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A Palm-Worn Device to Quantify Rigidity in Parkinson's Disease

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Highlights

- Rigidity measured using our instrument (BiRD) agreed with clinical ratings
- BiRD was able to identify the impact of deep brain stimulation therapy on rigidity
- Deep brain stimulation wash-out took significantly longer than wash-in
- BiRD had ample sensitivity to detect contralateral activation even in the healthy

Abstract

***Background*:** Parkinsonian rigidity is identified on clinical examination as resistance to passive movement. Measurement of rigidity commonly relies on ordinal rating scales (MDS-UPDRS), however instrumented objective measures may provide greater mechanistic insight.

***New Method*:** We present a palm-worn instrument to objectively quantify rigidity on a continuous scale. The device employs a miniature motor to flex the third digit of the hand about the metacarpophalangeal joint whilst transducers record flexion/extension forces. We aim to determine congruence with the MDS-UPDRS, investigate sensitivity to the impact of deep brain stimulation (DBS) and contralateral movement, and make comparisons with healthy individuals. Eight participants with Parkinson's disease underwent evaluation during conditions: on and off DBS, and with and without contralateral limb movement to activate rigidity. During each DBS condition, wash-

in/out effects were tracked using both our instrument and two blinded clinical raters. Sixteen healthy volunteers (age-matched/young) served as controls.

***Results*:** Rigidity measured using our instrument had moderate agreement with the MDS-UPDRS and showed differences between therapeutic state, activation conditions, and disease/healthy cohorts. Rigidity gradually worsened over a one-hour period after DBS cessation, but improved more rapidly with DBS resumption.

***Comparison with Existing Methods*:** Previous attempts to quantify rigidity include manual approaches where a clinician is required to manipulate limbs while sensors passively gather information, or large automated instruments to move the wrist or elbow.

Conclusion: Given its ability to track changes in rigidity due to therapeutic intervention, our technique could have applications where continuous measurement is required or where a suitably qualified rater is absent.

Abbreviations

BiRD: Bionics Institute Rigidity Device
DBS: Deep Brain Stimulation
ICC: Intraclass correlation coefficient
MDS-UPDRS: Movement Disorders Society-Sponsored Revision of the Unified Parkinson's disease Rating Scale

Keywords

Rigidity; Stiffness; Parkinson’s disease; Objective monitoring; Movement disorders

1. Introduction

Rigidity is a cardinal symptom of Parkinson’s disease [1] caused by increase in muscle tone and changes within passive connective tissues [2–5]. Over 89% of people with Parkinson’s disease experience rigidity rendering them stiff and making movement strenuous [6]. It is one of the most responsive symptoms to treatment [3] and can be used to deduce therapeutic efficacy [4]. Under clinical evaluation, rigidity is defined as resistance to passive movement [4,5]. Typically, an examiner moves the wrist, elbow, and knee joints about their full range of motion and subjectively grades resistive force [5]. The patient is instructed to relax their muscles during examinations, and may also perform an activation task using the contralateral limb [1,5]. Rigidity is generally graded (score/4) using Item 3.3 of the Movement Disorders Society-Sponsored Revision of the Unified Parkinson's disease Rating Scale (MDS-UPDRS) [5].

Assessment of rigidity is important during: 1) clinical consultations for diagnosis and management of Parkinson's disease; 2) clinical trials where new therapeutic interventions are investigated; and 3) research to determine mechanistic insights about pathophysiology. Although instrumented quantification of rigidity may be advantageous for each case, here, we will focus on its application in clinical trials.

Inter- and intra-rater variability, as well as bias, can influence clinical scores [6,7] and unlike other symptoms such as tremor, rigidity cannot be video recorded and shown to an independent panel to mitigate bias [8]. Thus, a suitably qualified and experienced rater must be physically present onsite to administer the MDS-UPDRS. Unfortunately, having multiple blinded raters physically present to conduct independent assessments is challenging. Clinical ratings are limited by poor sensitivity due to ordinal five-point demarcations (fractional ratings cannot be given) and are prone to floor/ceiling effects (a rating beyond the 0 to 4 scale cannot be given) [13]. However, they offer important knowledge regarding quality-of-life and disability. Although an instrumented method may provide superior sensitivity on a continuous scale that is quantifiable, it provides little information regarding the underlying functional disability. Thus, validation of new techniques must either provide evidence to support clinical interpretation or be congruent with existing standardized rating scales.

Previous attempts to quantify rigidity include manual approaches where a clinician is required to manipulate limbs while sensors passively gather information [5,14–22], or automated techniques utilizing electric motor-driven extension and flexion [4,8,23–29]. Others have also experimented with pendulum-driven devices [30]. Manual approaches often rely on a metronome to keep flexion/extension cycles consistent, yet this ultimately introduces a human element to data acquisition. Metacarpophalangeal joints, wrist, elbow, knee, and trunk have been studied with automated electric motors making further investigation into automation promising. Nonetheless, these instruments rely on bulky benchtop mechanisms often requiring limbs to be braced and tethered to large motors evoking reluctance and apprehension in patients [20].

