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Split-belt treadmill walking in patients with Parkinson's disease: A systematic review

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ABSTRACT

Background: Walking on a split-belt treadmill (SBT) can help to modulate an asymmetric gait, particularly for people with neurological conditions, such as Parkinson's disease (PD), where asymmetry plays a role due to the laterality of the disease.
Research question: This systematic review critically evaluates the literature on SBT in PD. First, different SBT paradigms and methodological approaches were evaluated. Second, the review explored how people with PD adapt their gait to different SBT conditions compared to healthy controls (HC).
Methods: We conducted a systematic search of the PubMED, PsychINFO, and Web of Knowledge databases. Original research articles, published in English and investigating SBT walking in people with PD, were included.
Results: From the 925 studies originally identified, seven met the inclusion criteria and were selected for evaluation (n = 118 individuals with PD of whom 44 had freezing of gait (FOG)). The SBT paradigms varied across studies regarding the SBT settings, definitions of gait variables, and criteria for determining dominance of body side. Gait variability and bilateral coordination were found to adapt to the SBT condition similarly in people with PD and healthy controls (HC). Inconsistent results were found with respect to the adaptation of gait asymmetry, for the differences between PD and HC participants. The subgroup of people with PD and FOG showed reduced accuracy in detecting belt speed differences and slower adaptation to SBT conditions.
Conclusion: Individuals with mild to moderately severe PD adapted similarly to HCs to SBT walking for gait variability and bilateral gait coordination. However, those with FOG had impaired perception of belt speed differences and did not adapt their gait so readily. Although SBT can be useful for modulating gait asymmetry in some people with PD, it was not beneficial for all. We recommend standardization of SBT protocols for clinical practice in future studies.

1. Introduction

Parkinson's disease (PD) is one of the most prevalent neurodegenerative disorders, especially in elderly people [1], with an increased risk of mortality [2]. Pharmacological treatment does not always bring relief for all symptoms, and alternative methods, such as physical therapy, are arguably necessary [3,4]. Most rehabilitation research has focused on improving gait and balance in people with PD. Different exercise interventions (e.g., balance and gait training, treadmill training, cycling, resistance training) appear to improve gait in individuals with PD [5]. Recent work on complex motor training requiring high postural and cognitive demands has shown positive effects on balance and a reduction in the fear of falling in people with PD [6] along with an increase in postural stability and a better gait [7]. Furthermore, treadmill training was associated with increased stride length, lower cadence, and better foot clearance [8]. Beside the immediate effects, long-term treadmill training also induced clinically relevant improvements of over-ground gait speed and stride length [9].

A split-belt-treadmill (SBT) has two belts, which can either run at the same speed (tied) or at different speeds (split). A SBT can be used to modulate gait and to investigate the ability of an individual to adapt to novel gait patterns, as the system imposes asymmetric walking. When a

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split belt condition is imposed, an individual's walking pattern adapts by modifying spatial and/or temporal gait parameters [10]. Healthy individuals adapt their walking to SBT conditions by immediately increasing the stance time of the leg on the slow belt, inducing step length asymmetry [11]. Over time, this initial asymmetry of step length, double support time, and inter-limb phasing diminishes [11]. When returning belts to the same speed, short-term aftereffects are present because asymmetry parameters are elevated compared to baseline [11].

The impact of the SBT has been studied in unimpaired people and those with neurological conditions, such as stroke [12–18] and cerebral palsy [19]. The SBT was shown to be effective in restoring a more symmetrical walking pattern in individuals who had suffered a stroke with gait adaptations being retained for up to 3 months [18]. In individuals with PD, the cardinal motor symptoms generally present asymmetrically with one side initially being more affected than the other due to the lateral progression of the disease [20]. Hence, a SBT is arguably useful for investigating gait asymmetry and motor skill learning in patients with PD [21–27].

Freezing of gait (FOG) is defined as the inability to perform effective sequential steps despite having the intention to walk [28]. Depending on the disease stage, between 20–80% of people living with PD are affected by FOG [29]. FOG frequently occurs during asymmetric motor tasks, such as gait initiation and turning [30]. People with PD who have FOG (PD + FOG) show increased gait asymmetry compared to those without FOG (PD-FOG) [31]. Those persons with FOG also have greater deficits in switching from one motor pattern to another [32]. Both gait asymmetry and motor switching can be investigated using SBT training. This suggests that the investigation of SBT walking in PD + FOG is particularly interesting as it may offer further insight into FOG pathology. In addition, manipulating gait asymmetry using deep brain stimulation has been shown to diminish FOG [33].

