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RESEARCH

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The inertial-based gait normalcy index of dual task cost during turning quantifies gait automaticity improvement in early-stage Parkinson's rehabilitation

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Abstract

Background The loss of gait automaticity is a key cause of motor deficits in Parkinson's disease (PD) patients, even at the early stage of the disease. Action observation training (AOT) shows promise in enhancing gait automaticity. However, effective assessment methods are lacking. We aimed to propose a novel gait normalcy index based on dual task cost (NIDTC) and evaluate its validity and responsiveness for early-stage PD rehabilitation.

Methods Thirty early-stage PD patients were recruited and randomly assigned to the AOT or active control (CON) group. The proposed NIDTC during straight walking and turning tasks and clinical scale scores were measured before and after 12 weeks of rehabilitation. The correlations between the NIDTCs and clinical scores were analyzed with Pearson correlation coefficient analysis to evaluate the construct validity. The rehabilitative changes were assessed using repeated-measures ANOVA, while the responsiveness of NIDTC was further compared by t tests.

Results The turning-based NIDTC was significantly correlated with multiple clinical scales. Significant group-time interactions were observed for the turning-based NIDTC ($F = 4.669$, $p = 0.042$), BBS ($F = 6.050$, $p = 0.022$) and PDQ-39 ($F = 7.772$, $p = 0.011$) tests. The turning-based NIDTC reflected different rehabilitation effects between the AOT and CON groups, with the largest effect size ($p = 0.020$, Cohen's $d = 0.933$).

Conclusion The turning-based NIDTC exhibited the highest responsiveness for identifying gait automaticity improvement by providing a comprehensive representation of motor ability during dual tasks. It has great potential as a valid measure for early-stage PD diagnosis and rehabilitation assessment.

Trial registration Chinese Clinical Trial Registry: ChiCTR2300067657

Keywords Parkinson's disease, Rehabilitation assessment, Gait analysis, Dual task cost, Gait normalcy index, Inertial sensors

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Background

Motor automaticity refers to the ability to coordinate movement with minimal attention-demanding executive control resources [1]. It is an important mobility function in healthy adults. The loss of gait automaticity is a key cause of motor deficits in Parkinson's disease (PD) patients due to abnormal basal ganglia circuits. Patients with PD shift their locomotor control strategy from automatic to attentional executive control, resulting in common motor symptoms, such as bradykinesia, postural instability and gait disorders [2]. Novel rehabilitation approaches (i.e., action observation training (AOT) and dual-task training) have been proven to be effective at improving gait automaticity and enhancing patients' quality of life [3]. However, an efficient assessment approach for these interventions against normal physical practice is still lacking.

Clinical scales are commonly used for the evaluation of rehabilitation effects [4, 5]. The scale scores are generated based on the doctor's subjective observations and the patient's self-reports, which may result in lower sensitivity to subtle changes [6]. Physical measures (i.e., the 10 m walking test and Time Up and Go Test) have also been widely employed in clinical assessments where walking speed and stride length are usually evaluated [7]. Inertial sensors have great potential for providing reliable and quantitative spatiotemporal gait parameters because of their unique advantages of good wearability and lack of laboratory environment constraints [8, 9]. However, due to PD patients would exhibit gait disorders in various perspectives, a single parameter may be insufficient to reflect gait changes in specific rehabilitation intervention for PD patients. Bezerra et al. [10] demonstrated that the AOT intervention reduced freezing of gait (FoG) episodes, but there was no significant difference in walking speed between the experimental group and controls. Similar results were reported by Jaywant et al. [11]. This suggests that the absence of a notable effect on walking speed does not necessarily render the intervention ineffective but may influence aspects such as gait automaticity. The assessment of motor control capability should not rely solely on a single gait parameter.

The dual task paradigm is a powerful method for evaluating motor automaticity in which a participant performs a primary motor task with a secondary cognitive or motor task. The dual task condition yields a deterioration in both task performances compared to the single-task condition. The performance decrements are interpreted as resulting from a competition of executive control resources, so-called "dual task cost" (DTC) [12, 13]. Although the determinants of DTC are multifactorial and complicated in that the given instructions, task priorities, and task difficulties are known to impact DTCs [14], complex primary motor tasks may guarantee an unavoidable demand for attentional executive control resources. The neural response underlying gait automaticity was investigated in a turning-based dual task test [15, 16]. Koçer et al. reported that PD patients exhibited an increased DTC of turning-based dual task duration [13]. The DTCs of the turning peak velocity, turning duration, and number of turning steps were used to identify patients with and without FoG [17, 18]. Our previous study developed an inertial-based quantitative gait assessment model that enables the estimation of gait spatiotemporal parameters and joint kinematics in various domains [19]. The gait spatiotemporal parameters significantly represent postural instability and gait abnormalities in early-stage PD. Early-stage PD patients exhibit more discriminative gait variables (i.e., stride length and joint range of motion) during turning than healthy controls [20, 21]. The fusion of gait variables during turning significantly improved the classification accuracy of early PD patients. Current studies have mostly focused on PD classification using machine learning methods [22–24]. A general comprehensive indicator for evaluating the effectiveness of rehabilitation interventions for early-stage PD is still lacking [25].

This study aimed to propose a novel normalcy index based on the DTC (NIDTC) during turning-based dual tasks and to evaluate its validity and responsiveness for early-stage PD rehabilitation intervention assessment. The NIDTC integrates the DTCs of gait spatiotemporal parameters derived from a complex motor task comprising straight walking and turning with/without a secondary serial-3 subtraction task. As the effectiveness for alleviating FOG by improving the patient's gait automaticity of the AOT approach has been proven [26, 27], a 12-week AOT intervention was administered to a group of early-stage PD patients. AOT works by enhancing motor learning [28, 29] specifically to improve gait automaticity by leveraging the Mirror Neuron System (MNS) [30] and promoting neuroplastic changes [27]. Meanwhile, an active control group engaged in 12-week stretching exercises to counteract the rehabilitation effects of physical activity. We hypothesized that both interventions could improve the severity of motor impairment but that only the AOT intervention is effective at improving gait automaticity. We assessed the validity of the NIDTC by calculating its correlation with clinical scales before the intervention. The responsiveness of the NIDTC was evaluated by comparing the rehabilitation changes between the two groups. Sensitivity was then assessed by comparing the effect sizes.

