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Article

Gait Study of Parkinson's Disease Subjects using Haptic Cues with A Motorized Walker

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Abstract: Gait abnormalities are one of the distinguishing symptoms of patients with Parkinson's disease (PD) that contribute to fall risk. Our study compares the gait parameters of people with PD when they walk through a predefined course without assistance, with a conventional walker, and with a motorized walker under different speed cues. Six PD subjects were recruited at the New York Institute of Technology College of Osteopathic Medicine to participate in this study. Spatial posture and gait data of the test subjects were collected via a VICON motion capture system. We developed a framework to process and extract gait features and applied statistical analysis on these features to examine the significance of the findings. The results showed that motorized walkers with haptic cues significantly improved gait symmetry of PD subjects. Specifically, the asymmetry index of the gait cycle time was reduced from 6.7% when walking without assistance to 0.56% and below when using a walker. Furthermore, the double support time of a gait cycle was reduced by 4.88% compared to walking without assistance.

Keywords: Parkinson's Diseases, motorized walker, haptic cue, gait pattern, statistics study.

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1. Introduction

Individuals with Parkinson's disease (PD) may suffer from movement disorders[1]. The symptoms usually start with involuntary hand, arm, or leg tremors, slow movement, rigidity, and postural instability, which leads to different gait disturbances[2]. Stolze *et al.*found that people with PD had a significant spatiotemporal parameters reduction in step length and walking velocity compared with the matched healthy individuals [3]. Individuals with PD may also experience difficulties in step initiation and in postural changes [4]. Although dopaminergic medications, which increase the levels of dopamine[1] in the brain, may help improve gait, their effectiveness decreases as the disease progresses [5].

A growing body of research has demonstrated that individuals with PD can benefit from various cueing devices [6–8]. Individuals with PD increased their pedaling rate under auditory cueing (provided by a metronome) and visual cueing (presented as central road markers) conditions [9,10]. Individuals with PD can benefit from haptic (touch and proprioception) feedback to improve balance. The use of a walking stick or a laser cane improves the forward/backward and side to side movements comparing to the use of a vibrating metronome [6,11]. Gait patterns of PD patients walking straight on a level ground without assistance were well investigated [2,4,12,13]. However, there is very little information available in the literature on how individuals with PD modify their gait characteristics when using different assistive ambulatory devices with haptic cues.

[1] In the brain, dopamine functions as a neurotransmitter - a chemical released by neurons (nerve cells) to send signals to other nerve cells.

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The aim of this study is to investigate the immediate gait modifications of individuals with PD when they switch from walking without assistance to walking with a conventional or a motorized walker. We attempt to answer the questions whether haptic cues mitigate patients motor performance and how PD subjects adapt to various speed cues.

In this study, we collected spatiotemporal postural and gait data from six PD subjects walking in a predesigned course via the VICON motion capture system (Vicon, Denver, CO) under three conditions of manual gait aids: none (without assistance), with a conventional rolling walker, and with a motorized walker, where the motorized walker can be set up to operate at three different speeds ranges: low (32-52 cm/s), medium (52-72 cm/s), and high (72-96 cm/s). The postural and gait data was filtered and processed to extract gait features. We applied statistical analysis on the extracted gait features to determine the significance of the gait modifications and used asymmetry index [14] to analyze the bilateral coordination of the locomotion.

Our analysis showed that test subjects walking with a conventional walker and a motorized walker showed better gait symmetry performance than walking without assistance. Subjects also walked faster with an increasing haptic speed cue and increased stride height and stride length while using the motorized walker with a speed cue above the medium speed range. We also observed that test subjects walking with a conventional walker and a motorized walker exhibited less double support time out of the gait cycle time. When walking with the motorized walker on a medium speed cue, subjects had on average 4.88% less double support time, which indicated a faster gait initiation under this condition.

