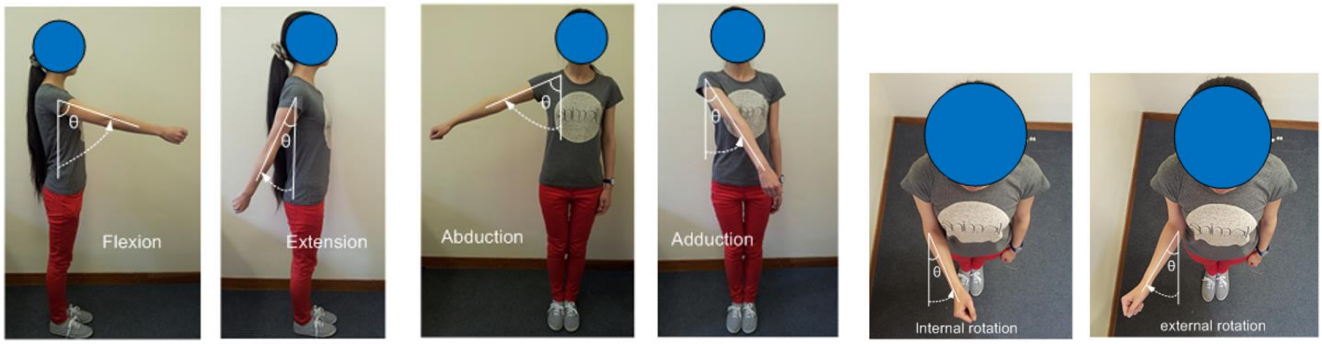
Total Acceleration and Total Velocity

Total acceleration is calculated using the equation below which is the normalised acceleration with the gravity removed.

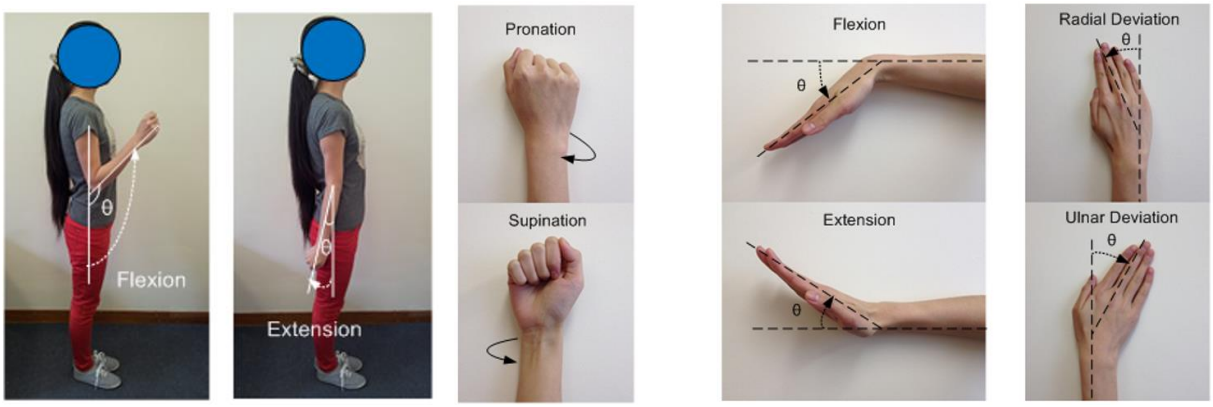
$$A_{total} = \sqrt{A_x^2 + A_y^2 + A_z^2} - g \quad (1)$$

Speed of movement is fundamental to human movements [40]. Total velocity is calculated using the equation (2) below.

$$V_{total} = \sqrt{V_x^2 + V_y^2 + V_z^2} \quad (2)$$

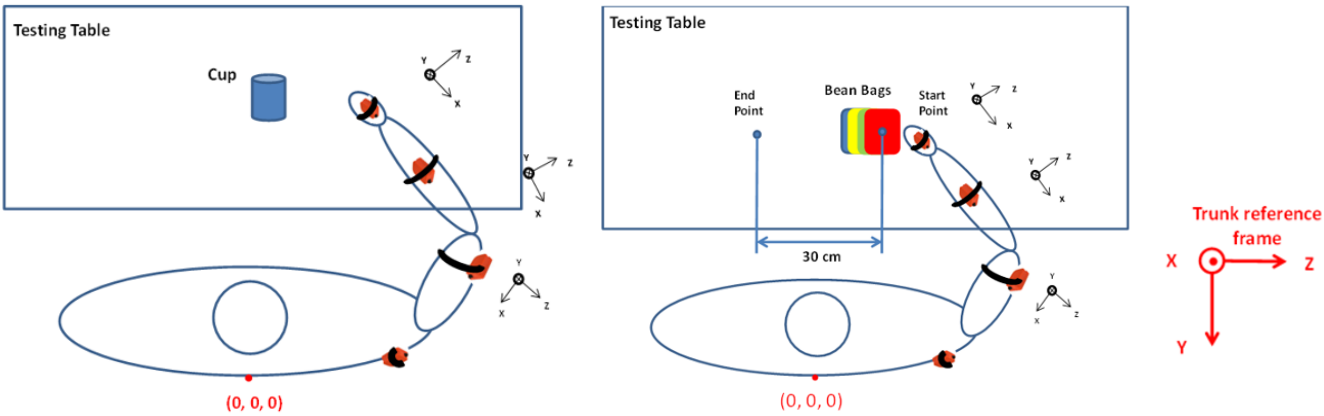


Shoulder flexion & extension Shoulder abduction & adduction Shoulder internal & external rotation

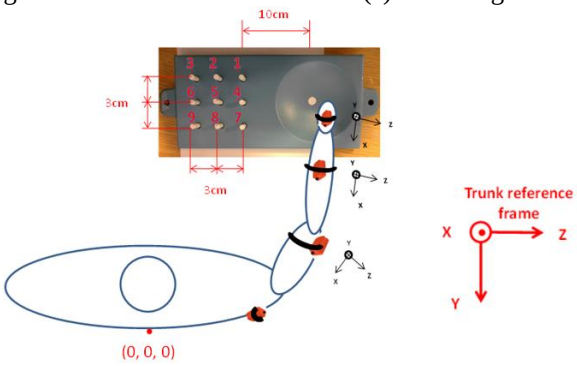


Elbow flexion and extension; Forearm pronation & supination; Hand flexion & extension; Radial Deviation & Ulnar Deviation

(a) Upper limb AROM test



(b) Drinking test (c) Bean Bag test



(d) NHPT

Figure 2. Illustration of the Experimental Tests (a) Upper limb AROM test (b) Drinking test (c) Bean Bag test (d) NHPT

Range of Motion and Position Tracking

ROM is calculated for each of the range of motion test for all the participants using the equation (3).

$$ROM = \theta_{\max} - \theta_{\min} \quad (3)$$

Movement Smoothness

Movement smoothness is an important aspect used in assessing upper limb motion. And in evaluation of the patient's motor recovery, it has been investigated in stroke patients. There are a few useful parameters which have been used in quantitation of smoothness measures including NMU and NJS. The parameters for movement smoothness were calculated for all the participants.