This systematic review and critical evaluation of the literature summarizes the existing evidence on SBT walking in individuals with PD. First, we discuss different SBT paradigms and methodological approaches. Second, we summarize how people with PD adapt their gait to different SBT conditions in comparison to HC.

2. Methods

2.1. Search strategy

A systematic literature search was conducted of the *PubMED, PsychINFO,* and *Web of Science* databases until April 2018. The following search strategy was used: *([split-belt* OR split belt OR splitbelt OR walking adaptation OR gait adaptation OR locomotor adaptation OR motor adaptation OR motor learning] AND parkinson*)*. The key terms were selected based on keywords in articles focusing on SBT walking. Only original research articles, published in English, investigating SBT in people with PD were included.

2.2. Study selection

The search employed "All Fields" (*PubMED, PsychINFO*) or "Topics" (*Web of Knowledge*). Fig. 1 shows the flow diagram of the literature search. A total of 925 results were identified from the following databases: 218 results for *PubMED* (from 1950); 162 results for *PsychINFO* (from 1806) and 545 results for *Web of Knowledge* (from 1900). After removing duplicates and screening titles, 399 publications were retained for further screening. After screening abstracts or keywords, seven studies were selected for full-text evaluation. The excluded studies either investigated cohorts other than PD or did not include an SBT paradigm. The seven full texts were checked for eligibility according to the predefined criteria and were all included in the evaluation. Due to the small number of included studies and the variable used methodologies, the conduction of a meta-analysis was not feasible. Although a preliminary study of SBT usage with individuals with PD was performed in 1995, the literature on this topic remains scarce. A rating for the level of evidence was conducted according to Gross & Johnston [34]. The main criteria for quality evaluation were randomization, a control group, and the blinding of subjects and investigators.

3. Results

The level of evidence was found to be III for all included articles. Studies either had a control group of healthy individuals or participants served as their own controls when different SBT conditions were compared [34].

3.1. Participants

The studies varied with regard to the number of participants with PD and ranged from n = 10 [23] up to n = 25 [26] (Table 1). The age of the participants ranged between 58.3 and 66.8 years, with the disease severity varying between Hoehn & Yahr (H&Y) scale 2.1 and 2.6 [22–26]. The percentage of female participants was on average 25% for people with PD (three studies did not report gender distribution). In five studies, healthy controls (HC) served as a control group receiving the same intervention/walking protocol [22,23,25–27]. Within the HC group, age ranged between 60.6 and 65.3 years with an average of 35.3% female participants [22,25,26]. One study also included young healthy adults with a mean age of 22.3 years (n = 15) [24]. Four studies investigated the differences between PD + FOG and PD-FOG [21,22,25,26]. The PD + FOG and PD-FOG groups showed similar disease severity in two studies [22,26], whereas disease duration was different in one study [26] and similar in others [21,22,25]. In most of the studies, participants had not previously walked on a SBT [21,23–26]. Participants with PD were tested in the medication OFF state [21,22,25], ON state [24,26,27] or both ON and OFF states [23].

3.2. Intervention

Fig. 2 provides an overview of the different phases of a SBT paradigm. Tied-baseline refers to the period when both belts run at the same speed (normal treadmill walking) before a SBT condition is applied. Split-adaptation is the adaptation phase when both belts run at different velocities. This is followed by tied-adaptation in which both belts run at the same speed again and aftereffects can be studied. The SBT paradigms varied across the reviewed studies (Table 2). The duration of the applied SBT conditions ranged from 2 to 20 min. Five studies used fixed SBT velocities [22,23,25–27], whereas SBT velocity was adjusted according to over-ground walking speed in the other two studies [21,24]. The split-belt ratio, which describes the ratio of the two belts' velocities, varied between 3:4 and 1:2 [21–25,27]. In one study, a steadily increasing ratio of up to 1:1.6 [26] was applied (Table 2). Two studies used a SBT configuration referring to only one body side (e.g., reducing the velocity of the least affected side) [23,24]. The other studies tested the effects of SBT on both limbs [21,22,25–27]. The use of handrails was allowed in one study [24] whereas in other studies, it was not allowed [25,26] or not further specified [21–23,27]. One study used special glasses to block the lower visual field of the participants to evaluate their perception of belt speed without visual input from the belts [26].