Here we present a novel palm-worn apparatus to quantify rigidity in Parkinson's disease. The Bionics Institute Rigidity Device (BiRD) automatically flexes the third digit about the metacarpophalangeal joint and a force transducer generates quantifiable data. In this feasibility study we sought to: 1) validate BiRD against the MDS-UPDRS, 2) demonstrate sensitivity to the therapeutic impact of Deep Brain Stimulation (DBS), 3) demonstrate sensitivity to the impact of contralateral hand movement, and 4) compare Parkinsonian rigidity to healthy volunteers.

2. Methods

Eight participants (mean ± standard deviation age 53.6±5.7 years; 2 female) diagnosed with levodopa-responsive Parkinson's disease receiving bilateral subthalamic nucleus DBS were recruited as the primary study cohort. Age-matched healthy volunteers (N = 8, aged 54.1±7.3 years; 2 female) and young healthy subjects (N = 8, 30.9±4.8 years; 2 female) served as controls. Participants had no known musculoskeletal or other neurological disorders (other than Parkinsonian symptoms for that respective cohort). This study received approval from the St. Vincent's Hospital Human Research Ethics Committee and all participants gave informed written consent.

2.1. Bionics Institute Rigidity Device (BiRD)

The BiRD (figure 1) is a palm-worn instrument designed to quantify the force required to flex the third digit of the hand. A miniature on-board electric motor (TGY-DS3509MG, Turnigy, Kwun Tong, Hong Kong) automatically flexes and extends the digit. An increase in rigidity will require greater force to flex the digit, thus our device aims to monitor the same fundamental phenomenon as the clinical rating scale albeit limited to just the metacarpophalangeal joint.

A force transducer (5 mm circular FSR 400, Interlink Electronics, California, USA) mounted beneath the finger harness measures flexion and extension force. Additionally, an electronic sensor (LMP8480, Texas Instruments, Texas, USA) monitors current drawn by the motor as a surrogate for torque. Generally, motor current is linearly proportional to the torque output of the motor [27,31]. The motor has integrated gearing with sufficient torque to flex the finger by 45-degrees at a continuous rate of one extension/flexion cycle per second. Furthermore, the motor has internal feedback control allowing precise positioning. A microprocessor actuates the motor and gathers time-stamped motor position (displacement), force, and current data at 250 samples/s which is then transmitted to a computer for offline analysis.

Participants were familiarized with the device and a practice trial was conducted prior to formal assessment. Each rigidity assessment consisted of 15 continuous extension/flexion cycles applied without removing the device. There were no hold periods where movement did not occur. The first five cycles were discarded to avoid confounds from oppositional paratonia (involuntarily resisting movement) and any startle effects. The entire assessment was rejected if abnormally low force (< 10 mN) was detected in more than 50% of the remaining cycles. This removed trials where facilitatory paratonia (involuntarily assisting passive movement) may have been present. In each extension/flexion cycle, periods relating to movement onset and change in direction were excluded to avoid confounds of inertial force. Any baseline offset was subtracted. The following features were extracted from the average of the ten cycles separately for extension and flexion:

1) Force Rate - the slope of the force vs. displacement curve expressing force per degree required to move the finger (figure 1c)
2) Peak Force - the maximum of the force vs. displacement curve
3) Work Estimate - the total area under the force vs. displacement curve
4) Charge - the total area under the current vs. time curve (figure 1d)

To deduce a measure of rigidity that is continuous and quantifiable, we selected the flexion Force Rate and Work Estimate to be used in subsequent analysis as stand-alone measures of rigidity. These metrics have meaningful units and are easy to interpret with a higher value indicating greater rigidity. Others have previously found both Force Rate and Work Estimate to be concordant with clinical ratings [5,14,20,21,29].

2.2. Clinical Assessment of Rigidity

As per the instructions in the MDS-UPDRS Item 3.3, assessment of rigidity for the upper extremities was performed by slow movement of the limp wrist and elbow joints [9]. Participants were seated comfortably in a relaxed state and were instructed to make their body as relaxed as possible. For the activation maneuver, participants were instructed to draw a large imaginary circle in the air using their contralateral arm. Neck and lower extremities were not examined. Two physiotherapists, experienced in movement disorders and the MDS-UPDRS, rated rigidity on a scale of 0 (normal) to 4 (severe) as per descriptors in the MDS-UPDRS. Both raters were blinded to the protocol and directed not to discuss their ratings with each other until the conclusion of the study. Raters were only present in the assessment area to perform ratings. The mean clinical rating from the two physiotherapists was used in subsequent analysis.

