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REVIEW ARTICLE

# Rehabilitative interventions for impaired handwriting in people with Parkinson's disease: a scoping review

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## Abstract

**Background** People with Parkinson's disease (PD) often complain about handwriting difficulties. Currently, there is no consensus on the rehabilitative treatment and outcome measures for handwriting rehabilitation in PD.

**Objectives** This study aims to investigate evidence on handwriting rehabilitation in people with PD, examining characteristics of interventions and outcomes.

**Methods** A scoping review was conducted according to Arksey and O'Malley's framework and PRISMA-ScR List. We searched electronic databases of PubMed, Physiotherapy Evidence Database, Cochrane Central Register of Controlled Trials, and Embase since inception to January 2023. We included interventional studies assessing the effects of structured rehabilitation programs for impaired handwriting in people with PD. Two reviewers independently selected studies, extracted data, and assessed the risk of bias using the Cochrane Collaboration's tool for assessing Risk of Bias version 2 or the Risk Of Bias In Non-randomized Studies. We performed a narrative analysis on training characteristics and assessed outcomes.

**Results** We included eight studies. The risk of bias was generally high. Either *handwriting-specific* or *handwriting-non-specific* trainings were proposed, and most studies provided a home-based training. *Handwriting-specific* training improved writing amplitude while *handwriting-non-specific* trainings, such as resistance and stretching/relaxation programs, resulted in increased writing speed.

**Conclusions** The current knowledge is based on few and heterogeneous studies with high risk of bias. *Handwriting-specific* training might show potential benefits on handwriting in people with PD. Further high-quality randomized controlled trials are needed to reveal the effect of handwriting training in people with PD on standardized outcome measures. Handwriting-specific training could be combined to resistance training and stretching, which seemed to influence writing performance.

**Keywords** Handwriting · Parkinson's disease · Rehabilitation · Micrographia · Review

## Introduction

The diagnosis of Parkinson's disease (PD) is based on the characteristic motor signs: bradykinesia, rigidity, and tremor [1]. When rigidity and bradykinesia affect the dominant hand, one of the initial complaints is the alteration of handwriting ability [2, 3]. "Micrographia" is the most common parkinsonian handwriting abnormality, which is defined as "an impairment of a fine motor skill manifesting mainly as a progressive or stable reduction in amplitude during a writing task" [2]. Studies on prevalence of writing disturbances in people with PD reported that up to 75% of patients presented with micrographia [2]. Micrographia has been associated with poor coordination between simultaneous wrist and finger movements and with stiffness during wrist extension. It is usually exacerbated by increased cognitive demand during

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the handwriting task, similarly to other motor abilities such as gait and postural control that usually worsen performing a dual task [3, 4]. Handwriting abnormalities other than micrographia in people with PD include several dynamic and kinematic features, such as reduced velocity and altered fluency of the writing strokes [3, 5]. "Dysgraphia" is a term that includes all the possible handwriting alterations and it can be easily detected using conventional paper-and-pencil tools or computerized analysis of handwriting [2].

In the last years, growing evidence suggested that non-pharmacological interventions including different rehabilitative approaches improve functional activities in people with PD [6]. However, research in the rehabilitation field in PD mainly focused on gait, transfers, and balance [6–8] and, despite being very common, handwriting deficits did not receive such attention. Studies assessing handwriting in people with PD used kinematic analysis or explored modulating factors such as cues, feedback, or dual task, but only few authors investigated the effects of a training on handwriting or used specific outcome measures of handwriting in rehabilitation studies.

For these reasons, we conducted a scoping review to systematically map the research studies on the rehabilitative treatment of handwriting abnormalities in people with PD, and to identify any existing knowledge gap that can be addressed with future research.

## Methods

### Study design and registration

The protocol was registered with Protocols.io (dx.doi.org/10.17504/protocols.io.5jyl891z8v2w/v1) according to the Preferred Reporting Items for Systematic Reviews and Meta-analysis Protocols (PRISMA-P). This review adheres to the PRISMA extension for Scoping Review checklist (PRISMA-ScR) [9]. Moreover, we followed the five-stage methodological framework for scoping studies proposed by Arksey and O'Malley [10] and the relative additional recommendations by Levac and colleagues [11].