3.3. Various methodological approaches in SBT studies

3.3.1. Dominance of body side

Five studies investigated SBT walking and accounted for a specific body side [21,23–26]. Table 2 shows that four of the included studies defined the best side as the body side with lower UPDRS motor subscores [23–26]. One of the studies defined the best/worst side according to the body side with the leg with a longer/shorter step length during baseline testing [21]. Two studies did not account for any

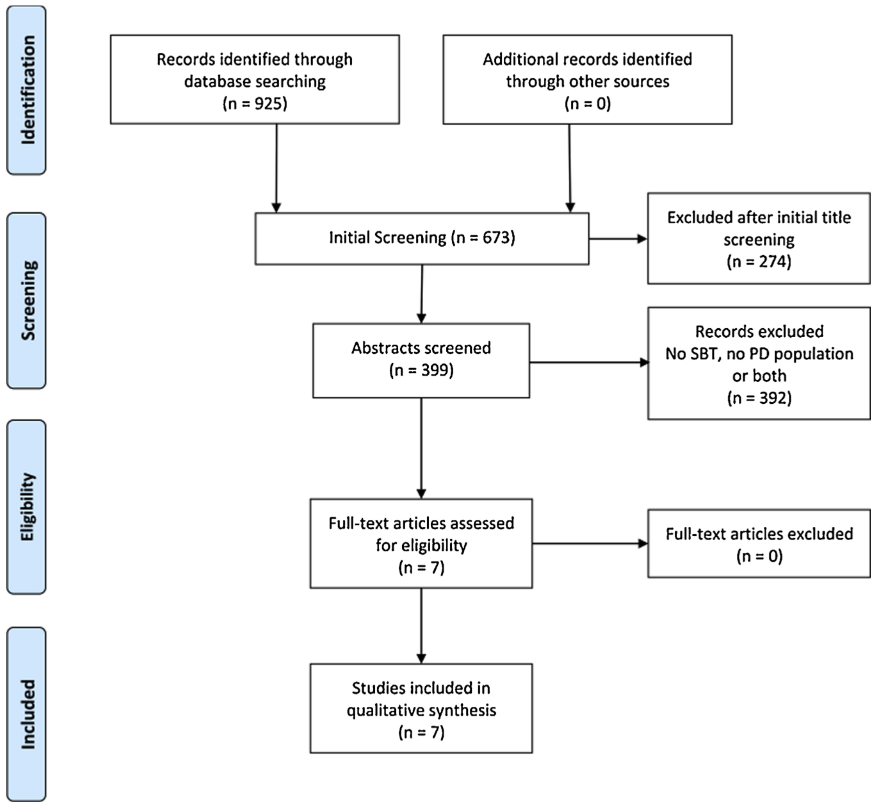

Fig. 1. PRISMA flow diagram of systematic literature search and study selection; n = number of publications; SBT = Split-Belt Treadmill; PD = Parkinson's Disease.

specific body side [22,27].

The study conducted by Fasano et al. [21] was the only one that interpreted adaptations to SBT walking with respect to body side, with shorter versus longer step length reported separately. The authors found that reducing the belt's velocity of the side with the longer step length (best side reduction (BSR)) led to improvements in symmetry and bilateral coordination of gait in tied walking after SBT. Step length asymmetry improved through an increase in step length of the side with the shorter step length following SBT-BSR. In contrast, when reducing the belt of the side with the shorter step length (worst side reduction (WSR)) different aftereffects were found. This condition resulted in significantly increased asymmetry and an elevated phase coordination index (PCI, a measure of bilateral coordination between the legs) in comparison to the tied-baseline condition.

3.3.2. Testing procedure and gait variables

Some studies divided the protocol into early, mid, and late split-adaptation conditions [21,23,24]. Other studies averaged the findings over the split-adaptation phase [22,27]. The aftereffects for the tied-adaptation condition were analyzed in most cases [21,23–25].

With one exception [27] all studies used motion-capture systems to analyze gait with sampling frequencies between 100 and 240 Hz. The studies used different methods to calculate spatial gait parameters making it difficult to compare the results: Three of the studies calculated step length as suggested by Hoogkamer et al. [35] using the distance of ankle markers at heel strike [23–25] whereas one study defined step length as the product of step time and belt velocity [21]. Others did not report how step length was calculated, stating merely that ground reaction forces were used to determine gait events [26].

The following temporal parameters were investigated: cadence [21,23], stride time [21,22], duration of stance- [21,23,24,26], swing- [21] and double limb support phase [21,27]. Furthermore, gait variability [21,22,25,26] and PCI [21,22] were evaluated. Table 3 summarizes the different formulas used to calculate asymmetry. All of the studies that evaluated gait asymmetry used spatial asymmetry parameters [21–26] and only two studies additionally calculated temporal asymmetry parameters [22,24].