2.3. Study 1: Parkinson's Cohort

Participants with Parkinson's disease arrived at the clinic on-DBS and off-dopaminergic medication following overnight withdrawal. Rigidity of both arms was measured first using the BiRD, then by the two raters in quick succession at baseline (on-DBS), and at 10-minute intervals following therapy withdrawal (off-DBS) over a one-hour period. Rigidity was then assessed by the BiRD alone at 5-minute intervals following DBS resumption over a 30-minute period. At the last trial within this period, the two raters also assessed rigidity. This protocol sought to monitor the wash-out and -in effects of DBS. As previous studies [7,32] suggest that the wash-in period is shorter than wash-out, we decreased the assessment interval during this phase to capture the underlying change in greater detail. This meant that sufficient time was not available between measurements to perform clinical ratings.

2.4. Study 2: Healthy Cohort

All healthy volunteers were assessed with the BiRD and no clinical examination was conducted. The dominant hand of each individual was assessed while they were at rest or performing a contralateral activation task (as described previously). Ten trials (5 rest, 5 activation) were performed in random order. Participants were seated and asked to make their body as relaxed as possible.

2.5. Predict MDS-UPDRS Scores using BiRD

Using the pooled data from the Parkinson's cohort (each arm treated as independent), stepwise multiple linear regression was used to develop a model to predict clinical ratings using metrics derived from the BiRD. The correlation coefficient (R_{adj}, adjusted for the number of terms in the model) and the root-mean-squared error (RMSE) were used as performance indicators to determine how well the model predicted the clinical scores. To gauge the robustness of the model, we used 10-fold stratified cross validation (repeated over 50 iterations). Briefly, this involved randomly partitioning the data into ten groups where each group had a representative sample of measurements. Nine groups were used to train the model, with the remaining one retained for evaluating predictions. This process was repeated ten times where each group was used exactly once as the validation data. This cross validation procedure was repeated 50 times to reduce any effect of estimator bias arising from the dependent sampling strategy. A marked decline in model performance during cross validation indicates that the model is inappropriate or is overfitting the data (characterizing random fluctuations within the observations). Multicollinearity was deemed to be acceptable if variance inflation factors (VIF) were below ten [33].

We further applied leave-one-out cross validation to clarify the within-subject performance of our regression model. Here, the model determined earlier was trained using data from all but one participant. Ratings were predicted for the omitted participant and the performance of the model was evaluated. This process was repeated, successively excluding one participant each time. As before, R_{adj} and RMSE were calculated for each individual.

2.6. Statistical Analysis

A two-way repeated-measures analysis of variance (RM-ANOVA) was conducted to determine if DBS therapy and the contralateral activation task influenced rigidity. Post-hoc paired *t*-tests were applied to further define any differences. A two-way ANOVA was conducted to deduce if there were differences between healthy volunteers (coded for both age-matched and young) and those with Parkinson's disease as well as any influence arising from the activation task. Post-hoc independent *t*-tests were performed to evaluate any specific differences within cohorts. Cohen's *d* was calculated

for each post-hoc comparison to indicate effect size. Values of *d* can be interpreted as the effect size being: very small (0.01), to medium (0.5), large (0.8), and huge (2.0) [34].

Cohen's Kappa (κ) was used to determine inter-rater reliability. Test-retest reliability was calculated using two-way random single-measures intraclass correlations (ICCs) for both the BiRD and clinical scores using data from the first assessment at baseline and the last assessment following DBS resumption. All statistical analyses and data processing was performed using MATLAB (Mathworks Inc., Natick, Massachusetts, USA).

3. Results

Overall, we recorded eight clinical ratings across both hands in eight Parkinson's participants resulting in a dataset of 128 observations. Participant 4's left hand data (8 observations) were excluded due to BiRD mechanical failure. Participant 5's left hand data (8 observations) were excluded due to limited range of movement in finger joints. A further 22 observations were removed due to facilitatory paratonia (force < 10 mN detected), bringing the total number of observations to 90. Inter-rater reliability between the two examiners was fair [35] (κ= 0.356). Test-retest reliability for the clinical scores (ICC = 0.740), Force Rate (ICC = 0.633), and Work Estimate (ICC = 0.748) were good [36].