### Stage 1 - Identifying the research question

We articulated the research question following the PICOS (Population, Intervention, Comparison, Outcomes, Study design) paradigm to establish an effective search strategy. The research question was: "*What are the effects of a rehabilitative program on handwriting in people with PD*?". Rehabilitation is defined by the World Health Organization as "a set of interventions designed to optimize functioning and reduce disability in individuals with health conditions in interaction with their environment" [12].

### Stage 2 - Identifying relevant studies

We followed the PICOS paradigm [13] to formulate the search strategy: P (population) — people with PD; I (intervention) — any rehabilitation intervention; C (comparison) — any/no comparator; O (outcomes) — measures of handwriting; S (study design) — any longitudinal study design.

We searched MEDLINE (PubMed), Embase, the Cochrane Central Register of Controlled Trials (CENTRAL), the Physiotherapy Evidence Database (PEDro), and the Cumulative Index to Nursing and Allied Health Literature (CINAHL) up to January 3, 2023 (update of the original search dated April 2022). The terms "Parkinson's Disease," "rehabilitation," "upper extremity," "dexterity," and "handwriting" were used to generate a list of search terms, then combined into search strategies adapted to each database (complete search strategies for all databases are reported in the Online Resource 1) without language restriction. The retrieved references were compared for duplicates using the "find duplicate" tool in EndNote 20 and then manually crosschecked by one author. Lastly, we checked reference lists of selected studies to find any potentially relevant trial unidentified with the electronic search.

### Stage 3 - Study selection

We included interventional studies in which people with idiopathic PD received a structured rehabilitation program and with at least one outcome measure assessing handwriting performance (e.g., measures of writing size/speed) using standardized or customized tests. We excluded case reports and studies in which the intervention consisted of only one session of training.

Two reviewers independently screened titles and abstracts and excluded irrelevant reports. Full text of records that could not be excluded by title/abstract reading alone were then retrieved. The same two reviewers independently screened them to determine eligibility and noted reasons for exclusion. Discrepancies were resolved through discussion with a third reviewer.

### Stage 4 - Charting the data

All reviewers jointly developed a data-charting form to determine the variables to extract, and two reviewers extracted the data from the included studies. The following variables were extracted: first author, publication date, country, study design, description of the intervention and comparator (materials, procedures, duration of a single training session, frequency of sessions, whole duration of training, modes of training delivery), sample size, sample mean age, percentage of male/female, years of education, handedness, Levodopa-equivalent daily dose (LEDD), disease duration, clinical evaluation scores, outcome measures, and main study results.

### Stage 5 - Collating, summarizing, and reporting the results

We described and categorized interventions as "*handwriting-specific*" or "*handwriting-non-specific*" according to the main focus of the training: a "*handwriting-specific*" training had to include handwriting exercises; a "*handwriting-non-specific*" training had to include exercises focusing on different motor characteristics such as hand strength, without handwriting tasks. We also divided interventions according to their delivery modes: "home-based" or "in-clinic," and we collected the frequency of visits provided by therapists during home-based training.

### Assessment of risk of bias

Two reviewers independently assessed the risk of bias of included studies by using the of the Cochrane Collaboration's tool for assessing Risk of Bias version 2 (RoB-2) [14] and the Risk Of Bias In Non-randomized Studies (ROBINS-I) [15] according to study design of included trials (randomized or non-randomized).

The RoB-2 considers five domains: *i* — bias arising from the randomization process; *ii* — bias due to deviations from intended interventions; *iii* — bias due to missing outcome data; *iv* — bias in measurement of the outcome; *v* — bias in selection of the reported result. Our assessment focused on quantifying the effect of assignment to the interventions at baseline and on handwriting-related outcomes.

The ROBINS-I considers seven domains: *i* — bias due to confounding; *ii* — bias in selection of participants into the study; *iii* — bias in classification of interventions; *iv* — bias due to deviations from intended interventions; *v* — bias due to missing data; *vi* — bias in measurement of the outcome; *vii* — bias in selection of the reported result.

RoB-2 and ROBINS-I provide an overall risk-of-bias judgment for every study, for every outcome (RoB-2: low risk of bias, some concerns or high risk of bias; ROBINS-I: low, moderate, serious, critical risk of bias or no information), based on every domain-level judgment according to responses to signaling questions. Disagreement was resolved through discussion and a third reviewer was contacted when disagreement persisted.

