Observational Study

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A training approach to improve stepping automaticity while dual-tasking in Parkinson's disease

A prospective pilot study

Taylor Chomiak, PhD*, Alexander Watts, BHSc, Nicole Meyer, BSc, Fernando V. Pereira, PhD, Bin Hu, MD, PhD*

Abstract

Background: Deficits in motor movement automaticity in Parkinson's disease (PD), especially during multitasking, are early and consistent hallmarks of cognitive function decline, which increases fall risk and reduces quality of life. This study aimed to test the feasibility and potential efficacy of a wearable sensor-enabled technological platform designed for an in-home music-contingent stepping-in-place (SIP) training program to improve step automaticity during dual-tasking (DT).

Methods: This was a 4-week prospective intervention pilot study. The intervention uses a sensor system and algorithm that runs off the iPod Touch which calculates step height (SH) in real-time. These measurements were then used to trigger auditory (treatment group, music; control group, radio podcast) playback in real-time through wireless headphones upon maintenance of repeated large amplitude stepping. With small steps or shuffling, auditory playback stops, thus allowing participants to use anticipatory motor control to regain positive feedback. Eleven participants were recruited from an ongoing trial (Trial Number: ISRCTN06023392). Fear of falling (FES-I), general cognitive functioning (MoCA), self-reported freezing of gait (FOG-Q), and DT step automaticity were evaluated.

Results: While we found no significant effect of training on FES-I, MoCA, or FOG-Q, we did observe a significant group (music vs podcast) by training interaction in DT step automaticity ($P<0.01$).

Conclusion: Wearable device technology can be used to enable musically-contingent SIP training to increase motor automaticity for people living with PD. The training approach described here can be implemented at home to meet the growing demand for self-management of symptoms by patients.

Abbreviations: DT = dual-task, FES-I = Falls Efficacy Scale-International, FOG-Q = Freezing of Gait Questionnaire, HY = Hoehn and Yahr scale, MoCA = Montreal Cognitive Assessment, MT = mono-task, PD = Parkinson's disease, SH = step height, SIP = stepping-in-place, UPDRS-III = Unified Parkinson's Disease Rating Scale Part 3.

Keywords: automaticity, dual task, music, Parkinson, step, training

1. Introduction

The role of cognitive and executive functions in walking, standing, and various stepping-in-place (SIP) paradigms is now increasingly appreciated.[1–5] In Parkinson's disease (PD), subtle cognitive and cognitive-motor dual-task (DT) deficits are prevalent and are an early and consistent hallmark of declines in cognitive function associated with impairments in gait functioning, poor health outcome, increased fall risk, and a poor quality of life.[1,4–7]

Exercise and interventional programs for PD that include SIP are an effective means to prevent falls, maintain functional independence, and to promote rehabilitation following injury.[8] Kinematically, SIP involves rhythmic alternated stepping of the left and right legs, requiring bilateral coordination of the legs for single support, and shifting of the centre of mass over the stance leg at each step in order to maintain balance.[9] Given that the ability to maintain postural stability while transiently standing on a single leg is essential for normal gait and activities of daily living such as stepping over obstacles, turning, stair climbing, and dressing,[10] improving SIP DT performance may lead to a new interventional strategy with favorable long-term outcomes in PD patients.[1,11]

Previous institution-based studies have suggested that rehabilitation programs aimed at improving DT ability and motor movement automaticity may be effective in people living with PD.[12–14] Now, however, home-based interventions are receiving increasing attention because they offer several advantages

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TC and AW contributed equally to this work.

Disclosure: BH, TC, and FVP developed the SIP protocol and measurement method and reserve the right to commercialize. It is still under investigational use.

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including less travel time, easier access to the intervention, and, with respect to fall risk prevention, the ability to train in the very environment where falls are most likely to occur.[15] In addition, home-based care and monitoring may not only be more economical,[15] but also permit the acquisition of large-scale datasets that have the potential to vastly improve medical decision making through the development of population-specific screening and assessment guidelines.[16,17]

