IJEAST

INTERNATIONAL JOURNAL
OF ENGINEERING APPLIED SCIENCE
AND TECHNOLOGY

VOLUME : 7 ISSUE : 02 Print / Issue Publication Date: 05-Aug-2022

ISSN : 2455-2143

DOI : 10.33564/IJEAST.2022.v07i02.004

Indexed In

Google Scholar OPEN ACCESS doi Crossref

WWW.IJEAST.COM

editor@ijeast.com

International Journal of Engineering Applied Sciences and Technology, 2022
Vol. 7, Issue 2, ISSN No. 2455-2143, Pages 24-35

REVIEW OF UPPER LIMB MOTION ASSESSMENT IN NEUROREHABILITATION

Lu Bai
School of Computing
Ulster University, Belfast, UK

Abstract— **It is of importance to monitor and assess the upper limb motion for patients who are under Neurorehabilitation. Traditionally, scale based methods were commonly used in daily clinic, however, these scale based methods were subjective. With the development of the sensing techniques and advancement of the computational algorithms, a number of new technologies and algorithms have been developed to determine the upper limb motion objectively. This paper provides a overview of the different methods and sensing systems involved in upper limb motion assessment in Neurorehabilitation. The results from this review may help the clinicians with the selection of the appropriate methods for upper limb motion assessment for patients under Neurorehabilitation.**

Keywords— **Upper limb motion, Motion assessment, Neurorehabilitation, Kinematic modelling, Dead reckoning**

I. INTRODUCTION

Neurorehabilitation is concerned with seeking to restore as much function as possible through the appropriate rehabilitation programs. In order to measure the outcome of rehabilitation and the efficacy of any particular regime a reliable method for assessing the progress of the patient throughout the program is desirable. In order to help to acquire the background knowledge and clarify the contribution of this research in upper limb assessment, the literature review explains the background of the upper limb disability from neurological disorders, the treatment and most importantly the assessment techniques used for upper limb rehabilitation in clinic.

This paper presents an overview of the treatment and assessment of upper limb motion disability from neurological disorders in neurorehabilitation. The advantages and disadvantages of different assessment techniques and measurement systems are presented and compared. Then a discussion is made to identify a suitable inertial measurement system for upper limb motion assessment in a clinical rehabilitation setting.

II. NEUROREHABILITATION OF THE UPPER LIMB

Rehabilitation programs involve occupational therapy and physiotherapy to help the patients to ease the symptoms, regain upper limb mobility and further more to lead an independent life. In addition, there are also speech and language therapists, nurses and other specialists working together in a typical multidisciplinary rehabilitation team.

Occupational therapy takes an important role in rehabilitation to help the patients to carry out the activities of daily living (e.g. washing or making a drink). The therapists may also help patients to develop compensatory strategies to offset the effect of any impairment to their affected limbs. Additionally, the Occupational Therapists may also prescribe equipment to assist the patients with recovery, for example, non-slip plate mat or cutlery designed for easier holding [1].

Physiotherapy exercises are important in helping with the relearning of upper limb motor patterns, restoring strength and skill training with standard care. Physiotherapy is often focused on helping relieve the effect of joint stiffness or muscle tightness. If the patients have muscle spasticity, Botox injections may also be prescribed [2,3].

A. Traditional rehabilitation regimes

Muscle spasticity, contracture, weakness and loss of dexterity often happen after brain injury [4]. The above symptoms such as muscle dysfunction are all associated with dysfunction of the nervous system. Neuromuscular training is usually an important part of the rehabilitation regimes. It trains the muscle and can also improve communication between the peripheral and Central Nervous System (CNS) [5]. However before any rehabilitation program can be prescribed the patients' level of disability has to be assessed. The Disability Assessment Scale (DAS) [6], Activities of Daily Living (ADL) [7] and Barthel Index (BI) [8] are usually used to measure disability and functional abilities in daily living. In addition, there is also clinical scale used for assessing the muscle spasticity e.g. Modified Ashworth Scale (MAS) [9]. Once the type and severity of the disability has been diagnosed, an appropriate therapy program can be prescribed. Traditional physical therapies such as Bobath [10], Brunnstrom [11], proprioception neuromuscular facilitation [12] and motor relearning have been used for many years.

B. Assistive technologies for upper limb rehabilitation

In recent years, there has been an increase in the development in assistive technology such as rehabilitation robots, virtual reality systems and Functional electrical stimulation (FES) to help patients undergoing upper limb rehabilitation [13]. Assistive and supportive devices are also being used in the neurorehabilitation, such as treadmills, biofeedback equipment, and robotics. These assistive technologies will be presented in the following sections.

1) Rehabilitation robot

Though physiotherapy exercises are effective, the augmentation and enhancement of exercise therapy using assistive technology is of interest to the clinicians [14]. Robotics has proved to be a useful tool in physiotherapy. By using the computer to control the robot, the constraints and movement patterns are adjustable to suit the required movement for different patients in different stages of recovery, which makes it possible to optimise the restoration of the patients' upper limb function [15]. ARM in has been proposed as a new robot for arm therapy [16], which is based on a mechanical structure providing six DOF rotations. DC motors are used to actuate the arm movement and are equipped with sensors for position and velocity measurements and a closed-loop control system is used for processing the outputs and providing the new input for the robot. A user interface provides visual feedback to the patient and some control over the system settings. Both passive-mode and active-assisted mode are available with most of the robotic devices. In the passive mode, there is no patient's voluntary movement, and patient's arm is moved along the prescribed trajectory by the robot. In the active-assisted mode, the patient initiates the movement and is provided with mechanical assistance by the robot [17].

By using the rehabilitation robotic, the patients' movements can be constrained to follow a fixed and predetermined movement trajectory. It is claimed to be a promising and useful approach in upper limb rehabilitation treatment [18]. The rehab-robots could be worked as a tireless system to replace therapists once the treatment has been prescribed and the system set-up. This system can also provide more therapy without trying up the limited therapy resources. Additionally, the system can also record the patient movement to provide feedback in the patient's progress during rehabilitation. The above features are some of the advantages that using a robot can have over the standard therapy. At present there are several kinds of rehab-robots available for physiotherapy in patients' rehabilitation [19]. Different assistive robots have been assessed, such as the MIT-Manus [20], Mirror Image Motion Enabler (MIME) [21], ARM in [16], and ARM Guide [22]. Robot can provide the movement if there is no patient's voluntary movement and also facilitate the patients' voluntary movement through providing assistance and guidance. For example, using the MIT Manus, the patient's forearm and wrist are attached to the robot arm. Usually a display screen is used to present a specific arm movement assessment test such as connecting dots to create a picture. A similar rehab-robot, the MIME can move the upper limb through the prescribed pattern as well as provide assistance for active movement [21]. There are also other types of rehab robots which allow the three degrees of freedom (DOF) shoulder movement, elbow flexion & extension, forearm pronation & supination and wrist flexion & extension. For example, ARM in has six DOF and works like a robotic orthosis, since the upper limb (both the upper arm and forearm) are placed inside of the orthotic shell.