## Results

### Flow of studies through the review

Database searching resulted in 1036 records. After duplicate removal, 803 papers were screened based on title and abstract reading, and 49 papers were considered as potentially relevant. Forty-one records were excluded after the full-text reading (Fig. 1 and Online Resource 2 report reasons for exclusion). Eight studies were included in the review [16–23]. Hand searching did not identify any additional paper. The flow of studies through the review is shown in Fig. 1.

### Characteristics of included studies

We included four randomized controlled trials [17, 20–22] and four non-randomized trials [16, 18, 19, 23]. The included studies took place in five countries: four in Belgium (by the same research group) [18–21], one in the USA [16], one in the UK [17], one in Thailand [22], and one in Argentina [23]. The included studies were published from August 2015 to April 2022.

#### Risk of bias

Overall risk of bias for each study is reported in Table 1 (assessment of bias in each domain is reported in Online Resource 1).

Risk-of-bias assessment in randomized controlled studies showed "high risk" of bias or "some concerns" due to the allocation procedures, statistical analysis (handling of missing outcome data), and unavailability of planned outcome measures (selection of the reported results). Only two studies [17, 22] had blinded assessors. Non-randomized studies were all at "serious risk of bias" due to the impossibility to characterize confounding time trends and patterns, handling and reporting of missing outcome data, and unavailability of planned outcome measures (selection of the reported results).

#### Participants

The total number of patients in the included studies was 317 (189 in the randomized controlled trials; 128 in the non-randomized trials). The randomized controlled studies included 92 patients in the experimental groups and 97 in the control groups. Ninety-eight patients received handwriting training in the non-randomized studies; 30 received no treatment. The mean ± standard deviation of the age of patients was 65.4 ± 2 years (ranging from 63 to 70 years) and 42% of patients were females. Mean (Movement Disorder Society-Sponsored Revision of the) Unified Parkinson's Disease Rating Scale part three [(MDS-) UPDRS-III] score ranged from 16 to 38. Some relevant information about the included sample such as handedness, years of education, Hoehn and Yahr stage (H&Y), UPDRS-III, and LEDD were missing in some studies. Table 1 reports the participants' characteristics in the included studies.