3.1. Congruence with MDS-UPDRS and Predictive Features

The model resulting from the stepwise linear regression is summarized in table 1. Comparison between predicted estimates and clinical ratings showed the model performed moderately well (R_{adj} = 0.676, RMSE = 0.712). Stratified 10-fold cross validation resulted in only a marginal decrease in performance (R_{adj} = 0.673, RMSE = 0.720) suggesting the model did not overfit the data. Moreover, the model residuals were normally distributed indicating no underlying pattern or occurrence of outliers (one-sample Kolmogorov-Smirnov test: W = 0.064, p = 0.831). The terms which had the greatest influence in the model were: Force Rate during finger flexion with hands at rest (β= 0.481), Peak Force during extension with activation task (β= 0.438), Work during flexion with activation task (β= -0.518), and the interaction between Force Rate and Peak Force (β= -0.783). Within-subject validation of the model revealed correlations (R_{adj}) between 0.646 and 0.709 with RMSE ranging from 0.468 to 0.995.

3.2 Sensitivity to the Therapeutic Impact of DBS and Contralateral Activation

In subsequent analysis two metrics (Force Rate and Work Estimate during finger flexion) were used to characterize rigidity. Though these metrics alone had relatively low congruence with clinical

ratings (linear regression; Force Rate: R = 0.413, $p < 0.001$, Work Estimate: R = 0.450, $p < 0.001$), they offer a quantifiable measures of rigidity on a continuous scale. Importantly, both metrics emerged as important terms in the stepwise linear regression analysis.

Force Rate can be used to differentiate therapeutic states and characterize disease (figure 2). A two-way RM-ANOVA indicated a statistically significant main effect for DBS setting (on vs. off) [$F(1, 184) = 46.45$, $p < 0.001$] and test condition (rest vs. activation) [$F(1, 184) = 3.96$, $p = 0.048$]. Post-hoc tests revealed that the absence of DBS therapy resulted in greater Force Rate ($p < 0.001$, $d = 1.071$) and a contralateral activation exercise led to an increase in Force Rate both on ($p = 0.011$, $d = 0.329$) and off ($p = 0.021$, $d = 0.236$) DBS (figure 2a).

A two-way RM-ANOVA indicated that Work Estimate can be used to differentiate therapeutic states [$F(1, 184) = 10.51$, $p = 0.001$], but not rest vs. activation [$F(1, 184) = 1.35$, $p = 0.246$]. Post-hoc tests revealed that DBS therapy significantly reduced Work Estimate ($p = 0.001$, $d = 0.513$).

3.3 Ability to Differentiate Healthy and Parkinsonian Cohorts

A two-way ANOVA for Force Rate revealed a statistically significant main effect for cohort (Parkinson's disease off-DBS vs. age-matched controls vs. young controls) [$F(2, 243) = 68.29$, $p < 0.001$] and test condition (rest vs. activation) [$F(1,243) = 5.52$, $p = 0.020$)]. Post-hoc tests revealed a significant increase in Force Rate due to Parkinson's disease when compared to age-matched controls during both rest ($p < 0.001$, $d = 1.347$) and activation tasks ($p < 0.001$, $d = 0.802$) (figure 2b). Age-matched controls had a higher Force Rate than their younger counterparts during the activation task ($p = 0.014$, $d = 0.134$), but no difference in resting Force Rates. Also, contralateral activation compared to resting led to an increase in Force Rate in the age-matched group ($p = 0.039$, $d = 0.504$), but not in young controls.

DBS therapy in the Parkinson's cohort decreased Force Rate towards levels found in age-matched controls suggestive of therapeutic effect, yet a significant difference remained in the resting condition ($p < 0.001$, $d = 0.790$). This across-group comparison must be interpreted with caution since subjects were only matched for age and the sample size was low.

A two-way ANOVA indicated that Work Estimate can be used to differentiate study cohorts [$F(2, 243) = 25.54$, $p < 0.001$], but not rest vs. activation conditions [$F(1, 243) = 1.51$, $p = 0.230$]. Post-hoc tests revealed no significant difference in Work Estimates between age-matched controls and those with Parkinson's disease ($p = 0.171$, $d = 0.296$). However, age-matched controls had a lower Work Estimate compared to younger volunteers ($p < 0.001$, $d = 0.937$).

3.4 Transient Effects of DBS Wash-In/Out

The transient wash-in/out effects of DBS were documented using clinical ratings, Force Rate, and Work Estimate (figure 3). DBS cessation led to a steady increase in rigidity over a one-hour period, and DBS resumption resulted in an almost immediate improvement in rigidity back towards baseline levels. Work Estimate displayed greater variability than Force Rate.

4. Discussion

In this feasibility study, we found that the BiRD had moderate agreement with clinical rigidity ratings and was able to distinguish differences between therapeutic conditions, contralateral activation exercises, as well as participants with and without Parkinson's disease. Though a multitude of metrics derived from the BiRD were used in the regression model to predict clinical ratings, a single metric (Force Rate) was sufficient to provide further characterization. We found that Force Rate, the amount of force required per degree of finger flexion, increased over the period of one hour when DBS was ceased. Resuming DBS therapy decreased Force Rate back to baseline levels within five minutes. Additionally, Force Rate was markedly increased in participants with Parkinson's disease compared to age-matched healthy controls. Although Work Estimate (another common metric [8,21,26,29]) was able to differentiate therapeutic states, it was insensitive to contralateral activation and could not distinguish between age-matched controls and those with Parkinson's disease.