3.4. Adaptation of gait in people with Parkinson's disease compared to healthy controls

The following results focus only on the interaction-effects between individuals with PD and HC when comparing the adaptation to different SBT conditions. Inconsistent results were found with respect to the adaptation of gait asymmetry. Roemmich et al. found that PD and HC adapted similarly in step length asymmetry during SBT walking, despite a higher baseline asymmetry in individuals with PD [24]. They showed that for the late split-adaptation condition, step length asymmetry reached values close to the tied-baseline condition. The aftereffect was characterized by a change in step length asymmetry (side with initially shorter step length took longer steps). Furthermore, people with PD adapted comparably to HC for stride length and stride time asymmetry [22]. In contrast, Mohammadi et al. observed a significantly increased step length asymmetry and limb excursion asymmetry during the switch to split-adaptation in PD-FOG compared to HC and in PD + FOG compared to PD-FOG [25]. Roemmich et al. detected a significant group by time interaction in stride length asymmetry, showing that PD did not increase stride length from early to late split-adaptation like it did in HC [24]. For stance time asymmetry, the group by time interaction was also significant, indicating that people with PD did not increase stance time asymmetry as much as healthy younger adults (HYA) during split-adaptation conditions or as younger and older adults during tied-adaptation conditions [24].

For gait variability, no differences in adaptation were found between individuals with PD and HC. Furthermore, the bilateral coordination of gait (measured by the PCI) was modulated in various SBT conditions to the same degree in the PD group as in HC group [22]. Additionally, no significant differences in the changes of upper and

Table 1
Characteristics of the studies.

Study	Subjects PD	Subjects HC	Main Outcome Measures	Main Results
Dietz et al. (1995)	n = 14 Age: 61.0 (± 11.4) **Med-ON** Disease severity: mild (n = 10) moderate (n = 4)	n = 10 Age: 60.6 (± 6.0)	• EMG activity and modulation (M. tibialis anterior & M. gastrocnemius medialis)	• PD do not tolerate higher differences in belt speeds • PD patients show smaller range of stride frequencies in different SBT and TB velocities • Greater co-activation in antagonistic leg muscle in PD during SBT and TB
Nanhoe-Mahabier et al. (2013)	PD-FOG: n = 7 Age: 62.1 (± 2.7) **Med-OFF** H&Y: 2.1 (± 0.1) DD: 6.3 (± 0.9) UPDRS III: 26.0 (± 2.6) PD + FOG: n = 7 Age: 64.1 (± 2.3) **Med-OFF** H&Y: 2.4 (± 0.1) DD: 8.4 (± 1.4) UPDRS III: 29.0 (± 0.6)	n = 10 Age: 62.4 (± 1.7)	• Stride length and stride time • Stride length and stride time asymmetry • Stride length and stride time variability • Interlimb coordination • Phase coordination index (PCI)	• Stride time asymmetry and variability was significantly increased in PD + FOG compared to PD-FOG during SBT, stride length asymmetry does not seem to differ in between PD + FOG and PD-FOG
Roemmich et al. (2014a)	n = 13 Age: 64.1 (± 8.8) **Med-ON** UPDRS III: 24.6 (± 9.4)	HYA: n = 15 Age: 22.3 (± 3.3) HOA: n = 15 Age: 65.2 (± 8.1)	• Step length • Limb excursion* • Stance time • Asymmetry of the mentioned parameters	• Step length of worst side (HC: non-dominant leg; PD: MAS) exceeded step length of best side after split-belt walking with best side walking on the slow belt • Step length and limb excursion* asymmetry showed different patterns during different split-belt conditions • PD had worse step length asymmetry at baseline, but adapted similarly to HC
Roemmich et al. (2014b)	n = 10 Age: 66.8 (± 7.3) **Med-ON and -OFF** H&Y ON: 2.5 (± 0.4) H&Y OFF: 2.6 (± 0.3) DD: 5.4 (± 2.7) UPDRS ON: 36.7 UPDRS OFF: 39.6	N/A	• Step length • Step length asymmetry • Anterior-Posterior Ground Reaction Forces (AP-GRFs) • Limb propulsive impulse	• Locomotor adaptation and savings (re-adaptation to SBT) were unaffected by medication state • Aftereffects (tied-adaptation) for step length asymmetry were diminished in the Med-OFF
Mohammadi et al. (2015)	PD-FOG: n = 12 Age: 62.4 (± 7.4) **Med-OFF** H&Y OFF: 2 (n = 8) 3 (n = 4) DD: 11.9 (± 4.8) UPDRS III OFF: 34.6 (± 10.5) PD + FOG: n = 10 Age: 60.4 (± 5.4) **Med-OFF** H&Y OFF: 2 (n = 4) 3 (n = 6) DD: 14.6 (± 5.7) UPDRS III OFF: 38.1 (± 7.8)	n = 12 Age: 61.9 (± 6.2)	• Step length • Step length asymmetry • Limb excursion	• PD + FOG adapt step length asymmetry slower compared to PD-FOG and HC in during SBT and after SBT • During split-adaptation PD + FOG increased limb excursion of the faster leg to a lower extent compared to Non-Freezers and HC • PD + FOG reduced limb excursion of slower leg to a larger extent compared to PD-FOG and HC • The freezing severity (N-FOGQ) is associated with changes in step length asymmetry and larger asymmetry values
Fasano et al. (2016)	PD-FOG: n = 6 Age: 58.3 (± 10.9) **Med-OFF** H&Y: 2-3 DD: 12.7 (± 6.0) UPDRS III OFF: 31.7 (± 5.2) UPDRS III ON: 14.7 (± 1.4) PD + FOG: n = 14 Age: 61.4 (± 7.7) **Med-OFF** H&Y: 2-3 DD: 12.0 (± 5.6) UPDRS III OFF: 31.4 (± 8.5) UPDRS III ON: 15.3 (± 9.7)	N/A	• Step length • Symmetry of gait (symmetry ratio) • Phase coordination index (PCI) • Stride time • Stride time variability	• In contrast to reducing the speed of the side with the shorter step length, reducing the side with the longer step length leads to an improvement in spatial symmetry (step length) and bilateral limb coordination (PCI) and reduced sequence effect in PD patients (in tied-adaptation). • Step length of worst side was significantly higher in post-tied compared to tied-baseline • Gait features associated with FOG are interrelated
Beckers et al. (2017)	PD-FOG: n = 12 Age: 63.0 (± 8.6) **Med-ON** H&Y: 2.2 (± 0.4)	n = 12 Age: 65.3 (± 8.1)	• Perception accuracy • Perception threshold • Step length asymmetry • Stance time asymmetry	• PD + FOG show worse accuracy to correctly detect speed differences between both legs • No difference in perception threshold between groups and sides