We recently developed and validated a home-based amenable method for screening general cognitive-motor DT deficits and evaluating cognitive-motor rehabilitation training while SIP.[4] In the current pilot study, we sought to build on these findings by testing the feasibility and potential efficacy of a home-based 4-week music-contingent SIP training program for the improvement of DT performance. Here, repetitive stepping is positively reinforced with pleasurable music playback.[4] Our rationale is based on the evidence that musical cues, enriched with rhythm, vocal singing, and uplifting emotional salience stimulate cognitive and arousal systems which in turn can influence motor learning and automaticity (i.e., the ability to perform a skilled movement with minimal executive control).[11,18,19] Modern attentional theories of learning predict that long-term motor memory of automatic gait control may benefit from cueing approaches that activate reward and attentional networks. Indeed, if reduced movement automaticity contributes to dual-task deficits in people with PD, then rehabilitation strategies designed to improve the automatic control of motor control should improve DT motor automaticity.[1]

2. Methods

2.1. Subjects

Ethics approval was obtained from the University Ethics Board for Human Research and informed written consent was obtained. Eleven participants (n=6 podcast, 4 males 2 females; and n=5 music, 5 males) who were already enrolled in the on-going *Ambulosono* walking program (Trial Number: ISRCTN06023392) agreed to participate in this prospective pilot study. Participants were tested pre and post intervention (Fig. 1) while maintaining a consistent medication regimen to minimize bias associated with medication effects. Participants had to be able to step-in-place (SIP) a minimum of 5 minutes, and had to have a confirmed diagnosis of PD by a movement disorder specialist. None of the participants presented with neurological deficits such as hearing impairments or dementia. Since this was a feasibility study, a formal sample size calculation was not required. However, we did aim for a target sample size of at least 5 participants per group (n=10) as group sizes of 5 or greater provide robust parameter estimates for parametric tests.[20]

2.2. Stepping motor automaticity assessment

Motor automaticity is the ability to perform motor skills with minimum cognitive resources directed toward these motor skills.[21] Motor automaticity, by definition, is resistant to interference and is therefore commonly evaluated by a dual-task paradigm such that if the performance of one or both tasks deteriorates under dual-task conditions, then the motor task is not automatic.[21] The evaluation method used to assess the participant's step automaticity ability is referred to as the stepping-in-place dual-task (SIP-DT) assessment that we recently developed (Fig. 1 and see Chomiak et al[4]). Essentially, a mono-task (MT) stepping trial is performed and step height (SH) is measured by a leg sensor, which is then followed by 4 dual-task (DT) trials where patients answer questions of varying difficulty while continuing to step[4] (see Fig. 1B). Measurement accuracy using this approach has been previously described, with average measurement difference of <1 cm and standard deviation of <2 cm when compared to and validated by kinematic video analysis software.[4] The ratio of motor decrement (i.e., <1) under dual and MT conditions (i.e., DT_{SH}/MT_{SH}) is used as a motor automaticity index.[1]

2.3. Clinical testing and questionnaires

The eleven patients completed clinical tests (Unified Parkinson's Disease Rating Scale Part 3 (UPDRS-III); Hoehn and Yahr (HY)) and self-reported questionnaires including The Falls Efficacy Scale International (FES-I) survey for fear of falling, the Freezing