Researchers have, therefore, been using a range of rehab robots in Neuro Rehabilitation [23,24] and comparing their effectiveness with standard physiotherapy exercise. One advantage of the robotic rehabilitation is that the robots are able to provide passive movements for the upper limb [25]. The advantages lie in that not only are the therapists freed from assisting the patients with physical exercises, but also this kind of equipment can standardise the quality of the patients' exercise performance. Kinematic movement information such as acceleration, velocity, position information can easily be recorded during the rehabilitation exercise and this information can be useful in assessing the patients' limbs motor progress. In addition, another major advantage might be that the patient can have therapy more regularly than is possible with the limited time available from the therapist. Furthermore, together with the virtual reality, the patients are provided with an interface through which the patients are able to participate in the rehabilitation training that can be made into games - game therapy, which is interesting and motivating to the patients. However the disadvantages are cost (e.g. a standard ARM in cost is about £20,000 [26]), physical size, set up requirements and maintenance. Additionally, another disadvantage lies in that the therapist now no longer has physical contact with the patients and therefore the information fed back to this assessment technique is lost.

2) Virtual Reality (VR)

The concept of VR used in patients' rehabilitation usually contains a computer which creates a virtual environment. Here, VR is a development of the dot joining or maze tracing exercises and is a simulated world environment created by the computer. Robotic tools and visualisation techniques are used to assist the rehabilitation of the patients' upper limb physiotherapy and training. For example, the patient can play a game which is shown on the audio-visual Patient Robot Interface (PRI) display. In this game-therapy mode, the robot can guide the patient when the patient is able to complete the movement with the support of the robot [16].

The sensors on the rehab robots are also able to collect the human kinematic movement data. This data can then be used as an input to the VR world. Take ARM in as an example, the game therapy of the ARM in uses the audio-visual PRI display to support patients in arm tasks [16]. The effectiveness of this treatment method has been supported by some recent research that gives evidence that intensive practice using VR systems may be useful to help upper limb function (range of motion and speed of movement) recovery of stroke patients, for example, the patient had an 20% improvement of the finger range of motion after a 2-week training program in a case study [27].

The rehabilitation robots together with the VR concept have made the traditionally manually assisted movement training less labour-intensive and can provide objective measurements, which benefits both the patient and the therapist. During this treatment, the residual muscle activity and upper limb movements have been trained [28].

Besides its applications with robot therapy, VR has been utilised in the rehabilitation games use input devices (e.g. gaming controller or joystick) based on motion sensing technologies. The Nintendo Wii is a game controller which was initially developed for playing video games but has been used in the patients' rehabilitation regime. It has been found that gaming can help the patients have fun, hence improving motivation, while they are involved in rehabilitation exercises. The use of rehabilitation robots and VR is to help apply rehabilitation programs to train the patients' muscle activities through which the patients are engaging into more muscle exercises. When the CNS is damaged, but the peripheral nerves are still intact, then functional electrical stimulation can be applied to these peripheral nerves to control specific muscles.

3) **FES**

In the traditional treatment methods, muscle strength and power are trained during the rehabilitation program. If the nerve connections between the muscle and the CNS are damaged or no longer functional then the direct stimulation of these affected muscles is possible using FES [29]. FES either uses electrodes placed on the skin above the muscles or electrodes surgically implanted under the skin to activate the neural tissues of the affected extremities (mainly the arms and legs) for the purpose of restoring some of the muscle function. In Neuro Rehabilitation, FES can be used as one component of the treatment because the muscle activation should strengthen the weak muscle and reduce the spasticity [30]. There is evidence showing that FES is able to enhance the recovery of upper limb movement (wrist function has been investigated) and improve the upper limb functional use in patients in task orientated training [31]. However it is still not clear how long the improvements are maintained. Initially, FES was developed by Liberson in the 1960's [32], for treatment of Drop Foot, which is still its most common use. The FES systems are good at engaging muscles in task execution but have disadvantages in that the FES is not able to generate the more complex upper limb motion as robotic systems can [33].

This brief overview has presented of several neurorehabilitation techniques developed to help the patients to restore their upper movement function. However as has been mentioned the patient's recovery and the efficacy of treatment also needs to be assessed during and after rehabilitation. Therefore a brief overview of some of the assessment techniques will be presented in the next section.

III. ASSESSMENT OF UPPER LIMB FUNCTION

Rehabilitation treatment has the important goal which is to help the patients to recover their limbs motor ability to the highest level so as to help increase their independence and quality of life. Therefore, the availability of quantitative assessment for evaluating patients' progress and the effectiveness of the treatment are important. The measurement of the recovery is complex and different clinical measure scales and methods are used [34]. However, current assessment methods are very insensitive and subjective, often based on the clinicians' experience and some basic measurement e.g. timing of specific movements. In some cases, the assessment results fail to show any measureable changes in the patients' performance even when the patient feels that there has been improvement of the strength and movement.

At present a range of assessment tests are available to try and monitor the recovery of the patient and to help the clinician gauge whether the prescribed rehabilitation program is helping the patient. Typical tests include the nine-hole peg test (9HPT) [35], bean bag test [36], water drinking test [37] and range of motion (ROM) tests [38]. The following section reviews the different methods and technologies for patients' mobility assessment.

A. Traditional assessment techniques

A range of therapy of assessment scales is available to help assess the recovery of the patient throughout rehabilitation. Some scales are used to evaluate the physical and cognitive disability (e.g. BI, DAS, and Functional Independence Measure (FIM) [39]). To assess the outcome of upper limb rehabilitation the Fugl-Meyer (FM) Test [40] (impairment scales), Action Research Arm Test (ARAT) [41], Motion Assessment Scale, Box-Block Test, and 9HPT are most commonly used in clinic [42]. Though the above assessment methods are widely used, they are not able to capture the dynamic performance of the limb which is thought to be especially important when assessing motor recovery.

1) **DAS**

The DAS test has been developed to assess the level of functional disability of the upper-limb spasticity in several areas, including dressing, hygiene, limb position and pain [6]. The item score range is from 0 to 3. Though DAS is very simple, its validity and reliability has been proved and it is one of the standard assessments used in rehabilitation.