NMU

Considered as a useful parameter used in the quantitative measurement of movement smoothness, NMU has been used to analyse the movement of upper limb segments including upper arm, lower arm, shoulder and hand in this work. It is defined as the total number of zero crossings in the acceleration signal [23], which is also the number of the velocity maximum during the movement period. Usually the visual presentation of the healthy volunteers' movement data (orientation or position) against time will be very smooth with clear peaks in acceleration and velocity. In contrast, the patient's movement may have a jerkier movement with multiple peaks and irregularities. A smaller value of NMU indicates a smoother movement.

NJS

The NJS is another estimate of the movement smoothness related to stroke patients' movement for the evaluation of the sudden change of the movement and is an indication of the trajectory smoothness [24]. The value of the NJS will decrease while the trajectory is getting smoother. The evaluation of this variable will be carried out on a range of experimental measurements of the healthy volunteers and patients. Equation (4) [24] below is used to calculate the NJS. In this equation, the third derivative of the position with respect to time is the parameter of motion trajectory smoothness.

$$NJS = \sqrt{0.5 \times \int_{t_1}^{t_2} \left(\left(\frac{d^3x}{dt^3} \right)^2 + \left(\frac{d^3y}{dt^3} \right)^2 + \left(\frac{d^3z}{dt^3} \right)^2 \right) \times dt \times \frac{t^5}{l}} \quad (4)$$

where NJS: Normalised Jerk Score, t1 and t2: start and end of the motion time, t: movement time, l: movement distance, (x, y, z): position coordinates.

Movement Trajectory

It has also been noted that patient movement has more submovements than healthy volunteers. It has been proposed that a measure related to the length of the position trajectory can be used as a quantitative vector to evaluate the subject's performance. The length of the 3D trajectory is calculated using the equation below.

$$Dis = \sum_{i=2}^{n} \sqrt{(x_i - x_{i-1})^2 + (y_i - y_{i-1})^2 + (z_i - z_{i-1})^2} \quad (5)$$

As described in the Section of Experiment Tests, all four upper limb joints/segments (Shoulder, Elbow, Wrist and Hand) are measurement by 4 inertial sensors. The sample rate is 50Hz. Two most important measurements parameters are orientation and trajectory tracking of the different segments. Besides, a series of parameters have been calculated to assess the performance of the rehabilitation including total velocity, total acceleration, NMU, and NJS. All the above parameters have been calculated for all the experiment tests described above.

Results

All the five patients had attended for two sessions for experiment tests. The pre- test was done before the injection of BTX and the post- test was done one week after the injection. The Patient No.2 had completed additional two follow-up sessions with one week interval. Table 2 is an overview of the task completion status for each patient and some tests had only partially completed with assistance from less affected side. All the patients were able to complete the tests such as Bean Bag Test and Drinking Test which mainly using gross motor dexterity of the affected upper limb. For AROM tests, Shoulder flexion & extension and Elbow flexion & extension are the top completed tasks. None of the patients were able to complete the NHPT since it requires distal manipulation and finger flexion. One week after the BTX treatment,

Pre											
	Orientation Task							Trajectory Tracking Task			
Patient No.	Shoulder Flexion & Extension	Shoulder Internal & External Rotation	Shoulder Abduction & Adduction	Elbow Flexion & Extension	Forearm Pronation & Supination	Wrist Flexion & Extension	Hand Ulnar & Radius Deviation	Drinking Test	Bean Bag Test	NHPT	Completion Score
1	P-C			P-C				P-C	P-C		20%
2	C			C				C	C		40%
3	C			C		C		C	C		50%
4	C		C	P-C				C	C		45%
5	C	C	C	C	P-C	P-C		C	C		70%
Post											
	Orientation Task							Trajectory Tracking Task			
Patient No.	Shoulder Flexion & Extension	Shoulder Internal & External Rotation	Shoulder Abduction & Adduction	Elbow Flexion & Extension	Forearm Pronation & Supination	Wrist Flexion & Extension	Hand Ulnar & Radius Deviation	Drinking Test	Bean Bag Test	NHPT	Completion Score
1	C			C				C	P-C		35%
2	C	C	C	C				C	C		60%
3	C	C	C	C	C	C		C	C		80%
4	C		C	P-C		P-C		C	C		50%
5	C	C	C	C	C	C	C	C	C		90%

C: Completed, P-C: Partial Completed

Table 2 Patient Test Completion Review

the task completion rate of patients increased significantly (p=0.011).

Clinical outcome measures

The scores of DAS, MAS and Motor Assessment Scale were compared before the BTX injection and one week after injection. Clinical assessment scores for the pre- and post- BTX treatment has been presented in Table 3-5. DAS scores for the Limb posture improved significantly (P = 0.004) at post-BTX treatment, and the sum of the DAS scores improved significantly (P=0.005). MAS scores for the shoulder, elbow, wrist, fingers and Thumb all decreased indicates the reduce of the muscle spasticity. Scores for Motor Assessment Score show that scores in sitting G1 (p=0.007) and in Advanced H3 (p=0.033), H4 (p=0.025) and H5 (p=0.035) improved significantly post-BTX.

