

Genome-Wide Association Study Meta-Analysis for Parkinson Disease Motor Subtypes

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Abstract

Objective

To discover genetic determinants of Parkinson disease (PD) motor subtypes, including tremor dominant (TD) and postural instability/gait difficulty (PIGD) forms.

Methods

In 3,212 PD cases of European ancestry, we performed a genome-wide association study (GWAS) examining 2 complementary outcome traits derived from the Unified Parkinson's Disease Rating Scale, including dichotomous motor subtype (TD vs PIGD) or a continuous tremor/PIGD score ratio. Logistic or linear regression models were adjusted for sex, age at onset, disease duration, and 5 ancestry principal components, followed by meta-analysis.

Results

Among 71 established PD risk variants, we detected multiple suggestive associations with PD motor subtype, including *GPNMB* (*rs199351*, $p_{\text{subtype}} = 0.01$, $p_{\text{ratio}} = 0.03$), *SH3GL2* (*rs10756907*, $p_{\text{subtype}} = 0.02$, $p_{\text{ratio}} = 0.01$), *HIP1R* (*rs10847864*, $p_{\text{subtype}} = 0.02$), *RIT2* (*rs12456492*, $p_{\text{subtype}} = 0.02$), and *FBRSL1* (*rs11610045*, $p_{\text{subtype}} = 0.02$). A PD genetic risk score integrating all 71 PD risk variants was also associated with subtype ratio ($p = 0.026$, $\beta = -0.04$, 95% confidence interval = $-0.07-0$). Based on top results of our GWAS, we identify a novel suggestive association at the *STK32B* locus (*rs2301857*, $p_{\text{ratio}} = 6.6 \times 10^{-7}$), which harbors an independent risk allele for essential tremor.

Conclusions

Multiple PD risk alleles may also modify clinical manifestations to influence PD motor subtype. The discovery of a novel variant at *STK32B* suggests a possible overlap between genetic risk for essential tremor and tremor-dominant PD.

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International Parkinson's Disease Genomics Consortium coinvestigators are listed in the appendix 2 at the end of the article.

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Glossary

BCM = Baylor College of Medicine; ET = essential tremor; GRS = genetic risk score; GWAS = genome-wide association study; IPDGC = International Parkinson's Disease Genomics Consortium; MAF = minor allele frequency; MDS-UPDRS = Movement Disorder Society revised UPDRS version; PD = Parkinson disease; PIGD = postural instability/gait difficulty; TD = tremor dominant; UPDRS = Unified Parkinson's Disease Rating Scale.

Parkinson disease (PD) is a clinically heterogeneous disorder.^{1–6} PD subtypes have been described based on common patterns of phenotypic features.^{1,7} One of the earliest and widely used subtyping classifications recognizes tremor dominant (TD) and postural instability/gait difficulty (PIGD) motor subtypes.^{8,9} These subtype categories have implications for disease progression, with prospective studies showing that PIGD is characterized by increased cognitive impairment and decreased response to levodopa.^{10,11} Although some studies have sought to identify pathologic correlates for PD motor subtypes,^{12,13} the mechanisms underlying these clinical and prognostic differences remain incompletely understood.⁷ Others have raised questions about the stability of PD motor subtypes over the disease course and their potential to be influenced by medications^{14–16}

A strong genetic contribution to PD etiology is well established, including several rare, monogenic forms of the disease and a large number of common variant PD risk alleles identified in genome-wide association studies (GWASs).¹⁷ There is mounting evidence for genetic variants as modifiers of PD phenotype as well. Variants in *LRRK2* or *GBA* modify disease motor progression (slower or faster, respectively) and also affect risk of cognitive impairment.^{18,19} Genetic association studies have also nominated genetic modifiers of PD progression, cognitive impairment, age at onset, and risk of insomnia, including established PD risk alleles.^{19–28} Of interest, *LRRK2(G2019S)* carriers appear to have a higher incidence of the PIGD subtype, despite early reports of asymmetrical tremor as a prominent clinical feature.^{18,29} A recent analysis of 10 PD risk variants from GWAS in a sample of 251 subjects (plus 559 subjects for replication) demonstrated an association of an *SNCA* locus polymorphism with the TD subtype.²³

We performed a GWAS meta-analysis for PD motor subtype in 3,212 subjects, examining potential associations for 71 established PD risk alleles and further testing for novel modifiers of TD vs PIGD motor phenotypes.

