Using Wearable Technology to Generate Objective Parkinson's Disease Dyskinesia Severity Score: Possibilities for Home Monitoring

Mehdi Delrobaei, *Member, IEEE*, Navid Baktash, Greydon Gilmore, Kenneth McIsaac, *Member, IEEE*, and Mandar Jog

***Abstract*— A variety of clinical scales are available to assess dyskinesia severity in Parkinson's disease patients; however, such assessments are subjective, do not provide long term monitoring, and their use is subject to inter- and intra-rater variability. In this paper, an objective dyskinesia score was developed using an IMU -based motion capture system. Deep brain stimulation (DBS) surgery is currently the only acute intervention that results in the rapidly progressive reduction of dyskinesia's severity; hence, this form of therapy was selected as a model to validate the proposed method. Thirteen Parkinson's disease participants undergoing DBS surgery and 12 age-matched healthy control participants were assessed using the motion capture system. Concurrent Unified Dyskinesia Rating Scale (UDysRS) ratings were also performed. Parkinson's disease participants were assessed pre-operatively and for five visits post-operatively while seated at rest, during arms outstretched and while performing an action task. The kinematic data were used to develop an objective measure defined as the dyskinesia severity score. Generally, a strong correlation was observed between the UDysRS ratings and the full-body dyskinesia severity scores. The results suggest that it is feasible and clinically meaningful to utilize an objective full-body dyskinesia score for the assessment of dyskinesia. The portable motion capture system along with the developed software can be used remotely to monitor the full-body severity of dyskinesia, necessary for therapeutic optimization, especially in the patients home environment.**

***Index Terms*— Dyskinesia, objective assessment, Parkinson's disease, deep brain stimulation.**

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I. Introduction

WHILE significant progress has been made towards the management of motor symptoms of Parkinson's disease (PD), objective assessment of motor symptoms including dyskinesia remains a challenge [1]. A variety of clinical scales (such as Unified Dyskinesia Rating Scale (UDysRS), Lang-Fahn Activities of Daily Living Dyskinesia Rating Scale, and modified Abnormal Involuntary Movements Scale) are available to assess dyskinesia in PD. These clinical scales variably focus on anatomical distribution, phenomenology, time, severity, and disability of the disease.

However, clinical scales: (1) may not be sensitive enough to detect all treatment-related changes over-time [2], (2) provide rudimentary scoring, (3) are affected by inter- and intra-rater variability, and (4) can only be performed in clinic or laboratory, not representative of patients home environment [3], [4]. These unmet needs in dyskinesia assessment call for a more objective system in which dyskinesia severity can be quantified and analyzed reliably. This could potentially allow for remote monitoring and ultimately aid in optimization of therapeutic interventions such as medication and deep brain stimulation (DBS) setting adjustments.

A variety of technologies have been recently developed to assess movement disorders associated with PD [5]. Single accelerometers and gyroscopes have been widely used to detect and quantify dyskinesia [4]–[10]. A limited number of commercial movement analysis systems are also available for remote-monitoring of PD patients, including: Opal wearable sensors [11], Kinesia system [12], and Motus Movement Monitor [13]. Optical 3D motion trackers are also used in lab environments; however, developing an accurate portable and easy-to-use tool, which quantitatively records whole body movements such as dyskinesia of PD patients and could allow health professionals to remotely and consistently monitor them, remains an unmet need [14].

Dyskinesia is a complex movement disorder, affecting different body segments with variable severities [6], [8], [15]–[17] and single sensor systems do not capture full–body dyskinesia. Additionally, the output needs to be clinically relevant and easily interpretable to make appropriate, individualized therapeutic changes. Hence, a new approach

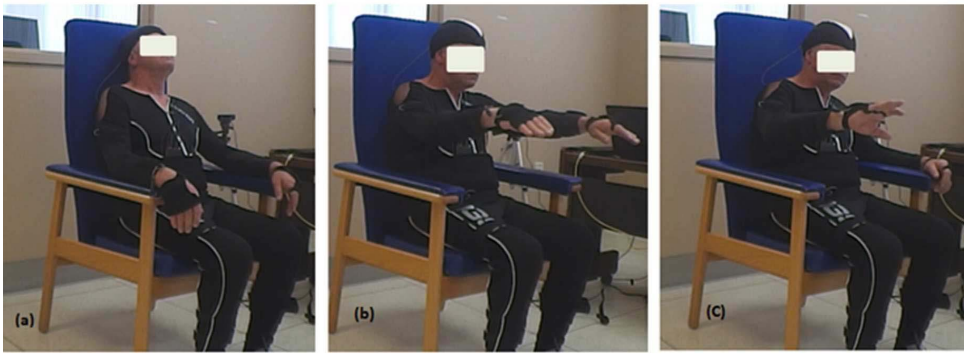

Fig. 1. All participants were asked to perform three standard tasks: (a) Rest, (b) Posture, and (c) Action while seated, wearing IGS-180 motion capture suit.

needs to be investigated to monitor patient's progress and track motor changes after treatment, enabling individualized therapy to enhance clinical care and improve patients quality of life.

Inertial motion measurement using Attitude and Heading Reference Systems (AHRS) is an emerging technology, proposed as an alternative to optical motion capture systems [18]. Such technologies have recently been evaluated and used for applications such as tele-rehabilitation [18]–[20]. However, the applicability and feasibility of these systems to quantify effects of acute interventions such as DBS surgery have not been used to validate these technologies [21]. Given that DBS electrode implantation is the only acute intervention that results in rapid, progressive reduction in dyskinesia in a relatively short time [22], this form of therapy can be used to reliably validate sensor technology, analyzing the biomechanics of dyskinesia over time, and potentially develop a new objective metric for whole body dyskinesia.