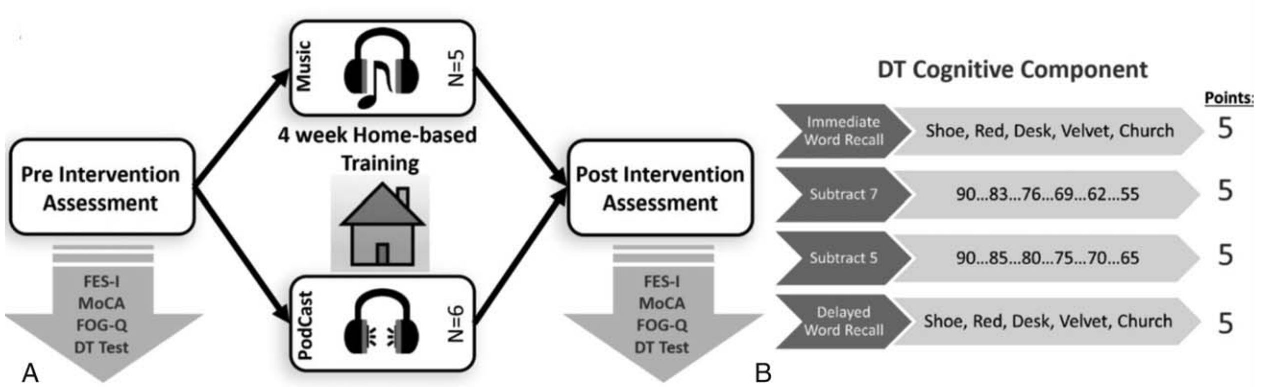

Figure 1. Overview of study design. Schematic of the study design (Panel A). Participants were tested before ("pre") and after ("post") a 4-week in-home Ambulosono intervention program. Participants were asked to use the device in-home a minimum of 3 times per week, for 10 to 20 minutes per training session. Pre- and post assessments included The Falls Efficacy Scale International (FES-I) survey for fear of falling, the Freezing of Gait Questionnaire (FOG-Q) for freezing, and The Montreal Cognitive Assessment (MoCA) for general cognitive functioning. The dual-tasking test (DT test) consisted of measuring step-height decrement while SIP and simultaneously performing cognitive tasks (shown in Panel B). The order was standardized as done previously.[4] The control group was identical to the *Ambulosono* music group with the exception that instead of contingent music playback, they received contingent auditory feedback in the form of a CBC podcast (*CBC Quirks and Quarks segment: The Sloth's Pharmaceutical Fur*).

Table 1

Comparison of mean and standard deviation assessment scores of participants at baseline and posttraining.

Psychometric outcome measures			
Variable	**Baseline**	**Post Training**	***P***
Music			
FES-I	32.2 (8.6)	33.6 (9.3)	0.63
MoCA	26.8 (1.9)	26.6 (2.3)	0.62
FOG-Q	10.2 (4.6)	10.2 (3.6)	1.00
DT cognitive score*	12.4 (4.0)	13.6 (6.0)	0.46
Podcast			
FES-I	26.0 (7.8)	27.3 (10.1)	0.49
MoCA	26.5 (1.5)	26.8 (2.6)	0.79
FOG-Q	6.5 (3.1)	7.0 (2.4)	0.74
DT cognitive score*	12.0 (4.6)	12.3 (5.1)	0.74

DT = dual-task, FES-I = Falls Efficacy Scale International, FOG-Q = Freezing of Gait Questionnaire, MoCA = Montreal Cognitive Assessment.
* Dual-task cognitive score represents the number of questions (of which there were 20) that were answered correctly during the dual-task assessment. The maximum cognitive score for the assessment is 20.

of Gait Questionnaire (FOG-Q) for freezing, and The Montreal Cognitive Assessment (MoCA) for general cognitive functioning as done previously in the published aging and PD literature[4,7,13,22–24] for comparison pre- and post intervention (Fig. 1 and Table 1).

2.4. The Ambulosono platform and in-home Ambulosono-SIP training

Ambulosono is a therapeutic platform based on the premise that specific behavioral conditioning techniques can be utilized to remodel brain neuroplasticity and compensatory mechanisms associated with PD, thereby modifying disease symptoms and progression.[25,26] With *Ambulosono*, natural reward stimuli such as musical cues of high emotional salience can be delivered through an iPod Touch strapped to the patient's knee.[4] To seek and maintain music play, patients have to repetitively and transiently stand on 1 leg while lifting the other leg high (SIP) to maintain music playback. Small amplitude steps or shuffling will lead to sudden music stoppage, thereby providing a salient reminder to re-engage patients to initiate greater foot clearance (Fig. 2). The *Ambulosono* training paradigm is realized through multiple levels of interactive cues embedded within and enabled by motivational musical stimuli, gait reinforcement, and contingent auditory reminders.[25,26] Following baseline assessments, individuals completed in-home *Ambulosono* SIP-training. Thresholds were set on-site based on an individual's MT SH. Participants tested their individualized threshold setting to ensure consistent auditory feedback was attainable before leaving. Accordingly, thresholds (6–20 cm) typically ranged a few centimeters below their MT SH. As such, participants were training to achieve an automatic phase of stepping,[21] not training to increase MT SH level. For this, the threshold would need to be set above the individualized MT SH.

To avoid confusion and the possibility that participants were actually walking at home instead of SIP, participants were given a separate iPod clearly marked with a blue sticker indicating that this was to be their stepping iPod. The "notes" section on the App also indicated this on the screen of their iPod, reminding them to use this device while SIP training. Participants were given one-on-one instruction on how to use the iPod and its components (pair headset, put on leg strap, start SIP playlist and where to place it in the leg band) before leaving. They were also given an instructional guide which explicitly stated the importance of the device only being used for in-home SIP training, and participants were encouraged to mark a spot on the floor at home and SIP in that location every time they did the training. These points were reiterated with weekly phone call follow-ups by the same study researcher, and the same questions were always asked; "if they were having any problems using the device; and whether they were able to hear music/podcast play and for approximately what percentage of the time." This allowed us to ensure appropriate threshold training was taking place and to determine whether minor threshold adjustments were needed (i.e., not too hard or easy).