(*continued on next page*)

Table 1 (*continued*)

Study	Subjects		Main Outcome Measures	Main Results
	PD	HC		
	DD: 5.7 (± 3.5) MDS-UPDRS III: 29.5 (± 11.2) PD + FOG:n = 13 Age: 67.0 (± 7.2) **Med-ON** H&Y: 2.6 ± 0.5 DD: 13.7 ± 5.2 MDS-UPDRS III: 38.1 ± 14.4		• Limb excursion	• For all participants the correct identification of belt speed differences correlated with gait asymmetry and step length • Within PD + FOG response accuracy correlated with step length and gait variability

Vel. = velocity; LAS = least affected side; MAS = most affected side; SBT = Split-Belt Treadmill; OG = Overground; TB = Tied-Belt; HC = healthy control; HYA = healthy young adults; HOA = healthy older adults; H&Y = Hoehn & Yahr scale; DD = Disease duration; Med-OFF = medication OFF state; Med-ON = medication ON state; M = Musculus; PD = people with Parkinson's Disease; PD-FOG = PD without FOG; PD + FOG = PD with FOG; UPDRS III = Unified Parkinson's Disease Rating Scale motor score; N/A = not available; *in this study referred to as stride length.

lower limb coordination were found between the PD and HC groups [22].

Muscular activity was investigated by Dietz and colleagues during SBT walking in the PD group. They found significantly greater co-activation in antagonistic leg muscles in people with PD during tied-baseline and split-adaptation conditions [27] as compared to HC.

3.5. Altered adaptation of people with PD with freezing of gait

With respect to individuals with PD with FOG, Mohammadi et al. showed that PD + FOG adapted their step length asymmetry more slowly compared to PD-FOG [25]. This was the case in both the split-adaptation and the tied-adaptation conditions and was explained by the differences in gait parameter adaptation. Fasano and colleagues found that the detrimental effect of reducing the speed of the side with the larger step length (best side reduction, BSR) during split-adaptation was significantly correlated with FOG severity, indicating that more severe FOG led to a larger reduction in step length [21]. Furthermore, FOG severity, as measured by the Freezing of Gait Questionnaire (FOGQ), seemed to be linked to step length asymmetry after switching to SBT [25]. This study also reported difficulties with SBT walking for one PD + FOG patient who experienced FOG and another one who had a festination episode during the switch from tied-baseline to split-adaptation [25].