Methods

Participants

Thirty-five idiopathic PD outpatients were recruited from the Unit of Neurology, Tianjin Medical University General Hospital, Tianjin, China. The inclusion criteria were as follows: (1) Hoehn & Yahr (H &Y) score between 0.5 and 2.5; (2) age between 55 and 75 years; and (3) stable dopaminergic medication for at least 4 weeks. Participants were excluded if they had (1) a diagnosis of other neurological diseases, (2) severe orthopedic disease that affects gait performance, (3) any previous AOT rehabilitation experience, or (4) ongoing participation in other rehabilitation programs. At entry, all patients underwent neurological evaluations and MRI scans by a neurological specialist to rule out other neurological diseases. A total of thirty patients were included in this study. The patients were randomly divided into an experimental group (AOT) and a control group (CON) at a 1:1 ratio using the Research Randomizer website (https://www.randomizer.org), and the participants were assigned to different groups by an independent researcher who was not involved in any other aspects of the study.

This study was approved by the Ethics Committee of Tianjin Medical University General Hospital (IRB2022-KY-300) and Tianjin University (TJUE-2023-003). The clinical rehabilitation part of this study has been registered at the Chinese Clinical Trial Registry (ChiCTR2300067657). All the patients provided written informed consent before participating but were blinded to the intervention hypothesis of each group. The clinical rehabilitation in this study was conducted following the CONSORT guidelines to standardize the process, as shown in Fig. 1.

Rehabilitation interventions

The AOT group underwent an action observation training program that involved an eight-form routine based on 24-form Tai Chi, which gradually increased movement difficulty from simple to complex [31]. Each form was split into a 2-min video clip. Patients were instructed to observe and imitate the movements in a structured format consisting of "2 min of observation—5 min of execution", which was repeated five times followed by a 15-min movement practice session. To eliminate the impact of physical activity on rehabilitation, patients in the control group were instructed to perform 1-h stretching training twice a week. Both groups underwent a 12-week intervention at the Intelligent Rehabilitation Lab of Tianjin University. All patients who participated in the trials were in the "medication-ON" state. More details are provided in the supplementary materials.

Clinical assessment

At enrollment, an experienced neurologist performed physical examinations and evaluations of the H &Y score for all patients in the "medication-OFF" state. The Movement Disorders Society Unified Parkinson's Disease Rating Scale part III (MDS-UPDRS-III), Mini-Mental Status Examination (MMSE), Montreal Cognitive Assessment (MoCA), Berg Balance Scale (BBS), Mini-Balance Evaluation System Test (Mini-BESTest), and Parkinson's Disease Questionnaire 39-item version (PDQ-39) were evaluated in the "medication-ON" state (approximately 2 h after regular dopaminergic medication) by standardized trained physicians before and after 12 weeks of rehabilitation. The physicians were blinded to the group allocation.

Dual-task protocol

The patients performed a single motor task first as a baseline, where they were instructed to walk along a 5-m pathway with two 180° turns at their self-selected comfortable walking speed for 5 laps. In the dual task paradigm, participants were given a three-digit number below 300 and were required to subtract 3 sequentially from the given number when performing the "straight walking—180° turn" motor task and to speak out the calculation results. The serial-3 subtraction task performance (calculation number and accuracy) was recorded by a blinded assessor. The experiment was conducted in a controlled indoor environment. Five inertial sensors (myoMOTION, Noraxon, USA) were placed on the pelvis, shanks, and feet on both sides of each patient for motion data collection. Video of gait performance was also recorded for data quality assurance and compliance checking.

DTC calculation

The orientational angles and acceleration data of lower limb segments were used to derived gait spatiotemporal parameters, namely stride length (STL), stride time (SRT), stance phase time (STT), swing phase time (SWT), and walking speed (WAS) based on our proposed inertial-based gait spatiotemporal model [21]. The data was segmented into straight walking and turning tasks using the gait task recognition algorithm [32]. The STL and WAS were normalized to the individual's height. Each patient completed a total of 11 straight walking segments and 10 turning segments. The first and last segments of the straight walking and turning tasks were excluded because of gait transitions. Eight segments of each gait task were selected for further data analysis.