With in-home training, the real-time computed step-height was used to trigger music playback through wireless headphones with a threshold averaged over 1 to 3 steps to minimize fluctuations in music triggering signals. Data were locally auto-saved, archived, encrypted, and uploaded to and processed on our secured server.[4] Participants were asked to use the device in-home a minimum of 3 times per week, for 10 to 20 minutes per training session. Following 4 weeks of in-home SIP training (i.e., auditory contingent SIP training without any DT training), participants were brought back on site to reperform the DT step-automaticity assessment as well as complete the MoCA, FES-I, and FOG-Q (Fig. 1). The control group was identical to the *Ambulosono* music group with the exception that instead of contingent music playback, they received contingent auditory feedback in the form of a CBC podcast (*CBC Quirks and Quarks segment: The Sloth's Pharmaceutical Fur*).

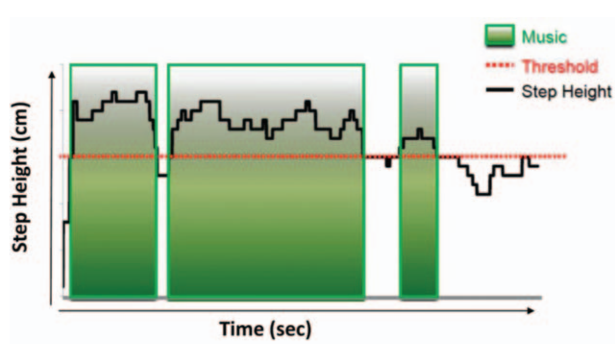

Figure 2. Basic concept of *Ambulosono* Music-Contingent Training. The basic concept of the *Ambulosono* technological platform is to computationally link auditory musical reward stimulation to scalable motor action. Based on an individuals' mono-task SIP step height, a predefined step-height training threshold (red dotted line) can be set for auditory feedback. Therefore, during training, if step height (black trace) is above the threshold (red dotted line), music will play (green regions), while if step height is below the threshold, music does not play. This allows participants to use real-time step measurements and analytics that provide biofeedback to help self-motivate and self-activate reward networks with training.

2.5. Statistical analysis

All data were obtained from our secure server and analyzed with SPSS or GraphPad Prism statistical software. Data are expressed as mean ± SD unless otherwise stated. Paired comparisons of pre- and posttraining FES-I, MoCA, and FOG-Q scores, a paired *t* test was used. A linear mixed effects model was used to examine the effect of training (i.e., pre vs post), condition (i.e., DT task), and group (music vs podcast) on step automaticity (DT/MT SH ratio). The advantage of the linear mixed model is that the heterogeneity and correlation of step automaticity measurement under different DT conditions are taken into account.[2] Furthermore, the changes in separate step automaticity performance indices (i.e., under different DT conditions) due to training can be directly compared through a linear mixed effects model. Effect size was estimated by mean difference scores that were calculated by subtracting the mean estimated change from baseline to post-intervention for the treatment group from the mean estimated change from baseline to post intervention for the control group.[27] Predicted values from the linear mixed effects analyses generated these difference scores. Mean difference scores were divided by the control group baseline standard deviation to estimate Cohen's *d*.[27]

3. Results

At Baseline, the average age (70.8 ± 5.6 vs. 69.0 ± 5.7 years; $t_{(9)}=0.53$; $P=0.61$), disease duration (15.4 ± 5.4 vs. 11.2 ± 5.0 years; $t_{(9)}=1.34$; $P=0.21$), Unified Parkinson's Disease Rating Scale Part 3 (UPDRS-III) (18.2 ± 6.4 vs. 20.3 ± 4.7; $t_{(9)}=-0.64$; $P=0.54$), and Hoehn and Yahr (HY) scores (2.5 ± 0.50 vs. 2.7 ± 0.41; $t_{(9)}=-0.90$; $P=0.38$) were not significantly different between music and podcast groups respectively. The average FES-I, MoCA, and FOG-Q scores at baseline are shown in Table 1, along with the average scores post training. There was no significant change in these scores (Table 1). Data tracking found that the total training time varied widely among participants with an average total usage of almost 20 minutes per week (74 ± 52 minutes). Patients trained for an average of 5.4 ± 2.9 different days, and 8.4 ± 4.3 minutes per session. Although the music group (total usage 89 ± 74 minutes, average number of days 5.8 ± 3.9; minutes per session 7.7 ± 4.8) tended to train slightly more than the podcast group (total usage 61 ± 22 minutes, average number of days 5.2 ± 2.0; minutes per session 9.1 ± 4.2), this difference was not statistically significant ($t \leq 0.89$; $P \geq 0.39$ for all tracking measures).