Methods

Standard Protocol Approvals, Registrations, and Patient Consents

Subjects derived from multiple North-American and European PD research cohorts (table e-1, links.lww.com/NXG/A373): Baylor College of Medicine (BCM), University of Maryland, Baltimore PD Genetics Study, Parkinson's Progression Markers Initiative, Parkinson's Disease Biomarkers

Program, Profiling Parkinson's disease study (Netherlands), Tracking Parkinson's study (United Kingdom), and the Oslo Parkinson's Disease study (Norway). All participants provided written informed consent for genomic studies, including permission for sharing of deidentified data between institutions, before enrollment in the respective studies. We obtained all clinical and genetic information with approval of the respective local institutional review boards.

Participants

All subjects were diagnosed with PD. The following data were required for inclusion in this study: sex, age at symptom onset, age at diagnosis, age at first evaluation, and earliest available (baseline) itemized rating using the Unified Parkinson's Disease Rating Scale (UPDRS) parts 2 and 3 or the equivalent parts of the Movement Disorder Society revised UPDRS version (MDS-UPDRS).^{30,31} Disease duration in years was defined as age at first evaluation minus age at symptom onset. If age of symptom onset was not available, age at diagnosis was used. The BCM cohort included subjects evaluated with either version of the UPDRS, and these subjects were therefore evaluated as separate cohorts (BCM1 and BCM2, see table e-1, links.lww.com/NXG/A373). All other cohorts exclusively used either the UPDRS or the MDS-UPDRS.

Motor Subtypes

PD motor subtypes, TD and PIGD, were determined using previously published algorithms.^{1,2} Subjects are classified as either TD, PIGD, or indeterminate using scale-specific cutoffs based on the ratio of tremor score to PIGD score from the UPDRS or MDS-UPDRS parts II and III. Applying these algorithms to our pooled cohort, 383 subjects with a tremor/PIGD score ratio in the indeterminate range could not be assigned to either the TD or PIGD dichotomous trait. As a complementary approach, we therefore used the tremor/PIGD score ratio as a continuous outcome, permitting inclusion of all subjects (including those classified as indeterminate). To accommodate subjects with PIGD score = 0 in these analyses, we transformed the tremor/PIGD score ratio as follows:

$$\log \sqrt{\frac{\text{Tremor score} + 0.01}{\text{PIGD score} + 0.01}}$$

Genotyping

Genotyping data (all Illumina platform based) were obtained from International Parkinson's Disease Genomics Consortium (IPDGC) members, collaborators, and public resources. As previously described, all data sets underwent quality

control separately, both on individual-level data and variant-level data, as implemented using PLINK v1.90b5.3.^{27,32} Briefly, we excluded individual samples with low or excess heterozygosity or discordant sex. We also excluded ancestry outliers following principal component analysis. We required that SNPs have a minimum call rate of 95%, minor allele frequency (MAF) > 5%, and Hardy-Weinberg equilibrium p values > 1E-04. Imputation was performed using the Michigan imputation server and the Haplotype Reference Consortium (r1.1 2016), with Eagle v2.3 phasing available at: imputationserver.sph.umich.edu.

Statistical Analysis

Our GWAS followed prior published IPDGC analytic pipelines,^{27,32} and an analysis plan was formulated before execution of the study. For each included cohort, the imputed genotyped dosages were analyzed using regression, implemented in RVTESTS.³³ Logistic regression was used for the dichotomous motor subtype trait (TD vs PIGD), and linear regression was used for the continuous tremor/PIGD score ratio trait. Both models were controlled for age at onset, sex, disease duration, and the first 5 ancestry principal components. Fixed effects meta-analysis combining the summary statistics from the 8 studies was performed using METAL with default parameters.³⁴ For the GWAS, we computed $\Lambda_{1000} = 0.88$ for the dichotomous subtype outcome and $\Lambda = 0.99$ for the continuous ratio trait. Heterogeneity statistics are included in e-tables, links.lww.com/NXG/A373. As in prior IPDGC analyses, we conservatively filtered the top GWAS results, excluding 6 SNPs with heterogeneity $I^2 > 60\%$ and $p < 0.05$. For the candidate analysis of PD risk alleles, 71 variants had an imputation quality >0.8 in our data set and were therefore included in our analyses.³⁵ The significance threshold was set at $p < 0.0007$ based on 71 independent tests using the Bonferroni method ($p = 0.05/71$); we secondarily considered $p < 0.05$ as evidence of a suggestive association. The 71 PD risk variants were also evaluated in combination using a weighted genetic risk score (GRS), implemented in PLINK.^{32,35} For ease of interpretation, GRS scores were converted to Z scores as previously described.³⁶ Association with the 2 subtype outcome traits was tested using the formula:

$$\text{Trait} \sim \text{GRS_Zscore} + \text{AgeAtOnset} + \text{Sex} + \text{PC1} - \text{PC5}$$