2) **MAS**

The Ashworth Scale was originally developed to measure muscle resistance and spasticity in Multiple Sclerosis with a score system ranging from 0-4. Ashworth scores are tested flexing the patients' joints (shoulder, elbow, wrist and fingers). The scoring is based on the muscle tone according to the Ashworth scale. A modified scale is made by adding a 1+ into the existed measurement scale in order to present the muscle resistance between the score 1 and 2 [43].

3) Motor Assessment Scale

The Motor Assessment Scale was developed by Carr and Shepherd [44] based on many years' experience and is designed to measure the patient's ability to move with low tone or in a synergistic pattern and finally move out of the synergistic pattern to normal movement. It assesses eight areas of motor function, including supine to side lying, supine to sitting over side of bed, balanced sitting, sitting to standing, walking, upper-arm function, hand movements and advanced hand activities. Under each of the eight activities, there are six sub items. Each item is scored based on the scale from 0 to 6. The upper arm function, hand movements and advanced hand activities are used for assessing upper limb function. In this scale, 0 is scored if the patient cannot complete any part in a measurement item while 6 is scored for an optimal motion behaviour.

4) Box and Block Test

The Box and Block Test [45] is an assessment of gross manual dexterity. During the test, the patient is asked to transport the blocks for a time of one minute from one compartment over the partition board in the middle to the other compartment. Timing is done by the therapist. The score is the number of blocks transported to the other compartment.

5) Nine-hole peg test

The 9HPT [35] is a test to assess fine motor control and coordination (finger dexterity). The patient is asked to pick up the pegs one at a time from the container and insert them into the nine holes and the patient is asked to use his or her preferred way to complete the task. During the test, the therapist uses a stopwatch to measure the time taken to carry out the test. This time and whether the task is completed will be part of the score. The typical completion time for healthy adults is about 20 seconds [35]. In addition to the above commonly used clinical assessment tests, there are also other assessments which focus on the functional ability of the patients, for example, drinking water, shaving and combing hair.

B. New measurement techniques for rehabilitation assessment

Though the above presented assessment techniques and tools provide a quantifiable score and concerning information on the performed movement, but the patients' performance are based on the therapists' subjective and observational analysis. Again the evaluation is fairly crude and subjective. Therefore additional assessment techniques have been developed which provide the clinician with additional and more objective data concerning upper limb function.

1) Visual tracking system

The availability of the video capturing systems has made visual tracking an effective method for upper limb motion tracking. A typical visual tracking system consists of one or multiple cameras. These systems can be divided into marker-based and marker-less systems [46].

a) Marker-based visual tracking system

There are several marker-based motion capture systems, such as the Qualisys and Vicon systems. The Qualisys is a motion capture system that contains several cameras (usually 5 to 24 cameras), each of which emits a beam of infrared light. Small reflective markers are placed at specified sites on the subject. An infrared source located on the camera illuminates the markers. The reflected light is then picked up by the cameras. Similarly, the Vicon system was specifically designed for use in virtual and immersive environments. The application of these optical systems can often be found in clinical and research applications, especially in gait analysis and are considered to be the gold standard in motion analysis. The Vicon Bonita's (1 megapixel camera) can provide 0.5 mm in translational accuracy. For the Qualisys and Vicon motion capture system, there is offered end-user biomechanics analysis tools for use in clinical and research studies. The biomechanical analysis includes skeleton models which enable animation and 3D visual tracking of different human body segments. In rehabilitation assistive technology, researchers at Salford University use the Qualisys system for the analysis of movement disorders [47]. For Qualisys system, the cameras emit infrared light onto the markers attached on the subjects, and the reflected light sensed by the camera sensor. Then the position of the subject is calculated through the above information and a sophisticated human skeleton model. The biomechanical model and marker positions are used together to estimate the movement of the skeleton segments or joints. In addition, there are some general rules should be followed of markers attachment e.g. the markers should be placed as close to the bone as possible and the subject should wear tight fitting clothes to minimise marker movement.

The Vicon system is also used in life sciences, animation and engineering. The marker-based visual tracking systems have been developed for building up the biomechanical model of the subject with markers attached over known joints or points on the body. However there are some disadvantages with this system. The main disadvantages of the visual tracking system lie in the cost of the system and system set-up. The cost of a Vicon MX camera system which includes eight cameras is about £130,000 and is needed for a typical setting. Though these marker-based visual tracking systems have very good tracking accuracy, the marker attachment and system set-up is complicated and the marker may move with the soft tissue. Considering about using the marker-based visual tracking systems for clinical motion assessment on the patients, the limitation not only lie in the system cost but also complicated system set-up (wearing of the tight fitting clothes and the placement of the markers), making such systems unsuitable for use in general clinic situations.

b) Marker-less visual tracking system

Compared with the skin-mounted marker-based visual tracking system, marker-less visual tracking system seem to offer a simpler and less restrictive motion capture technique. The difficulty of using this method is the challenge of having software which can reliably identify the boundaries or features of human bodies so that the joints and segments can be identified in order to construct an accurate 3D kinematic model [48]. A single or multiple cameras can be used. Compared with the marker-based visual tracking system, this marker-less visual tracking system requires additional computation in order to recognise and segment the image. Once this has been done the kinematic model can be built up.

The video capturing system generally engages multiple cameras with high resolution (the camera's resolution can be up to 10 Megapixels). Its cost is acceptable (less than £100 per camera) but its calibration and localisation makes it infeasible for the daily rehabilitation assessment. Compared with the marker-based system, the data processing of utilising the marker-less system is more complicated because the human movement information needs to be extracted from frames of images. However, this type of system is not currently commercially available.

The complexity, cost and space requirements also make the visual tracking system unsuitable for use in the general clinic of this project. Additionally the patients may feel unsettled of knowing that they are being monitored by a camera during assessment. Therefore, the visual tracking system was not considered suitable for this project.