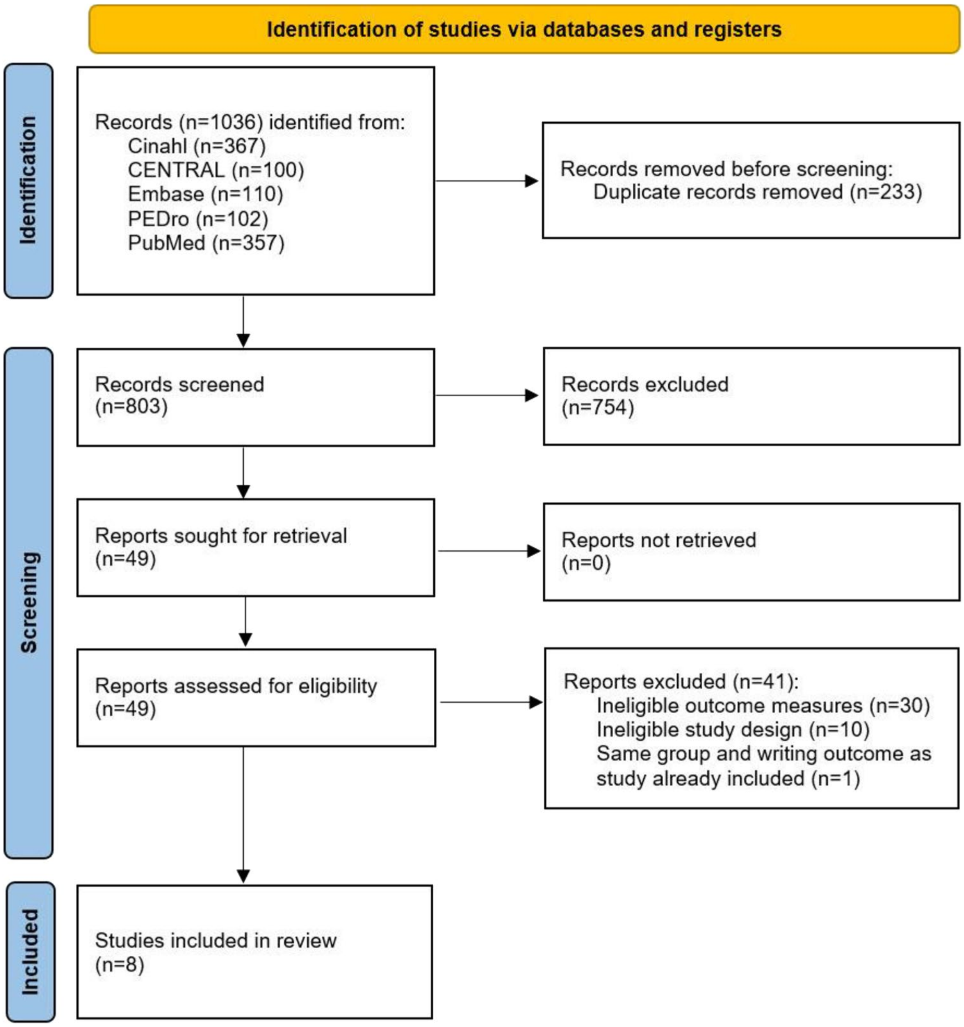

**Fig. 1** Flow diagram of the study selection

## Intervention

The included studies assessed the efficacy of different types of training on handwriting in people with PD. Seven studies [17–23] provided a *handwriting-specific* training and one study [16] a *handwriting-non-specific* training. The latter consisted of home-based hand resistance exercises using a dumbbell (3.63 kg), hand exercise putty, and hand grip exercises [16].

Among the studies providing *handwriting-specific* trainings, six studies [17–22] provided a home-based training. Exercises were performed independently by the patients and consisted of a printed handbook (cued and free writing exercises and copy tasks — patients also performed dexterity exercises) [17], paper–pencil and on-tablet writing exercises focusing on writing amplitude (pre-letters, letters and words with cues, and dual task) [18–21], and a handwriting practice book (30 Thai letters to write per page) [22]. Only one study [23] provided an in-clinic training: the training focused on performance of the handwriting task in a less automatic manner by using different external stimuli and was held by a graphologist.

Where present, the comparison group received a stretch-and-relaxation program provided on a DVD consisting of breathing exercises, progressive relaxation, and yoga [20, 21] or aerobic/resistance training provided through an exercise booklet (30 min of aerobic training followed by 30 min of resistance training at a local leisure center) [17]. Table 2 reports details on intervention intensity, duration, and frequency and therapist's visits frequency during home-based training for both experimental and comparison training. Online Resource 3 provides detailed description of interventions in each study.

## Outcomes

Retrieved studies used different outcome measures to assess the impact of training on handwriting abnormalities in people with PD.