In order to address the clinical unmet need of objectively measuring whole body dyskinesia, this study utilizes a mobile and easy to use full-body wearable motion capture system to detect and quantify dyskinesia in PD participants prior to and post DBS intervention. The present study has three objectives: (1) to investigate the applicability, feasibility, and reliability of using an inertial full-body motion capture system in PD participants pre and post DBS-surgery to track the biomechanics of dyskinesia in all body segments; (2) to develop methods and algorithms that can detect, segment, and comprehensively output a clinically meaningful dyskinesia score; (3) to evaluate the clinical utility of the kinematic measure by correlating this feature with UDysRS scores during standard motor tasks. Therefore, this work is not intended to investigate the effects of DBS surgery and this treatment option was selected as a model therapy.

This paper is organized as follows. Section II presents the methods, including the details of the assessment tool, tasks, and data analysis framework. Section III presents the results including the statistical analyses. Finally, Section IV discusses the results and observations, and Section V presents the final remarks.

II. Methods

A. Participants

Dyskinesia was measured using UDysRS and kinematics obtained from the full–body wearable motion capture system one week before and up to three months following subthalamic nucleus deep brain stimulation (STN–DBS) surgery in thirteen PD participants and twelve healthy age-matched control participants. These participants were recruited from the Movement Disorders Center in London Health Sciences Center (London, ON, Canada).

The inclusion criteria for the PD participants were: (1) idiopathic Parkinson's disease, (2) Hoehn–Yahr stage II-III, (3) severe motor fluctuations with disabling off periods and dyskinesia during ON phases, (4) able to give informed consent, (5) able to visit the clinic for assessment, and (6) no dementia or psychiatric abnormalities as per formal neuropsychological assessment.

Twelve healthy age-matched control participants were also recruited from the general public. The inclusion criteria for the control participants were: (1) no comorbidity, (2) within the same age range as the PD participants, and (3) understand and consent to the study procedures. The study was approved by the Human Subjects Research Ethics Board (HSREB # 103928) at Western University (London, ON, Canada) and all participants provided written informed consent prior to participating.

B. Data Collection

To quantify and evaluate full-body dyskinesia, a wearable motion capture system with 17 sensing units was used at each visit (Synertial IGS–180, UK - Fig. 1). The system integrates 3D accelerometers, 3D gyroscopes, and 3D magnetometers within each sensing unit as well as a fusion algorithm (using quaternion method [23], [24] – commercially available by Inertial Labs Inc., Virginia, USA) allowing relative joint angles to be computed from the sensing units.

The calibration procedure of the present system has been previously studied [18], [23]. The fusion software is implemented on a main processing unit (MPU) and communicates wirelessly to a receiver linked to a personal computer. Data acquisition was performed at 60 Hz sampling rate using IGS–Bio software Version 2.56 configured for full-body human motion (a video is available as supplemental material). The sensors placement as well as the list of joint angle measurements can be seen in Appendix.

The items of the UDysRS relevant to the kinematic tasks (communication and ambulation) that were performed were used to rate PD participant's whole body dyskinesia.

TABLE I
PARTICIPANTS DEMOGRAPHICS

	Controls (n=12)	PD Participants					
		V0 (n=13)	V1 (n=13)	V2 (n=13)	V3 (n=13)	V4 (n=13)	V5 (n=13)
Age (yrs)	63.1 (5.7)[1]	61.7 (6.6)	–	–	–	–	–
Females, n (%)	9 (75%)	5 (38%)	–	–	–	–	–
PD Duration (yrs)	–	10.3 (4.0)	–	–	–	–	–
LED (mg/day)[2]	–	1390.9 (508.9)	1090.7 (264.6)	1027.9 (316.4)	772.1*[3] (290.6)	551.7* (376.8)	438.3* (290.6)
UPDRS ON score	–	23.2 (12.8)	16.0 (9.6)	16.6 (8.9)	16.1 (9.5)	12.4* (5.1)	11.9* (5.7)
DBS Settings							
Left STN (V, Hz, μsec)	–	–		–	1.3, 130, 90	2.3, 130, 90	2.9, 130, 92.3
Right STN (V, Hz, μsec)	–	–	–	–	1.4, 130, 90	2.4, 130, 90	2.8, 130, 87.7

[1]Means are displayed with standard deviation in brackets.
[2]LED, Levodopa equivalency dosage. Calculation for LED was based on a standardized formula [29];
[3]* indicates significant difference ($p<.05$) compared to baseline, p-value was corrected for multiple comparisons, $p>.01$.

Tasks such as putting on the coat and drinking from a cup (performed only to elicit dyskinesia) were not used since they were not part of the kinematic assessments. The Unified Parkinson's Disease Rating Scale - part III motor scores (UPDRS) was also given to evaluate overall mobility changes during every visit. Kinematic data were collected pre-operatively, and 1 week postoperatively with DBS–off, 2 weeks post–operatively with DBS–off, 1 month, 2 months, and 3 months following surgery with DBS–on. The PD participants were on clinically optimized medication dosage during each post-operative assessment (Table 1). Control participants were evaluated once, using the full–body motion capture system.

C. Procedure

All participants were asked to perform three standard tasks twice while seated:

(1) Rest: the participants rested both of their forearms on the arms of a chair with hands hanging loose off the edge. The participants were asked to hold this position for 20 seconds.
(2) Posture: while sitting, participants fully extended their arms forward with hands pronated at shoulder height level and asked to hold this position for 20 seconds.
(3) Action: same position as the posture task, the participants were asked to perform forearm pronation–supination (so that their palms face up and down alternatively) as fast as possible, one arm at a time for a minimum of 10 seconds for each arm.