Only two previous studies investigated rigidity in the metacarpophalangeal joint [30,37] with benchtop instruments requiring arms to be fixed to large contraptions. Notably, these studies only examined a single Parkinsonian participant limiting our ability to provide a comparative analysis. Wrist and elbow joints were commonly studied, with only one group attempting to quantify trunk rigidity [29]. Correlations with clinical ratings ranged from poor ($R = 0.38$) [20] to excellent ($R > 0.85$) [17,18,25]. The moderate congruence ($R = 0.68$) reported in the present study is therefore comparable to previous findings. The moderate fit and large RMSE suggest that either BiRD did not capture all aspects of rigidity, or clinical assessments had inherent inaccuracies and the BiRD was more sensitive to subtle fluctuations in resistance to passive motion. Moreover, the moderate relationship may be expected given our measures were of two disparate origins (BiRD using the metacarpophalangeal joint and clinicians using the wrist and elbow as per MDS-UPDRS guidelines). Since increased neuronal activity mediates muscle tone in Parkinson's disease [26], we posit that this may be generalizable to all proximal muscles though the effects of rigidity may influence each muscle group variably. Sensitivity to detect therapeutic change is of fundamental importance to

clinical applications and we have demonstrated this using the BiRD. However, correlation with existing instrumented techniques examining other joints may further validate our technique.

Elastic, viscous, inertial, and frictional stiffness of muscles are independent components [30] that contribute to the overall rigidity felt as resistance to passive movement during clinical examination. Force Rate primarily quantifies elastic stiffness and is usually presented in units of torque per degree (Nm/deg) [5,8,20]. Our method may not be specific to elastic stiffness as it may detect involuntary muscle reflexes to passive movement; this may also explain the moderate agreement with clinical ratings. Conversion to torque typically entails measurement of the limb segment length under evaluation to determine the distance from a pivot (joint) where force is applied [20]. This measurement is prone to error and must be repeated for each individual. In our study, the finger harness was designed to standardize the distance at which force was applied to pivot the metacarpophalangeal joint and our results can easily be converted to torque via simple scaling.

We found Force Rate increased as a result of therapy, contralateral activation, and disease (Parkinson's vs. controls). This is supported by previous work reporting that torque-angle slopes typically become steeper with worsening rigidity [2,16,18,20,21,27,38]. As far as we know, only one group have reported decreasing slopes associated with worsening rigidity [8,39–41] with only [39,41] showing statistical significance.

Work Estimate or the "Rigidity Work Score" is often presented with units (N-deg) or normalized by the range of motion (N-deg/deg). Work Estimate has been previously shown to differentiate controls and those with Parkinson's disease as well as contralateral activation and rest [26,39]. Our results do not support these findings possibly due to a number of methodological differences. Notably, comparable studies used either the wrist or elbow joints to determine Work Estimate. Moreover, they adopted a greater range of motion and slower movement speed than our instrument, with both factors known to influence rigidity assessment [24,26,42].

Manual joint manipulation was required in approximately half of the techniques previously reported, with transducers either attached to specialized handles [20–22] or affixed to the participant [16] to capture flexion/extension force. Motorized techniques required large powerful motors to generate adequate torque to displace limbs. Importantly, limb segments require bracing against support surfaces to constrain movement to a single joint and axis. Our palm-worn instrument incorporates a miniature motor with geared output to drive the finger, the base of the instrument acts as the support surface and is tethered to the palm of the hand. This leads to minimal restriction of joint movement. Consequently, raters in our trial were able to carry out the standard MDS-UPDRS assessment on the wrist and elbow without removing the device from the palm.

Furthermore, participants were not tethered to a large instrument and were free to move their arms during periods of rest.

Historically, the Froment Maneuver (voluntary contralateral shoulder movement) was used to elicit rigidity [43]. We observed activated rigidity in all but the young healthy cohort – a finding corroborated by others [26,44]. Rigidity can be enhanced by activation throughout the course of Parkinson's disease and provides a clinical sign for diagnosis [1,44,45]. Moreover, age-related changes to muscle mechanical properties and connective tissues are well established [30]. Exploration of the underlying mechanism causing activated rigidity is beyond the scope of this paper; however, [1] provides further discussion.