2) Non-visual tracking system

Several sensing technologies, such as inertial sensing, mechanical sensing, acoustic sensing, magnetic sensing, radio and microwave sensing [49], have been developed. In general, sensors are attached to the human body in order to collect movement information. Because the sensors are attached to the body these tracking systems do not need a specialised space for use. In other words, they may be more suitable for use in a general clinical setting.

a) Electro-Mechanical sensing - the goniometer

A typical electro goniometer uses a potentiometer to provide an output related to the rotation of the joint. However, these systems are bulky, can restrict the subjects' movement and may be uncomfortable to wear for long periods of time [49]. Additionally, although it is a straightforward way to track simple joint angles, a major disadvantage is that because joint movement and measurement is restricted to two dimensions (2D) this system cannot be used to measure complex joints such as the shoulder.

b) Robotic aided motion tracking

As described in the section II.B.1, the robotic aided systems (e.g. MIT-MANUS, MIME robotic system) had been developed to assist the patient in their rehabilitation programs. In addition, these systems can also be used to measure limb movement during the exercises. The disadvantage of this kind of system lies in their sizes, complexity of set up and cost. Currently, a simple ARM guide (using only one motor) can cost several thousand pounds and the cost of the MIT-MANUS and MIME systems are even higher (about £ 50,000) [50].

c) Electromyography

Measurement of the electrical activity of the muscles, EMG, can also be used to give an indication of the muscle activity in the affected limb during the exercise. The EMG can be used as a measure of strength of muscle contraction [51] and can be combined with biomechanical data to provide additional information when analysing limb segment kinematic movement, for example, the significant EMG activity in both agonist and antagonist muscles can reflect the co-contraction of these muscles. When the measured muscle is relaxed, the magnitude of the EMG is very low but when the measured muscle is contracted, the magnitude of the EMG increases. Besides the application in the clinical diagnosis, the EMG signals can also be used in human computer interface in which the EMG signals can be used as the signal input for a 2D computer cursor control [52]. Though the EMG results is not directly related to the 3D motion tracking data, EMG still can be a good complementary measurement for the motion tracking results as it provides some information on muscle activity during that movement.

d) Instrumented Glove

Glove based sensing is essentially focused on monitoring hand and finger motion and it can be good complementary method for other upper limb motion tracking technologies which are more focused on the other upper limb segments e.g. upper arm and lower arm [53]. The glove systems allow dynamic measurement of joint ROM of the fingers, and even the grip and pinch strength. These objective measurements can be used in diagnosis and rehabilitative assessment. The disadvantages can be the material of the glove, which can constrain or support to the patients hand movement. The glove based sensing system is only suitable for the patients who still have finger movement but not for stroke patients who may not have active finger movement.

e) Inertial sensors

Inertial sensors combine data from accelerometers, magnetometers and gyroscopes to measure the change of position and orientation [49]. The development of Micro Electro Mechanical Systems (MEMS) technology has resulted in the availability of small inertial sensors which are designed for attachment to the human upper limb. An inertial measurement system will usually consist of several inertial sensors and a biomechanical model to interpret the sensor.

Initially typical applications were used to track head motion where the accelerometer was used as an inclinometer and the gyroscope senses the orientation [54,55]. However it was realised that in order to improve accuracy of measurement, data from magnetometers had to be fused with that from the accelerometer and gyroscopes [56,57]. Comparison of inertial measuring system with optical system for position tracking using multiple sensors and kinematic models were carried out [58]. It has been shown that the inertial measuring system has RMS position errors that are normally less than 1 cm [59], which indicates the motion sensing accuracy should be acceptable for monitoring upper limb motion. Recently, inertial sensors to monitoring motion have been used in the clinic to track stroke patients [60].

However, in theory all that is required to track limb segment orientation and movement is to attach the inertial sensors to the limb segments under test and apply the appropriate biomechanical model. Such a system would not require a specialised set-up as required by the video systems of Vicon and Qualisys and could be used in any environment.

Inertial sensors for human biomechanics

There are several commercial inertial sensors which are suitable for human motion tracking. These sensors combine a tri-axial accelerometer, a tri-axial gyro, and a tri-axial magnetometer. The X sens MTx sensors have been used for many years in movement science and also industrial applications. The OSV3 sensor from Inertial Labs is the smallest available inertial sensor and is suitable for human motion tracking. The 3DM-GX3™-25 is from Micro Strain along with the rest of the GX3 family. Inertia Cube BT™ from Inter Sense is also used in 3D orientation tracking. A detailed comparison between these sensors and the cost of a single sensor is presented in Table 1.

Table -1 Comparison between different commercial inertial sensors

Performance specification	Xsens MTx	Inertial Labs OSV3	MicroStrain 3DM-GX3™	InterSense InertiaCube BT™
Wireless	No	No	Yes	Yes
Orientation Static accuracy	Roll &Pitch 0.5º Yaw 1.0º	Roll&Pitch 0.2º Yaw 1.0º	Roll&Pitch 0.5º Yaw 1.0º	Roll&Pitch 0.5º Yaw 1.0º
Angular resolution	0.05° RMS	0.01° RMS	0.1° RMS	0.01° RMS
Update rate	User settable Max 120Hz, Max 256Hz raw data	Max 500 Hz	Max 1000Hz	180 Hz
Dimensions (mm)	38×53×21 (W×L×H)	32×12×4 (W×L×H)	38×24×12 (W×L×H)	60×54×32 (W×L×H)
Weight	30 grams	12 grams	11.5 grams	67 grams
O/S Compatibility	Windows Linux	Windows	XP/Vista/ Windows 7	XP/Vista/ Windows 7
Software features	MT software	OSv3 OEM Developer	SDK provides data	SDK with full Inter-Sense API

	development kit	's Kit	communications	
Maximum	Up to 10 MTx sensors per Xbus Master	20 sensors on the sensor bus	N/A	N/A
Cost (Per sensor)	£1200	£500	£1500	£1300

In terms of the cost, it should be noted that there will be cost for additional hardware and software. For example, a 6-sensor Xsens MTw system will cost £11,000 plus the cost for their biomechanical model. Among the above presented sensors, Osv3 is one of the smallest inertial motion tracking sensors and has been available since 2011. Xsens MTx has been used in many researches as it is the gold standard inertial sensor which is designed for biomechanical measurements. It is very easy to get started by using the MT Manager software for Windows user interface. The newly developed (released in 2012) wireless inertial sensor Inertia Cube BT (with a rechargeable battery), Xsens MTw (released in 2011) and Osv2 (released in 2011) are also the ideal choices for human motion capture and should be considered for future use. One disadvantage of the Xsens MTx sensor is that it is not completely wireless. Cables are used to connect the MTx sensors to the Xbus master which provides the power and con-nection to the PC. This connection can be either by Bluetooth or with a USB cable. The present of cables will have some effect on the natural movements of the subject. Therefore in 2011, Xsens release their newest product - the MTw, which is a wireless sensor removing the need for cabling and the XBus. In a recent release, the new MVN BIOMECH A wind enables full-body motion tracking with wireless inertial sensors which reduces the impact of attaching sensors to the subject and increases their freedom of movement.

Full body inertial motion capture - Xsens MVN system

The Xsens Company has released the human motion tracking capture suit (Xsens MVN) which includes 17 MTx inertial sensors, a comfortable lycra suit with embedded cabling. The accuracy of the position tracking is claimed to be about 2% error over a travelled distance of several metres. The Xsens software for the MVN uses a biomechanical/kinematic model which is similar to the software used in the Vicon and Qualisys motion tracking systems. This whole body suit MVN inertial measurement system makes motion capture much easier for the researcher - there is no need to develop a kinematic model. But the number of the sensors required can be a limitation of the applicability of this system, since the system cost increases as well as set-up and calibration getting more complex.