2. Related Work

Human gait is the periodic movement of limbs, trunk, and arms during locomotion. The bipedal gait cycle consists of right-side and left-side steps. De Rossi *et al.*introduced a six-phase gait model, where each side has an initial, a swing, and a stance phase [15]. An eight-phase gait model was introduced that expands the initial phase into two additional sub phases: initial contact and loading response phases [16]. Gait cycle time, stride length, stride height, gait initiation and other gait parameters are of interest to clinicians in understanding the disease progression of patients with PD [13,17]. It has been shown that the stance phase for the control subjects occupies approximately 60% of the gait cycle, and the swing phase occupies the remaining 40% [18]. Individuals with PD have difficulty controlling balance and gait, which can lead to falling, injury, dependence and loss of quality of life. Toledo *et al.*showed that individuals with PD have shorter steps, reduced stride height and extended stance phase compared to the healthy controls [19]. Impaired balance and gait, including freezing of gait, in PD has been attributed in part to changes in the attention. Freezing of gait often occurs during situations requiring gait changes or divided attention such as turning or narrow passages [20]. Hausdorff *et al.*demonstrated PD subjects who experience freezing of gait have distinctive impairments in the bilateral coordination of locomotion [21].

Auditory timing cues can have positive rehabilitative effects on various gait characteristics of PD [22], stroke [23], and hemiparesis [24] patients. For patients with PD, visual cues have shown to improve stride length, while auditory cues have shown to improve cadence [22]. However, Morris *et al.*[25] reported that the beneficial effects disappeared when the visual and attentional cues were removed. Thus, the cues should always be present to maintain their rehabilitative effects. Baldan[26] reviewed different experiments on the effect of light touch on postural sway in individuals with balance problems. The findings suggested that the maintenance of the fingertip lightly touching an external surface provided additional somatosensory information for individuals with poor balance and improved the control of upright standing during intervention programs [27]. Assistive ambulatory devices such as walking canes and walkers have been used to maintain constant haptic cue. Bryant showed that persons with PD walked with slower gait speed and reduced stride length when using a cane and a wheeled walker compared to walking without any device [28]. However, Kegelmeyer stated that PD subjects produced the natural gait pattern when using a wheeled walker, by not slowing

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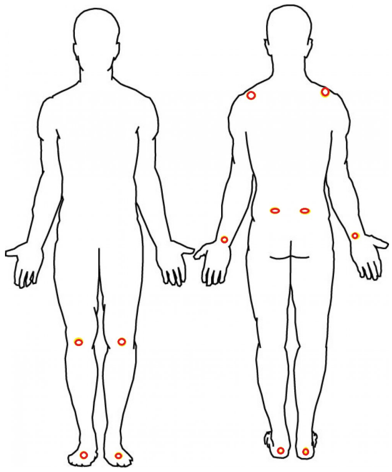

Figure 1. Red circles show the location of the retroreflective markers.

velocity or increasing variability as other devices do [29]. In this study, we tested whether gait of people with PD would improve when following haptic speed cues from a self-propelled walker.

3. Methods

3.1. Subjects and Protocols

Six PD patients (five males and one female) between the ages of 44 and 77 (median: 66) and at Hoehn and Yahr stage 2-3, were recruited at the New York Institute of Technology College of Osteopathic Medicine to participate in this study. This study was reviewed and approved by NYIT Institutional Review Board. The Unified Parkinson's Disease Rating Scale (UPDRS) scores for the subjects ranged from 18 to 33, and Mini-Mental State Examination (MMSE) scores ranged from 26 to 30. Years diagnosed was between 1 and 27 years (median: 24). Each patient was instructed to walk in a preset course for 4-5 meters and perform a 90-degree turn under the following haptic cue conditions: 1) without assistance, 2) with a conventional walker, and 3) with a motorized walker with various speed cues.

Task: With each of the three experimental conditions, patients walked alongside a 25-foot board, then proceeded to make a 90 degree turn, and continued walking alongside another 25-foot board. The two boards were at a right angle to each other, and the patients walked on the left side of each board.

For each patient, two to three trials of walking without assistance, two to three trials of walking with conventional walker, and six to ten trials of walking with motorized walker were recorded. Incomplete trials were excluded from the study. Notations representing each trial are listed in Table 1.

3.2. Apparatus

A nine-camera VICON motion capture system (Vicon, Denver CO) with a sampling rate of 100 Hz was used for recording the gait and postural parameters of the subjects by measuring ongoing position of reflective markers attached to the following body landmarks: bilateral metatarsals, achilles tendons, lateral collateral ligaments of the knees, iliac crests, wrists, and acromions as shown in Fig. 1. Two additional markers were placed on each walker.