Our findings support the notion that an instrumented rigidity measure offers advantages over conventional clinical ratings. It may be used to guide DBS surgery and assess intraoperative effects of stimulation [19,21], determine optimum therapeutic windows [22], and provide insight into mechanism of therapeutic action [20,46]. Importantly, instrumented methods allow continuous monitoring [16], delivering insight into temporal characteristics of symptom changes. We have highlighted this benefit by characterizing the wash-in/out effects of DBS. Our findings support previous work indicating rigidity worsens over a period of 60 to 90 minutes following DBS cessation [7]. We also found the wash-in period to be much more rapid than initially expected (in-line with other Parkinsonian symptoms such as tremor [32]). Further studies are required to characterize this transient effect with greater temporal resolution.

Previous studies have also found considerable variability between raters (ICC = 0.49) using the UPDRS rigidity subscore [47], with one study suggesting that the interpretation of the scale varies amongst raters even when presented in written form prior to assessment [16]. The latest revision to the scale, MDS-UPDRS, sought to resolve this issue by improving explanatory instructions and clearly defining each demarcation [9]. In our study, raters only achieved a fair agreement despite both being experienced physiotherapists in the movement disorders field and receiving written instructions prior to each trial. Remarkably, test-retest reliability for the clinical rating was higher than for the objective measure. We hypothesize that this is likely due to the increased sensitivity of the objective measure, and is indicative of the retest condition not being equivalent to the baseline. In the retest condition, participants had only received DBS for a 30-minute period which may have been insufficient to allow complete amelioration of rigidity.

Our cohorts were relatively small and our results may not be generalizable to a larger population. Multiple within-subject measurements during the DBS wash-in/out periods afforded adequate samples to train a regression model; but these samples were not independent. Also, the cross validation approach used to assess the performance of the regression model may have been

less robust than an approach where independent datasets were used for training and testing. Paratonia was not assessed using EMG, therefore we are uncertain if the low-force readings leading to trial omissions were directly related to this phenomenon. Furthermore, Parkinson's disease is associated with exaggerated muscle shortening reflexes [39], which could have confounded our findings. The BiRD measures rigidity at the metacarpophalangeal joint which is susceptible to bone and joint disease (arthritis, gout, etc.). The emergence of such comorbidities may reduce the applicability of our instrument to the broader Parkinsonian population.

This paper introduces a novel palm-worn instrument to quantify finger rigidity in Parkinson's disease. We have shown our device can track rigidity over time in moderate agreement with clinical observations. Importantly, the capability to detect changes arising from therapeutic intervention may prove useful in clinical trials or as a home-based monitoring tool to track symptom fluctuations. Further work is needed to improve the robustness and usability of the device and to validate the technique in a larger cohort.

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Figures

Figure 1. The Bionics Institute Rigidity Device (BiRD) is a 3D-printed prototype (a) designed to be worn on the palm. A miniature electric motor flexes the third digit and a transducer embedded at the interface between the harness and finger measures force. The amount of force per degree of flexion quantifies rigidity. The photograph (b) shows the right-hand version of the device; a second mirrored device was manufactured for the left hand. Force (c) and current (d) data for a single flexion/extension cycle with and without deep brain stimulation (DBS) therapy are shown. The slope of the force curve indicates Force Rate and is specified by dotted lines (c). The baseline offset in the raw force data has been removed.