D. Data Analysis

Signals containing angular displacement of all body joints were obtained from the motion capture system. The signals were band-pass filtered from 0.5 Hz to 2 Hz to eliminate voluntary movements as well as tremor (see Discussion Section for details). The standard deviation of each filtered signal was then considered as the severity of dyskinesia in that body joint. Therefore, the dyskinesia severity score (DSS) can be calculated as

$$DSS = \sum_{i=1}^{n} STD[F_{0.5-2Hz}(J_i)] \quad (1)$$

where J_i is the ith body joint, n (=47, see Appendix) is the maximum number of joints involved in the calculation, $F_{0.5-2Hz}(\cdot)$ is the function which filters the signal from 0.5 Hz to 2 Hz, and $STD[\cdot]$ is a function to calculate the standard deviation of all points forming the signal. Therefore, all the numbers presented as DSS throughout this manuscript are in degrees. This method was developed based on a review of the relevant literature (see Discussion Section).

The head dyskinesia severity was calculated by adding the severities of dyskinesia in head flexion/extension, head lateral tilt, and head axial rotation.

For each arm independently, the arm dyskinesia severity was calculated by adding the severities of dyskinesia in wrist flexion/extension, wrist ulnar/radial, wrist pronation/supination, elbow flexion/extension, elbow pronation/supination, shoulder flexion/extension, shoulder abduction/adduction, and shoulder rotation.

For each leg independently, the leg dyskinesia severity was calculated by adding the severities of dyskinesia in hip flexion/extension, hip abduction/adduction, hip rotation, knee flexion/extension, knee rotation, ankle flexion/extension, ankle inversion/eversion, and ankle rotation.

The trunk dyskinesia severity was calculated by adding the severities of dyskinesia as axial rotation in right and left clavicles, right and left clavicular depression and elevation, right and left clavicular protraction/retraction, thoracic flexion/extension, thoracic lateral flexion, thoracic rotation, pelvic flexion/extension, pelvic lateral flexion, and pelvic rotation.

The total body dyskinesia was calculated as the sum of all body segments dyskinesia (i.e., head, right arm, left arm, right leg, left leg, and trunk). Each task was performed twice to compensate variability; so, the results of both trials were averaged to get the final DSS.

In order to analyze dyskinesia during the action task, the body joints involved in the performance of the task were not considered. For instance, while performing the action with the right arm, the right arm dyskinesia was not calculated. So, the dyskinesia severity of the right arm was calculated while the task was performed with the left arm.

Individual body segment dyskinesia ratings and kinematic measurements were carried out in every participant at all visits. Since such separate body segment dyskinesia ratings are not

clinically relevant to alter treatment parameters (total body dyskinesia is commonly used), only whole body dyskinesia severity score of the kinematic measurement and UDysRS are presented as the global measure of dyskinesia.

PD participants were video-taped while performing the tasks. The videos (294 episodes in total) were de-identified/randomized and dyskinesia was rated by two trained movement disorder researchers using the UDysRS. The ratings were performed separately and the means of the ratings were used for further evaluations. The raters were blinded to the clinical information.

The whole body dyskinesia kinematic data were then rendered as an animation in order to produce an equivalent of what is observed in the actual video recording for visual comparison (Please see the Appendix as well as the supplemental video).

E. Statistical Analysis

Statistical analyses included the examination of the severity of dyskinesia over multiple visits using Friedman test with follow-up Wilcoxon signed-rank test for pairwise comparison of the baseline and post-operative measures. The PD participants outcomes were also compared with the control participants using a Mann-Whitney U test, as well as the UDysRS scores using a Pearson correlation analysis. Either parametric or non-parametric statistical tests were selected following Shapiro-Wilks test of normality. The results are reported with 95% confidence intervals (CI).

The percentages of improvement (PI) were calculated by comparing the pre-operative DSS to each subsequent visit using the following criteria:

$$PI\% = \frac{(DSS - Preop.DSS)}{Preop.DSS)} * 100 \qquad (2)$$

The statistical analyses were carried out with SPSS software, version 19.0 (SPSS Inc., IL).

III. Results

A. Reliability of the DSS

In order to test the reliability of the DSS measure, the following approach was initially adopted. It is noted that what follows is a reliability test and it is not intended to be part of the final analysis. For all PD and control participants, the values of DSS were first separated for trial one and trial two (as each task is performed twice). The numbers were only considered for the pre-operative visit of PD participants as they showed the highest amount of dyskinesia in that visit.

The dyskinesia severities for each trial of each participant were then averaged between rest and posture to present one single number for the dyskinesia severity. Finally, the differences between the two trials were observed to make sure there are no significant differences between the two trials. Fig. 2 shows the results.

The statistical analysis (Wilcoxon signed-rank) showed no significant difference between the two trials, both for PD participants ($p = 0.382$) and control participants ($p = 0.209$). This identifies that the results are consistent over the two trials.

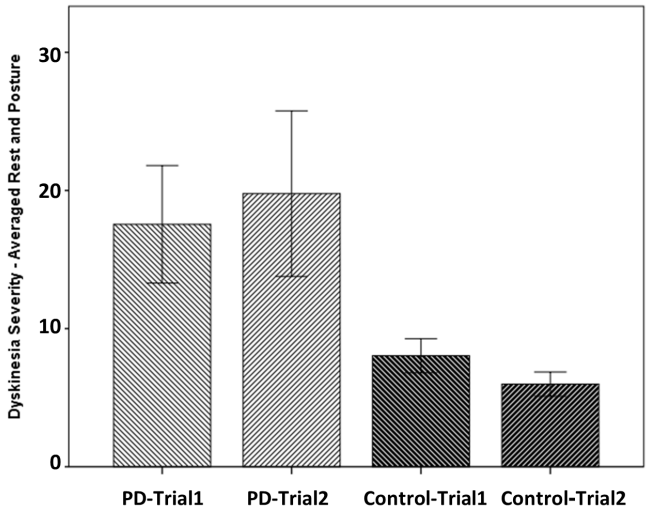

Fig. 2. The reliability test; the differences in the DSS values generated by the software determined from kinematics between the two trials for PD participants (Visit 0) and controls. Error bars represent the standard errors. There is no statistical difference between the two trials in the PD participants or controls.