Bekkers et al. found that PD + FOG had reduced accuracy to detect gait speed differences of the two belts, although the perception threshold of SBT condition did not differ between groups [26]. Furthermore, increased gait variability, along with smaller step length and limb excursion, were associated with perception deficits. Therefore, the authors concluded that this perception deficit in PD + FOG may partly explain the SBT differences found between the PD + FOG and PD-FOG groups. Interestingly, no elevated proprioceptive deficit was found in the PD + FOG group through joint position sense testing. Regarding the side dominance, there were some patients who were unable to identify any speed difference with increased belt velocity on the most affected side. This could point toward a perception deficit that is side dependent [26].

3.6. Effect of levodopa

The effect of dopaminergic medication was investigated in only one study [23]. The authors did not find an effect of dopaminergic medication on the split-adaptation and re-adaptation (repeated SBT walking after over-ground washout) of the newly learned gait pattern during SBT walking. However, withholding levodopa led to decreased after-effects in tied-adaptation [23]. The authors concluded that interventions using SBT in PD patients should test participants in the optimally medicated state.

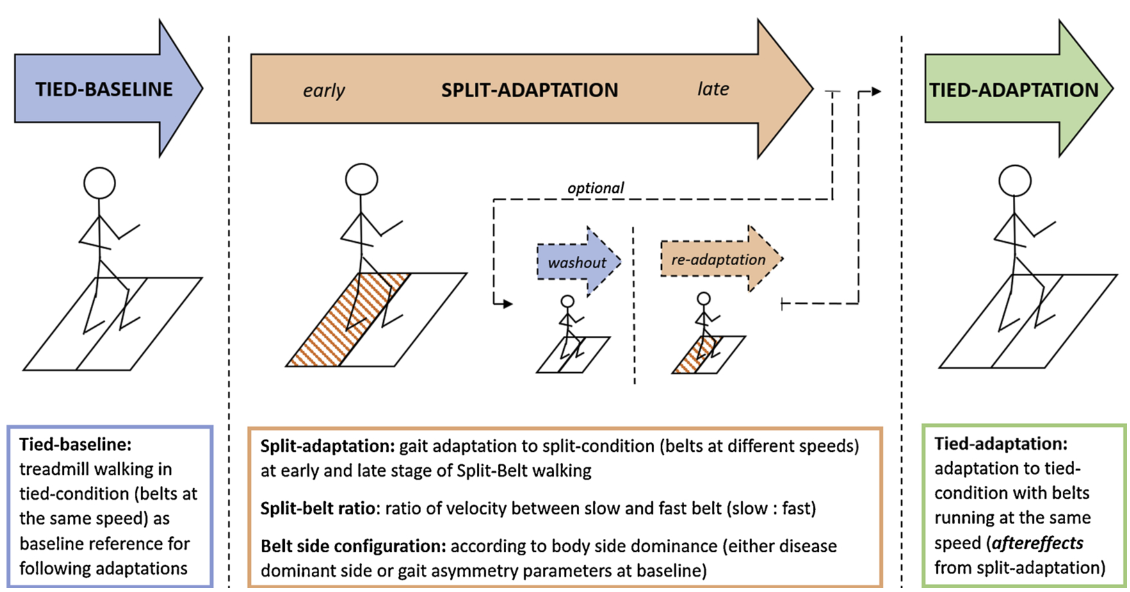

Fig. 2. Overview of phases and terms in Split-Belt Treadmill walking.

Table 2
SBT paradigm characteristics of the included studies.

Study	SBT Duration	Belts' speed	Split-Belt Ratio	Belt Side Configuration	Definition of body side dominance
Dietz et al. (1995)	2 x 1 min	1.8 km/h 3.6 km/h	1:2	both	not assessed
Nanhoe-Mahabier et al. (2013)	2 x 2 min	2 km/h 3 km/h	2:3	both	not reported
Roemmich et al. (2014a)	10 min washout 3 min	fast comfortable walking speed for fast belt	1:2	BS on slower belt	WS/BS: more/less PD affected body side as self-reported and confirmed by highest/lowest lateral UPDRS III subscores
Roemmich et al. (2014b)	10 min washout 5 min	1.8 km/h 3.6 km/h	1:2	BS on slower belt	WS/BS: more/less PD affected body leg as self-reported and confirmed by highest/lowest lateral UPDRS III subscores
Mohammadi et al. (2015)	2 x 2 min	3 km/h 4 km/h	3:4	both	WS/BS: more/less PD affected body side as defined by highest/lowest lateral UPDRS III subscores
Fasano et al. (2016)	2 x 10 min	Individual walking speed	3:4	both	WS/BS: body side with shorter/longer step length during baseline
Bekkers et al. (2017)	Until perception of belt speed difference (max. 3 min) x2 per side	3 km/h at baseline	max. 1:1.6 (steadily increasing)	both (x2)	WS/BS: more/less PD affected body side as defined by highest/lowest lateral MDS-UPDRS III subscores

min = minutes; SBT = Split-belt Treadmill; BS = best side; WS = worst side; PD = Parkinson's Disease, (MDS)-UPDRS = Unified Parkinson's Disease Rating Scale.