**Table 1** Characteristics of the included studies

| Author and publication year (month) | Study design | Participants | Overall risk of bias |
|---|---|---|---|
| *Handwriting-specific* training | | | |
| Collett 2017 (Dec) [17] | RCT | Handwriting group:<br>*N* = 51<br>Age (years) = 67 ± 7<br>M/F = 30/21<br>Education (years) = N.R<br>Handedness = N.R<br>PD duration (years) = 5.3 ± 4.1<br>MDS-UPDRS-III (score) = 19.9 ± 9.9<br>H&Y (stage) = N.R<br>LEDD (mg) = N.R[#]<br>Aerobic/resistance group:<br>*N* = 54<br>Age (years) = 66 ± 9<br>M/F = 31/23<br>Education (years) = N.R<br>Handedness = N.R<br>PD duration (years) = 4.8 ± 4.1<br>MDS-UPDRS-III (score) = 16.7 ± 10.1<br>H&Y (stage) = N.R<br>LEDD (mg) = N.R[#] | Some concerns[§] |
| De Vleeschhauwer 2022 (Apr) [18] | Single-group pre–post trial | *N* = 25<br>Age (years) = 64.2 ± 8.5<br>M/F = 15/10<br>Education (years) = N.R<br>Handedness = 100% right<br>PD duration (years) = 6.8 ± 4.1<br>MDS-UPDRS-III (score) = 29.7 ± 13.9<br>H&Y (stage I/II/III) = 2/21/2<br>LEDD (mg) = 644.2 ± 291.5 | Serious risk* |
| Heremans 2016 (Feb) [19] | Non-randomized interventional trial | Non-freezers PD:<br>*N* = 19<br>Age (years) = 63.4 ± 8.9<br>M/F = 11/8<br>Education (years) = N.R<br>Handedness (EHI) = 100 (87.5; 100)<br>PD duration (years) = 7.3 ± 5.0<br>MDS-UPDRS-III (score) = 27.4 ± 12.1<br>H&Y (stage) = 2 (2; 2)<br>LEDD (mg) = 571 ± 313<br>Freezers PD:<br>*N* = 16<br>Age = 64.7 ± 8.6<br>M/F (years) = 13/3<br>Education (years) = N.R<br>Handedness (EHI) = 95 (40; 100)<br>PD duration (years) = 8.8 ± 4.7<br>MDS-UPDRS-III (score) = 38.2 ± 17.5<br>H&Y (stage) = 2 (2; 2)<br>LEDD (mg) = 560 ± 327 | Serious risk* |
| Nackaerts 2016 (Aug)/2017 (Dec) [20, 21] | RCT | Handwriting group:<br>*N* = 18<br>Age (years) = 62.6 ± 8.4<br>M/F = 10/8<br>Education (years) = N.R<br>Handedness = 100% right<br>PD duration (years) = 7 (3;8)<br>MDS-UPDRS-III (score) = 27.3 ± 12.5<br>H&Y (stage) = 2 (2; 2)<br>LEDD (mg) = 607.5 (337.5; 719)<br>Control group:<br>*N* = 20<br>Age (years) = 63.6 ± 10.9<br>M/F = 13/7<br>Education (years) = N.R<br>Handedness = 100% right<br>PD duration (years) = 4.5 (3;6)<br>UPDRS-III (score) = 23.4 ± 11.1<br>H&Y (stage) = 2 (2; 2)<br>LEDD (mg) = 310 (150; 615) | High risk[§] |

**Table 1** (continued)

| Author and publication year (month) | Study design | Participants | Overall risk of bias |
|---|---|---|---|
| Vorasoot 2020 (Feb)<br>[22] | RCT | Handwriting group:<br>*N* = 23<br>Age (years) = 66.7 ± 10.8<br>M/F = 12/11<br>Education (years) = 10.09 ± 6.45<br>Handedness = 95.65% right<br>PD duration (years) = 4.4 ± 4.2<br>UPDRS-III (score) = 17.6 ± 4.5<br>H&Y (stage) = 2 (2; 2.5)<br>LEDD (mg) = 370.79 ± 252.31<br>Control group:<br>*N* = 23<br>Age (years) = 69.5 ± 10.3<br>M/F = 13/10<br>Education (years) = 10.04 ± 4.82<br>Handedness = 100% right<br>PD duration (years) = 3.4 ± 2.4<br>UPDRS-III (score) = 16.3 ± 5.3<br>H&Y (stage) = 2 (2; 2.5)<br>LEDD (mg) = 512.96 ± 339.33 | Some concerns[§] |
| Ziliotto 2015 (Aug)<br>[23] | Non-randomized controlled trial | Handwriting group:<br>*N* = 30<br>Age (years) = 64.6 ± 8.1<br>M/F = 16/14<br>Education (% < 8 years) = 36.7<br>Handedness = 100% right<br>PD duration (years) = N.R<br>UPDRS-III (score) = N.R<br>H&Y (stage) = N.R<br>LEDD (mg) = N.R<br>Control group:<br>*N* = 30<br>Age (years) = 66.5 ± 10.2<br>M/F = 11/19<br>Education (% < 8 years) = 50<br>Handedness = 100% right<br>PD duration (years) = N.R<br>UPDRS-III (score) = N.R<br>H&Y (stage) = N.R<br>LEDD (mg) = N.R | Serious risk* |
| *Handwriting-non-specific* training | | | |
| Bryant 2018 (Jan–Mar) [16] | Single-group pre–post trial | *N* = 8<br>Age (years) = 65.9 ± 7.2<br>M/F = 8/0<br>Education (years) = N.R<br>Handedness = 100% right<br>PD duration (years) = 5.4 ± 3.1<br>UPDRS-III (score) = 23.3 ± 9.9<br>H&Y (stage) = N.R<br>LEDD (mg) = N.R.[#] | Serious risk* |

Values are reported as mean ± standard deviation or median (1st quartile; 3rd quartile). All the reported clinical evaluations were performed during on medication state.