B. Correlation Between DSS and UDysRS

A Pearson correlation analysis (with 95% confidence interval) was performed to assess the strength of the association between the UDysRS results and the kinematically measured dyskinesia severities. The comparison identifies strong correlations for all visits and tasks (Fig. 3).

In different ranges of DSS data, the slope of the linear fits illustrated in Fig. 3 were averaged to generate a mapping between DSS and UDysRS. The UDysRS rating which changes between 0 and 4, as an ordinal measure, was linearly equivalent to the kinematic assessment DSS in the range of 2.1° to 48.2°, as a continuous measure. Therefore, a level difference of 1 in the UDysRS rating is expected to be the equivalent of a level difference of roughly 12° in total from the kinematic assessment. This makes it possible for the DSS to essentially replace the UDysRS scoring system without losing any communicability. A full list of the kinematic and UDysRS ranges is presented in the supplemental table (Appendix).

C. DSS in PD Compared With Control

While sitting at rest, DSS for PD participants baseline (mean rank = 16.23) were significantly higher than control participants (mean rank = 9.5), $U = 36$, $p = .022$ (Fig. 4(a)). For all the remaining visits (after the surgery), the DSS decreases and the difference in the dyskinesia severities of PD participants and control participants were not significant (Fig. 4(a)).

While performing the posture task, the DSS for PD participants baseline (mean rank = 16.54) were significantly higher than the control participants (mean rank = 9.17), $U = 32$, $p = .011$. At all the remaining visits (after the surgery), the difference in the dyskinesia severities of PD participants and controls were not statistically significant. However, the same analysis indicated that during the performance of action task, the DSS for PD participants were not statistically significant, compared to the control participants (Fig. 4(a)).

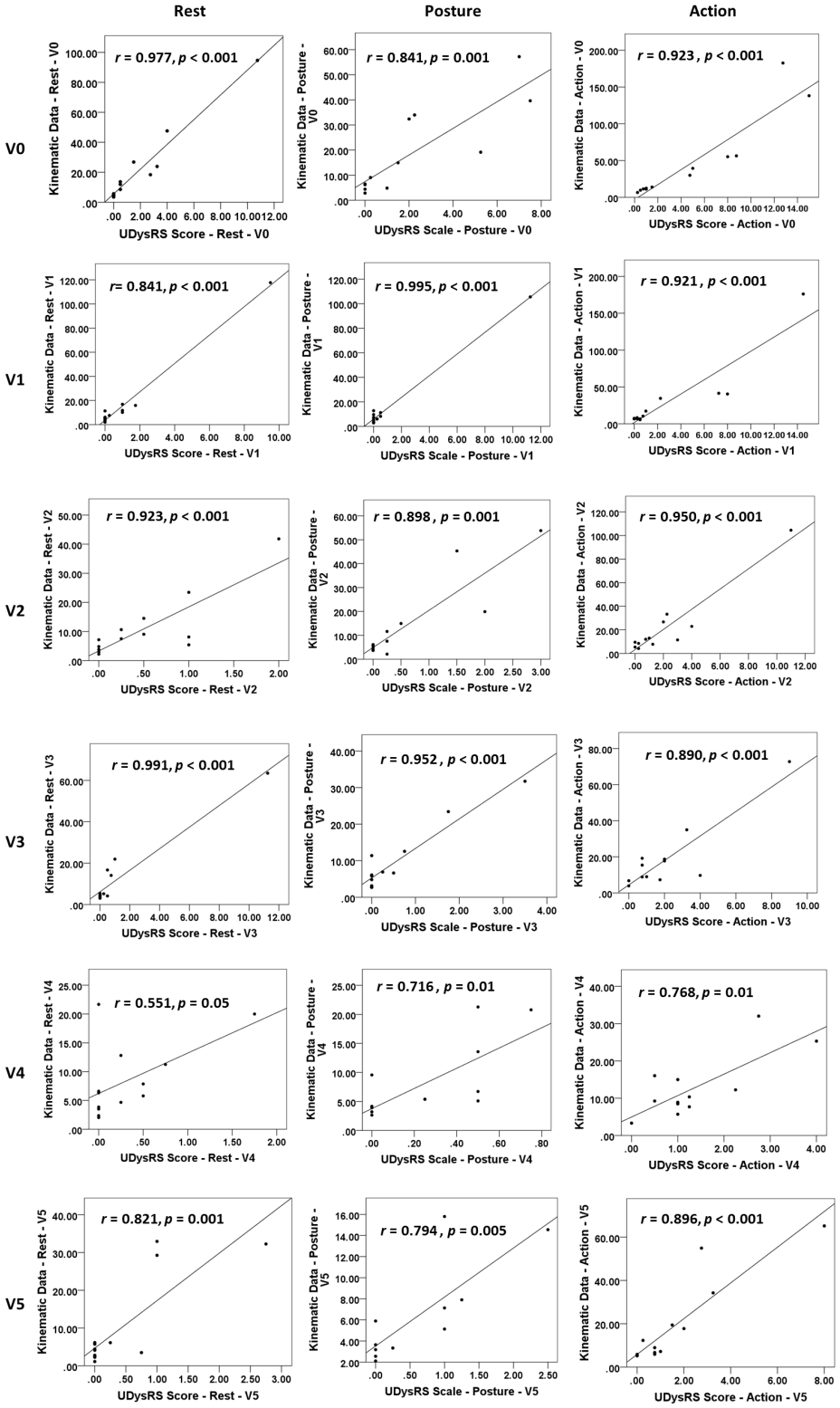

Fig. 3. Correlations between the measured dyskinesia severity scores (DSS) on the y-axis and the UDysRS scores on the x-axis for all visits and tasks.