Low cost inertial sensors

The use of inertial sensors has also seen major application in game controllers and smartphones, primarily to improve the gaming experience by improving the tracking of the gaming controller. This development occurred because the original motion sensing based 3D games relied on the video tracking of the controller. There are several examples where video tracking was implemented, such as Nintendo Wiimote, Xbox 360, and Sony PlayStation Move. However, one of the disadvantages of these systems is that they are not able to cope with the situation when the controller is hidden from the camera, for example, during the game the controller may be obscured behind the player's back. Therefore inertial sensors were added to help estimate controller position when the camera data is not available.

For example, Nintendo released the Wii Remote in 2005 which contains an accelerometer to sense movement. The tracking ability of the Wii Remote was improved in 2008 with the release of an attachment, the Wii MotionPlus which contains a gyroscope unit. In 2010, Sony also released a gaming controller containing inertial sensors, the Sony PlayStation Move. Compared with the Nintendo Wii, the Sony also includes a magnetometer, which should improve the accuracy of 3D orientation and position tracking [61,62]. These low cost (£30) inertial sensors are of interest as they may be possible replacements for the more costly (£1400) commercial inertial sensors. Therefore one objective of a recent research [62] is to evaluate their suitability for upper limb tracking and to identify when they might be viable replacement for the sensors specifically designed for biomechanical measurements.

More recently Smartphones containing all three inertial sensors are now appearing on the market. In theory this could give them the same functionality as Wii MotionPlus, the Sony Move and possibly the inertial sensors specifically designed for biomechanical measurements. Although their cost is currently higher than that of the gaming controllers, their popularity means that they are already acceptable to a wider range of users than gaming controllers. Additionally their incorporation into a phone offers the possibility of remote monitoring. Therefore the possibility of using these devices for upper limb motion tracking where only a single sensor is required is an interesting option.

IV. REVIEW OF INERTIAL TRACKING STRATEGIES

Once data from the inertial sensors has been obtained it is necessary to process this data to obtain information about segment orientation [63] and position. There are two basic methodologies used to do this - Kinematic modelling and Dead Reckoning (DR) method. A brief overview of these methodologies and their advantages and disadvantages will now be given.

A. New measurement techniques for rehabilitation assessment

a) Kinematic modelling

Kinematics deals with body segment movement (focussing on joint orientation and segment position) rather than the force exerted on them, which differs from kinetics [64]. A number of studies have used inertial sensors and kinematic modelling for upper limb motion tracking [59,61,65–68]. At least two sensors (on elbow and wrist) are required to construct an upper limb link kinematic model. In the study by Zhou et al, 2008 [59], the shoulder position has been predicted by the optimisation technique which uses the upper limb biomechanical constraints to estimate the shoulder movement from the motion of the elbow and wrist joints. Therefore, in order to carry out a systematic evaluation of whole upper limb motion the shoulder movement must also be measured and a kinematic model using at least four inertial sensors has to be implemented. Multiple sensors have been used in Kinematic modelling, but DR method is of interest because it offers to track the motion of one segment using a single rather than multiple sensors. Therefore the feasibility using this method will be investigated.

b) Dead reckoning

Initially, the process of deduced reckoning (called dead reckoning) was used in satellite, marine and aircraft navigation starting from a known latitude and longitude and travelling in a known direction for a known time [69]. This inertial navigation deduces the current location by adding the estimated distance travelled to the previous value. The first inertial sensors used gyroscopes and accelerometers to measure orientation and acceleration. The velocity of the ship or aircraft can then be computed by integration of the acceleration and the distance travelled can be computed by double integrating the acceleration. The gyro-scope outputs provide information about changes in direction and a magnetometer is used to identify direction relative to magnetic north. It is claimed that its accuracy can be within 2% of the actual distance travelled. It has been used in the places where the GPS signal is not available. DR method has also been used for tracking pedestrians indoors [70,71]. However one of the major disadvantages of this technique is the major errors introduced by the double integration of any offsets and noise in the accelerometer signal. Therefore significant effort has been put into minimising this error and several techniques have been developed to do this. The application of this technique for motion tracking of a single segment is of interest because, unlike the Kinematic model which requires several sensors, the DR method offers the measurement of orientation and position tracking using a single sensor. This is attractive in terms of simplicity of set-up in a busy clinic, reduced cost and simpler data analysis and presentation. The research [58] presented that under controlled conditions the errors in measurement using the DR method can be reduced to an acceptable level of 0.5 cm over a 30 second measurement period.

V. REVIEW OF UPPER LIMB MOVEMENT ANALYSIS OF NEUROLOGICAL PATIENTS

The use of measurement systems where movement data is recorded e.g. the video tracking systems has resulted in developments in data analysis to investigate additional parameters which it is thought may also be useful indicators of motor recovery. Examples of these parameters are segment sub movements and movement smoothness.

A. Submovement

The research done by Neville et al., 1999 [72] found that the patient movements can be broken down into a series of submovements. Some researchers have identified changes in limb segment submovements during rehabilitation. In one recent study using the MIT-MANUS robot [73], a comparison of the kinematic motion analysis before and after recovery showed that the submovements become fewer, longer, and faster. The research analysis indicates that after the therapy, the patient has fewer submovements [74].

A. Movement smoothness

Movement smoothness is the smoothness of the measured movement which is defined as a distinctive characteristic related to skilled and coordinated movement [75]. It is also related to the sub movement analysis. Movement smoothness has been characterised as another important characteristic in assessing the patients’ movement ability when recovering from neurological disorders. Movement smoothness is the blending of the sub-movements and the smoother the movement the less discrete sub movements of the position or velocity data will be present. The healthy volunteers’ movement trajectories are considered to be smooth [76]. The healthy subject also tends to have a smooth acceleration, velocity and position output in contrast with the patient whose movement presents the multiple peaks and discrete sub movements which make the motion trajectory less smooth. It is expected that for the patient undergoing rehabilitation that there will be a reduction in the number of sub movements and that the smoothness of the overall movement will increase. There are, therefore, several movement smoothness parameters, e.g., position, velocity and acceleration that can be used in order to quantify the smoothness of a movement.