Orientation and position trajectory tracking visulisation

The Fig. 3 shows orientation and position tracking of elbow flexion test of a healthy volunteer and a patient the pre and post the BTX treatment. There is visible changes of the trajectory and orientation tracking for different patients. Fig. 3 shows a comparison between a patient position trajectory tracking with a health volunteer. The visualisation of the range of motion and position trajectory tracking can be useful through observation of the

DAS Measures	Mean ± Std		P-Value
	Pre-	Post-	
Hygiene	1±0	0.8±0.447	0.374
Dressing	1.8±0.447	1.8±0.447	-
Limb Posture	2.4±0.548	1.2±0.447	0.004
Pain	0.2±0.47	0.2±0.447	-
All	5.4±1.140	4±0.447	0.005

Table 3 Assessment scores for DAS pre- and post- BTX injection

MAS Measures	Mean ± Std		P-Value
	Pre-	Post-	
Shoulder	2.8±1.304	2.4±1.140	0.178
Elbow	4.0±1.225	3.4±0.894	0.07
Wrist	3.8±1.643	3±1	0.294
Fingers	3.2±1.304	2.2±0.837	0.089
Thumb	3.2±1.304	2.2±0.837	0.089
All	17±5.874	13.4±4.099	0.113

Table 4 Assessment scores for MAS pre- and post- BTX injection

clinicians and researchers. It can be seen from Fig. 3 that the movement after BTX treatment is much smooth compared with the movement before BTX treatment. In order to quantify these changes, Kinematic parameters and parameters from quantification of the movement smoothness have been used to provide additional insights for clinicians. Fig. 4 and Fig. 5 show the position tracking of 3 axes for both healthy volunteer and patients in bean bag test and drinking test respectively. In Fig. 4 and Fig 5, "ph-x", "ph-y", "ph-z" are the positions of the hand in x, y and z plane. Fig 6 and Fig 7 show the multiple trials results for both healthy volunteer and patients.

Motor Assessment Scale Measures		Mean ± Std		P-Value
		Pre-	Post-	
In Lying	F1	3.6±2.074	4±1.581	0.374
	F2	3.8±2.168	4±1.581	0.621
	F3	1.4±1.949	3.8±2.168	0.061
	F4	3.4±1.817	3.8±1.095	0.477
	F5	2.8±1.789	3.2±0.837	0.541
	F6	0.4±0.894	0±0	0.374
	F-All	15.4±9.209	18.8±6.907	0.202
In Sitting	G1	0.6±1.343	3.2±0.836	0.007
	G2	0±0	2±1.225	0.022
	G3	0.8±1.789	2±1.414	0.07
	G4	2.8±1.095	3.4±1.342	0.426
	G5	1.4±1.949	2.6±1.949	0.178
	G6	0.6±0.894	1±1.414	0.178
	G-All	6.2±4.817	14.2±3.768	0.006
Advanced	H1	1±1.732	2.2±1.095	0.07
	H2	0.4±0.894	0.6±1.342	0.374
	H3	0.4±0.894	1.6±1.140	0.033
	H4	0.6±1.342	2±1.871	0.025
	H5	1±1.732	2.6±1.140	0.035
	H6	0.4±0.894	1.6±0.894	0.07
	H-All	3.8±5.495	10.6±4.827	0.006

Table 5 Assessment scores for Motor Assessment Score pre- and post- BTX injection

Kinematic parameters pre- and post-BTX treatment

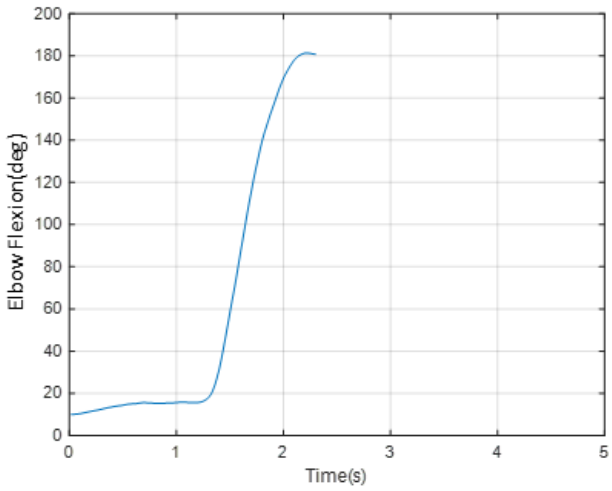
For movement smoothness quantification, three quantification parameters improved significantly from pre-to post-BTX treatment as shown in Table 6. In general, NMU, NJS and movement trajectory for all the upper limb segments are improved. NMU decreased at all the four upper limb segments after the BTX treatment and the significant decrease is for wrist ($p=0.039$) and elbow ($p=0.037$) which is a strong indication of the movement improvement. The value of the total velocity increased while the value of the total acceleration decreased, which explains the fact the patients completed the experimental quicker but the movement is much smoother after the BTX treatment.

Comparisons between the Statistical analysis with the kinematic measures on the changes pre and post BTX treatment

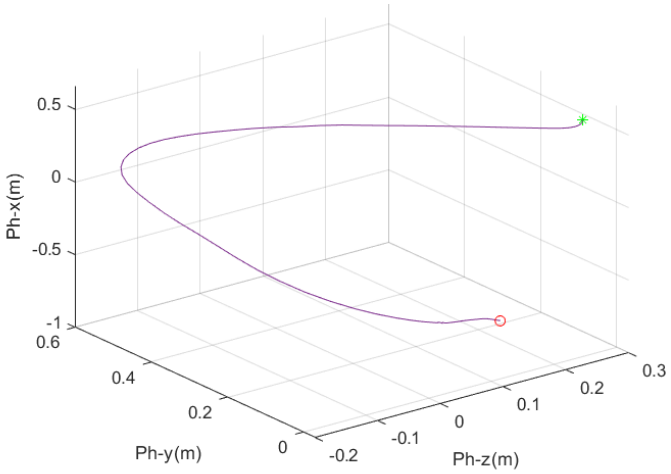
Correlations have been explored between the changes of the clinical assessment measures and kinematic measure regarding different upper limb segments. The results are presented in Table 7. The total acceleration shows good correlation with MAS score on the elbow ($r=0.946$, $p=0.054$) and wrist ($r=0.726$, $p=0.274$) joints while and total velocity significantly correlated with MAS score on the hand ($r=0.937$, $p=0.063$) and shoulder ($r=0.978$, $p=0.021$).