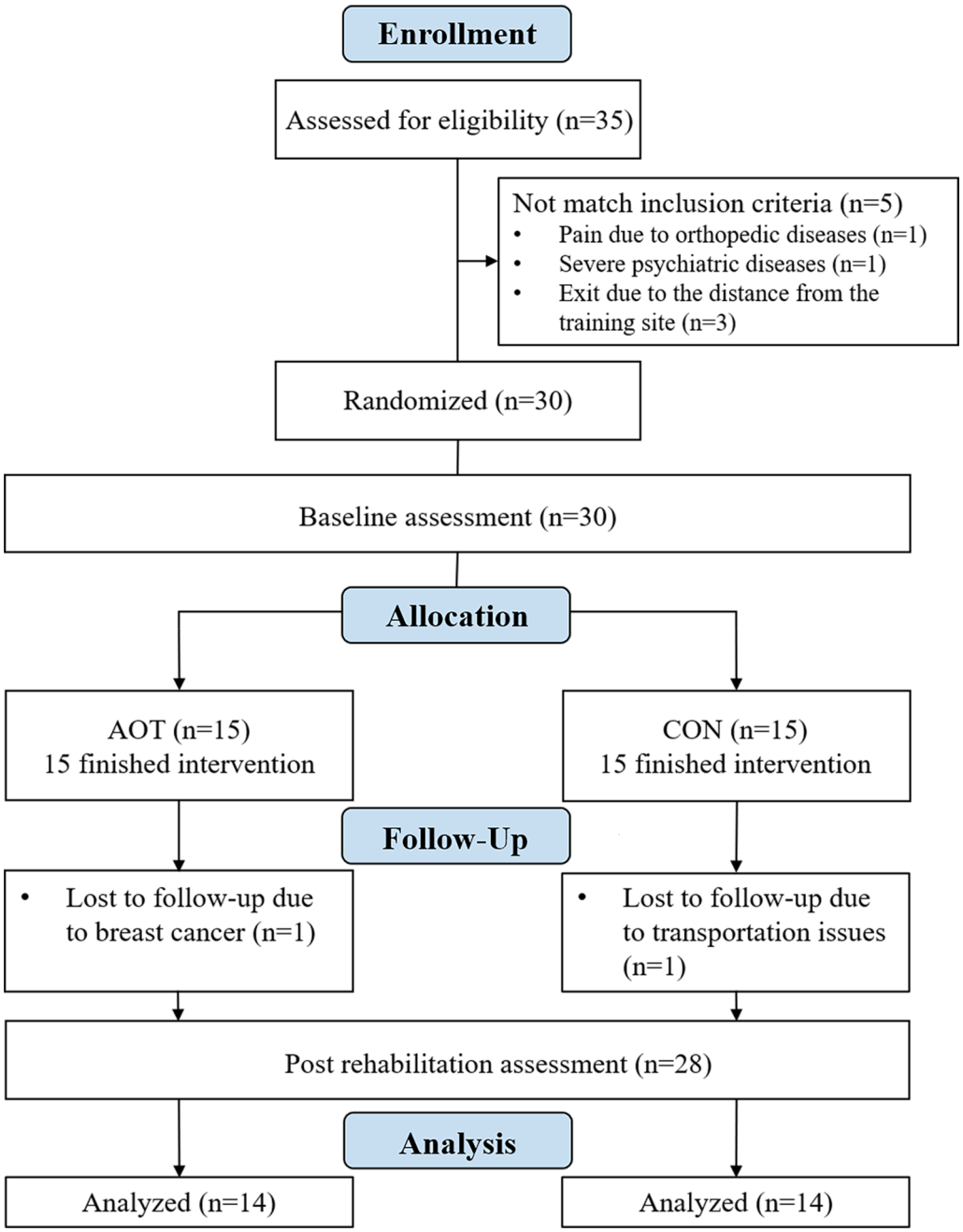

Fig. 1 CONSORT flow diagram

The DTCs of the individual gait parameters were calculated as follows:

$$DTC(\%) = \frac{Param_{DT} - Param_{ST}}{Param_{ST}} 100\% \quad (1)$$

where $Param_{ST}$ represents the gait parameters in a single-task condition and $Param_{DT}$ represents the gait parameters derived in the dual-task condition. Two gait tasks were considered in our study: straight walking (SW) or turning (T).

NIDTC calculation

Figure 2 visualizes the procedures of the gait protocol and data analysis for the NIDTC calculations. The means of DTCs based on gait cycles were calculated respectively for the left and right sides and then

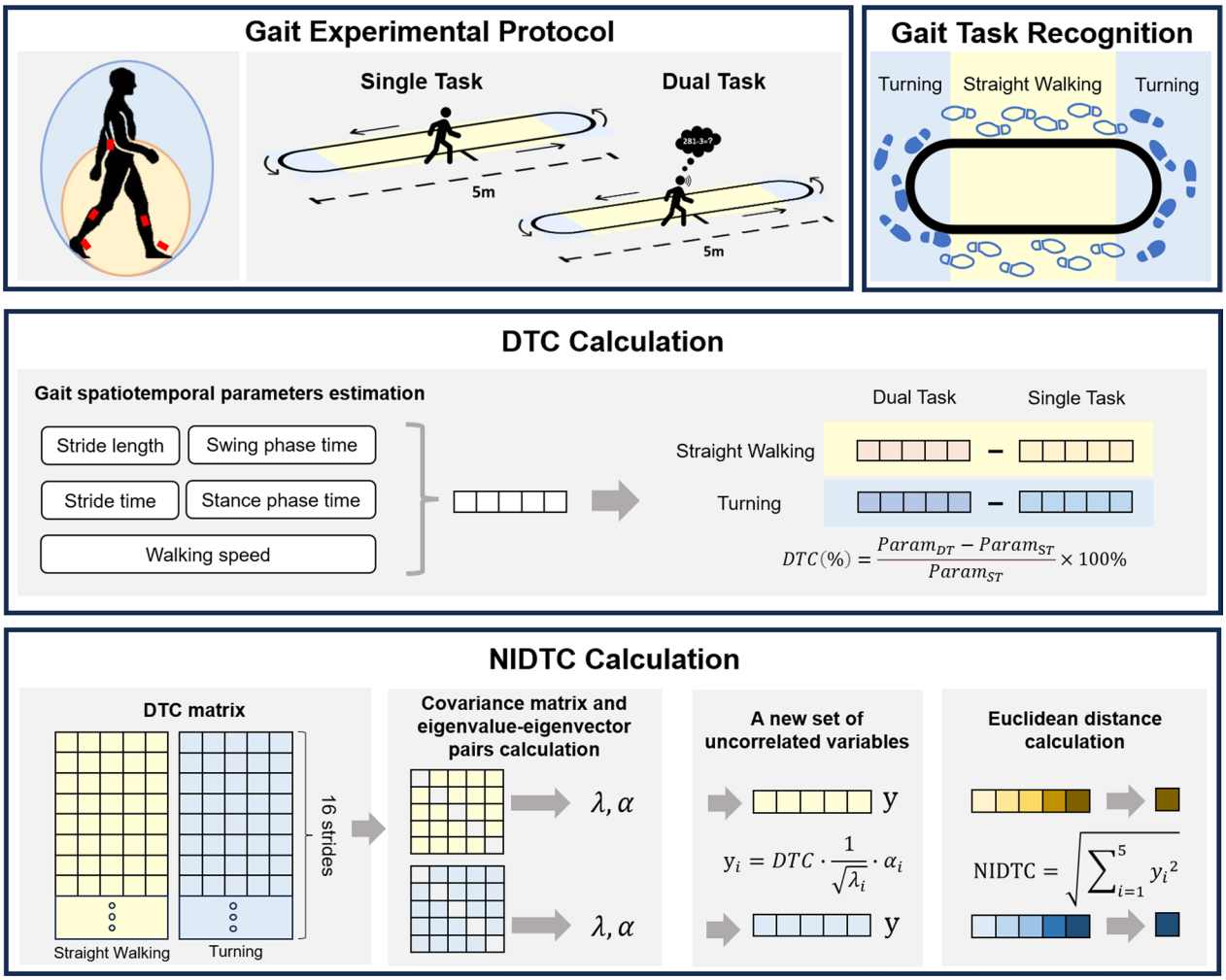

Fig. 2 Flowchart of the gait experimental protocol and feature calculation. All participants completed the single and dual tasks, and motion data were recorded by five inertial sensors placed on the pelvis, shanks, and feet of both legs. The data were segmented into straight walking and turning tasks, and gait spatiotemporal parameters were estimated. The dual task cost (DTC) of the five parameters was calculated based on those during the single task. The normalcy index based on dual task cost (NIDTC) was obtained via principal component analysis