VI. CONCLUSION

This paper has presented an overview of rehabilitation treatment and assessment methods for monitoring the progress of the rehabilitation of the upper limb. A series of traditional physiotherapy and new assistive techniques such as the rehabilitation robot, VR and FES are presented. The assessment of rehabilitation treatment therefore provides important feedback to the clinician and to the patient. The traditional assessment methods based on the scores of different assessment scales tend to be tedious, subjective and unable to provide the clinicians with objective information on the patients' upper limb motion. Then a range of more objective assessment or measurement systems have been introduced.

The video tracking system is able to provide the clinicians with quantitative data, however, the specialised space requirement, the complexity and time to setup as measurement and the system cost made it impracticable for the use in the general clinic. Many other non-camera based system such as mechanical sensing system, robotic aided motion tracking system as well as inertial sensing system have been reviewed. But the mechanical sensing system is bulky and restricts the subject's movement, and robotic aided motion tracking system can provide reliable motion tracking data but it has the disadvantages on the setup, cost and space requirement. EMG is able to provide muscle activity related signal but is not able to provide 3D motion data and the instrumented glove is only focused on the hand movement. The development of inertial sensors could provide a system for upper limb movement measurement which can be used in a general clinical setting and also provide the objective data for analysis currently only available with the more complex video systems or the more expensive rehabilitation robotic systems. The ability to measure discrete timing periods within an exercise and to investigate parameters such as move-ment smoothness are additional advantages provided by using an instrumented measurement system.

VII. REFERENCES

[1] Penrose, D. Occupational therapy for orthopaedic conditions; Springer, 2013; ISBN 148993085X.

[2] Bakheit, A.M.O. The pharmacological management of post-stroke muscle spasticity. Drugs Aging 2012, 29, 941–947.

[3] Bai, L.; Pepper, M.; Yan, Y.; Spurgeon, S.K.; Sakel, M.; Phillips, M. Quantitative Assessment of Limb Motion by Inertial Sensors Before and After Botulinum Toxin for Spasticity. Arch. Phys. Med. Rehabil. 2014, doi:10.1016/j.apmr.2014.07.205.

[4] O'dwyer, N.J.; Ada, L.; Neilson, P.D. Spasticity and muscle contracture following stroke. Brain 1996, 119, 1737–1749.

[5] Guido Jr, J.A.; Stemm, J. Reactive neuromuscular training: a multi-level approach to rehabilitation of the unstable shoulder. North Am. J. Sport. Phys. Ther. NAJSPT 2007, 2, 97.

[6] Brashear, A.; Zafonte, R.; Corcoran, M.; Galvez-Jimenez, N.; Gracies, J.M.; Gordon, M.F.; McAfee, A.; Ruffing, K.; Thompson, B.; Williams, M.; et al. Inter- and intrarater reliability of the Ashworth Scale and the Disability Assessment Scale in patients with upper-limb poststroke spasticity. Arch. Phys. Med. Rehabil. 2002, doi:10.1053/apmr.2002.35474.

[7] Edemekong, P.F.; Bomgaars, D.L.; Levy, S.B. Activities of daily living (ADLs). 2017.

[8] Quinn, T.J.; Langhorne, P.; Stott, D.J. Barthel index for stroke trials: development, properties, and application. Stroke 2011, 42, 1146–1151.

[9] Harb, A.; Kishner, S. Modified ashworth scale. In StatPearls [Internet]; StatPearls Publishing, 2021.

[10] Bobath, B. Adult hemiplegia. 1990.

[11] Brunnstrom, S. Movement therapy in hemiplegia. A Neurophysiol. approach 1970, 113–122.

[12] Sharman, M.J.; Cresswell, A.G.; Riek, S. Proprioceptive neuromuscular facilitation stretching. Sport. Med. 2006, 36, 929–939.

[13] Kawashima, N.; Popovic, M.R.; Zivanovic, V. Effect of intensive functional electrical stimulation therapy on upper-limb motor recovery after stroke: case study of a patient with chronic stroke. Physiother. Canada 2013, 65, 20–28.

[14] Chien, W.; Chong, Y.; Tse, M.; Chien, C.; Cheng, H. Robot- assisted therapy for upper- limb rehabilitation in subacute stroke patients: A systematic review and meta- analysis. Brain Behav. 2020, 10, e01742.

[15] Prange, G.B.; Jannink, M.J.; Groothuis-Oudshoorn, C.G.; Hermens, H.J.; IJzerman, M.J. Systematic review of the effect of robot-aided therapy on recovery of the hemiparetic arm after stroke. 2009.

[16] Nef, T.; Mihelj, M.; Colombo, G.; Riener, R. ARMin-robot for rehabilitation of the upper extremities. In Proceedings of the Proceedings 2006 IEEE International Conference on Robotics and Automation, 2006. ICRA 2006.; IEEE, 2006; bll 3152–3157.

[17] Kahn, L.E.; Lum, P.S.; Reinkensmeyer, D.J. Selection of robotic therapy algorithms for the upper extremity in chronic stroke: Insights from MIME and ARM Guide results. Kaist, Daejeon, Repub. Korea 2003, 208–210.

[18] Molteni, F.; Gasperini, G.; Cannaviello, G.; Guanziroli, E. Exoskeleton and end-effector robots for upper and lower limbs rehabilitation: narrative review. PM&R 2018, 10, S174–S188.

[19] Qassim, H.M.; Wan Hasan, W.Z. A review on upper limb rehabilitation robots. Appl. Sci. 2020, 10, 6976.

[20] Krebs, H.I.; Hogan, N.; Volpe, B.T.; Aisen, M.L.; Edelstein, L.; Diels, C. Overview of clinical trials with MIT-MANUS: a robot-aided neuro-rehabilitation facility. Technol. Heal. Care 1999, 7, 419–423.

[21] Lum, P.S.; Burgar, C.G.; Van der Loos, M.; Shor, P.C.; Majmundar, M.; Yap, R. MIME robotic device for upper-limb neurorehabilitation in subacute stroke subjects: A follow-up study. J. Rehabil. Res. Dev. 2006, 43, 631.

[22] Reinkensmeyer, D.J.; Kahn, L.E.; Averbuch, M.; McKenna-Cole, A.; Schmit, B.D.; Rymer, W.Z. Understanding and treating arm movement impairment after chronic brain injury: progress with the ARM guide. J. Rehabil. Res. Dev. 2014, 37, 653–662.

[23] Park, J.H.; Park, G.; Kim, H.Y.; Lee, J.-Y.; Ham, Y.; Hwang, D.; Kwon, S.; Shin, J.-H. A comparison of the effects and usability of two exoskeletal robots with and without robotic actuation for upper extremity rehabilitation among patients with stroke: a single-blinded randomised controlled pilot study. J. Neuroeng. Rehabil. 2020, 17, 1–12.