Discussion

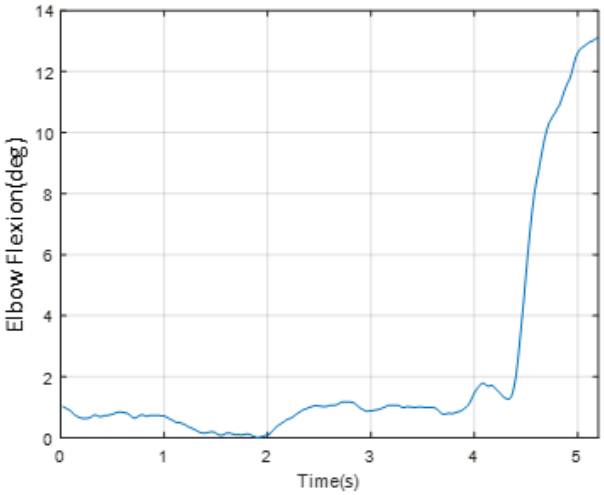
The aim of this study is to examine the changes pre and post the BTX treatment utilising kinematic measures in order to better understand the changes of upper limb motor function besides the spasticity. In order to understand the upper limb segments motor changes in a broader view, we recorded the sensors data from all four upper limb segments during a range of different rehabilitation experimental tests. All the clinical assessments are improved after the BTX treatment. The clinical assessments are focusing the completion of a specific target while the experimental tests for kinematic measures are focusing on understanding the performance of the different upper limb segments and coordination between these segments. The changing patter for each patient on different segments are different. The recovery of the movement for different segments can be complexed. By analysing the total acceleration of upper limb segments, it can be seen that for the experimental tests, the total acceleration is reduced especially for the wrist and elbow segments which contribute more during in the bean bag test and drinking test. It indicates that the patients are getting better control of their movement.



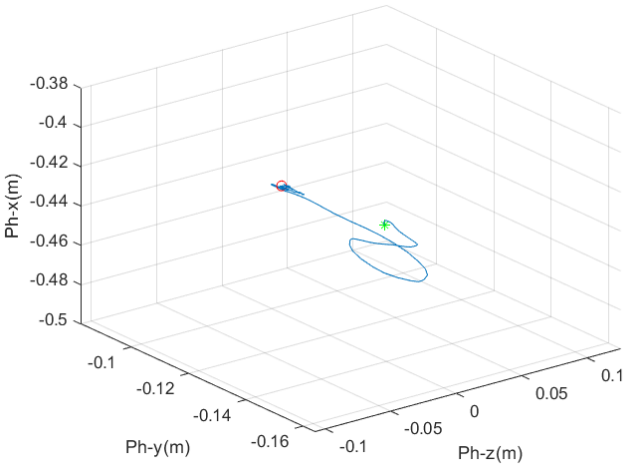
(a) Healthy Volunteer AROM



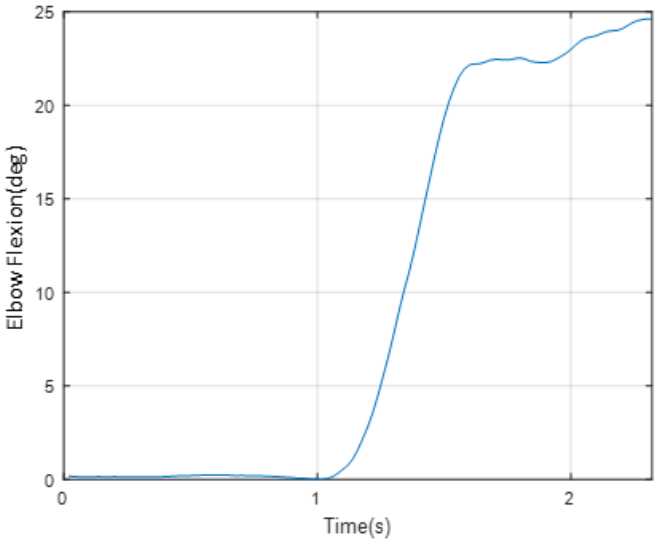
(b) Healthy Volunteer 3D position trajectory