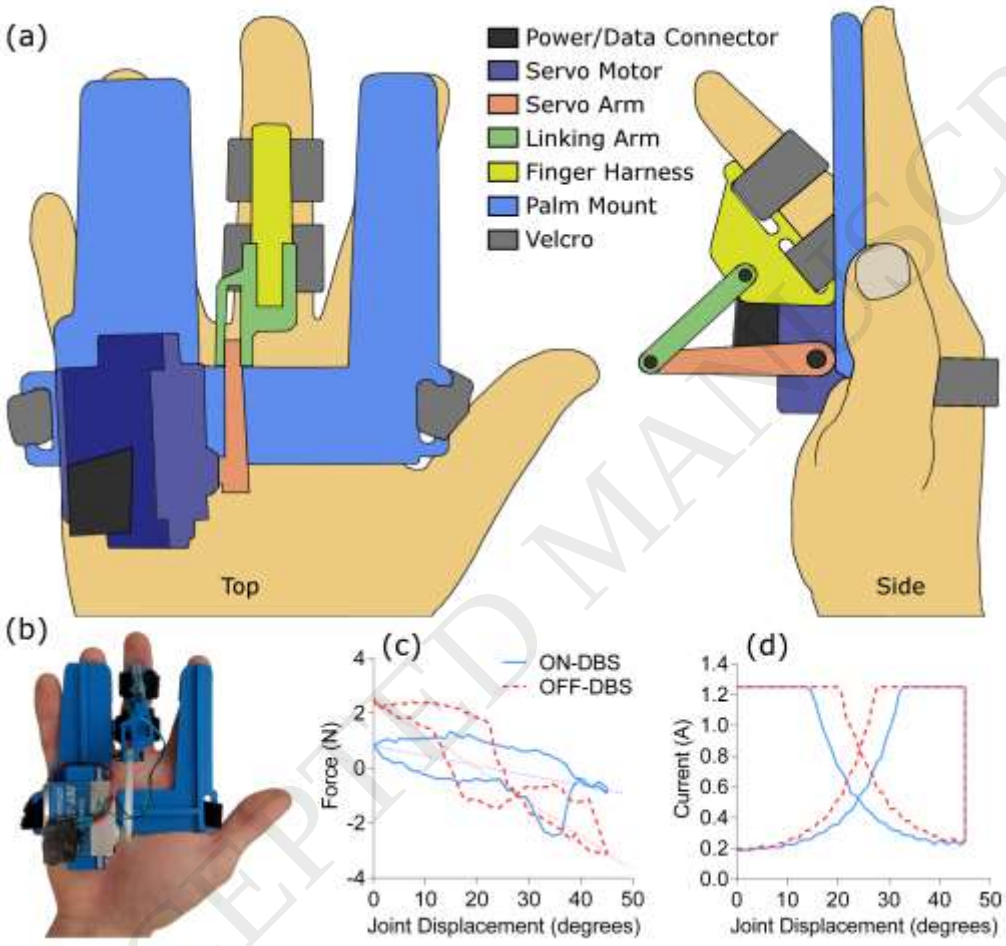


Figure 2. Rigidity, measured with the BiRD, is represented as Force Rate (the amount of force required per degree of finger flexion) and Work Estimate (area under the force vs. displacement curve). Force Rate can differentiate between Deep Brain Stimulation (DBS) therapeutic states (a), as well as those with and without Parkinson's disease (b). Furthermore, Force Rate can be used to characterize the increase in rigidity due to the performance of an activation task (contralateral arm movement). Though Work Estimate was able to distinguish therapeutic states (c), it was unable to distinguish activation trials and age-matched cohorts (d). HC = Healthy Controls. Error bars indicate standard deviations; * $p < 0.05$; ** $p < 0.001$.

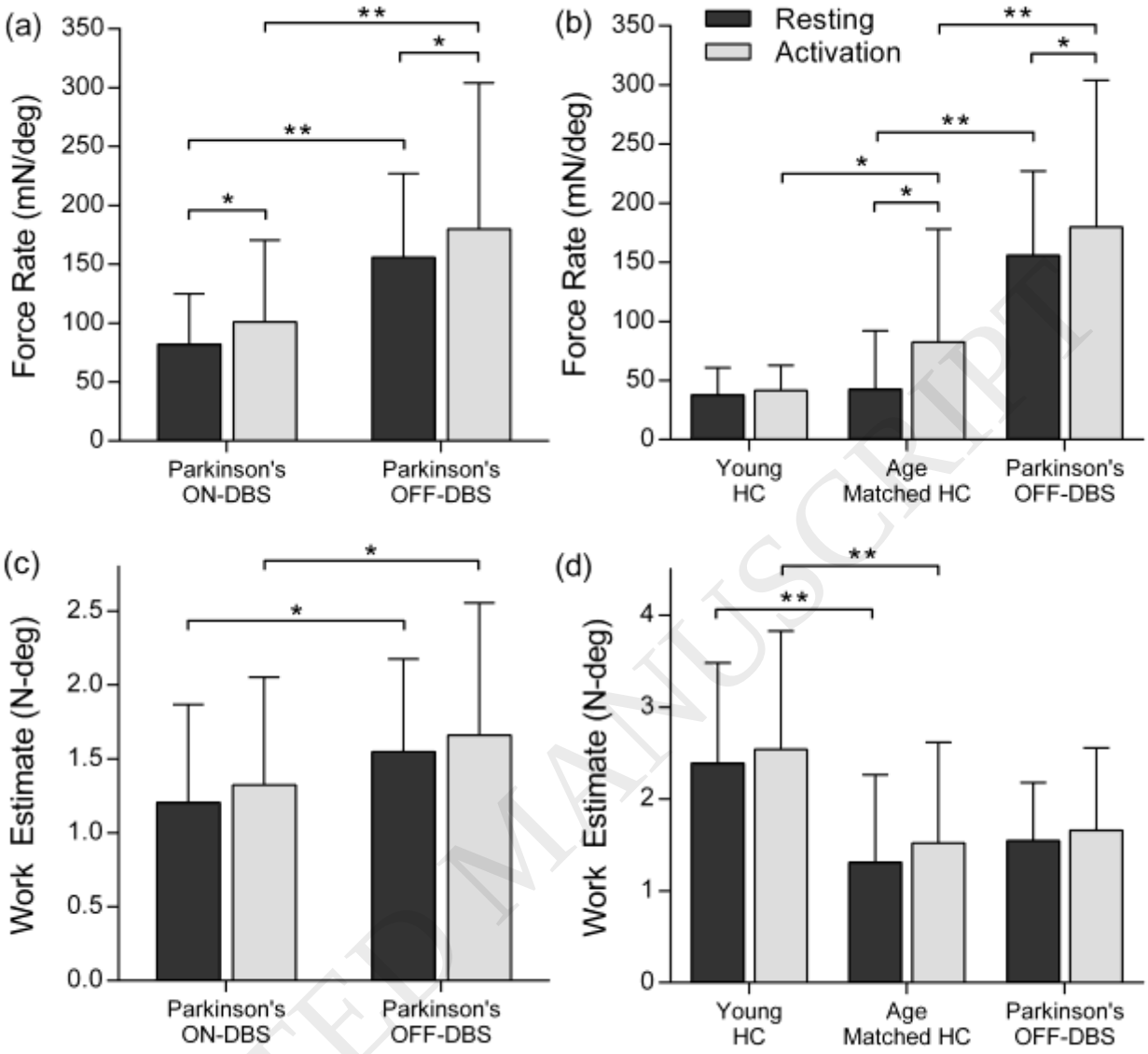
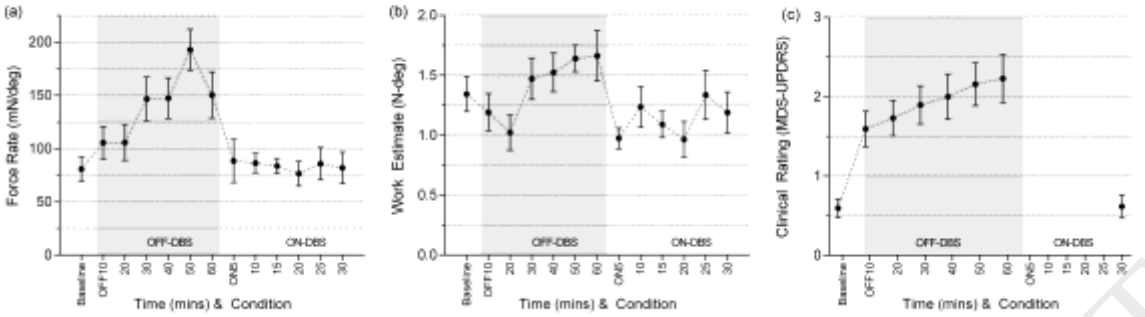