constructed into a 16×5 matrix. The covariance matrix was first computed to obtain eigenvalue-eigenvector pairs [33]. Uncorrelated variables were calculated [34]:

$$y_i = DTC \cdot \frac{1}{\sqrt{\lambda_i}} \cdot \alpha_i \tag{2}$$

where DTC is the constructed 16×5 matrix, λ_i and α_i are the ith eigenvalue-eigenvector pair, and y_i is the ith uncorrelated new vector.

The vectors y_i with contributions of less than 1% to the variance were excluded based on the Variance Accounted For (VAF) criterion [35]. The NIDTC was calculated as the total Euclidean distance of y_i:

$$NIDTC = \sqrt{\sum_{i=1}^{5} y_i^2} \tag{3}$$

The NIDTC during the overall motor task (NIDTC_MT) was calculated with the combination of the 10 DTC parameters during straight walking and turning tasks.

Sample size calculation

Based on Sarasso et al.'s study [36], an effect size d of 1.087 was calculated using G*Power 3.1 software by comparing significant changes in dual task turning velocity between the AOT and control groups. A sample size of n = 15 per group, including a 10%

dropout rate, was used to detect a significant interaction between time and group, with an α of 0.05 and a power of 80%.

Statistical analysis

Independent-sample t tests were conducted to compare the demographic differences between the two groups at baseline. The normality of the clinical scale, DTC, and NIDTC results at both time points was tested using the Shapiro–Wilk test, while Levene's test was used to assess the homogeneity of variance. Pearson's correlation coefficient (PCC) was calculated to assess the correlation between the NIDTC and clinical scale scores at baseline, thereby assessing the construct validity. The outcomes of the rehabilitation interventions were examined using a 2-factor mixed repeated-measures ANCOVA (2 groups × 2 time points). Covariates in the model included disease duration, age, levodopa equivalent dose (LEDD), and baseline assessment data. The group × time interaction represents the outcome difference between the interventions over time and therefore was considered an indicator of the intervention effect difference. We conducted independent samples t tests comparing the rehabilitation changes between the two groups to evaluated the responsiveness of the NIDTC. Cohen' s d effect size was calculated to evaluate the indicator sensitivity in the rehabilitation assessment . We also use PCC to investigate the correlation between functional improvements and changes in the NIDTC induced by the two rehabilitation interventions. The strength of the correlation was categorized as poor ($r < 0.30$), moderate ($0.30 \leq r < 0.50$), good ($0.50 \leq r < 0.70$), or strong ($r \geq 0.7$). Cohen's d effect size was classified as small, medium, or large for values of 0.20, 0.50, and 0.80, respectively. Statistical significance was set as $p < 0.05$. Missing data caused by the dropouts was excluded for further analysis. All the statistical analyses were performed using SPSS (IBM V.25).

Results

Participants

A total of 35 patients were recruited, 30 of whom met the inclusion criteria and were enrolled and randomly assigned to the AOT or CON group in our study. As shown in Fig. 1, all patients received a baseline assessment and completed a 12-week rehabilitation intervention. One patient in each group dropped out at the post-rehabilitation assessment, leaving a total of 28 patients (14 patients in each group) for data analysis. Table 1 shows that the demographic and baseline clinical characteristics in the AOT and CON groups were similar.

Table 1 Demographic characteristics of PD patients at baseline

Characteristics	AOT (n = 14)	CON (n = 14)	p
Gender (M/F)	6/8	7/7	–
Age (years)	65.29 ± 4.60	63.86 ± 5.91	0.357
Height (m)	1.63 ± 0.09	1.65 ± 0.07	0.489
PD duration (years)	4.07 ± 2.16	2.86 ± 1.51	0.139
H &Y OFF	1.60 ± 0.57	1.50 ± 0.97	0.097
LEDD (mg)	433.81 ± 238.07	368.21 ± 182.81	0.565
UPDRS-III ON	14.29 ± 9.60	16.21 ± 5.89	0.213
BBS ON	48.64 ± 2.53	48.57 ± 2.14	0.907
Mini-BESTest ON	23.07 ± 1.86	23.57 ± 2.41	0.888
PDQ-39 ON	23.00 ± 10.62	23.64 ± 11.14	0.927

All values are represented as the mean ± standard deviation. ON and OFF represent the medication states

Correlations between baseline NIDTC and clinical scale scores

Figure 3 shows that the NIDTC during turning (NIDTC_T) exhibited stronger correlations with clinical scales than did the NIDTC during straight walking (NIDTC_SW), NIDTC during the overall motor task (NIDTC_MT), and the DTCs of gait spatiotemporal parameters. The NIDTC_T demonstrated a strong positive correlation with the UPDRS-III score ($r = 0.787$, $p < 0.001$), a good negative correlation with the BBS score ($r = -0.649$, $p < 0.001$) and Mini-BESTest score ($r = -0.581$, $p = 0.001$), and a moderate negative correlation with the MoCA score ($r = -0.443$, $p = 0.009$) and MMSE score ($r = -0.432$, $p = 0.011$), indicating a good construct validity. On the other hand, the NIDTC_SW exhibited only a moderate positive correlation with the UPDRS-III score ($r = 0.326$, $p = 0.045$). The NIDTC_MT exhibited a good positive correlation with the UPDRS-III score ($r = 0.509$, $p = 0.003$), a moderate negative correlation with the BBS score ($r = -0.498$, $p = 0.004$) and Mini-BESTest score ($r = -0.369$, $p = 0.027$), however, all of these correlations are weaker compared to those observed for NIDTC_T.