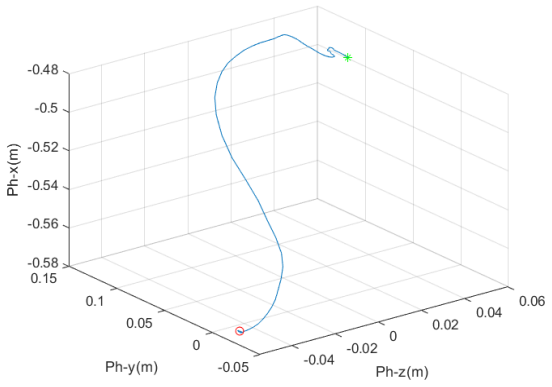
(c) Patient 2 Pre BTX AROM



(d) Patient 2 Pre BTX 3D position trajectory

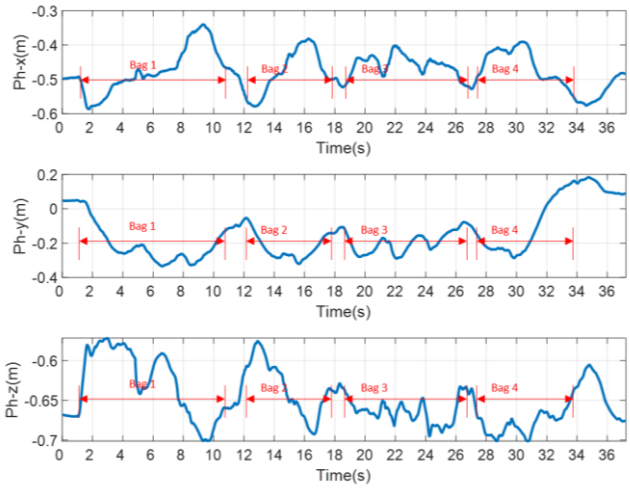


(e) Patient 2 Post BTX AROM

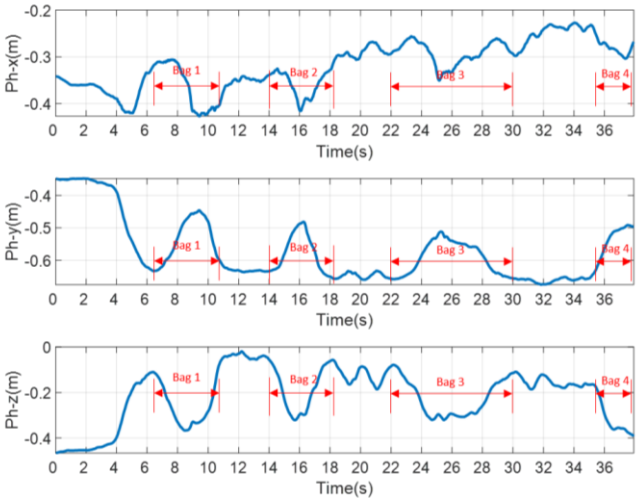


(f) Patient 2 Post BTX 3D position trajectory

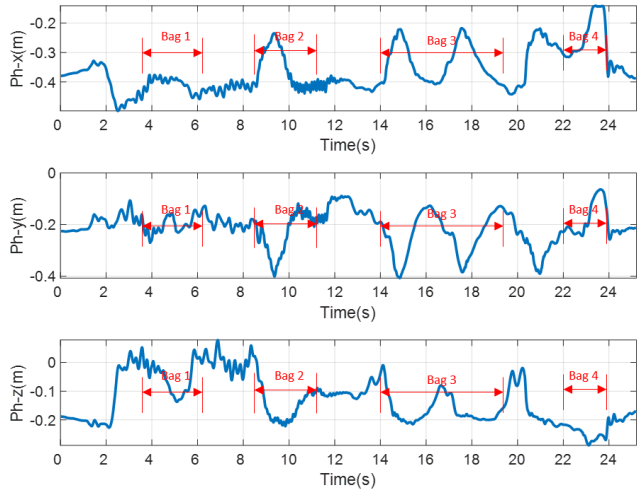
Figure 3. Orientation and 3D position tracking before and after BTX treatment of Patient No.2 and Healthy Volunteer in an elbow flexion test. (in (b), (d) and (f), "ph-x", "ph-y", "ph-z" are the positions of the hand in x, y and z plane)



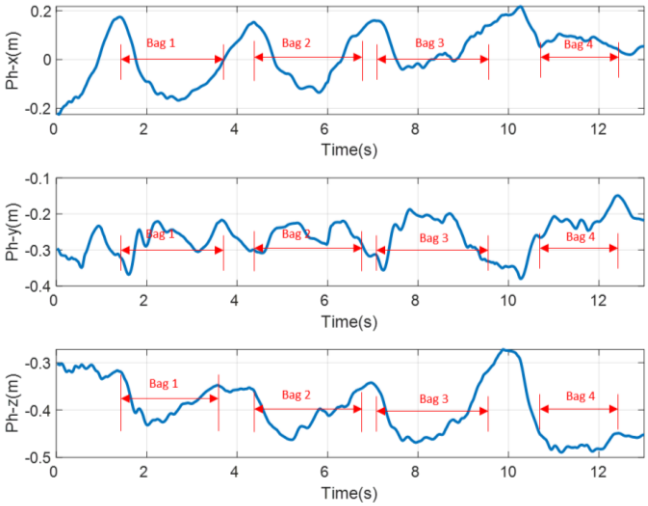
(a) Patient 2 Pre-BTX



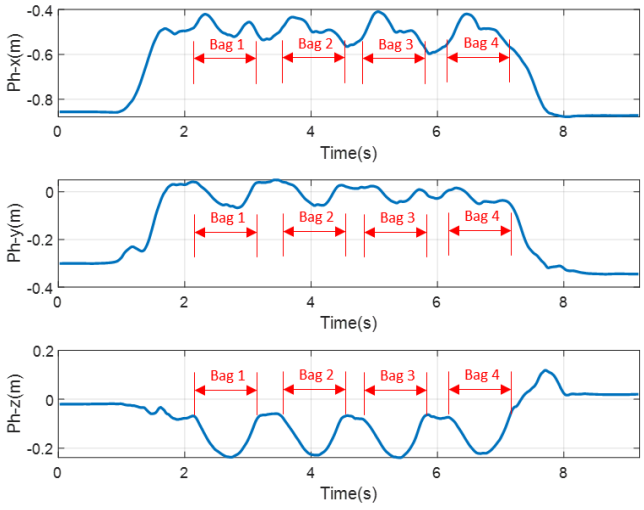
(b) Patient 2 Post-BTX



(c) Patient 4 Pre-BTX

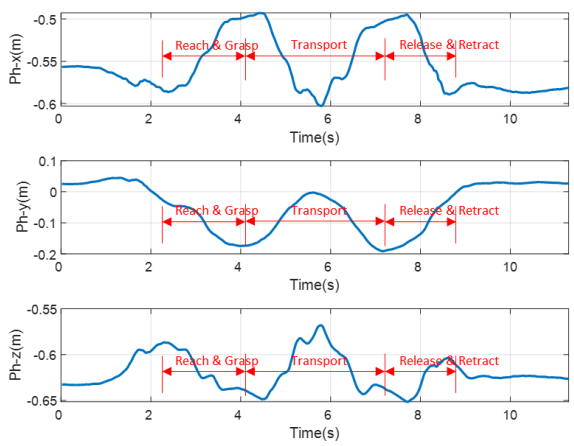


(d) Patient 4 Post-BTX

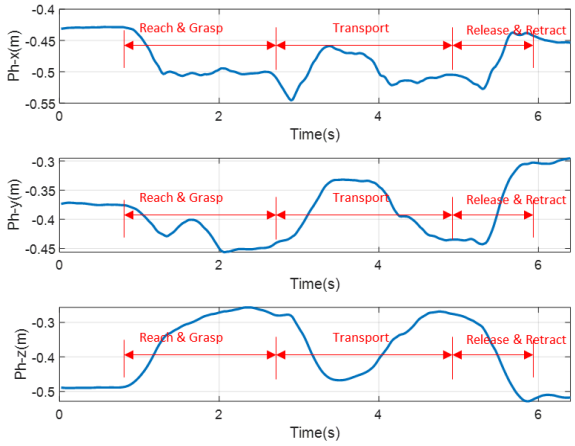


(e) Healthy Volunteer

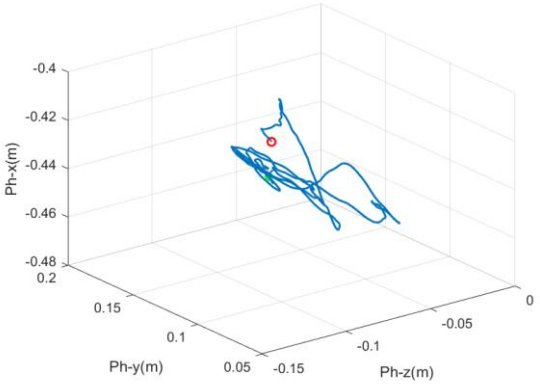
Figure 4. 3D position tracking before and after BTX treatment of Patient No.2&4 and Healthy Volunteer in a bean bag test.