A motorized walker as shown in Fig. 2 was designed to provide speed control and navigation in a preset course [30] by instrumenting a conventional walker with two 64 mm, 12 V gear head motors (Am Equipment, Jefferson, OR) on the rear wheels, a URG-04LX-UG01 laser range sensor (Hokuyo Osaka, Japan), and a micro-controller board (stored inside the compartment under the walker seat).

The motorized walker was configured to move forward and turn at various pre-set speeds. When using the walker, the user holds the handles of the walker where a haptic cue is provided with the

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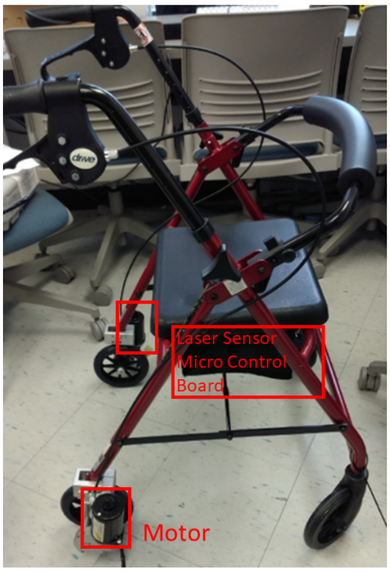

Figure 2. The motorized walker with speed control, preset course navigation, and obstacle avoidance.

automatic movement of the walker that leads the user to move and turn at a pre-set speed. Table 2 shows the various speed configurations for the motorized walker. As an example, let us consider the m01 trial, i.e., the first trial with the motorized walker. The motorized walker accelerates up to the maximum speed of 32 cm/s. The average acceleration is 24 cm/s^2 and the acceleration time is 0.06 s to reach the maximum speed. The configuration parameters can be changed depending on the movement ability of PD patients. In this study, some patients had trials with up to the 80 cm/s maximum haptic speed cues. Upon sensing an obstacle in its path, as a safety measure, the motorized walker proportionally decreases its speed and comes to a full stop.

Table 1. Trial notations.

Notation	Definition
c	walking without assistance
mxx	walking with motorized walker, trial number XX
ml	walking with motorized walker, low speed cue: $[32, 52)$ cm/s
mm	walking with motorized walker, medium speed cue: $[52, 72)$ cm/s
mh	walking with motorized walker, high speed cue: $[72, 96)$ cm/s
w	walking with conventional walker

Table 2. Speed settings for trials with the motorized walker.

Trial No.	Speed Range	Max Speed $[cm/s]$	Acceleration $[cm/s^2]$	Accel. Time $[s]$
m01	ml	32	24	0.06
m02	ml	44	24	0.06
m03	mm	52	24	0.06
m04	mm	60	20	0.1
m05	mm	64	20	0.1
m06	mh	72	12	0.2
m07	mh	80	12	0.2

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Table 3. Terminology

Terminology	Definition
GCT	Gait Cycle Time
SW	Swing Time
ST	Stance Time
DS	Double Support
IDS	Initial Double Support
TDS	Terminal Double Support
SH	Step Height
SL	Step Length

3.3. Data Analysis

Gait is a complex sensorimotor activity that involves spatiotemporal coordination of the legs, trunk, arms, and dynamic equilibrium, all of which are affected by PD. Table 3 outlines the terminology used in describing the gait model. The duration of a complete gait cycle as shown in Fig 3. a) is defined as the *gait cycle time* (GCT) [15,31]. GCT is divided into two phases: *stance time* (ST) and *swing time* (SW). ST denotes the duration when the foot is on the floor, while SW denotes the duration when the foot is in the air. *Double support* (DS) denotes the period when both feet are on the floor. DS can be divided into *initial double support* (IDS), which denotes the duration between the initial foot's heel contact and the other foot's toe off, and *terminal double support* (TDS), which denotes the duration of the subsequent opposite-side heel contact and toe off [32].

The gait parameters are calculated based on the spatiotemporal measurement of the marker locations attached on the subject' body. As shown in Fig. 3.b and 3.c, we use the vertical heel and toe position to identify the gait phases. We use the following spatial location measurements in identifying gait events and calculating gait parameters: $V(k)$ denotes the k^{th} valley of heel position in Z-axis, $P(k)$ denotes the k^{th} peak of heel position in Z-axis, and V_{to} denotes the nearest valley of toe position in Z-axis.