Figure 3. Force Rate (a) and Work Estimate (b) measured by the BiRD indicate a gradual increase in rigidity following Deep Brain Stimulation (DBS) cessation (grey shaded region). Rigidity returns to baseline levels almost immediately upon resumption of DBS. Both Force Rate and Work Estimate observations are generally in agreement with mean clinical ratings (c). Error bars indicate standard error.



Tables

Table 1. Regression model for estimating clinical ratings on the MDS-UPDRS using metrics derived from the BiRD. Each term of the model, the coefficient estimate (B), the standard error of the estimate (SE), t-statistic (t), p-value (p), standardized coefficient estimate (β), and the variance inflation factor (VIF) are shown. The terms are interpreted as follows: F = Force Rate, P = Peak Force, W = Work, Q = Charge, r = superscript identifier for hands at rest, a = superscript identifier for contralateral activation, e = subscript identifier for extension cycle, f = subscript identifier for flexion.

Term	B	SE	t	p	β	VIF
Constant	-14.431	3.299	-4.375	< 0.001		
F_f^r	0.089	0.022	4.148	< 0.001	0.481	2.576
F_f^a	-0.011	0.003	-3.070	0.003	-0.059	3.728
F_e^r	0.056	0.018	3.181	0.002	-0.115	2.771
P_e^a	4.267	0.923	4.622	< 0.001	0.438	8.124
W_f^a	-1.52E-03	4.73E-04	-3.209	0.002	-0.518	6.491
W_e^a	-3.32E-03	1.37E-03	-2.412	0.018	0.157	6.106
$F_f^r \times W_f^a$	7.16E-06	2.90E-06	2.465	0.016	0.389	7.105
$F_f^a \times F_e^r$	8.38E-05	1.70E-05	4.915	< 0.001	0.359	2.259
$Q_f^r \times F_e^a$	-9.43E-04	1.94E-04	-4.863	< 0.001	-0.179	1.178
$F_e^r \times P_e^r$	-0.015	0.004	-3.826	< 0.001	-0.164	1.926
$F_f^r \times P_e^a$	-0.021	0.006	-3.759	< 0.001	-0.783	7.766
$P_e^r \times W_e^a$	7.91E-04	2.98E-04	2.652	0.010	0.292	2.583