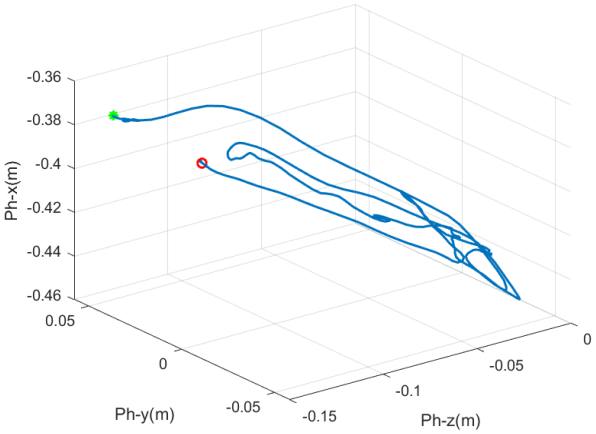
(a) Patient 2 Pre-BTX position tracking on 3 axis



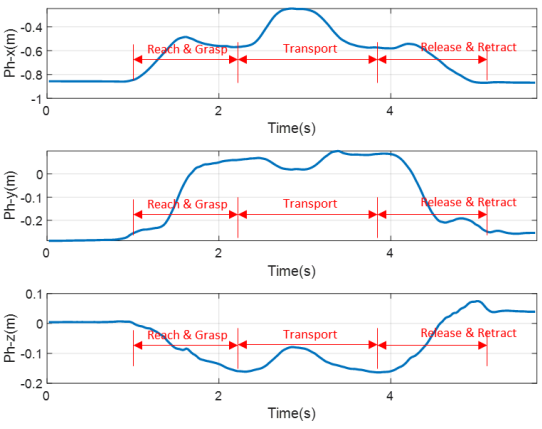
(b) Patient 2 Post-BTX position tracking on 3 axis



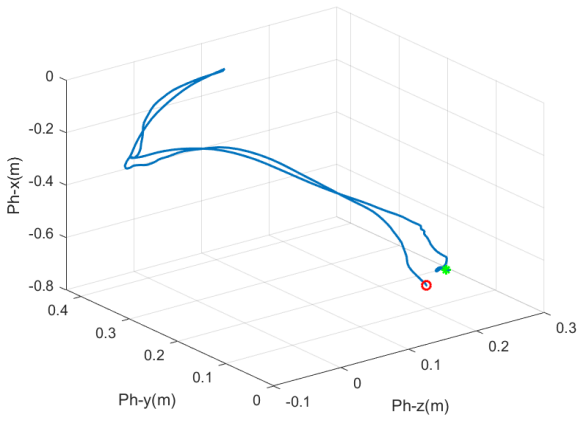
(c) Patient 2 Pre-BTX position tracking in 3D space



(d) Patient 2 Post-BTX position tracking in 3D space

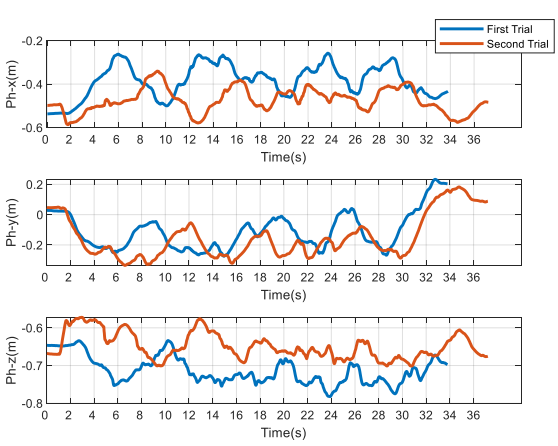


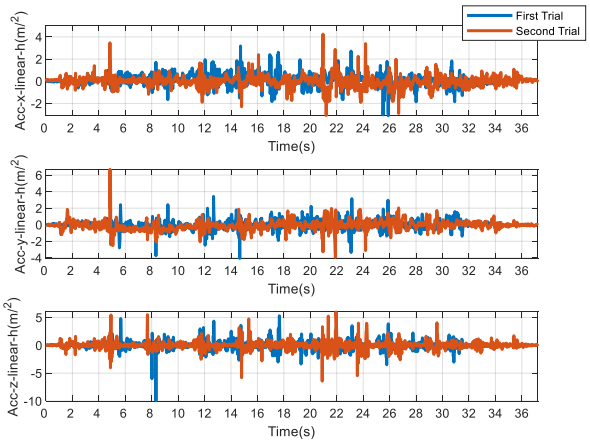
(e) Healthy volunteer position tracking on 3 axis



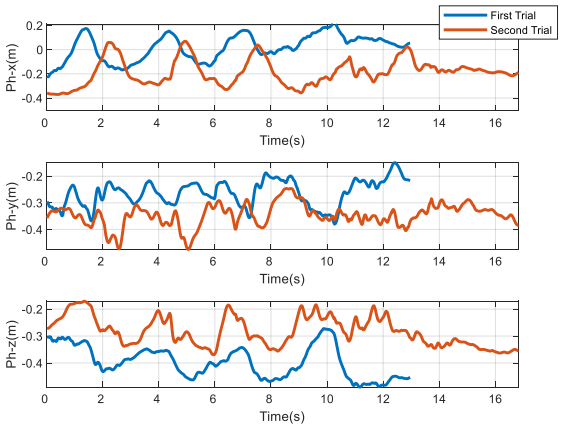
(f) Healthy volunteer position tracking in 3D space

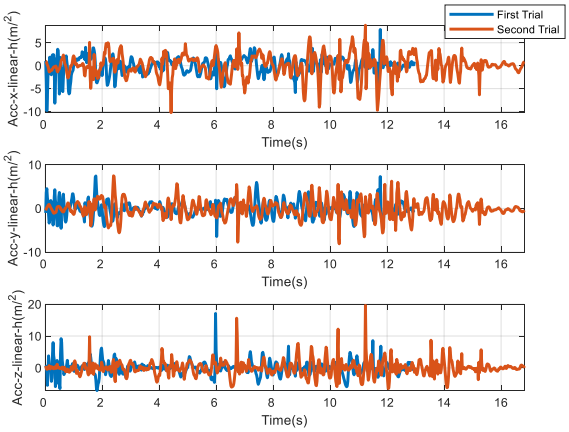
Figure 5. 3D position tracking before and after BTX treatment of Patient No.2 and Healthy Volunteer in a Drinking test.