[24] Miao, Q.; Li, Z.; Chu, K.; Liu, Y.; Peng, Y.; Xie, S.Q.; Zhang, M. Performance-based iterative learning control for task-oriented rehabilitation: a pilot study in robot-assisted bilateral training. IEEE Trans. Cogn. Dev. Syst. 2021.

[25] Robertson, J.V.G.; Jarrassé, N.; Roby-Brami, A. Rehabilitation robots: a compliment to virtual reality. Schedae 2010, 1, 77–94.

[26] Romer, G.; Stuyt, H.J.A.; Peters, A. Cost-savings and economic benefits due to the assistive robotic manipulator (ARM). In Proceedings of the 9th International Conference on Rehabilitation Robotics, 2005. ICORR 2005.; IEEE, 2005; bll 201–204.

[27] Merians, A.S.; Jack, D.; Boian, R.; Tremaine, M.; Burdea, G.C.; Adamovich, S. V; Recce, M.; Poizner, H. Virtual reality–augmented rehabilitation for patients following stroke. Phys. Ther. 2002, 82, 898–915.

[28] Brunetti, F.; Garay, A.; Moreno, J.C.; Pons, J.L. Enhancing functional electrical stimulation for emerging rehabilitation robotics in the framework of hyper project. In Proceedings of the 2011 IEEE International Conference on Rehabilitation Robotics; IEEE, 2011; bll 1–6.

[29] Popović, D.B. Advances in functional electrical stimulation (FES). J. Electromyogr. Kinesiol. 2014, 24, 795–802.

[30] Sivaramakrishnan, A.; Solomon, J.M.; Manikandan, N. Comparison of transcutaneous electrical nerve stimulation (TENS) and functional electrical stimulation (FES) for spasticity in spinal cord injury-A pilot randomized cross-over trial. J. Spinal Cord Med. 2018, 41, 397–406.

[31] Alon, G.; Levitt, A.F.; McCarthy, P.A. Functional electrical stimulation enhancement of upper extremity functional recovery during stroke rehabilitation: a pilot study. Neurorehabil. Neural Repair 2007, 21, 207–215.

[32] Liberson, W.T. Functional electrotherapy: stimulation of the peroneal nerve synchronized with the swing phase of the gait of hemiplegic patients. Arch Phys Med 1961, 42, 101–105.

[33] Rymer, W.Z.; Dietz, V.; Nef, T. Neurorehabilitation technology; Springer Verlag London Limited, 2012;

[34] Duncan, P.W.; Lai, S.M.; Keighley, J. Defining post-stroke recovery: implications for design and interpretation of drug trials. Neuropharmacology 2000, 39, 835–841.

[35] Mathiowetz, V.; Weber, K.; Kashman, N.; Volland, G. Adult norms for the nine hole peg test of finger dexterity. Occup. Ther. J. Res. 1985, doi:10.1177/153944928500500102.

[36] Bai, L.; Pepper, M.G.; Yan, Y.; Phillips, M.; Sakel, M. Quantitative measurement of upper limb motion pre- and post-treatment with Botulinum Toxin. Meas. J. Int. Meas. Confed. 2021, doi:10.1016/j.measurement.2020.108304.

[37] Murphy, M.A.; Sunnerhagen, K.S.; Johnels, B.; Willén, C. Three-dimensional kinematic motion analysis of a daily activity drinking from a glass: a pilot study. J. Neuroeng. Rehabil. 2006, 3, 1–11.

[38] Clarkson, H.M. Musculoskeletal assessment: joint range of motion and manual muscle strength; Lippincott Williams & Wilkins, 2000; ISBN 0683303848.

[39] Tinetti, M.E. Performance-oriented assessment of mobility problems in elderly patients. J. Am. Geriatr. Soc. 1986.

[40] Fugl-Meyer, A.R.; Jääskö, L.; Leyman, I.; Olsson, S.; Steglind, S. A method for evaluation of physical performance. Scand J Rehabil Med 1975, 7, 13–31.

[41] Lyle, R.C. A performance test for assessment of upper limb function in physical rehabilitation treatment and research. Int. J. Rehabil. Res. 1981, 4, 483–492.

[42] Platz, T.; Pinkowski, C.; van Wijck, F.; Kim, I.-H.; Di Bella, P.; Johnson, G. Reliability and validity of arm function assessment with standardized guidelines for the Fugl-Meyer Test, Action Research Arm Test and Box and Block Test: a multicentre study. Clin. Rehabil. 2005, 19, 404–411.

[43] Bohannon, R.W.; Smith, M.B. Interrater reliability of a modified Ashworth scale of muscle spasticity. Phys. Ther. 1987, doi:10.1093/ptj/67.2.206.

[44] Carr, J.H.; Shepherd, R.B.; Nordholm, L.; Lynne, D. Investigation of a new motor assessment scale for stroke patients. Phys. Ther. 1985, doi:10.1093/ptj/65.2.175.

[45] Mathiowetz, V.; Volland, G.; Kashman, N.; Weber, K. Adult norms for the Box and Block Test of manual dexterity. Am. J. Occup. Ther. 1985, 39, 386–391.

[46] Gil-Agudo, A.; del, A.; los Reyes-Guzman, A. de; Bernal-Sahun, A.; Roco, E. Applications of Upper Limb Biomechanical Models in Spinal Cord Injury Patients. In Biomechanics in Applications; 2011.

[47] Khan, W.S.; Jones, R.K.; Nokes, L.; Johnson, D.S. How accurate are lockable orthotic knee braces? An objective gait analysis study. Knee 2007, 14, 497–499.

[48] Corazza, S.; Muendermann, L.; Chaudhari, A.M.; Demattio, T.; Cobelli, C.; Andriacchi, T.P. A markerless motion capture system to study musculoskeletal biomechanics: visual hull and simulated annealing approach. Ann. Biomed. Eng. 2006, 34, 1019–1029.

[49] Schepers, H.M. Ambulatory assessment of human body kinematics and kinetics. 2009.

[50] Reinkensmeyer, D.J.; Pang, T.; Nessler, J.A.; Painter, C.C. Java Therapy : Web-Based Robotic Rehabilit ation.; 2001.

[51] Chae, J.; Yang, G.; Park, B.K.; Labatia, I. Muscle weakness and cocontraction in upper limb hemiparesis: relationship to motor impairment and physical disability. Neurorehabil. Neural Repair 2002, 16, 241–248.

[52] Barreto, A.; Scargle, S.; Adjouadi, M. A practical EMG-based human-computer interface for users with motor disabilities. 2000.

[53] Dipietro, L.; Sabatini, A.M.; Dario, P. A survey of glove-based systems and their applications. Ieee Trans. Syst. man, Cybern. part c (applications Rev. 2008, 38, 461–482.