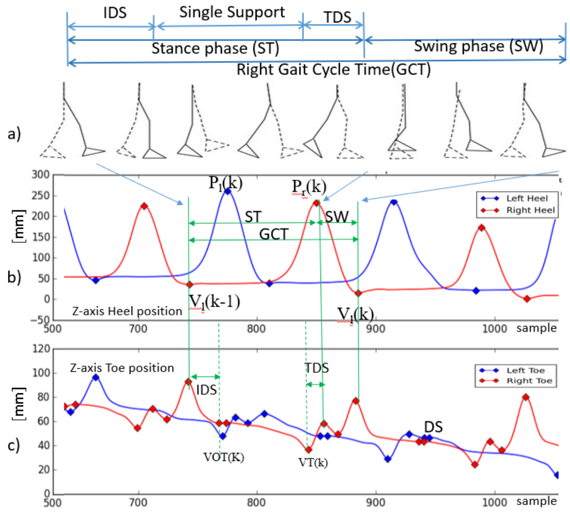

Figure 3. Gait cycle model. a) Gait cycle model b) Z-axis heel position c) Z-axis toe position.

Gait Cycle Time (GCT) is calculated as the duration between two consecutive valleys of the heel position as:

$$GCT(k) = V(k) - V(k-1) \tag{1}$$

Swing Time (SW) is calculated as the duration between two consecutive valley and peak of the heel position:

$$SW(k) = V(k) - P(k) \tag{2}$$

Stance Time (ST) is the remaining period of a GCT minus swing time:

$$ST(k) = GCT(k) - SW(k) \tag{3}$$

Initial Double Support (IDS) time is the duration between the valley of the heel position and its nearest valley of the toe position:

$$IDS(k) = V_{to} - V(k) \tag{4}$$

Terminal Double Support (TDS) time is the duration between the peak of the heel position and its nearest valley of the toe position:

$$TDS(k) = P(k) - V_{to} \tag{5}$$

The step height is the difference between the heel position and its nearest valley position:

$$SH(k) = P(k) - V(k-1) \tag{6}$$

The step length is defined as the difference between the x coordinate of the heel position between two consecutive peaks:

$$SL(k) = P_x(k) - P_x(k-1) \tag{7}$$

where the subscript x indicates the x coordinate. Finally, the velocity is defined as:

$$\text{Vel} = \frac{SL}{GCT} \tag{8}$$

Previous studies showed that the ratio of stance/swing of healthy subjects is about 3:2 [33,34]. IDS warrants the upright stability during walking [35]. It reduces to zero when a subject is running, which means both feet are airborne twice during the gait cycle [36]. Sofuwa *et al.*[37] also showed that PD patients have decreased gait speed and stride length and increased double support time.

Morris et al. [38] reported that patients in the earlier stages of PD may have extended stance time which allows PD subjects maintain their gait stability. The IDS may increase in the the late stage of PD. This long IDS can give the impression that the PD subjects *glue* their feet on the ground.

4. Signal Processing for Gait Analysis

In this section, we introduce the signal processing procedure for gait signal analysis. A block diagram of the procedure is outlined in Fig. 4.

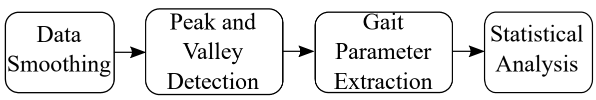

Figure 4. Signal processing procedure for gait analysis.

First, we smoothed raw data to remove noise and identify gait cycle based on [39] through peak and valley detections. Then we extracted the gait parameters following the definition in Section 3-c. Finally we studied the statistical significance of the observations. We explain each procedure in detail in the following section.

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4.1. Data smoothing

To remove noise in the measured signal to find peaks and valleys, two types of filters were evaluated for data smoothing: (1) Convolution [40], and (2) Savitzky-Golay low-pass filter [41]. Convolution did not decrease the amplitude of the signal and retained more of the gait details, and in general performed better than Savitzky-Golay low-pass filter in this context. Thus, we chose convolution for smoothing. A 40-sample Hanning window is used for convolution, so that the window size is less than half of the gait cycle time (0.5 second).