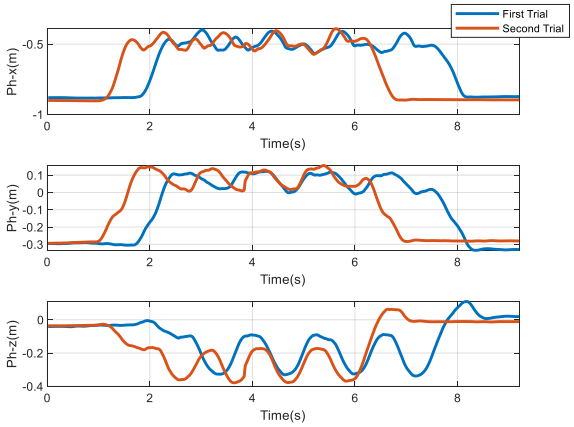


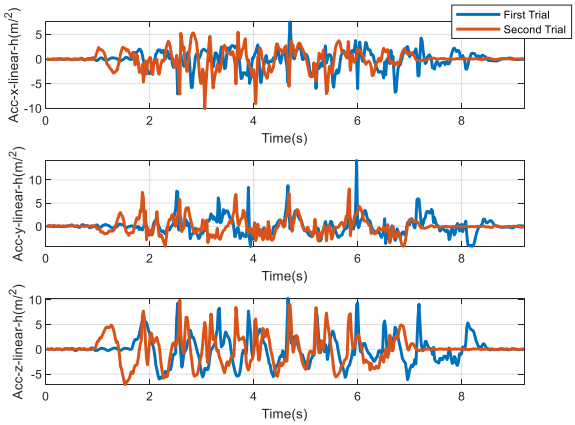
(a) Patient 2 3D position Pre-BTX Bean Bag Test (b) Patient 2 3D acceleration Pre-BTX Bean Bag Test





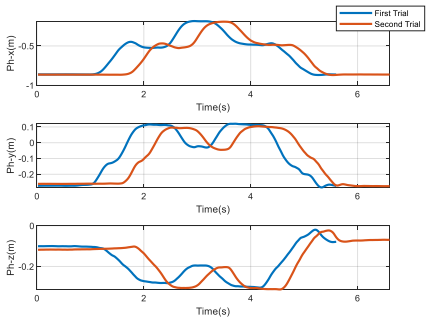
(c) Patient 4 3D position Post-BTX Bean Bag Test (d) Patient 4 3D acceleration Post-BTX Bean Bag Test



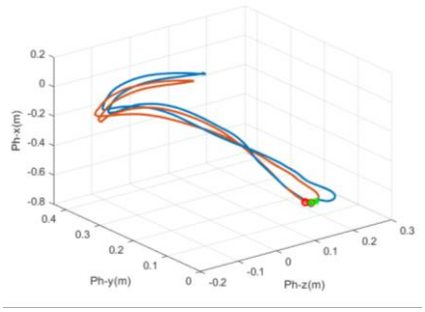


(e) Healthy volunteer 3D position Post-BTX Bean Bag Test (f) Healthy volunteer 3D acceleration Post-BTX Bean Bag Test

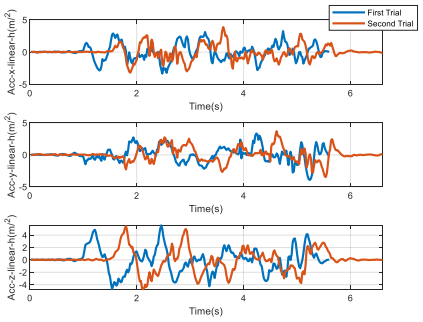
Figure 6. Results from Multiple Trials for Patients and Healthy volunteers for a bean bag test.



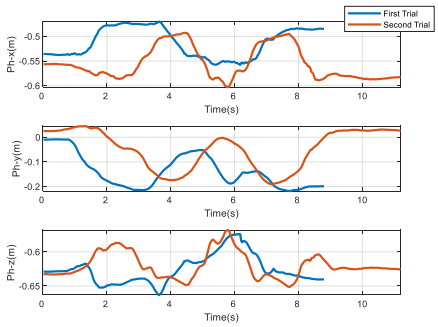
(a) Healthy volunteer 3D position



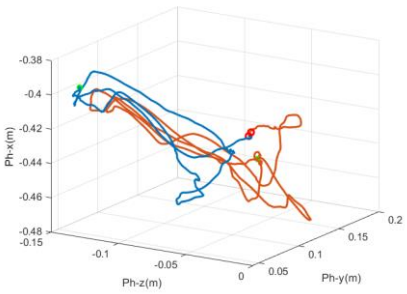
(b) Healthy volunteer 3D position in 3D plot



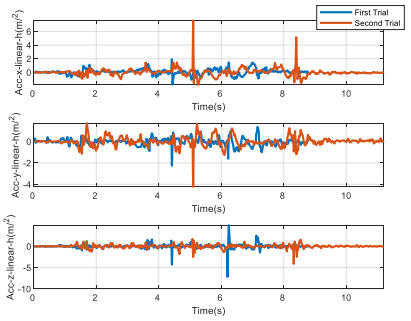
(c) Healthy volunteer 3D acceleration



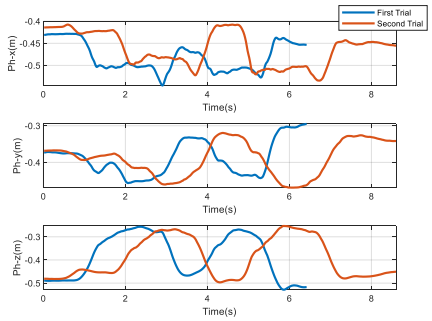
(d) Patient 2 3D position Pre-BTX



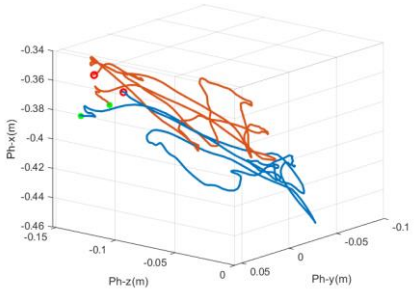
(e) Patient 2 3D position Pre-BTX in a3D plot



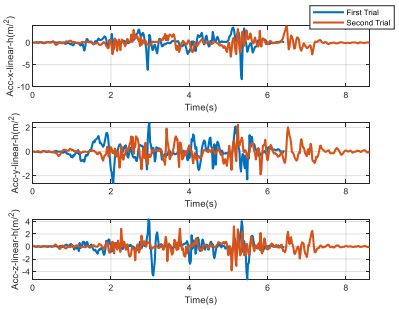
(f) Patient 2 3D acceleration Pre-BTX



(g) Patient 2 3D position Post-BTX



(h) Patient 2 3D position Prost-BTX in a3D plot



(i) Patient 2 3D acceleration Post-BTX

Figure 7 Results from Multiple Trials for Patients and Healthy volunteers for a drinking test.