Forest plots and association meta p -values were calculated using the R package metafor.³⁷ For the genome-wide analysis, significance was set at $p < 5 \times 10^{-8}$, whereas $p < 1 \times 10^{-5}$ was considered suggestive evidence of association. Locus plots were generated using LocusZoom.³⁸ Linkage disequilibrium pruning was performed using the module SNPclip, which is part of LDlink application using the default parameters ($r^2 = 0.1$ and $\text{MAF} = 0.01$) and a genomic window of 500kb.³⁹ For the lookups of variant associations with essential tremor (ET) susceptibility, significance was set at $p < 0.0013$ based on 39 tests. Statistical power was estimated using the Genetic Association Study Power Calculator (csg.sph.umich.edu/abecasis/gas_power_calculator/). We performed 2 sets of

calculations considering power to detect association of (1) an established PD risk allele (*rs199351*, frequency = 0.6, risk ratio = 1.11) or (2) a novel variant (*rs10937625*, frequency = 0.12, risk ratio = 1.25). Disease prevalence was set to 0.0041.

Data Availability

Summary statistics for the analyses presented in this study will be made available on the IPDGC website (pdgenetics.org/resources).

Results

Overall, our study included 3,212 subjects with complete clinical data and genotypes passing all quality control filters (see Methods). Clinical and demographic information along with the frequency of motor subtypes is shown in table 1. The TD subtype was more common than PIGD, but subtype proportions varied between cohorts (table e-1, links.lww.com/NXG/A373). Consistent with prior reports,^{14,15,40} the proportion of patients with TD was inversely related to average disease duration (correlation coefficient -0.57). Because of individuals with indeterminate subtype classification, 2,829 subjects were available for the GWAS using the dichotomous subtype trait (TD vs PIGD), whereas all 3,212 patients were included in the GWAS for the tremor/PIGD subtype ratio.

We first examined associations for 71 established PD risk variants with PD motor subtypes. Overall, we identified suggestive associations ($p < 0.05$) between risk variants at the *GPNMB*, *SH3GL2*, *HIP1R*, *FBRSL1*, and *RIT2* loci and the subtype trait, but none of these associations remained significant following multiple test correction (table 2 and e-2, links.lww.com/NXG/A379). In 2 of 5 loci (*GPNMB* and *FBRSL1*), the PD risk-increasing allele was associated with PIGD subtype. Variants at *GPNMB* and *SH3GL2* also showed

Table 1 Cohort Characteristics

	N (%) or mean (SD)
N	3,212
Male	2,078 (64.7)
Age at evaluation (y)	66.0 (9.5)
Age at onset (y)	61.0 (10.6)
Disease duration (y)	4.1 (4.5)
TD subtype	1,570 (48.9)
PIGD subtype	1,259 (39.2)
Indeterminant subtype	383 (11.9)

Abbreviations: PIGD = postural instability/gait difficulty; TD = tremor dominant.
Demographic information and frequency of motor subtypes of the study population combined from all 8 cohorts.

Table 2 Association of Established PD Risk Variants With PD Motor Subtype

chr: position	SNP	Gene	Allele ^a	Frequency	Subtype (TD vs PIGD)			Subtype ratio		
					Effect	SE	p Value	Effect	SE	p Value
7: 23300049	rs199351	GNMB	A/C	0.61	0.16	0.06	0.011	-0.05	0.02	0.033
9: 17727065	rs10756907	SH3GL2	A/G	0.76	0.16	0.07	0.019	-0.06	0.03	0.017
12: 123326598	rs10847864	HIP1R	T/G	0.38	-0.15	0.06	0.018	0.017	0.02	0.47
12:133063768	rs11610045	FBRSL1	A/G	0.51	0.14	0.06	0.023	-0.03	0.02	0.17
18: 40673380	rs12456492	RIT2	A/G	0.67	0.15	0.06	0.019	-0.008	0.02	0.73