4.2. Peak and valley detection and principle gait parameters extraction

We implemented the peak and valley detection algorithm in Python based on the algorithm presented by Ferrari *et al*. [42]. We used the *argrelextrema* function from the SciPy Python library's signal processing toolbox [43] to identify the peak and valley candidates. Portions of the data that correspond to the turning phase might still be mistaken as peaks and valleys. To remove the turning phase peaks and valleys detection errors, only one peak between two valleys and only one valley between two peaks were selected. Fig. 5 shows the peaks and valleys identified after the smoothing operation is completed and turning phase peaks and valleys are removed. Once the peaks and valleys are identified SW, ST, IDS, SL, and SH are calculated using (2)-(7).

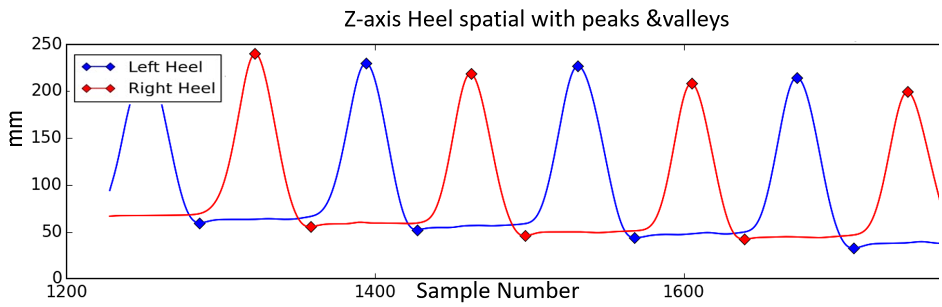

Figure 5. Peaks and valleys of Z-axis heel position

4.3. Statistical Analysis

In this study, we are interested in the variability among the different sets of trials when subjects walk without assistance, with a conventional walker, and with a motorized walker providing haptic speed cues. Towards that goal, we evaluated the mean and standard deviation from five sets of trials (c, ml, mm, mh, w) and applied statistical hypothesis testing, analysis of variance (ANOVA) [44] to test the null hypothesis that two groups have the same population mean. ANOVA is used to examine differences between groups such as PD subjects' velocity vs. speed cues, left side GCT vs. right side GCT.

5. Results

In this section, we present the results comparing the gait parameters observed at different trials and analyze gait symmetry and individual gait performance.

5.1. Gait Parameters

Table 4 shows the spatiotemporal gait parameters for all subjects measured (mean $\pm$ SD) for different trials, i.e., walking without assistance (c), walking with a conventional walker (w), and walking with the motorized walker (m) with low (ml), medium (mm) and high (mh) speed cues. It is clear that the subjects' walking speed closely follows the cueing speed of the motorized walker

($p < 0.01$). For instance, PD subjects walking velocity is 29.24 ± 7.94 cm/s on low speed cues; 52.80 ± 10.56 cm/s on medium speed cues; and 67.33 ± 11.67 cm/s on high speed cues.

We observe that the stride height and stride length also increase with the cueing speed ($p \ll 0.01$). At the lowest cueing speed, the subjects have the lowest stride height (SH: 14.52 ± 4.09 cm) and shortest stride length (SL: 49.72 ± 12.58 cm). At the highest cueing speed, the subjects have the highest stride height (SH: 21.08 ± 2.97 cm) and length (SL: 74.76 ± 12.11 cm).

Table 4. Mean and standard deviation of gait parameters for PD subjects walking without assistance (c), with conventional walker (w), and with motorized walker (m) at low (ml), medium (mm), and high (mh) haptic cue speeds.

Gait Parameters			m		
(unit)	c	w	ml	mm	mh
GCT (s)	1.29 ± 0.25	1.34 ± 0.21	1.68 ± 0.28	1.4 ± 0.2	1.31 ± 0.13
SW (s)	0.35 ± 0.05	0.39 ± 0.06	0.43 ± 0.10	0.38 ± 0.06	0.38 ± 0.06
ST (s)	0.94 ± 0.22	0.95 ± 0.2	1.25 ± 0.28	1.02 ± 0.17	0.94 ± 0.1
IDS (s)	0.24 ± 0.69	0.24 ± 0.11	0.28 ± 0.14	0.22 ± 0.01	0.21 ± 0.06
TDS (s)	0.22 ± 0.03	0.22 ± 0.12	0.25 ± 0.13	0.21 ± 0.13	0.21 ± 0.05
SL (cm)	92.98 ± 1.24	70.61 ± 27.70	49.72 ± 12.58	68.59 ± 11.86	74.76 ± 12.11
SH (cm)	21.19 ± 3.14	20.78 ± 3.40	14.52 ± 4.09	19.02 ± 3.31	21.08 ± 2.97
Vel (cm/s)	75.28 ± 12.99	65.89 ± 17.36	29.24 ± 7.94	52.80 ± 10.56	67.33 ± 11.67