*EHI* Edinburgh Handedness Inventory, *F* females, *H&Y* Hoehn and Yahr stage, *LEDD* Levodopa-equivalent daily dose, *M* males, *N* number, *N.R.* not reported, *RCT* randomized clinical trial, *PD* Parkinson's disease, *(MDS-)UPDRS-III* (Movement Disorder Society–Sponsored Revision of) Unified Parkinson Disease Rating Scale part III.

Risk of bias is assessed using the Cochrane Collaboration's Risk of Bias assessment tool version 2 (RoB-2) ([§]) for randomized controlled trials or Risk Of Bias In Non-randomized Studies of Interventions (ROBINS-I) tool (*) for non-randomized studies.

[#] Only medication type was reported.

Four studies used a touch-sensitive tablet and a repetitive pre-writing task consisting of a three-loop sequence to assess writing amplitude (percentage of the target amplitude), coefficient of variation of amplitude [18, 19, 21], stroke duration, writing velocity, and normalized jerk [20]. All the other studies used paper–pencil tasks. Two studies [16, 23] measured the area of a sentence or of a word written on a blank sheet of paper. Two studies [17, 23] measured the area of a word repeated two times in a sentence to assess micrographia. Two studies measured the time to write a sentence [17] or to complete a page with 25 different letters of the Thai alphabet [22]. Two studies [17, 22] assessed the subjective rating of writing with the MDS-UPDRS part II. One study [21] used the Systematic Screening of Handwriting Difficulties (SOS) test. One study [22] assessed writing accuracy and another the direction of handwriting [23]. In one study [17], patients were asked to write as fast as possible during assessment. Three studies [19–21] used different conditions during the assessment (single task/dual task, cues/no cues, trained/non-trained task).

### Effect of handwriting training

The only study [16] using a *handwriting-non-specific* training (resistance training) showed no effect on writing amplitude. The studies assessing the effects of *handwriting-specific* trainings showed preliminary interesting and promising findings. Home-based handwriting training was compared to aerobic/resistance training in one study [17], and resulted in increased amplitude and improved self-reported writing abilities. On the other hand, aerobic/resistance training resulted in a little improvement in writing speed. Studies comparing home-based handwriting training with a stretching and relaxation program showed an increased writing amplitude, a reduced amplitude variability, and an improved paper–pencil performance after writing training, while the control group showed increased writing speed [20, 21]. Two studies compared handwriting training (home based [22] or held by a graphologist [23]) to no intervention and showed increased writing speed and self-perceived writing ability [22] and a small effect on writing amplitude [23].

## Discussion

With this review, we investigated the state of the art on handwriting rehabilitation in people with PD. We identified eight studies evaluating the effects of a structured rehabilitation program compared to stretching and relaxation, resistance/aerobic training, or no intervention.

Assessment using RoB-2 and ROBINS-I showed generally high risk of bias; thus, results of these studies should be taken with caution.

Studies were very heterogeneous in terms of training protocols and outcome measures. Six studies [17–22] explored the effect of a home-based handwriting training with different types of tasks. Four of these [18–21] (studies from the same research group that followed the same protocol) included exercises on a tablet in addition to pencil–paper tasks. Only in one study [23] the training protocol was held in a clinic by a graphologist. One study [16] evaluated the effect of a resistance training program on handwriting showing no effects. Moreover, duration and frequency of the training sessions were very different as well: frequency ranged from one to seven times per week, training session duration from 30 to 90 min (one study [22] asked to write five pages a day without time indication), and total training duration from 4 weeks to 6 months.

Handwriting-specific rehabilitation significantly improved handwriting amplitude relative to other interventions. The letters amplitude is important to allow an adequate intelligibility of words and sentences; thus, we could hypothesize that a specific handwriting training could help to improve a core feature of handwriting. Interestingly, two studies assessing the neural correlates of handwriting improvements showed a more efficient coupling in the visuomotor and cerebellar networks and a functional reorganization of the dorsal attentional network after handwriting training [18, 24]. On the other hand, a stretching and relaxation program relative to handwriting training seemed to have a greater effect on writing speed. One hypothesis to explain this result is that amplitude improvement came at the expense of writing speed; an alternative hypothesis is that stretching can reduce rigidity and improve mobility resulting in a more fluid and faster movement [20].