Parameters	Upper limb segment	Pre		Post		P-Value
		Bean-Bag Test	Drinking Test	Bean-Bag Test	Drinking Test	
MUN	Elbow	223.3±110.0	67.9±28.7	155.8±76.2	52.4±10.7	0.037*
	Wrist	245.0±90.2	72.3±20.9	194.0±113.7	49.8±10.7	0.039*
	Hand	292.9±110.0	86.0±25.9	262.6±176.5	60.5±14.4	0.168
	Shoulder	238.2±126.8	79.3±35.9	195.3±134.9	55.5±9.0	0.050
NJS	Elbow	157.5±100.0	3.0±1.0	63.3±50.5	1.6±1.1	0.160
	Wrist	368.1±236.3	6.9±5.6	110.4±68.8	2.2±1.5	0.147
	Hand	487.1±337.0	10.4±4.3	160.3±115.7	3.1±2.3	0.159
	Shoulder	101.0±77.1	2.5±1.9	62.7±71.1	1.3±0.9	0.080
Trajectory (mm)	Elbow	298.4±129.5	53.5±13.9	224.8±41.8	59.3±17.5	0.310
	Wrist	502.6±265.6	85.7±30.3	336.6±97.1	89.0±29.4	0.193
	Hand	578.2±338.3	94.6±30.0	385.9±86.2	106.1±34.6	0.264
	Shoulder	282.4±58.7	58.0±6.4	244.0±16.4	64.4±14.7	0.304
Total Velocity (mm/s)	Elbow	85.93±49.05	44.10±15.67	95.55±60.53	71.57±40.85	0.202
	Wrist	187.55±99.57	99.82±56.90	194.15±133.75	125.43±66.44	0.419
	Hand	217.25±125.99	112.47±59.28	222.94±146.19	158.62±87.54	0.336
	Shoulder	105.55±30.72	59.85±20.44	95.88±49.99	84.17±4.39	0.507
Total Acceleration (m/s^2)	Elbow	0.61±0.38	0.30±0.22	0.48±0.27	0.36±0.26	0.529
	Wrist	1.00±0.66	0.49±0.35	0.75±0.44	0.54±0.30	0.434
	Hand	1.08±0.85	0.47±0.19	0.81±0.41	0.53±0.29	0.524
	Shoulder	0.15±0.06	0.09±0.03	0.14±0.06	0.10±0.03	0.612
Time	All segments	26.4±7.4	8.6±1.8	21.8±9.2	7.1±1.4	0.059

Table 6 Kinematic measures and smoothness quantification parameters pre- and post- BTX treatment

	MAS - Elbow	MAS - Wrist	MAS - Hand	MAS - Shoulder
NMU	-0.055	0.121	-0.792	-0.666
NJS	0.558	0.249	-0.388	-0.141
Trajectory	0.750	0.336	-0.422	-0.762
Time	0.397	-0.209	-0.693	-0.693
Total_Velocity_Mean	0.376	0.615	0.937*	0.978*
Total_Acceleration_Mean	0.946*	0.726	-0.234	0.388

Table 7 Correlations between MAS score and kinematic measures with regard to different upper limb segments

The kinematic measures related to the movement smoothness are proved better indicators for the changes of upper limb functions. The AROM gives additional results compared with the passive ROM for evaluating the upper limb function after BTX treatment. The 3D position tracking of 4 different upper limb segments and the 3D trajectory tracking help to understand the proportional and joint coordination ability for each segment. The visualisation of the position tracking in 3D provides additional insights. As seen in Fig 4 (3), the 3-axes of the position tracking for Patient 4 shows a large number of small spikes in the signal which indicates the tremor from the patient's upper limb motion. In Fig. 4 (4) after the BTX treatment, it can be seen that the tremor have reduced significantly.

NMU is an important movement smoothness quantification parameter, for both BBT and drinking test, the value of NMU has reduced on all the four upper limb segments which indicate the functional recovery of the whole upper limb. It is also noted that the changes of NMU is more significant on the elbow and wrist segments than that of the shoulder and hand segments.

All the patients were satisfied with system. The entire assessment took less 20 mins. The four sensor MTx system and the experiment protocol can be suitable for daily assessment in clinical settings. Besides, the low cost version of the two sensor based system (utilising gaming controller) can be utilised as the home rehabilitation tool. Though this study has only been done on a small group of patients, but the collected dataset from two different multi-sensor system are adequate for evaluation of the proof of concept systems.

Clinical Indications

There have been very few studies on the upper limb voluntary motor function after BTX treatment as most of the study is to focus on evaluating the spasticity of the upper limb segments after BTX treatment but not includes the residual voluntary upper limb functions. Moreover, the analysing the upper limb function for each of the upper limb segments have gained the clinicians a comprehensive way of understanding data.

Conclusion

This study proves that the inertial sensing systems are able to provide kinematic analysis on the performance quality of the patients on different upper limb segments which current clinical scales fails to do so. The reduction in the NJS and NMU are the indication of the better motion functionality of the upper limb segments. The different changes for each upper limb segments show the compensation of the movement in order to complete in daily tasks.

Competing interests

The authors declare that they have no competing interests.

Ethics approval and consent to participate

All participants provided written informed consent and the study was approved by UK NHS National Research Ethics Committee and the Hospital Institutional Review Board (IRB) prior to experiment (09/H1103/44).

Availability of data and materials

Data and materials can be made available upon request to the authors.

Author's contributions

LB designed the study and MGP supervised the study. LB carried out the data collection, implemented the algorithm for data analysis, manuscript writing and revision. MS selected the participants and conducted the clinical evaluation. MGP, YY, MP and MS reviewed the manuscript. All authors read and approved the final manuscript.

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