Results on step automaticity before (pre) and following (post) training for both groups are shown in Fig. 3. There was a significant training effect ($F_{(1,69)}=4.08$, $P=0.047$), and more importantly, a significant group (i.e., music vs podcast) by training interaction ($F_{(1,69)}=9.20$, $P=0.003$) with patients showing a global improvement of DT step automaticity following music but not podcast training (Fig. 3). There was, however, no significant DT condition by training interaction ($F_{(3,69)}=0.07$, $P=0.98$). The increase in music DT step automaticity was also not due to decreases in MT SH as this did not decrease between pre- and post conditions ($t_{(4)}=-0.10$, $P=0.92$).

4. Discussion

4.1. Deficits in dual attention tasking and the Ambulosono platform

The clinical management of DT dysfunction in PD is complex due to the heterogeneity and near ubiquitous nature of cognitive and motor deficits.[1,28] Impairment in DT is associated with mobility impairment, falls, reduced quality of life, and is considered an early and consistent hallmark of declines in cognitive function.[1] While potentially modifiable, the key to effective interventional strategies rely on personalized physical training programs.[8,16,17] Such personalized programs, however, may benefit from novel technological solutions that can offer both home-based surveillance and interventional paradigms.[29]

Here, we propose a wearable sensor-enabled technological platform that allows for objective DT assessment and personalized in-home DT training with the potential to be adopted by a large number of community-dwelling seniors. In this pilot study, we tested the feasibility and potential efficacy of one such technological platform in individuals with PD designed to improve DT step automaticity.[1] Both human and animal research has shown that reduced DT motor automaticity associated with nigral–striatal degeneration can be masked by engaging more cognitive resources to the motor task.[1,4,30] Indeed, increased influence from the anterior putamen to motor cortex has been suggested to be an indication of using attentional control to overcome impaired automatic control in PD.[21] However, this compensatory strategy may lead to a false sense of functional mobility and can become quite problematic when patients undertake concurrent cognitive-motor tasks as the "system" may become over-loaded, lead to motor block, and subsequent falls.[4] The results of the present study suggest that reduced stepping motor automaticity in PD may not be irreversible.

Ambulosono's rich repertoire of sensorimotor cueing is purposely designed to activate physiological endogenous dopaminergic and nondopaminergic systems to stimulate attentional networks and motor vigor.[18,31–35] This allows participants to use real-time biofeedback that may help to self-motivate and self-activate reward networks with training.[36] As a result, improved gait automaticity likely relies on both the ventral reward

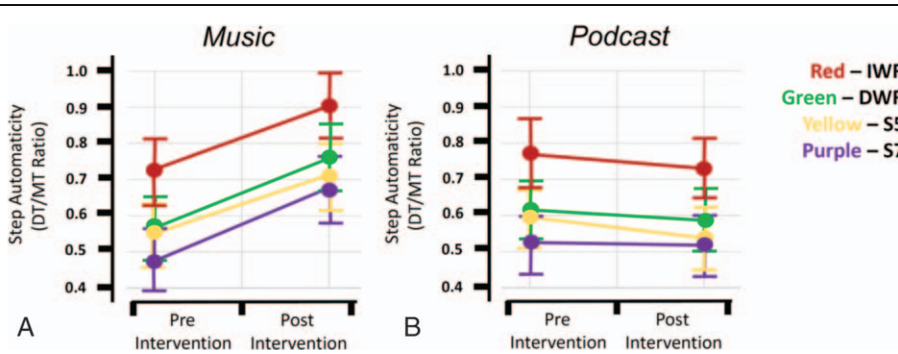

Figure 3. Improvements in Dual-Tasking Step Automaticity Following *Ambulosono* Training. Plotted are the fixed effects parameter estimates (i.e., mean and standard error) from the linear mixed-effect model. Colors represent average changes in automaticity ratio (DT/MT) for each DT condition (i.e., immediate word recall, red; delayed word recall, green; serial subtract 5, yellow; serial subtract 7, purple). While there was no significant DT condition by training interaction ($F_{(3,69)}=0.07$, $P=0.98$), there was a significant group (i.e., music vs podcast) by training interaction ($F_{(1,69)}=9.20$, $P=0.003$).