[54] Foxlin, E. Inertial head-tracker sensor fusion by a complementary separate-bias Kalman filter. In Proceedings of the Proceedings - Virtual Reality Annual International Symposium; 1996.

[55] Luinge, H.J.; Veltink, P.H. Measuring orientation of human body segments using miniature gyroscopes and accelerometers. Med. Biol. Eng. Comput. 2005, doi:10.1007/BF02345966.

[56] Zhou, H.; Hu, H. Reducing drifts in the inertial measurements of wrist and elbow positions. IEEE Trans. Instrum. Meas. 2010, doi:10.1109/TIM.2009.2025065.

[57] Roetenberg, D.; Slycke, P.J.; Veltink, P.H. Ambulatory position and orientation tracking fusing magnetic and inertial sensing. IEEE Trans. Biomed. Eng. 2007, doi:10.1109/TBME.2006.889184.

[58] Bai, L.; Pepper, M.G.; Yan, Y.; Spurgeon, S.K.; Sakel, M.; Phillips, M. Quantitative Assessment of Upper Limb Motion in Neurorehabilitation Utilizing Inertial Sensors. IEEE Trans. Neural Syst. Rehabil. Eng. 2015, doi:10.1109/TNSRE.2014.2369740.

[59] Zhou, H.; Stone, T.; Hu, H.; Harris, N. Use of multiple wearable inertial sensors in upper limb motion tracking. Med. Eng. Phys. 2008, doi:10.1016/j.medengphy.2006.11.010.

[60] Thies, S.B.; Tresadern, P.A.; Kenney, L.P.; Smith, J.; Howard, D.; Goulermas, J.Y.; Smith, C.; Rigby, J. Movement variability in stroke patients and controls performing two upper limb functional tasks: a new assessment methodology. J. Neuroeng. Rehabil. 2009, 6, 1–12.

[61] Bai, L.; Pepper, M.G.; Yana, Y.; Spurgeon, S.K.; Sakel, M. Application of low cost inertial sensors to human motion analysis. In Proceedings of the 2012 IEEE I2MTC - International Instrumentation and Measurement Technology Conference, Proceedings; 2012.

[62] Bai, L.; Pepper, M.G.; Yan, Y.; Phillips, M.; Sakel, M. Low Cost Inertial Sensors for the Motion Tracking and Orientation Estimation of Human Upper Limbs in Neurological Rehabilitation. IEEE Access 2020, doi:10.1109/ACCESS.2020.2981014.

[63] Bai, L. 3D Orientation Estimation Using Inertial Sensors. J. Electr. Technol. UMY 2022, 6, 12–21.

[64] Zatsiorsky, V.M.; Zaciorskij, V.M. Kinetics of human motion; Human kinetics, 2002; ISBN 0736037780.

[65] Hingtgen, B.; McGuire, J.R.; Wang, M.; Harris, G.F. An upper extremity kinematic model for evaluation of hemiparetic stroke. J. Biomech. 2006, doi:10.1016/j.jbiomech.2005.01.008.

[66] Bai, L.; Pepper, M.G.; Yan, Y.; Spurgeon, S.K.; Sakel, M.; Phillips, M. A multi-parameter assessment tool for upper limb motion in neurorehabilitation. In Proceedings of the Conference Record - IEEE Instrumentation and Measurement Technology Conference; 2011.

[67] Bai, L. Time-Frequency Analysis of Upper Limb Motion Based on Inertial Sensors. In Proceedings of the 2021 32nd Irish Signals and Systems Conference (ISSC); IEEE, 2021; bll 1–6.

[68] Bai, L. A Sensor Based Assessment Monitoring System for Patients with Neurological Disabilities. J. Robot. Control 2021, 2, 489–495.

[69] Lawrence, A. Modern inertial technology: navigation, guidance, and control; Springer Science & Business Media, 2001; ISBN 0387985077.

[70] Foxlin, E. Pedestrian tracking with shoe-mounted inertial sensors. IEEE Comput. Graph. Appl. 2005, 25, 38–46.

[71] Ojeda, L.; Borenstein, J. Personal dead-reckoning system for GPS-denied environments. In Proceedings of the SSRR2007 - IEEE International Workshop on Safety, Security and Rescue Robotics Proceedings; 2007.

[72] Hogan, N.; Doeringer, J.A.; Krebs, H.I. Arm movement control is both continuous and discrete. Cogn. Stud. Bull. Japanese Cogn. Sci. Soc. 1999, 6, 254–273.

[73] Dipietro, L.; Krebs, H.I.; Fasoli, S.E.; Volpe, B.T.; Hogan, N. Submovement changes characterize

generalization of motor recovery after stroke. Cortex 2009, doi:10.1016/j.cortex.2008.02.008.

[74] Lu Bai; Matthew G Pepper; Yong Yan; Malcolm Phillips; Mohamed Sakel Inertial sensor based quantitative assessment of upper limb range of motion and functionality before and after botulinum toxin: a pilot study. Glob. J. Eng. Technol. Adv. 2020, doi:10.30574/gjeta.2020.2.3.0008.

[75] Hogan, N.; Sternad, D. Sensitivity of smoothness measures to movement duration, amplitude, and arrests. J. Mot. Behav. 2009, doi:10.3200/35-09-004-RC.

[76] Tsao, C.C.; Mirbagheri, M.M. Upper limb impairments associated with spasticity in neurological disorders. J. Neuroeng. Rehabil. 2007, doi:10.1186/1743-0003-4-45.

IJEAST

INTERNATIONAL JOURNAL OF ENGINEERING APPLIED SCIENCE AND TECHNOLOGY

ABOUT IJEAST

International Journal of Engineering Applied Science and Technology (IJEAST) is a peer-reviewed, open access journal that publishes high-quality research papers in the field of Engineering, Applied Science and Technology.

IJEAST aims to provide a platform for researchers, academicians, and professionals to share their innovative ideas, research findings, and practical experiences with the global scientific community.

FOCUS AREAS

- Engineering
- Applied Science
- Technology
- Innovation & Development
- Interdisciplinary Studies

PEER REVIEWED

All submissions are rigorously peer reviewed to ensure quality.

OPEN ACCESS

Free and unrestricted access to research for all.

GLOBAL REACH

Connecting researchers and professionals worldwide.

TIMELY PUBLICATION

We ensure a swift and efficient publication process.

For more information, visit our website

www.ijeast.com

INTERNATIONAL JOURNAL
OF ENGINEERING APPLIED SCIENCE
AND TECHNOLOGY

✉ editor@ijeast.com
www.ijeast.com
India

2455-2143