In Table 5, we show that subjects walking with the motorized walker with medium speed cue (mm) exhibit a walking pattern similar to the walking pattern without any assistance (c) as indicated by the smallest p-value for c vs. mm except for swing time. The comparison of p value represents gait with mm produced a pattern most similar to the natural pattern to c.

Table 5. p-values for the pairwise comparison of gait parameters for PD subjects walking without and with motorized walker.

Gait Parameters	Pairwise Comparison of p-value		
(unit)	c vs. mm	c vs. mh	c vs. w
GCT (s)	0.006	0.459	0.245
SW (s)	0.014	0.025	0.0016
ST (s)	0.016	0.599	0.385
IDS (s)	0.083	0.575	0.23
TDS (s)	0.004	0.032	0.021
SL (cm)	$\ll 0.01$	$\ll 0.01$	$\ll 0.01$
SH (cm)	0.0006	0.86	0.582
Vel (cm/s)	0.001	0.00192	0.07

Table 6 compares the gait parameters of both sides on walking without assistance (c) and walking with motorized walker of the medium speed cues (mm). The results indicate that walking without assistance has higher GCT difference ($p = 0.24$) and velocity difference ($p = 0.12$) between right and left sides, whereas motorized walker of medium speed cues has relatively smaller GCT difference ($p = 0.006$) and velocity difference ($p = 0.02$). This result is consistent with the gait symmetry findings in Section 5.2.

Table 7 summarizes the ratio of ST, IDS, and TDS periods in a gait cycle. Accordingly, the motorized walker reduces the PD subjects' ST over GCT when the speed cues are present (74.40%, 73.10%, 71.53% respectively in ml, mm, mh). It infers that PD subjects use less time on the ground when the speed cues are increased. PD subjects walking without assistance present higher IDS and