Only few studies [17–21] provided follow-up data. Three studies [17, 18, 21] suggested that the improvement of handwriting amplitude could be maintained for 6 weeks; another study [19] showed that the retention of the effect was possible only in patients without freezing of gait. This result is in line with previous knowledge suggesting that patients with freezing present greater difficulties of consolidation and generalization of motor learning and have a higher dependency on cueing [25]. However, to date, we know that specific cognitive-motor trainings such as action observation or motor imagery might help to maintain the effects over time also in freezers, strengthening motor learning processes [26, 27].

Other rehabilitation approaches can be used to enhance motor learning in people with PD. For instance, feedback is fundamental for motor learning and technology that augments feedback, such as virtual reality, showed effects in improving upper limb function and hand dexterity in PD patients [28–32]. Some interesting insights for future development of handwriting training in people with PD come from single-session studies [33–40] that assessed the effects of cue/feedback manipulations on handwriting performance [41]. Visual cues (e.g., parallel or grid lines) as well as auditory cues seem useful tools to improve writing amplitude [33, 34, 36, 39, 40]; nevertheless, it is fundamental to provide appropriate cues, as their effect is task dependent [34, 36, 37, 40]. Visuomotor control of handwriting is the result of feed-forward and feedback mechanisms, and manipulation of cue amplitude can result in either improved or hindered writing performance [35,

**Table 2** Methods and results of included studies

| Author and publication year | Intervention (duration parameters) [frequency of visits for home-based training] | Handwriting outcomes | Main findings |
|---|---|---|---|
| *Handwriting-specific* training | | | |
| Collett 2017 (Dec) [17] | Handwriting group: home-based writing and hand exercises (60 min, 2 days/week for 6 months)<br>[first face-to-face practice then monthly visits]<br>Aerobic/resistance group: aerobic + resistance training at local leisure center<br>(30′ + 30′, 2 days/week for 6 months) | Writing speed: time taken to copy a sentence<br>Writing amplitude: sum of areas of a word repeated twice in a sentence<br>Progressive reduction in amplitude: ratio between the area of a word repeated twice in a sentence<br>Subjective rating: item 2.7 UPDRS-II | Moderate/small effect sizes for writing amplitude outcomes in favor of the handwriting group<br>Speed: overall direction of effect favored the aerobic/resistance group<br>Reduction in the proportion of people experiencing severe and moderate problems with handwriting in the handwriting group |
| De Vleeschhauwer 2022 (Apr) [18] | Home-based writing training (30 min, 5 days/week for 6 weeks)<br>[weekly visits] | Writing amplitude (% of target) during a pre-writing task°<br>COV of writing amplitude: ratio of standard deviation to the mean amplitude (pre-writing task°) | After training, patients showed improved accuracy (amplitude and COV) |
| Heremans 2016 (Feb) [19] | Home-based writing training (30 min, 5 days/week for 6 weeks)<br>[weekly visits] | Writing amplitude (% of target) during a pre-writing task°<br>COV of writing amplitude: ratio of standard deviation to the mean amplitude (pre-writing task°)<br>Writing speed (cm/s) during pre-writing task° | In both groups, significant improvements in handwriting were found after completing the training program: increased amplitude and decreases variability |
| Nackaerts 2016 (Aug)/2017 (Dec) [20, 21] | Handwriting group: home-based writing training (30 min, 5 days/week for 6 weeks)<br>[weekly visits]<br>Control group: home-based stretch and relaxation program (DVD) (30 min, 5 days/week for 6 weeks)<br>[weekly visits] | Writing amplitude (% of target) and COV of writing amplitude: (= Heremans 2016)<br>Writing speed (cm/s) during pre-writing task°<br>Normalized jerk^ (pre-writing task°): writing fluency<br>Stroke duration (pre-writing task°): duration of individual up- and down-strokes<br>Paper–pencil test: SOS test | Handwriting group: increased amplitude, improved COV, and decreased writing fluency and speed<br>Control group: no beneficial effects on writing amplitude; increased writing velocity and fluency |
| Vorasoot 2020 (Feb) [22] | Handwriting group: handwriting practice book at home (5 pages/day for 4 weeks)<br>[no visits]<br>Control group: no treatment | Writing speed: time to complete 1-page handwriting<br>Subjective rating: perception of writing ability (excellent/good/fair/poor)<br>Writing accuracy: how well patients' handwriting matched the dotted framework | Patients in the handwriting group were able to write faster after training; control group did not show improvement. Subjective rating was higher in handwriting group. No differences in accuracy |
| Ziliotto 2015 (Aug) [23] | Handwriting group: in-clinic handwriting training with a graphologist (90 min, 1 day/week for 9 weeks)<br>Control group: no treatment | Writing amplitude: area of a word repeated twice in a sentence; area of signature; others<br>Writing speed: number of letters per minute writing a sentence | Handwriting training was associated with an improvement in most of the graphological variables assessed (amplitude) |
| *Handwriting-non-specific* training | | | |
| Bryant 2018 (Jan–Mar) [16] | Home-based hand resistance exercises (6 exercises, 3 sets of 10–12 repetitions, 3 days/week for 6 weeks)<br>[weekly phone call] | Handwriting amplitude: area of a word and a sentence | No differences in area of handwriting samples for either the words or the sentence after training |