3.7. Safety and adverse events

In the reviewed studies, safety precautions were not always reported. Most often, it was noted that to prevent falls, a safety harness was used during treadmill walking [22,23,25,26]. The participants were also allowed to use the handrails, if necessary [23]. Furthermore, familiarization periods to normal treadmill walking [23–27] and SBT walking [27] were provided. To avoid injuries, some studies did not include participants with orthopedic contraindications [21,23,24]. However, the influence of anxiety when walking on a SBT was generally not assessed. None of the included studies reported on the occurrence of falls, even though walking on a treadmill that had spilt belts was novel for most of the participants. Mohammadi et al. [25]. reported that FOG and gait festination occurring during SBT walking for two participants. They speculated that this was associated with a switching deficit in PD + FOG. In the other trials, none of the participants experienced FOG [21,22]. Overall, studies had poor reporting of adverse events.

4. Discussion

This review provided preliminary evidence that gait training using a treadmill with a spilt belt can help to improve walking in some individuals with PD, particularly where asymmetry was evident. Various methodological approaches were used in the studies reviewed, such as different SBT conditions regarding belt velocity, belt speed differences, and a variety of gait parameters, as outcomes. The literature varied according to the definition of gait parameters in PD. Hoogkamer et al. [35] previously proposed a consistent definition for *limb excursion* as the distance traveled from heel strike until toe-off, for one foot, instead of using the term *stride length*. Furthermore, *step length* was defined as the distance between the feet for each gait event (either distance between toe markers before lift-off of the foot or the distance between ankle markers at heel strike of the leading foot) [35]. In contrast, some of the included studies used step time and belt speed to calculate step length [21] or did not provide the calculation method [26]. Different calculations were used for asymmetry variables. Gait asymmetry (defined as (fast leg parameter - slow leg parameter)/(fast leg parameter + slow leg parameter)) has been previously used in studies with HC [36–38] or neurological conditions [14,37,39]. The advantage of this definition is that no absolute values are used. Therefore, not only the degree of asymmetry is described, but also the laterality of the asymmetry (which side is longer/shorter). This aspect is important, as it has been shown that SBT walking can lead to a larger step length of the leg with the shorter initial step length in tied-adaptation conditions [23,24].

Another inconsistency in the evaluated studies related to the treadmill velocity used. There were a few studies using fixed belt speeds not accounting for the individual over-ground gait speed. This could bias the results, as gait speed can vary across participants.

Another important methodological issue was the belt side configuration according to the dominance of the leg or body side. The studies included in this review used different methods to define dominance of body side. The MDS-UPDRS III lateral subscore was mostly used to determine the most affected body side [23–26]. However, it has been suggested that gait asymmetry is not necessarily related to asymmetry as defined by the MDS-UPDRS III [31]. Using step length to determine the best and less able side is another approach closer related to gait asymmetry. Further research is necessary to investigate the relationship of step length asymmetry and disease laterality.

For the safe conduction of SBT interventions, several precautions

Table 3
Calculation of asymmetry parameters.

	Calculation of asymmetry parameters		Reference
A	$\frac{(\text{fast leg parameter} - \text{slow leg parameter})}{(\text{fast leg parameter} + \text{slow leg parameter})}$	a value of '0' indicates perfect symmetry, e.g. positive values indicate a longer step length of the fast leg and negative values a longer step length of the slow leg	[21,22]
B	$\frac{\lvert(\text{right step length} - \text{left step length})\rvert}{(\text{right step length} - \text{left step length})}$	a value of '0' indicates perfect symmetry, only measures the degree of asymmetry without indicating the side which performs the longer step	[23,24]
C	$\frac{(\text{max stride length-min stride length})}{\text{max stride length}} \text{x} 100\%$	describes the degree of asymmetry as a percentage with higher values indicating higher asymmetry	[25]
D	$\frac{\text{fast step length}}{\text{slow step length}}$	a value of '1' indicates perfect symmetry, whereas values below '1' indicate a longer step length of the slow side (leg walking on the slower belt) and values above '1' longer step length of the fast side.	[26]

need to be taken into account. Participants with contraindications (such as comorbidities, very advanced age, severe movement disorders, and advanced stages of disease) should be excluded, and a safety harness should be used. Additional use of handrails and extended familiarization to the SBT condition should be provided, if necessary. None of the included studies addressed the possible impact of anxiety on safety or motor performance, and none of the studies reported adverse events, which should be implemented in future studies.