Rehabilitation outcome differences between the interventions

Considering baseline variables as covariates, we observed a decrease in NIDTC_T in the AOT group and an increase in the CON group, with a significant group × time interaction ($F = 4.669$, $p = 0.042$, $\eta^2 = 0.175$). This indicates that the NIDTC_T can be used to distinguish rehabilitation outcomes effectively between AOTs and active control interventions. BBS ($F = 6.050$, $p = 0.022$, $\eta^2 = 0.216$) and PDQ-39 ($F = 7.772$, $p = 0.011$, $\eta^2 = 0.261$) also exhibited significant group × time interactions. Both

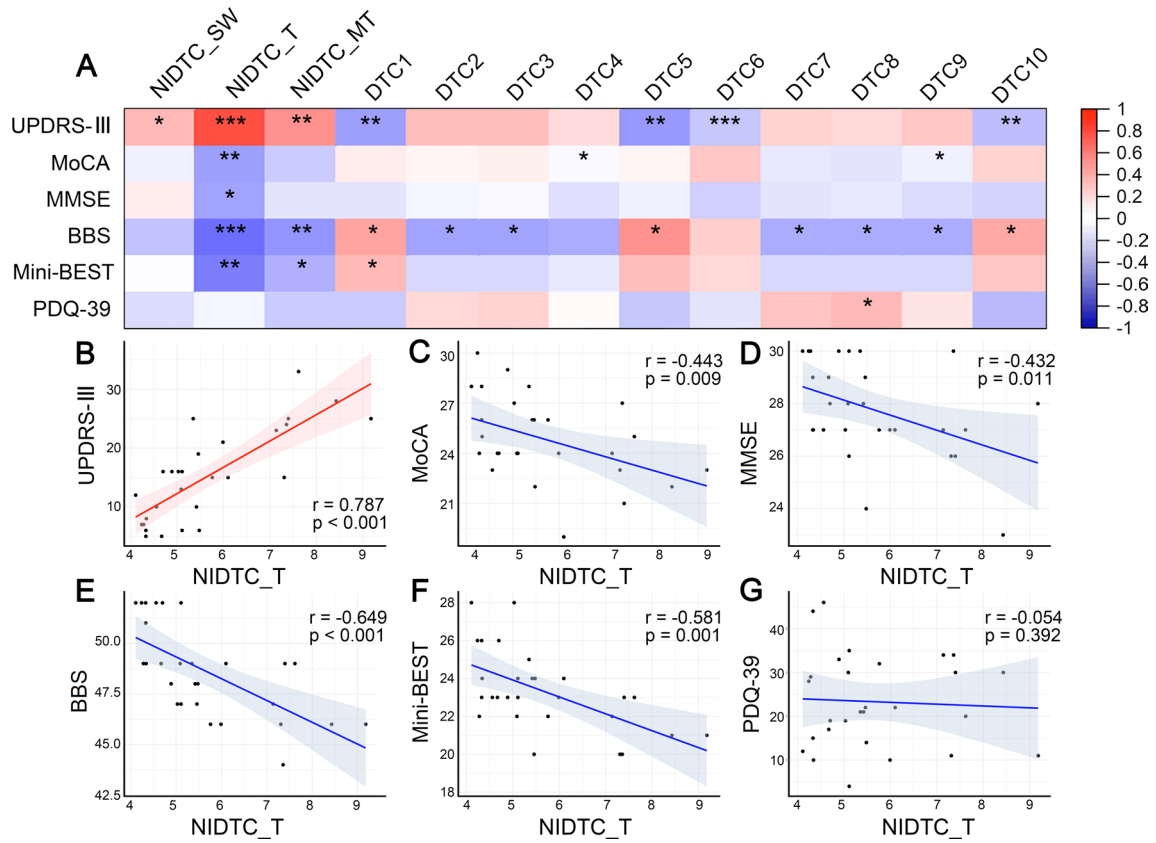

Fig. 3 Correlation analysis of clinical scores and gait indicator values in all patients at baseline. **A** Heatmap of the Pearson correlation coefficient matrix between clinical scores and gait indicators. **B**–**G** Scatter plots of the Pearson correlation coefficient between the clinical scores and NIDTC during turning. * = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$. DTC1-5 represent the stride length, stride time, stance phase time, swing phase time, and walking speed during straight walking, respectively, and DTC6-10 represent the DTCs during turning

groups had positive trends in changes in BBS and PDQ-39 scores, while the AOT group demonstrated more substantial improvements (AOT: BBS, 48.64 ± 2.53 vs 51.14 ± 1.35; PDQ-39, 23.00 ± 10.62 vs 5.64 ± 3.05; CON: BBS, 48.57 ± 2.14 vs 49.43 ± 2.59; PDQ-39, 23.64 ± 11.14 vs 15.14 ± 12.42). No significant group × time interactions were detected for single gait spatiotemporal parameters, single DTCs, cognitive scales or cognitive task performance (Table 2).

Figure 4A–F compares the correlation of clinical scale scores and NIDTC_T between the AOT and CON groups. There was a greater significant positive correlation between the NIDTC_T and UPDRS-III score ($r = 0.575$, $p = 0.001$) in the AOT group than in the CON group ($r = 0.433$, $p = 0.011$). A similar trend was also observed in the correlation between NIDTC and BBS (AOT: $r = -0.624$, $p < 0.001$; CON: $r = -0.480$, $p = 0.005$), MMSE (AOT: $r = -0.477$, $p = 0.005$; CON: $r = -0.326$, $p = 0.045$), and Mini-BESTest (AOT: $r = -0.449$, $p = 0.008$; CON: $r = -0.361$, $p = 0.030$). Moreover, NIDTC_T showed a moderate positive correlation with PDQ-39 in the AOT group ($r = 0.332$, $p = 0.042$) and MOCA ($r = -0.393$, $p = 0.019$) in the AOT group, while no significant correlation was observed in the CON group.