D. DSS in PD During Motor Tasks

A complete comparison between the profile of changes in kinematic whole body dyskinesia severity score, the UDysRS scores, the UPDRS scores, and the Levodopa equivalent dose (LED) are presented in Fig. 4.

Comparing pre-operative DSS to each subsequent visit in the rest position, PD participants showed 18.84% ($p = 0.133$), 47.29% ($p = .046$), 42.48% ($p = .013$), 64.68% ($p = 0.039$), and 50.44% ($p = .039$) reduction in the severity of dyskinesia at week one, two, one month,

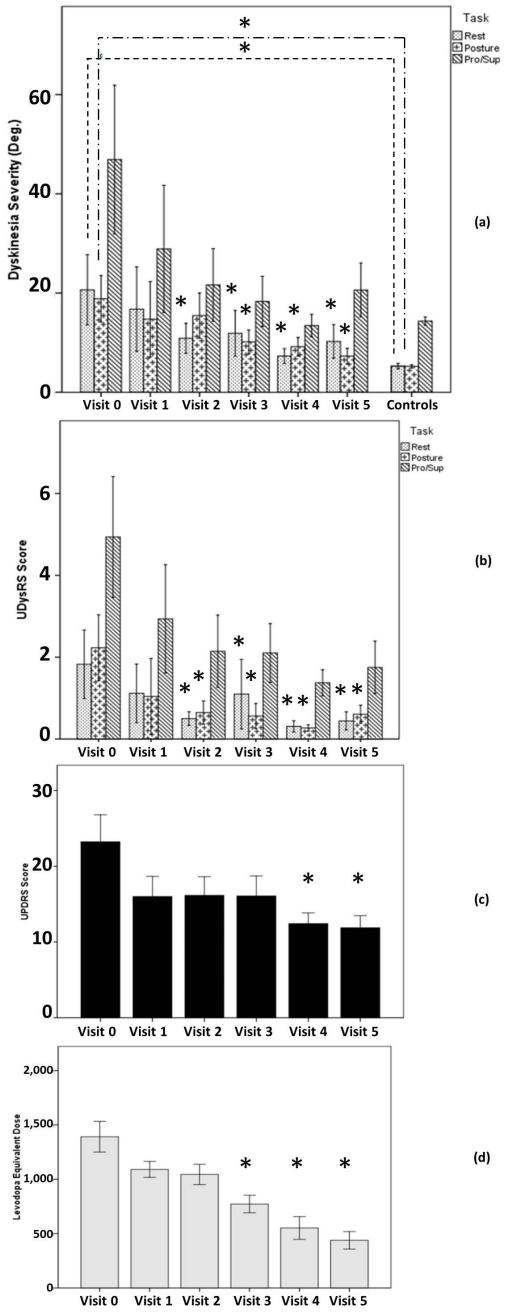

Fig. 4. (a) The difference between dyskinesia severity score (DSS) of PD participants before and at multiple visits after the surgery, compared with the baseline also with the controls (comparison with the controls is identified by dashed lines, the rest are compared with V_0). * Significance $p < 0.05$. Error bars in this figure and all the following figures represent the standard errors, (b) the profile of change in the UDysRS scores compared with the baseline (* Significance $p < .05$), (c) the profile of change in the UPDRS scores compared with the baseline (* Significance $p < 0.05$), (d) the profile of change in the Levodopa equivalent dose (LED) compared with the baseline (* Significance $p < 0.05$). Note: The control data in (a) has not been repeated in the following figures; so, the figures are left-aligned.

two months, and three months after the surgery, respectively (Fig. 4(a)).

As predicted, during the posture task, the DSS was significantly reduced at different time points during the follow-up visits. Relative to baseline, one week after the surgery, the severity of dyskinesia decreased by 21.92% ($p = .064$). Subsequently, PD participants experienced 17.99% ($p = .463$), 46.11% ($p = .006$), 51.33% ($p = 0.087$), and 61.39% ($p = .011$) reduction in the severity of dyskinesia while performing the posture, two weeks, one month, two months, and three months after the surgery, respectively when compared with the pre-operative levels (Fig. 4(a)).

The DSS while the PD participants perform an action (forearm pronation-supination task) was also assessed. Dyskinesia severity decreased from baseline to 3 months post-operatively, but the differences were not statistically significant, $\tilde{\chi}^2(5) = 10.319$, $p = .067$ (Fig. 4(a)).

As illustrated in Fig. 4(b), the UDysRS rating scores across all visits also show a parallel correlation to the DSS obtained from the kinematics. The UDysRS levels similarly decreases for all rest, posture, and action tasks across all visits and show similar statistical outcome when compared with the baseline. Fig. 4(c) and 3(d) also compare the UPDRS and medication trends with the PD participants baseline. It is noted that the UPDRS scores are presented only to show the progressive improvements of PD.

E. Segmentation of Dyskinesia

The presented approach used the kinematic contribution of each limb to generate the DSS. Hence, it is capable of reporting each limb's contribution to the total score. This approach is similar to the clinical rating measurement of dyskinesia per body part. In order to demonstrate this capability, the degree of change in the severity of dyskinesia is compared between pre-operative and three months post-operative state as a sample, for each body segment in the three states (Fig. 5).

For instance, our observation revealed that while at rest, all body segments showed a decrease in the severity of dyskinesia, but there was only a significant decline in right leg ($p = .033$); for the other body segments ($p > .064$) (Fig. 5a.). While performing the posture, the severity of dyskinesia significantly decreased in all body segments; right arm ($p = .033$), left arm ($p = .023$), right leg ($p = .011$), left leg ($p = .005$), trunk ($p = .046$), except for head ($p = .463$) (Fig. 5b.). During the action task, PD participants experienced a significant decline in the severity of dyskinesia in right leg ($p = .011$), and left leg ($p = .009$), and not in the rest of the body segments $p < .196$ (Fig. 5c.).