Online Resource 3 provides a detailed description of interventions in each study.

*COV* coefficient of variation, *SOS* Systematic Screening for Handwriting Difficulties, *UPDRS-II* Unified Parkinson Disease Rating Scale part II.

^Normalized jerk: change in acceleration, normalized for different stroke durations and sizes.

°Pre-writing task: repetitive loop sequence to avoid the involvement of language and allow measurement of pure motor performance.

40, 42]. Technology could be implemented in the training to generate personalized intelligent feedbacks on performance that may positively impact handwriting more than continuous one-fit-all visual cues [38].

Moreover, it is important to underline that different types of physiotherapy might have different effects in specific subtypes of patients [8]. This could be a consequence of the heterogeneous brain alterations and consequently brain plasticity mechanisms that might be exploited to improve motor functions following distinct trainings in different PD phenotypes [26, 27, 43–48]. Future studies should assess the effects of handwriting training associated to motor learning facilitation strategies, such as virtual reality, action observation, motor imagery, and cueing, and should include follow-up assessments and analyze different populations of PD patients separately.

Curiously, most studies analyzed in this review provided home-based rehabilitation. Usually, efficacy of training is first assessed in a controlled environment supervised by specialized therapists and then tested in a home-based setting. Indeed, home-based rehabilitation might suffer from lower adherence rate of patients due to the unsupervised nature of training and the lack of feedbacks [49]. Previous evidence on patients with PD showed that a supervised program can have greater effects on participants' behavior and perceptions relative to home-based treatment due to the presence of the therapist, as well as to the positive enjoyable environment and feedback [50]. Thus, the modality of administration of the intervention could have influenced the results of the studies. However, considering that a handwriting training is easily feasible at home, it would be interesting to assess the role of telerehabilitation that has been suggested as a promising way to monitor home-based training in neurological patients [51, 52].

This study is not without limitations. This is a scoping review and therefore it only provides an overview of the literature. Moreover, the literature on this topic is sparse and the studies are heterogeneous and of low quality. For these reasons, it was not possible to compare them with a meta-analysis to provide clearer information regarding the real efficacy of physiotherapy on handwriting in PD.

In conclusion, the few studies that assessed the efficacy of handwriting training in patients with PD led to inconclusive results, as they are not enough to draw conclusions on the effects of this rehabilitative training. Further high-quality large randomized controlled trials are needed to provide a deeper insight into the potentially beneficial mechanisms of handwriting rehabilitation and to reveal the different effects of various handwriting training applications in specific PD populations. Furthermore, future research should standardize outcome measures and realize adequate follow-up assessment to examine long-term effects of handwriting rehabilitation. Handwriting training could be combined to mobility and resistance trainings that seemed to influence writing performance. Moreover, intensive programs supervised by a therapist may be preferred to obtain adequate adherence and results, and new technologies such as virtual reality could be implemented to reinforce motor learning.

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3. Manuscript preparation: A. Writing of the first draft, B. Review and critique.

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E.S.: 1A, 1B, 1C, 2A, 2B, 2C, 3A, 3B
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M.F.: 2C, 3B
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