NIDTC_T (95% CI −2.319/−0.212, $p = 0.020$), BBS (95% CI 0.007/3.278, $p = 0.049$), and PDQ-39 (95% CI −17.629/−0.085, $p = 0.048$) had significant intergroup differences, as shown in Fig. 4G–J. However, only NIDTC_T showed a significant opposite trend of changes between the two groups and had the largest effect size (Cohen's $d = 0.968$).

Discussion

This study presented a novel complex dual-task gait indicator for assessing gait automaticity improvement in early-stage PD patients. The construct validity and responsiveness to rehabilitation interventions were evaluated. We found that the turning-based NIDTC demonstrated good construct validity and effectively revealed different rehabilitation effects between the AOT and CON groups with a large effect size. This suggests that

Table 2 Results of the rehabilitation effect assessment using NIDTC and other indicators

Indicators	AOT (n = 14)		CON (n = 14)		Group×Time		
	Pre	Post	Pre	Post	F	p	η^2
NIDTC							
Straight walking	3.58 ± 1.30	3.15 ± 0.92	3.96 ± 1.94	3.58 ± 1.17	0.987	0.331	0.043
Turning	5.97 ± 1.41	5.15 ± 0.97	5.37 ± 1.34	5.81 ± 1.16	4.669	0.042*	0.175
Clinical scales							
UPDRS-III	14.29 ± 9.60	11.29 ± 7.91	16.21 ± 5.89	16.36 ± 8.20	2.498	0.128	0.102
MoCA	24.50 ± 2.95	25.86 ± 2.77	25.21 ± 2.01	25.43 ± 2.50	1.325	0.262	0.057
MMSE	27.07 ± 2.06	28.71 ± 1.94	28.43 ± 1.34	28.14 ± 1.56	1.766	0.198	0.074
BBS	48.64 ± 2.53	51.14 ± 1.35	48.57 ± 2.14	49.43 ± 2.59	6.050	0.022*	0.216
Mini-BESTest	23.07 ± 1.86	24.57 ± 2.03	23.57 ± 2.41	23.79 ± 2.46	2.541	0.127	0.103
PDQ-39	23.00 ± 10.62	5.64 ± 3.05	23.64 ± 11.14	15.14 ± 12.42	7.772	0.011*	0.261
Spatiotemporal parameters (straight walking)							
Stride length	0.64 ± 0.08	0.65 ± 0.07	0.65 ± 0.06	0.66 ± 0.07	0.012	0.913	0.001
Stride time (s)	1.13 ± 0.12	1.10 ± 0.09	1.10 ± 0.08	1.08 ± 0.07	0.808	0.379	0.035
Stance phase time (s)	0.79 ± 0.09	0.76 ± 0.07	0.77 ± 0.06	0.75 ± 0.06	0.241	0.629	0.011
Swing phase time (s)	0.34 ± 0.03	0.35 ± 0.02	0.33 ± 0.02	0.34 ± 0.02	2.203	0.152	0.091
Walking speed (/s)	0.57 ± 0.09	0.59 ± 0.07	0.59 ± 0.07	0.61 ± 0.07	0.342	0.565	0.015
Spatiotemporal parameters (turning)							
Stride length	0.44 ± 0.06	0.44 ± 0.05	0.46 ± 0.05	0.45 ± 0.06	0.037	0.849	0.002
Stride time (s)	1.17 ± 0.13	1.14 ± 0.11	1.16 ± 0.10	1.14 ± 0.09	0.153	0.699	0.007
Stance phase time (s)	0.83 ± 0.11	0.80 ± 0.09	0.82 ± 0.09	0.80 ± 0.07	0.001	0.981	< 0.001
Swing phase time (s)	0.34 ± 0.03	0.34 ± 0.03	0.33 ± 0.02	0.34 ± 0.03	1.432	0.244	0.061
Walking speed (/s)	0.38 ± 0.07	0.39 ± 0.04	0.40 ± 0.07	0.40 ± 0.06	0.006	0.939	< 0.001
DTC (straight walking)							
Stride length (%)	−9.69 ± 11.28	−9.22 ± 7.20	−7.91 ± 6.65	−6.91 ± 5.22	0.015	0.902	0.001
Stride time (%)	6.55 ± 8.25	4.64 ± 3.70	2.79 ± 4.30	2.12 ± 3.46	0.549	0.467	0.024
Stance phase time (%)	8.31 ± 10.20	5.91 ± 4.53	3.84 ± 4.74	2.91 ± 3.78	0.484	0.494	0.022
Swing phase time (%)	2.45 ± 4.96	1.83 ± 2.77	0.41 ± 4.30	0.37 ± 3.11	0.423	0.522	0.019
Walking speed (%)	−14.00 ± 14.50	−12.43 ± 8.75	−10.22 ± 8.90	−8.72 ± 6.12	0.008	0.928	0.001
DTC (turning)							
Stride length (%)	−39.09 ± 6.50	−35.15 ± 6.86	−39.26 ± 4.87	−39.26 ± 6.30	2.021	0.169	0.084
Stride time (%)	11.86 ± 11.09	7.33 ± 10.98	9.07 ± 4.82	9.45 ± 5.14	0.633	0.435	0.028
Stance phase time (%)	16.42 ± 12.44	11.20 ± 14.57	12.76 ± 5.32	12.64 ± 5.71	0.255	0.619	0.011
Swing phase time (%)	1.30 ± 9.64	0.49 ± 4.41	0.69 ± 4.29	2.35 ± 4.71	2.570	0.123	0.105
Walking speed (%)	−44.50 ± 6.81	−38.19 ± 10.17	−43.78 ± 5.39	−43.96 ± 6.71	2.340	0.140	0.096
Cognitive task							
Accuracy (%)	94.49 ± 11.58	96.09 ± 5.21	92.22 ± 9.70	96.26 ± 7.35	0.770	0.390	0.034
Number	19.29 ± 7.18	20.36 ± 4.53	21.50 ± 7.00	21.64 ± 6.46	0.146	0.706	0.007

All values are represented as the mean ± standard deviation. The * symbol represents a significant group×time interaction ($p < 0.05$)

the NIDTC_T provides a comprehensive representation of gait automaticity beyond traditional clinical scales for early PD.