IV. Discussion

Currently, there are no studies showing the use of joint-angle data in measuring full-body dyskinesia. Therefore, the best range to filter the joint signals and calculate the severity of dyskinesia was found by a comparison between the studies focused on tremor and dyskinesia assessments using sensor data. Such studies use similar sets of sensor data, either accelerometric or joint angle data. Many studies measure dyskinesia using accelerometers and gyroscopes. Sama *et al.* used an accelerometer placed on PD participants waist [15], Manson *et al.* demonstrated the same procedure with an accelerometer located on PD participants shoulder [25], and

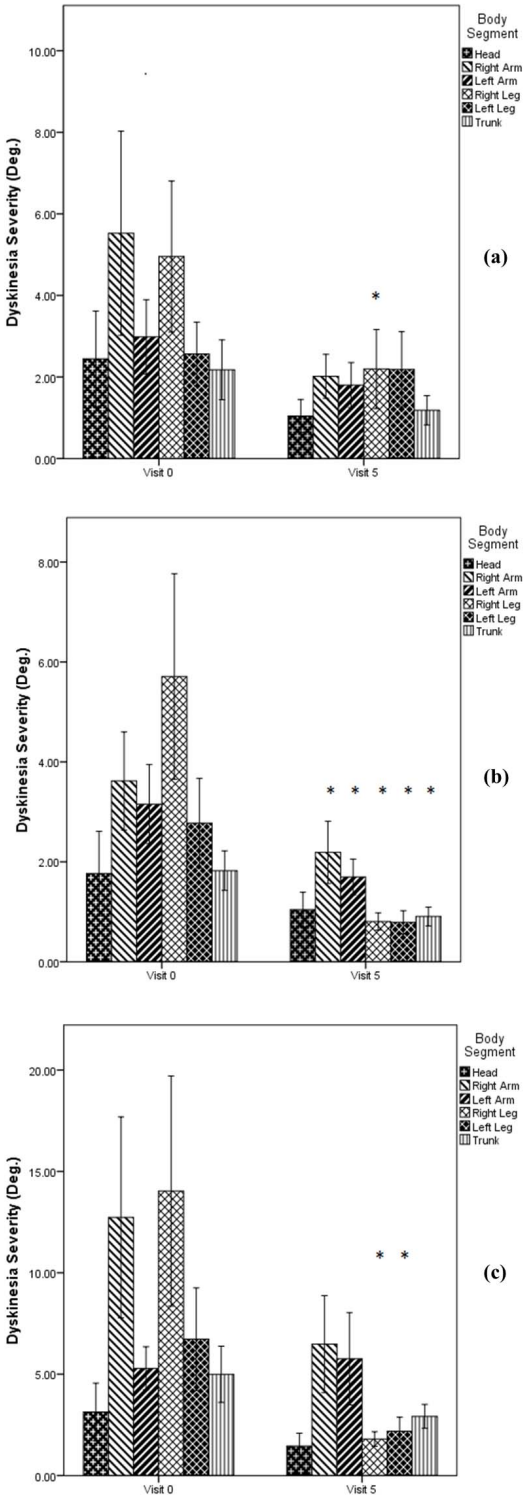

Fig. 5. A sample of the contribution of each body segment to the total dyskinesia severity; pre-operatively compared with three months post-operatively, while the PD participants sitting (a) at rest, (b) performing posture, (c) performing an action (* Significance $p < .05$ when compared to baseline).

Keijsers *et al.* [26] showed the results for 6 accelerometers located at upper arms, upper legs, wrist and trunk [2].

In all these studies, dyskinesia increased the power spectrum of the accelerometer signals frequency band between 1-4 Hz. On the other hand, it is known from the studies focusing on tremor analyses (which have been based on both accelerometric and joint angle data), that the dominant frequencies (at which the power spectrum is maximum) observed between dyskinesia and tremor analyses are different, the latter being higher [15]. The accelerometric measurements of tremor are performed on frequencies higher than 4 Hz, while joint angle band for tremor analysis are frequencies higher than 2 Hz [27]. Therefore, the frequency band between 0.5-2 Hz seems to be a relevant range to capture joint angles involved in dyskinesia.

The authors do not intend to suggest that the proposed system is superior to other systems as the study did not directly compare this. Working in the joint angle space was chosen since the emerging motion capture systems which have rapidly expanded in the marketplace use this technology. The results presented in joint angle space are closer to human experience hence easier to be interpreted by clinicians. From a technical perspective, transferring data into joint angle space allows producing an animation in real time and provides an easy transfer/playback to occur at any time after data collection. This is very strong benefit as not only can the system extract the quantitative information for the clinician, using the actual animation, the clinicians could easily visually watch patients performance remotely.

Calculating the root-mean-square (RMS) of a signal is a standard signal processing approach to measure severity of a signal. In this study, we have employed the standard deviation of the points forming the joint angles signal, which is in fact the RMS value of the de-trended signal to eliminate any possible signal bias.

The PD participants of this study all underwent STN-DBS and were followed up to three months after the surgery only because this therapy option would dramatically reduce dyskinesia in a short time, suitable for such study. So, reporting the acute effects of DBS surgery on the severity of dyskinesia is out of the scope of this work.