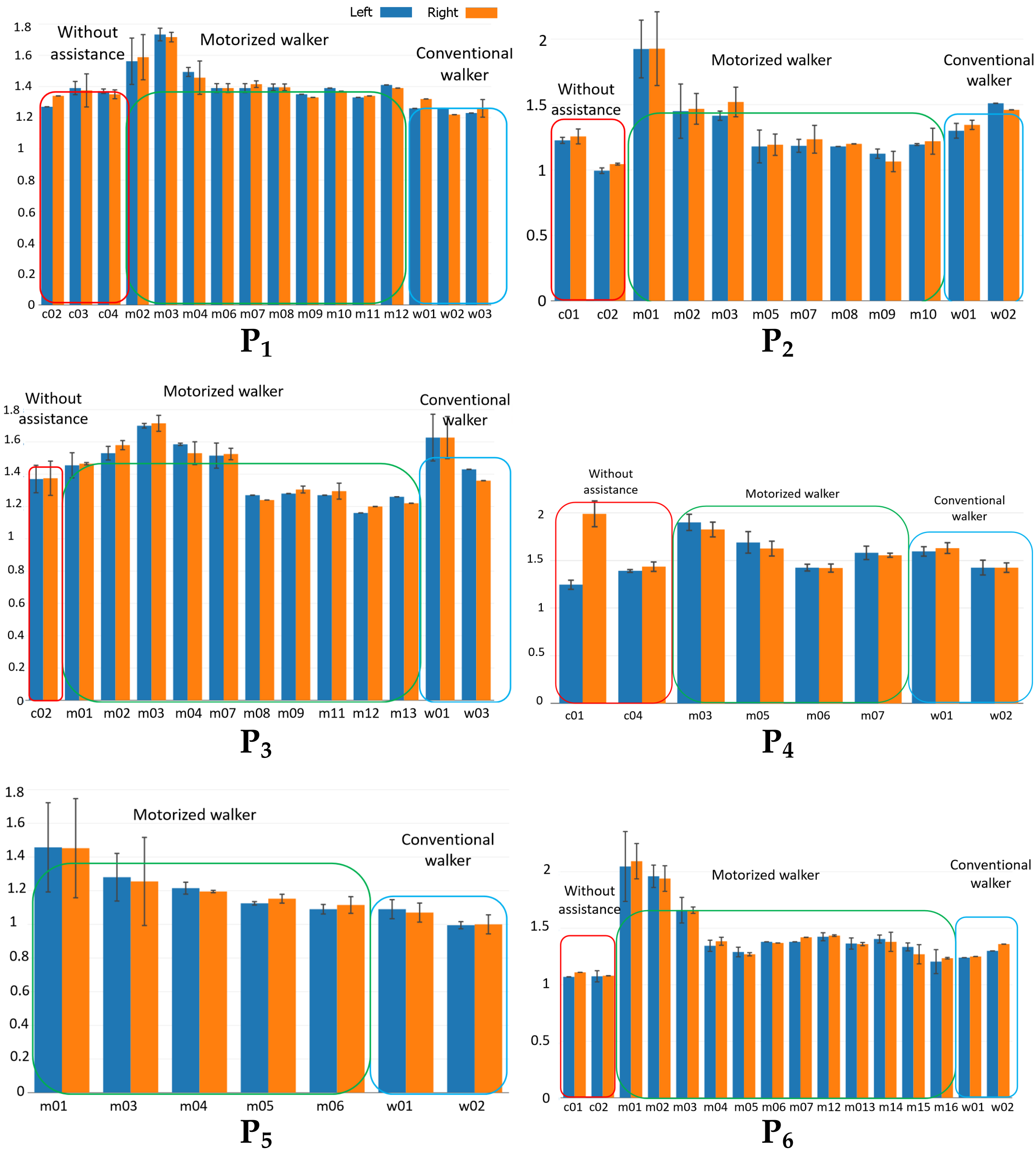

Figure 6. GCT for each of the 6 subjects ($P_1 - P_6$) without assistance, with motorized walker, and with conventional walker.

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Table 6. Comparison of walking with and without motorized walker.

Gait Parameters (unit)	c Right	c Left	c p-value	mm Right	mm Left	mm p-value
GCT (s)	1.33 ± 0.31	1.24 ± 0.16	0.24	1.39 ± 0.19	1.39 ± 0.20	0.006
SW (s)	0.36 ± 0.05	0.34 ± 0.05	0.25	0.38 ± 0.06	0.37 ± 0.05	0.018
ST (s)	0.98 ± 0.31	0.89 ± 0.13	0.14	1.01 ± 0.18	1.03 ± 0.17	0.03
IDS (s)	0.24 ± 0.07	0.24 ± 0.07	0.25	0.22 ± 0.10	0.25 ± 0.09	0.14
TDS (s)	0.22 ± 0.04	0.20 ± 0.02	0.04	0.24 ± 0.17	0.27 ± 0.19	0.05
SL (cm)	93.9 ± 11.05	92.12 ± 13.56	0.17	72.32 ± 13.53	73.38 ± 13.75	0.01
SH (cm)	20.56 ± 3.24	21.81 ± 0.98	0.08	18.69 ± 2.90	19.36 ± 3.67	0.02
Vel (cm/s)	73.97 ± 12.98	76.58 ± 13.19	0.12	52.40 ± 10.44	53.19 ± 10.77	0.02

Table 7. The ratio of ST, IDS, and TDS in a gait cycle.

Gait Parameters	c	m: ml	m: mm	m: mh	w
ST/GCT	72.76%	74.40%	73.10%	71.53%	70.98%
IDS/GCT	18.75%	16.78%	15.66%	15.72%	17.48%
TDS/GCT	16.88%	14.94%	15.09%	16.18%	16.59%
IDS/ST	25.77%	22.56%	21.43%	21.98%	24.63%
TDS/ST	22.45%	20.08%	20.65%	22.62%	23.37%

TDS to GCT ratios ($IDS/GCT = 18.75\%$, $TDS/GCT = 16.88\%$), while PD subjects walking with motorized walker on medium speed cues (mm) have lower ratios ($IDS/GCT = 15.66\%$, $TDS/GCT = 15.09\%$), corresponding to 3.09% and 1.79% lower IDS/GCT, and TDS/GCT ratios, respectively. These observations may indicate PD subjects have less hesitation in initiating a step when walking with motorized walker on medium speed cues.