To the best of the authors' knowledge, this is the first attempt to employ a dual-task gait normalcy index in the rehabilitation assessment of early PD patients. Gait normalcy index indicators have been used for the assessment of gait abnormalities in patients with cerebral palsy [33], Guillain-Barré syndrome [37], lower limb amputees [38], and anterior cruciate ligament deficiency combined with meniscus injury [39]. Wang et al. developed an IMU-based method of gait pattern analysis to classify three different neurological diseases (healthy control, peripheral neuropathy, poststroke and Parkinson's disease) [40]. They further proposed an inertial-based gait normalcy index to evaluate the overall gait performance of patients

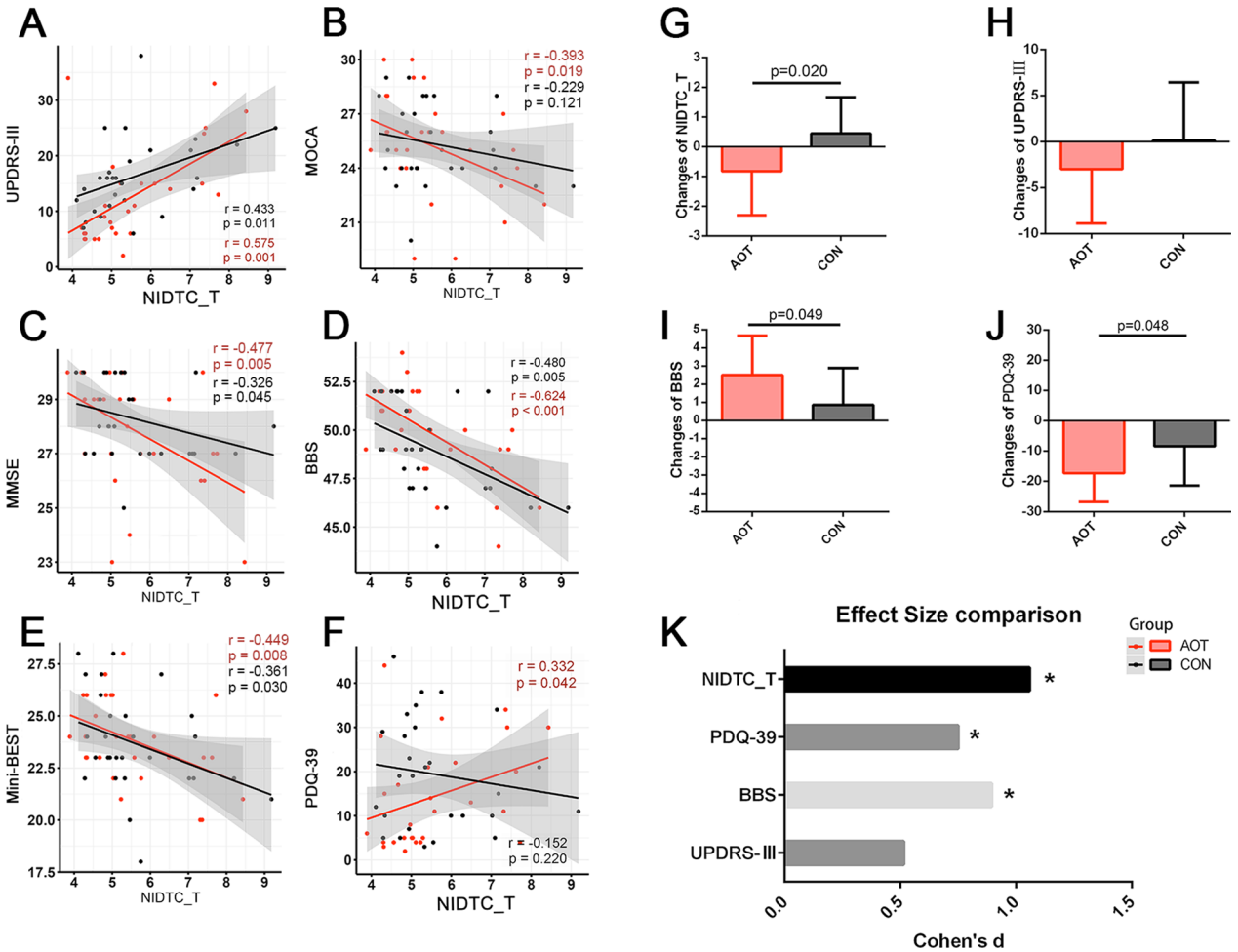

Fig. 4 Comparison of clinical scale scores and NIDTC_T between the AOT and CON groups. **A**–**F** Scatter plots of Pearson correlation coefficients between the NIDTC_T and clinical scale scores (UPDRS-III, MOCA, MMSE, BBS, Mini-BESTest, and PDQ-39) in the two groups. **G**–**J** Comparison of changes in the NIDTC_T and clinical scale scores between the two groups. **K** Effect sizes of NIDTC_T and clinical scales. * = $p < 0.05$

with n-hexane neuropathy during the rehabilitation process at different time points [34]. The selection of gait variables varied among these studies, and gait variables of healthy controls were usually used as a baseline to estimate gait abnormalities. However, a large sample size of healthy controls is needed to obtain a reliable baseline [41, 42]. Our study was the attempt to propose the evaluation of dual task gait performance with single-task gait performance as baseline. The NIDTC efficiently reflects changes of gait performance caused by dual task paradigm which is potential for gait automaticity assessment in early-stage PD.