To validate our measures, we compared the kinematic results obtained from the motion suit with the UDysRS scores. Amongst all clinical assessments of dyskinesia, UDysRS is validated for detecting treatment effects [2]. Tasks such as donning a coat or pouring water within the UDysRS are performed to elicit dyskinesia. Such tasks have a large voluntary component and we tailored our tasks for dyskinesia elicitation to reduce this voluntary bias, yet provide a comprehensive dyskinesia generation paradigm that could be reliably rated visually and kinematically. Analysis of the results showed that DSS and UDysRS are highly correlated across all visits. Moreover, the pattern of reduction in dyskinesia severity during all tasks closely resembles the reduction in UDysRS scores across visits, even immediately after surgery when the device is still off and medication has not changed. This is further reflected from improved general UPDRS scores following DBS surgery (defined as difference of 8.5 to 10.3 on the UPDRS [28]). These results suggest that the motion capture suit system and its output (the DSS) is a useful tool, capable of objectively measuring dyskinesia.

Many researchers have already addressed the need for quantitative detection of dyskinesia, using motion detection sensors [1], [4], [6], [8], [9], [11], [16]. However, such

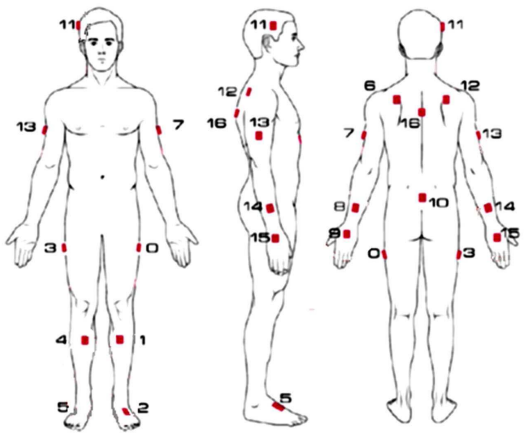

Fig. 6. The position of the IMU sensors.

tools only assess dyskinesia in selected body joints, hence potentially underestimating the severity of dyskinesia in other parts of the body. Our approach is capable of breaking down the overall DSS, across all joints with analysis of contributions of each joint to the total whole body dyskinesia. Interestingly, the results of this work showed a pattern of change in the level of dyskinesia severity for all body segments.

The translation of the UDysRs to the DSS clearly shows that it is possible for an automated system to provide to the clinician even better resolution for dyskinesia assessment, which remain well correlated with the clinically acceptable measurement tool of the UDysRS. A categorical correlation shows that dyskinesia scoring that is obtained in the UDysRS can be translated into similar objective scores along a scale for DSS. This makes the DSS score a clinically useful tool.

Based on our experience throughout the data collection, the donning of the suit was easy, taking less than three minutes for the PD participants. There were no complaints from the participants about any discomfort during or after performing the tasks.

Our tool was sensitive enough to also measure some level of involuntary motion in healthy controls. This is because of the fact that even healthy participants at rest may show some level of unintentional movements (similar to physiological tremor).Such uncontrolled behavior in healthy individuals has no clinical significance and clearly is not called dyskinesia. Therefore, a threshold could be considered to set any number smaller than that threshold to zero. We did not take that approach since: (1) setting a specific threshold would need more participants and assessments, (2) if all control values were set to zero, statistical analysis would be meaningless.

Minimum support was given to the patients to wear the suit and minimum details to perform the tasks. We received no complaints from the participants regarding donning of the device, therefore, we anticipate that PD patients will be willing to don and use the device in their home environment. All participants successfully completed the kinematic assessments and did not complain of any difficulty with the donning of the suit or the task performance. Participants that showed signs of cognitive impairment needed more help to perform the tasks. So, remote monitoring for such patients may require

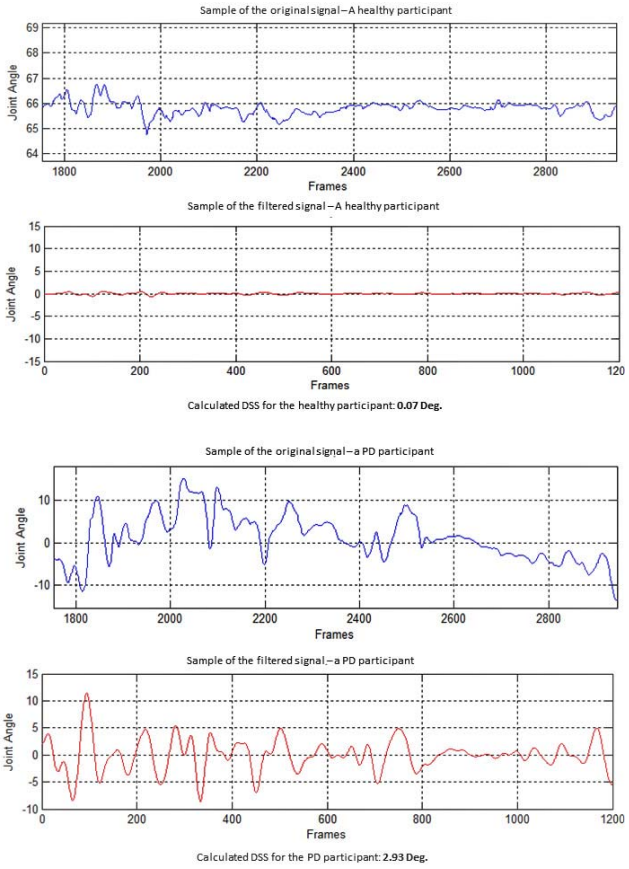

Fig. 7. Samples of original and filtered data for both healthy and PD participants, along with the calculated DSS. Both plots show wrist flexion-extension angle signal at rest, for PD and healthy participants. Positive wrist angle denotes flexion and this indicates that this technology also shows the bias (body gesture), although filtering the signal removes this bias.

more support. Although this was not tested in this study, we anticipate human instructions can be reliably replaced with either an animation or an audio/visual instruction set based on a predetermined routine. We also need to highlight that continuous data recording may not be necessarily beneficial, hence in a remote monitoring scenario, data collection could be performed in short predetermined time points to identify symptom fluctuations which is important for the clinicians.