This review showed that many people with PD were able to adapt to SBT walking in a similar way to HC. Although slowed down by a larger initial asymmetry, adaptations of step length asymmetry followed a similar pattern to HC. However, not all gait parameters showed preserved adaptation in response to this form of treadmill training [24]. Stride length and stance time asymmetry did not always adapt to the same extent in persons with PD as for HC. Moreover, the transfer of the newly learned gait patterns to over-ground walking was not investigated for the PD group. The aftereffects for over-ground walking were studied in HC and found to be lower compared to the retention of training for the treadmill, with greater retention for temporal gait parameters [40].

Fasano et al. found that reducing the belt velocity for the side with the longer step length led to more symmetrical gait in the PD group [21]. This has also been investigated in stroke, where gait was modulated during SBT using error augmentation mechanisms [16]. When the paretic leg walked on the slower belt, step length of the paretic leg increased for the early split-adaptation condition, creating larger step length asymmetry [41]. During the adaptation process, asymmetry reached values close to baseline, and asymmetry improved in the tied-adaptation condition. In chronic stroke patients, the exaggeration of initial step length asymmetry was found to be effective in improving step length asymmetry, relative to the tied-baseline condition. This error augmentation strategy was thought to be successful because attention was implicitly drawn to the error with the aim to correct it [41].

In the current review, the subgroup with freezing of gait had an adaptation deficit that might have been caused by higher baseline asymmetry [22,25]. It has been shown that SBT can lead to reduced gait coordination and increased sequence effect (progressive slowing of movement/stepping) [21]. This supports the link between asymmetry and FOG episodes [21]. A reduction of step length of the least affected side could lead to FOG episodes when a certain threshold is reached [42]. The theory of a specific threshold after which FOG occurs is supported by previous literature [43]. The authors proposed that several gait alterations could be causal for a FOG episode when they exceed a certain level. Others suggest that the asymmetry itself is not the main problem, rather the impaired switching ability is at fault [25]. Perception deficits might also play a role [26]. It is most likely that not just one gait characteristic is at the core of the difficulties with SBT walking in PD + FOG, but rather there is an interplay of various deficits.

Nanhoe-Mahabier et al. [22] proposed that the cerebellum might be involved in the adaptation deficit in people with FOG. This is supported by findings regarding altered structural [44–47] and functional [47] connectivity between the pedunculopontine nucleus (PPN) and the cerebellar locomotor region (CLR), suggesting a greater cerebellar deficit in PD + FOG [46]. Furthermore, there has been some work on resting state brain activity in PD + FOG that suggests that the cerebellum could play a role in the pathology [48]. Inter-limb coordination and temporal aspects of gait control are challenged in SBT walking, and the cerebellum plays an essential role in the coordination of these gait features [10]. Conversely, the implicit nature of split-adaptation conditions might enhance the activation of the cerebellum when it is used as a training tool [25].

SBT walking in PD has only been investigated in single sessions, and prolonged training interventions have not been conducted to date. From the work done with stroke patients, there is some evidence for the effectiveness of repeated SBT walking to lower gait asymmetry using the error augmentation strategy with improvements being sustained for one to three months [12,18]. Future studies should investigate the transfer to over-ground walking of repeated SBT training in people with PD.

There were several limitations of this systematic review. The number of existing studies about SBT in people with PD was small, and the level of evidence appeared to be comparatively low. Therefore, results have to be interpreted with caution. Safety precautions and contraindications were not adequately addressed. Furthermore, only a brief level of evidence analysis using the American Academy of Neurology classification scheme requirements for therapeutic questions was included. A further, more detailed, higher quality analysis, such as PEDro, was not used, as most of the items of the PEDro scale were not appropriate for the nature of the included studies (no randomized controlled intervention studies).

5. Conclusion

This systematic review showed that many people with mild to moderately severe PD adapted similarly to HC for gait variability and bilateral coordination when walking on a SBT. For some people, SBT enabled them to modulate gait asymmetry. People with FOG showed adaptation deficits and impaired perception of belt speed differences. Further research focusing on the detection of the most effective SBT conditions and transfer of training to over-ground walking is necessary. Additionally, future studies should address safety precautions and the impact of anxiety. The effectiveness of long-term SBT training interventions also awaits investigation as a rehabilitative strategy for people with PD.

Conflict of interest

No potential conflicts of interest.

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