5.2. Gait Symmetry

Gait symmetry is defined as the perfect agreement between the actions of the lower limbs [45]. *Asymmetry index*, denoted as I_a can be used to quantify gait symmetry or asymmetry [14]:

$$I_a = \frac{X_L - X_R}{\max(X_L, X_R)} \times 100 \tag{9}$$

where, $X \in [GCT, SH, SL, \text{Vel}]$, and subscripts L and R represent left side and right side, respectively. $I_a \in [-1, 0)$ represents right asymmetry (i.e., the value of the gait parameter is higher on the right side), and $I_a \in (0, 1]$ represents left asymmetry. $I_a = 0$ when there is no asymmetry.

Table 8 shows the asymmetry indices of gait parameters. Our results indicate that PD subjects exhibit better overall gait symmetry when they use a motorized or conventional walker compared to walking without assistance. The GCT asymmetry indices ($I_{a,GCT}$) of motorized walker (below 0.1 to 0.56%) or conventional walker (0.53%) are much lower than walking without assistance (6.7%).

Table 8. Asymmetry indices for straight walking.

Gait Parameters	c	m: ml	m: mm	m: mh	w
$I_{a,GCT}$	6.7%	0.56%	$< 0.1\%$	$< 0.1\%$	0.53%
$I_{a,SH}$	5.7%	-3.99%	3.46%	2.12%	1.48%
$I_{a,SL}$	-1.8%	-2.10%	1.44%	1.33%	-3.25%
$I_{a,\text{Vel}}$	3.4%	-9.50%	1.48%	2.03%	-2.75%

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For the stride height asymmetry index ($I_{a,SH}$), similarly, the subjects have more symmetric foot-raising posture with either of the walkers compared to walking without assistance (5.7%). The conventional walker (1.48%) has better stride height symmetry compared to the motorized walker (between -3.99 and 2.12%). For the stride length and velocity asymmetry index ($I_{a,SL}$, $I_{a,\mathrm{Vel}}$), the motorized walker with medium and high speed cues shows better symmetry with regards to stride length ($I_{a,SL}$) at 1.41% and 1.33%, respectively compared to walking without assistance and walking with conventional walker.

Hausdorff *et al.*[21,46] have proposed that gait control impairments (gait asymmetry, and bilateral dyscoordination), even during periods in which freezing is not present, set the stage for the occurrence of a Freezing of Gate (FOG) episode. Our study shows that the walker can immediately modify the gait regulation of PD subjects, demonstrating more bilateral gait symmetry. In this case, it can be hypothesized that the motorized walker giving out haptic cues can possibly improve the bilateral coordination of locomotion and can possibly reduce the FOG occurrence in PD subjects.

5.3. Individual gait performance

In this section, we study the individual PD subject's (P1-P6) trials and compare the results of gait performance for each individual. To determine whether cue speed affects (1) the quality of matching the cue speed and/or (2) amelioration of PD gait symptoms, we organize the trials such that, for each subject, the speed cue starts at a low speed, and gradually increases to higher speeds.

Fig. 6 (a-f) show the GCT for each subject for different trials (based on the notation introduced in Table 1. Each bar corresponds to the GCT mean value in seconds for a different trial (Blue bar: Left side mean, and Orange bar: Right side mean), the error bars indicate the variance of GCT for each case. Trials with noisy or corrupted data due to the data acquisition issues are excluded. The individual GCT bar chart indicates PD subjects need time to adapt to the motorized walker. We observe that PD subjects have high GCT and GCT variance when they start to use the motorized walker. However, after the first one to three trials, GCT drops to a relatively lower level and fluctuates in a smaller range. For instance, for subject P1, GCT $\in [1.5, 1.7]$ during the first three trials using the motorized walker, but drops to $[1.3, 1.4]$ after that.

A possible extension to this work is to reverse the order of the presentation of the speed cues such that trials start with higher speed cues, and gradually decrease to lower speeds to see the impact on the adaptation to use the motorized walker.

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