The artifacts in the data are likely to have affected our data collection mainly due to the subjectivity of the UPDRS scores. A more reliable procedure would involve the comparison of the proposed method with other reasonably acceptable technologies. However, such technologies are not themselves fully validated and accepted.

The findings in this study should generally be interpreted as a pilot proof of concept due to the small sample size. We did not assume a specific distribution of the data such as a normal distribution due to the relatively small sample size. This could have affected the correlation coefficients proposed in this study. Besides, we only considered linear relationship between the DSS and UDysRS data mainly to allow the clinical interpretation of data fast and intuitive.

In summary, our results validate our hypothesis that dyskinesia severity score is an effective tool that can objectively

TABLE II
THE LIST OF JOINT ANGLES, INCLUDED IN THE ASSESSMENT

Body Part	Segment	Motion
Head	Head	Flexion/Extension Lateral Tilt Axial Rotation
Trunk	Right Clavicle	Axial Rotation Depression/Elevation Retraction/Protraction
	Left Clavicle	Axial Rotation Depression/Elevation Retraction/Protraction
	Thorax	Flexion/Extension Lateral Flexion Rotation
	Pelvis	Flexion/Extension Lateral Flexion Rotation
Right Arm	Right Wrist	Flexion/Extension Ulnar/Radial Pronation/Supination
	Right Elbow	Flexion/Extension Pronation/Supination
	Right Shoulder	Flexion/Extension Abduction/Adduction Rotation
Left Arm	Left Wrist	Flexion/Extension Ulnar/Radial Pronation/Supination
	Left Elbow	Flexion/Extension Pronation/Supination
	Left Shoulder	Flexion/Extension Abduction/Adduction Rotation
Right Leg	Right Hip	Flexion/Extension Abduction/Adduction Rotation
	Right Knee	Flexion/Extension Rotation
	Right Ankle	Flexion/Extension Inversion/Eversion Rotation
Left Leg	Left Hip	Flexion/Extension Abduction/Adduction Rotation
	Left Knee	Flexion/Extension Rotation
	Left Ankle	Flexion/Extension Inversion/Eversion Rotation

quantitate dyskinesia, enabling the physician to remotely assess and monitor individuals with PD. The proposed hardware and software are easy to use and can potentially be enabled wirelessly in the patients own home environment. This type of technology is reaching a very cost effective point. The suit system is multi-use and washable.

We are currently completing the development of similar automated extraction tools for other relevant PD symptoms such as bradykinesia, tremor, and gait dysfunctions using the same technology. Such system would have applications for other movement disorders. In our ongoing studies, we are investigating optimization of different DBS parameters in reducing dyskinesia severity and applying it to home monitoring of individuals with PD. In case the proposed method is accepted for the purpose of home monitoring of PD patients, the suggested tasks could be illustrated via a web-based application and the patient would mimic the tasks while wearing the full-body suit. The web-based application would then transfer the recorded file online for further processing and treatment optimization.

TABLE III
COMPARISON BETWEEN THE RANGE OF NUMBERS IN UDysRS TOTAL SCORES AND THE KINEMATIC DATA

Rest UDys.	Rest Kin.	Posture UDys.	Posture Kin.	Action UDys.	Action kin.
0-1	1.1–11.5	0-1	2.1-11.3	0-1	3.3-15.3
1-2	11.6-21.8	1-2	11.4-20.5	1-2	15.3-27.2
2-3	21.9-32.2	2-3	20.6-31.7	2-3	27.3-39.2
3-4	32.3-42.6	3-4	31.8-40.5	3-4	39.3-51.1
4-5	42.7-52.9	4-5	40.6-50.0	4-5	51.2-63.1
5-6	53.0-63.3	5-6	50.1-59.2	5-6	63.2-75.0
6-7	63.4-73.7	6-7	59.3-68.4	6-7	75.1-87.0
7-8	73.8-84.0	7-8	68.5-79.6	7-8	87.1-98.9
8-9	84.1-94.4	8-9	79.7-89.8	8-9	99.0-110.9
9-10	94.5-104.7	9-10	89.9-98.3	9-10	111.0-122.9
10-11	104.8-115.1	10-11	98.4-103.2	10-11	123.1-134.8
11-12	115.2-117.7	11-12	103.3-105.5	11-12	134.9-146.8

V. CONCLUSION

This study aimed to develop, assess the feasibility, and validate an objective measure for full–body dyskinesia that is clinically meaningful. The results of the study showed that the measure defined as the the full-body dyskinesia severity score or DSS can indeed assess dyskinesia using a multi-sensor wearable motion capture system. The DSS correlates with the scores obtained from UDysRS, a clinical gold-standard measure of dyskinesia, during the tasks selected for this assessment.

This quantitative approach reliably separated the normal movements in control participants (low DSS) versus PD participants preoperatively. In addition, the calculated sensor-based DSS decreased following DBS surgery, confirming the chronic therapeutic improvement in dyskinesia and correlated well with the expert, visually-based clinical ratings. These findings suggest that a portable, wearable motion capture system can be used for automatically detecting full-body dyskinesia.

The effects on dyskinesia post DBS are not different than medication. Hence, the dyskinesia from medication and from DBS are within the same bandwidth, which makes it quite likely that the proposed method will also reliably detect dyskinesia in other settings and not just pre and post DBS.

An important feature of this system is that the accurate animations developed from the sensor data can be reviewed and monitored remotely by the treating physician. In the future, this may enable easy in-home assessment and management, reducing the frequency of visiting a professional healthcare facility.

APPENDIX

See Figs. 6 and 7 and Tables II and III.

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