Abbreviations: PD = Parkinson disease; PIGD = postural instability/gait difficulty; SE = standard error; TD = tremor dominant.
^a Effect/alternate alleles shown, PD risk allele denoted in boldface.

consistent associations with subtype ratio, but no additional PD risk alleles were associated with this outcome (table e-2, links.lww.com/NXG/A379). We next integrated genotypes across the 71 PD risk alleles to compute a GRS for each subject and examined for association with PD motor subtypes. Indeed, we detected a significant association between the PD GRS and the subtype ratio ($p = 0.03$, confidence interval = -0.07 to 0.00), although this result appeared to be driven by only 2 of 8 cohorts included in our meta-analysis (PDBP and BCM2, figure 1). The GRS was not associated with the dichotomous subtype trait (figure e-1, links.lww.com/NXG/A373).

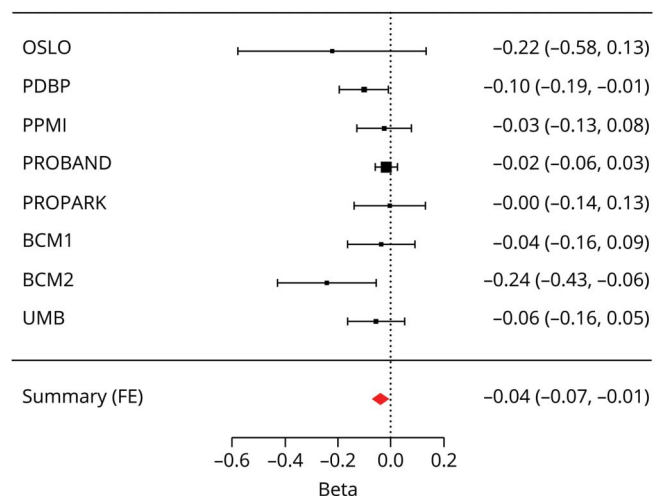
We next examined the results of our GWAS to identify novel candidate modifiers of PD motor subtype. Although no variants reached the genome-wide significance threshold, a number of variants showed suggestive associations ($p < 1 \times 10^{-5}$) with either PD motor subtype or subtype ratio (tables e-3 and e-4, links.lww.com/NXG/A373). The top variant associated with the subtype ratio outcome is rs2301857 ($p_{\text{ratio}} = 6.6 \times 10^{-7}$), located within an intron of the *STK32B* gene (figure 2). The minor allele, rs2301857^T (frequency = 0.12) was associated with reduced tremor/PIGD score ratio (effect = -0.19). Thus, the minor and major alleles for the rs2301857 SNP are associated with a polarization toward the PIGD vs TD phenotypes, respectively. In our complementary analysis, the association between rs2301857 and PD motor subtype was attenuated ($p_{\text{subtype}} = 0.044$).

Notably, an association signal at *STK32B* has been previously reported in a GWAS for ET.⁴¹ Although the lead variant from that study, rs10937625, is only 290 kb proximal from the top variant in our analysis, these SNPs do not demonstrate appreciable linkage disequilibrium ($R^2 = 0.002$, $D' = 0.184$). Based on the Genotype-Tissue Expression project database,⁴² rs2301857^T is associated with increased *STK32B* expression, but this expression quantitative trait locus was only significant in the testes, salivary gland, and prostate. We performed additional analyses to explore for a possible genetic overlap between ET and PD motor subtype. However, neither the *STK32B* variant nor any of the other 5 published ET risk variants⁴¹ were associated with either of our PD motor subtype traits (table e-5, links.lww.com/NXG/A373). Lastly, to

explore for further potential evidence of shared genetic architecture, we reciprocally examined whether any of our top candidate variants ($p < 1 \times 10^{-5}$; $n = 39$ variants) associated with PD motor subtype confers susceptibility for ET, based on lookup of the top results in the largest GWAS completed to date (2807 ET cases/6,441 controls).^{41,43} However, neither *STK32B*^{rs2301857} ($p = 0.18$) nor any other top suggestive results from our PD motor subtype GWAS were significantly associated with ET susceptibility.