network, which is intimately linked to behavioral habit formation and increased dopamine-dependent mental and physical stamina,[37] and the posterior attention network, responsible for sensorimotor cueing and task automation.[11,18,19,38] Furthermore, data has suggested that dopamine depletion in the posterior putamen induces a failure to shift automated motor skills to the sensorimotor striatum.[21] As such, an increase in dopamine from music-contingent *Ambulosono* feedback may increase efficient neural coding of movement and promote the shift of automated motor skills to the sensorimotor striatum.[21] This model may also help explain the fact that the podcast group did not seem to show the same effect as the music-contingent feedback group and that the observed effects were more global rather than targeted to specific DT conditions (Fig. 3). These findings also support the notion that repetitive motor activity alone is not enough for neural plasticity. Rather, it is necessary to "mark" the importance of a stimulus with input from limbic and paralimbic structures, here with the affective and emotional valence of music,[18,32] such that the task becomes rewarding and meaningful.[39]

4.2. Why SIP and not walking?

The results of the present study are in line with previous laboratory-based DT training studies[12,13] that use linear walking rather stepping. Of course, then, the question is why SIP and not walking? Interventional programs that include SIP are an effective means to improve neuromuscular function, postural control, and promote rehabilitation following injury.[8] Unlike linear walking, SIP requires little space. In addition, individuals with more severe mobility issues such as postural instability and gait disturbances may actually benefit the most, but may be deterred/excluded from traditional walking-based programs due to real/perceived mobility concerns. In fact, SIP can be performed safely even for those who rely on a walker for body support. Furthermore, it has recently been shown that self-selected SIP uses almost as much energy (kcal/h) as brisk walking (3 mph or 1.3 m/s).[40] Thus, motivating paradigms such as *Ambulosono* that promotes automatic stepping and transient balancing on a single leg may also serve as an effective in-home platform to effectively increase general physical activity in seniors with favorable long-term outcomes in activities of daily living.

4.3. Study limitations

This pilot study supports feasibility and suggests that in-home music-continent SIP training is efficacious. However, we acknowledge that there are important limitations to this pilot study. First, while we achieved our goal of feasibility testing of the *Ambulosono* in-home training paradigm, we cannot rule out the possibility that other factors led to the observed improvements such as other forms of physical activity or even continued participation in the PD walking program. However, these patients had already been in the walking program for over a year and were asked to maintain their regular pattern of activity. Nevertheless, future studies should evaluate the current program using a controlled design and covariate-adjusted analysis that can be guided by our calculated Cohen *d* effect size of approximately 1. Furthermore, although it was not possible to evaluate in the current version of the *Ambulosono* algorithm, future study and technological development may also aim to assess the number to times that music stopped during training as an index or biobehavioral marker of impaired capability of maintained attention or focus on the task. This potential marker may have important implications that extend beyond that of single disease management and relate to other neurological conditions that exhibit central fatigue.[37]

A second limitation and important but unanswered question in this study was whether music-contingent SIP, general music effects, or both, are involved in the observed increases in DT step automaticity, and whether this type of training can improve only stepping automaticity or other types of motor automaticity as well (i.e., transfer effects)? This pilot study was not able to address these specific questions and thus future study is needed. Still, given that The Canadian Centre for Activity and Aging's Home Support Exercise Program recommends SIP for physically inactive seniors,[8] these findings provide encouraging evidence that this type of music-contingent SIP training protocol may be an efficacious approach or provide an "entry level" strategy for certain mobility-restricted patients to increase their level of physical activity and step automaticity.

5. Conclusion

Here, we have tested the feasibility of a home-based rehabilitation approach that may offer benefit to improving DT step automaticity in PD. This approach is easy and safe to implement for in-home use and is not restricted for use for those with mobility aids such as walkers. It may also help standardize data collection, facilitate personalized rehabilitation-training program development, and improve reporting across disciplines; ultimately aimed at enhancing primary care delivery and patient monitoring.

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