Motor task complexity improved NIDTC performance in assessing motor symptoms in early-stage PD patients. As shown in Fig. 3, the NIDTC_T was significantly correlated with the UPDRS-III score, BBS score, and Mini-BESTest score, while the NIDTC_SW was significantly correlated with only the UPDRS-III score. The NIDTC_MT incorporates 10 parameters for both straight walking and turning, but its correlations with clinical scales were worse than those with the NIDTC_T. It suggests that the turning task contributes significantly to the validity of NIDTC while the inclusion of additional parameters may not improve the NIDTC performance. The complex motor task increased the continuous demand for attentional executive resources. PD patients have a significant loss of attention allocation capacity due to the decreased connectivity of the dorsal attention network [43] and experience more gait deficits at turns [13, 44]. Therefore, the NIDTC_T could provide a more comprehensive representation of the motor abilities of early-stage PD patients. Moreover, the NIDTC_T also showed significant correlations with the MOCA and MMSE scores. This indicates that the turning-based NIDTC reflects gait automaticity, which is related to not only motor but also cognitive functions in PD patients.

Correlations between NIDTC_T and PDQ-39 were higher in the AOT group compared to the CON group. As shown in Fig. 4, the NIDTC_T and PDQ-39 exhibited a significant positive correlation ($r = 0.332$, $p = 0.042$) in the AOT group, indicating that changes in NIDTC_T reflect not only improvements in gait but also enhancements in overall quality of life. The absence of significant correlation in the control group may be attributed to less improvement in PDQ-39. It is important to note that the PDQ-39 evaluates various dimensions of health-related quality of life in Parkinson's disease patients, extending beyond motor abilities [45]. As a subjective measure, it can vary depending on the patient's condition at the time, leading to high variability between individuals. This might explain the lack of significant correlation between NIDTC_T and PDQ-39 before rehabilitation. However, as gait automaticity improved, so did patients' quality of life, which likely explains the significant correlation observed post-rehabilitation.

The turning-based NIDTC distinguished the different rehabilitation effects between the AOT and CON groups. Strong clinical evidence has shown that AOT intervention is a reliable and effective rehabilitation approach for improving gait automaticity in PD patients by inducing reorganization of the cerebello-basal ganglia-thalamocortical network [46–48]. Level 1 evidence supported the effects of AOT interventions on improving BBS scores, PDQ-39 scores, and UPDRS-III scores [49]. However, significant differences between the AOT and active control groups were not observed when the TUG test was used for gait assessment [26, 50]. This may be because the TUG test, when performed conventionally, also evaluates turning activity, but this activity is not assessed separately. Our results for clinical scales, gait spatiotemporal parameters and single DTCs were consistent with those of previous studies (Table 2). The AOT and CON groups showed opposite changes in the proposed NIDTC_T, as shown in Fig. 4D. This suggested that the turning-based NIDTC is sensitive to improvements in gait automaticity induced by the AOT intervention.

The turning-based NIDTC demonstrated the largest effect size in the comparison of intergroup differences. Although the BBS and PDQ-39 also had medium to large effect sizes, this might be because the AOT intervention significantly improved participants' balance function and self-reported quality of life (Fig. 4I and J). In particular, the PDQ-39 is a subjective questionnaire for patients. Studies have shown that the PDQ-39 may underestimate dyskinesia and is not sufficient for patients with milder symptoms [51, 52]. These indicators did not detect the rehabilitation differences between the AOT and CON groups. Figure 4H indicates that the CON group did not have an improvement in the UPDRS-III score; however, the effect size of the UPDRS-III score was relatively low (Cohen's $d = 0.536$). Overall, our proposed turning-based NIDTC is more effective than clinical scales in evaluating gait automaticity in early-stage PD patients.

One limitation of this study is the relatively small sample size, which may affect the generalizability of the results. A multicenter rehabilitation study will be performed in the future to validate the proposed NIDTC in a larger group of early-stage PD patients. The inter-rater and test-retest reliability were not considered in the experiment, since the study's aim is to propose a novel index to evaluate the rehabilitation outcomes for PD patients, we will validate the proposed NIDTC in a larger study in future. Moreover, gait characteristics, such as joint kinematics, gait variability, and stability, can be considered in the calculation of the NIDTC, providing a more comprehensive evaluation of gait ability.

Conclusions

This study proposed a novel rehabilitation indicator method for evaluating gait automaticity in early-stage PD patients and evaluated its construct validity and responsiveness in a 12-week rehabilitation intervention. The results demonstrated that the turning-based NIDTC not only had significant correlations with multiple clinical scales but also exhibited greater sensitivity to identify gait automaticity improvement in the AOT rehabilitation compared to the active control group. This indicator has great potential for early-stage PD diagnosis and rehabilitation assessment in the clinic.

Abbreviations

AOT	Action observation training
BBS	Berg balance scale
CON	Control group
DTC	Dual task cost
FoG	Freezing of gait
H &Y	Hoehn & Yahr score
LEDD	Levodopa equivalent daily dosage
Mini-BESTest	Mini-balance evaluation system test
MMSE	Mini-mental state examination
MoCA	Montreal cognitive assessment
NIDTC	Normalcy index of dual task cost
NIDTC_MT	Normalcy index of dual task cost during the overall motor task
NIDTC_SW	Normalcy index of dual task cost during straight walking
NIDTC_T	Normalcy index of dual task cost during turning
PD	Parkinson's disease
PDQ-39	Parkinson's disease questionnaire 39-item version
SRT	Stride time
STL	Stride length
STT	Stance phase time
SWT	Swing phase time
UPDRS-III	Unified parkinson's disease rating scale part III
VAF	Variance Accounted For
WAS	Walking speed

Supplementary Information

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Supplementary Material 1.

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Author contributions
LM conceptualized the study, assisted in drafting the manuscript, and oversaw the data analyses. YS analyzed, interpreted the data, prepared figures/tables, and wrote the manuscript. DW assisted in ethics preparation, participant screening, and data collection. HZ assisted in data collection. XZ and DM conceptualized the study, assisted in data management, and provided research resources. All authors read and approved the final manuscript. All authors reviewed the manuscript.

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Availibility of data and materials
The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
This study was approved by the Ethics Committee of Tianjin Medical University General Hospital (IRB2022-KY-300) and Tianjin University (TJUE-2023-003). The clinical rehabilitation part of this study has been registered at the Chinese Clinical Trial Registry (ChiCTR2300067657). All participants were provided written informed consent before their participation.

Consent for publication
Not applicable.

Competing interests
The author(s) declare no potential Conflict of interest with respect to the research, authorship, and/or publication of this article.

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