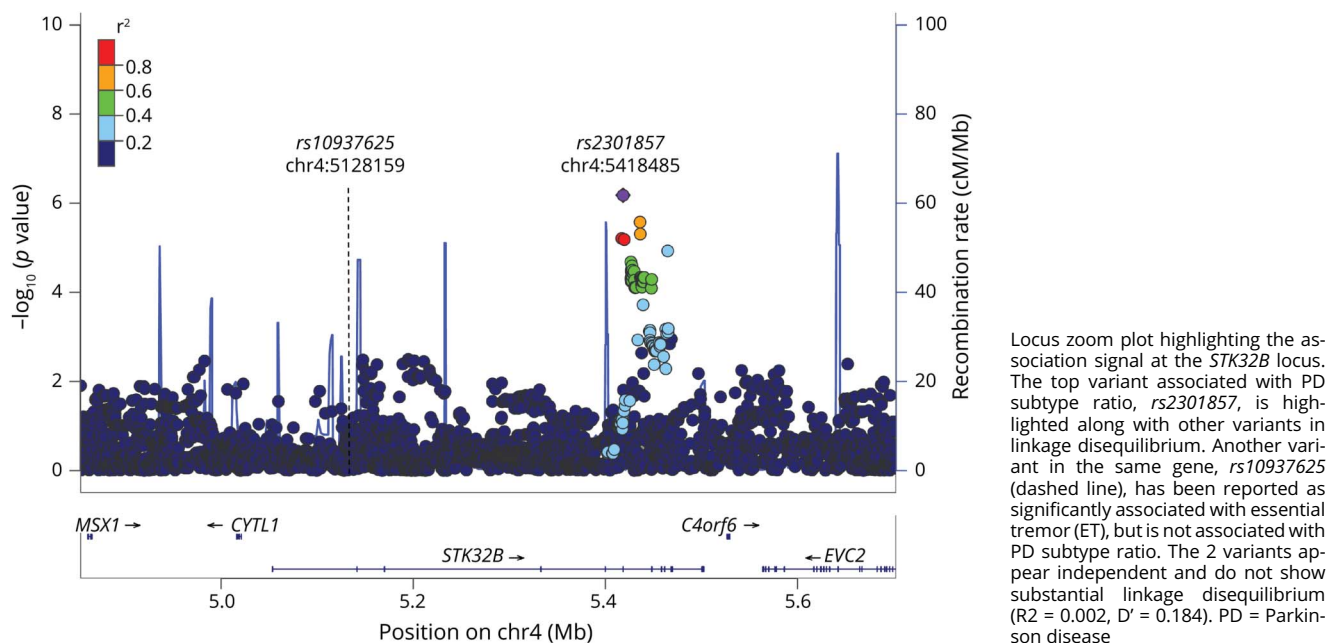
Discussion

Identification and characterization of PD subtypes has received increased attention in recent years, with the goal of predicting progression, stratifying patients based on risk of

Figure 1 PD Genetic Risk Score Associates With Tremor/Postural Instability/Gait Difficulty Score Ratio

Error bars represent 95% confidence intervals. The size of the black squares represents the effect size from each cohort. The combined estimate for all cohorts is represented by the red diamond with the width of the diamond representing the 95% confidence interval bounds. The summary effect = -0.0389 ($p = 0.0156$). PD = Parkinson disease.

Figure 2 STK32B Locus Association With PD Subtype Ratio



nonmotor complications (e.g., dementia), and elucidating mechanisms of disease heterogeneity.^{7-9,44} Recent studies strongly suggest that genetic factors can influence the presence and severity of many varied PD manifestations and therefore likely influence disease subtypes.⁷ We have performed a GWAS for PD motor subtype. Our results highlight some evidence for 5 established PD risk alleles as potential modifiers of motor subtype, and we further found that a PD GRS including 71 risk variants was associated with subtype ratio. One strength of our analysis was consideration of 2 complementary PD motor subtype outcomes. The TD/PIGD score ratio trait offers a continuous outcome and has the advantage of a larger sample size because subjects with indeterminate subtype can be considered. On the other hand, by including subjects with a mixed phenotype, it is also possible that the subtype ratio may dilute power to detect the effects of certain variants. In such cases, the dichotomous subtype outcome permits greater contrast between groups of subjects manifesting the TD or PIGD phenotype. In a prior, candidate-based analysis of 10 PD risk alleles in 810 PD cases, a variant at the *SNCA* locus (*rs356182*) was discovered to be associated ($p = 0.004$, $\beta = 0.7$) with a similar TD/PIGD score ratio outcome.²³ Although we did not replicate that association in our larger sample ($n = 3,212$, $p = 0.18$, $\beta = 0.03$), this may relate to modest differences in the derivation of the subtype score ratio, and additional replication analyses should be undertaken in the future.

Although no variants reached genome-wide significance in our GWAS, we identify many loci harboring suggestive associations that may be excellent candidates for follow-up and potential replication. The top result of the subtype ratio

GWAS, *rs2301857*, implicates the *STK32B* gene as a possible modifier of PD motor phenotypes. This gene has previously been genetically linked to ET.⁴¹ The potential relationship between ET and PD has long been a topic of discussion in the field of movement disorders.⁴⁵ Although most patients with ET do not develop parkinsonism, at least 1 study has shown that a prior diagnosis of ET may increase the risk of PD up to 4-fold.^{46,47} A possible genetic link is further suggested by reports of familial coaggregation of ET and PD.⁴⁸ In another study, patients with PD having family members with ET were more likely to exhibit the TD subtype of PD.⁴⁹ Importantly, the variant that we discovered in association with PD motor subtype does not show appreciable linkage disequilibrium with the previously reported ET susceptibility signal; therefore, these appear to be independent alleles at the *STK32B* gene locus. Thus, although intriguing, our results fall short of providing conclusive evidence of a shared genetic architecture of these 2 common movement disorders.

Despite including more than 3,000 subjects, statistical power appeared limiting. In fact, we estimate (see Methods) that nearly 14,000 subjects would be required to achieve 80% power to detect a significant association for either a candidate PD risk variant (e.g., *GPNMB*^{*rs199351*}) or a novel variant modifier of motor subtype (e.g., *STK32B*^{*rs2301857*}). Based on ongoing efforts, we anticipate that sufficiently large cohorts with detailed clinical phenotyping will likely emerge in the next few years. At the time that this analysis was undertaken, clinical and genetic data were available predominantly from European ancestry subjects. Whereas an ethnically homogeneous cohort design may reduce potential population stratification and thereby increase power, this also potentially limits

generalizability. In the future, it will also be important to study genetic modifiers of PD motor heterogeneity in diverse populations.

Although the TD and PIGD categories are the earliest and mostly widely used subtype classification,^{8,9} there are also several notable limitations. The cutoffs used for differentiating the TD or PIGD subtypes are somewhat arbitrary and without underlying biological or clinical rationale.¹ In addition, treatment with dopaminergic medication is known to alter the motor UPDRS examination—especially gait scores—which may in turn influence subtype classification.^{15,50} Information on medication status and other factors (e.g., dementia, lifestyle, and environmental exposures) was not universally available for consideration as potential confounders or genetic modifiers in this analysis. Lastly, several recent studies have suggested that PD motor subtypes may shift from TD to PIGD subtype along with disease progression,^{14–16} raising questions about the stability of these phenotypes over time. This relation between disease duration and subtype proportions was recapitulated among the cohorts included in this study (table e-1, links.lww.com/NXG/A373). Such observations suggest that motor subtypes may represent a transient state rather than a static trait.⁵¹ To control for potential shifts in subtype phenotypes, our analyses were adjusted for both onset age and estimated disease duration. In addition, we speculate that even if PD motor subtypes are dynamic, either completely or in part, they may nevertheless serve as a useful proxy for disease progression, which is likely itself under genetic influence.^{19,22,24,26} In sum, regardless of evolving interpretations for PD subtypes, we argue that analyses of such phenotypes may identify genetic variants that meaningfully modify the PD clinical course, whether motor manifestations, rate of progression, medication response, or some combination. Future genetic analyses of PD subtypes will also benefit from alternative outcome traits that are independent of medication status and disease duration.

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Rami Al-Ouran, PhD	Baylor College of Medicine	Conceptualization, investigation, data analysis, data curation, methodology, writing—original draft, and writing—review and editing
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Manuela Tan, BA	University College London	Conceptualization, data curation, and writing—review and editing
Calwing Liao, BA	McGill University	Data analysis and writing—review and editing
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Lisa M. Shulman, MD	University of Maryland	Conceptualization, data collection, writing—review and editing, resources, and supervision
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Mike A. Nalls, PhD	Data Technica International	Conceptualization, data curation, methodology, writing—review and editing, and supervision
Andrew B. Singleton, PhD	National Institutes of Health	Data generation, data curation, writing—review and editing, resources, and supervision

Appendix 1 (continued)

Name	Location	Contribution
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Appendix 2 Coinvestigators

Coinvestigators are listed at links.lww.com/NXG/A374.

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