Title: Falls in Parkinson's disease: kinematic evidence for impaired head and trunk control

Authors: Michael H. Cole[1, 2], Peter A. Silburn[1, 3], Joanne M. Wood[4], Charles J. Worringham[2], Graham K. Kerr[1, 2]

Affiliations:
1. Movement Neuroscience Program, Institute of Health and Biomedical Innovation, Queensland University of Technology, AUSTRALIA
2. School of Human Movement Studies, Queensland University of Technology, AUSTRALIA
3. School of Medicine, University of Queensland, AUSTRALIA
4. School of Optometry, Queensland University of Technology, AUSTRALIA

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Address for correspondence: A/Prof Graham Kerr
Movement Neuroscience Program
Institute of Health and Biomedical Innovation
Queensland University of Technology
60 Musk Avenue, Kelvin Grove
Brisbane, Queensland, 4059. AUSTRALIA

Email Address: g.kerr@qut.edu.au

Telephone: +61 7 3138 6303

Facsimile: +61 7 3138 6030

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Abstract

Changes in stride characteristics and gait rhythmicity characterise gait in Parkinson's disease and are widely believed to contribute to falls in this population. However, few studies have examined gait in PD patients who fall. This study reports on the complexities of walking in PD patients who reported falling during a 12 month follow-up. Forty-nine patients clinically-diagnosed with idiopathic PD and 34 controls had their gait assessed using three-dimensional motion analysis. Of the PD patients, 32 (65%) reported at least one fall during the follow-up compared with 17 (50%) controls. The results showed that PD patients had increased stride timing variability, reduced arm swing and walked with a more stooped posture than controls. Additionally, PD fallers took shorter strides, walked slower, spent more time in double-support, had poorer gait stability ratios and did not project their centre of mass as far forward of their base of support when compared with controls. These stride changes were accompanied by a reduced range of angular motion for the hip and knee joints. Relative to walking velocity, PD fallers had increased mediolateral head motion compared with PD non-fallers and controls. Therefore, head motion could exceed 'normal' limits, if patients increased their walking speed to match healthy individuals. This could be a limiting factor for improving gait in PD and emphasises the importance of clinically assessing gait to facilitate the early identification of PD patients with a higher risk of falling.

Keywords: Falls; Motion Analysis; Kinematics; Gait; Postural Control

Introduction

Parkinson's disease (PD) is an age-related neurodegenerative condition characterised by slowness of movement (bradykinesia)[1], muscle rigidity (akinesia)[1-3] and resting tremor[2, 4], but as the disease progresses postural instability[1, 5] and gait difficulties[1, 4] begin to affect activities of daily living. Declines in physical functioning effectively expose people with PD to a nine times greater risk of recurrent falls[6], and a five times greater risk of sustaining fall-related injuries[7] compared with healthy individuals of a similar age. A recent meta-analysis of six prospective studies showed that approximately 46% of the PD patients reported at least one fall in the 3-month follow-up period[8]. Cross-sectional studies indicate that difficulties with gait and dynamic postural control play an important role in many of these falls, of which nearly half occur during walking, turning or other forms of ambulation[9].

While there have been numerous studies documenting changes in the gait characteristics of PD patients with respect to healthy age-matched controls, only three have examined the gait patterns of PD patients who fall. In an earlier study, Schaafsma et al.[10] reported that stride timing variability was significantly greater in PD patients who had a history of falling while both on and off medication. More recently, a cross-sectional study by Latt et al.[11] showed that PD fallers walked more slowly than PD non-fallers and controls, took shorter steps than controls, but maintained the same stride frequency (cadence). Furthermore, PD fallers had lower harmonic ratios for pelvic and head movement in both the anteroposterior and vertical directions (less rhythmic), implying reduced walking stability in this sub-population[11]. In contrast, the subsequent prospective study of these patients by Latt et al.[12] reported that step length, walking speed and step timing variability was not significantly different for PD fallers compared with non-fallers, but cadence was significantly decreased. While this prospective study employed the gold-standard methods for recording falls[13], the analysis of the gait-

related data was limited to the temporospatial characteristics and did not include more complex parameters that are likely to contribute to balance control and falls. Therefore, this research aimed to examine the three-dimensional gait characteristics of PD patients who prospectively reported falling over a twelve month period, with the intent of identifying kinematic quantities that might characterise fallers and be amenable for modification through tailored interventions. It was hypothesised that PD fallers would show differences in temporospatial and joint kinematic quantities compared with non-fallers and controls and would have poorer control of the head and pelvis during walking.

Methodology

Study Population

Forty-nine participants who were clinically diagnosed with idiopathic PD (66.4 ± 1.2 yrs) were recruited from community support groups and neurology clinics in South-East Queensland between March 2005 and December 2006. During the same period, thirty-four healthy controls (67.6 ± 1.6 yrs) were randomly recruited from the Brisbane metropolitan area via the Australian electoral role. Participants were sent a letter of invitation and an information sheet, which outlined the potential risks and benefits of the research and were then contacted by telephone to establish their interest in participating. Participants were excluded if they had a recent or recurrent history of musculoskeletal injury or surgery, were unable to ambulate independently without the use of a walking aid, or had any significant visual (Bailey-Lovie high contrast visual acuity >0.30 logMAR) or cognitive impairment (Mini Mental State Exam[14] score <24 out of 30). Participants gave written informed consent to participate in accordance with the Declaration of Helsinki and the experimental protocol was approved by the Human Research Ethics Committee at the Queensland University of Technology. Based on previous studies of walking and postural stability in PD[15, 16], it was considered that a minimum of 15 people per group would be sufficient to detect differences between groups.

Insert Table 1 about here.

Clinical Assessment

During an initial session scheduled up to one week prior to the gait assessment, an experienced movement disorders specialist established patients' disease severity using standard clinical tests, including the Unified Parkinson's Disease Rating Scale[17] (UPDRS)

and the Hoehn & Yahr (H&Y) score[18]. Fear of falling and freezing of gait were assessed using the Modified Falls Efficacy Scale[19] and the Freezing of Gait (FOG)[20] questionnaire, respectively. A measure of postural instability and gait disability (PIGD) was derived by summing the scores for items 13 to 15 and 27 to 30 from the UPDRS. All but five PD patients (10.0%) were treated with levodopa or dopamine agonist supplementation and all procedures were undertaken within 1 to 2 hours of a medication dose to ensure that the patients were optimally-medicated at the time of testing.

Three-Dimensional Gait Assessment

Participants performed six trials consisting of walking barefooted at a self-selected pace along a firm walkway (L: 12 m x W: 2.2 m x H: 0.1 m). Twenty-eight spherical markers were positioned on the body in accordance with the Helen Hayes marker set[21], which was modified to include the upper body and head. Markers were attached over specific anatomical landmarks on the trunk (sacrum, sternum, C7 spinous process), arms (lateral border of the acromion, olecranon process of the humerus, radial and ulnar styloids), and head (supra-auricular point, top of the head). Markers were attached over bony landmarks by the same experienced movement specialist to minimise errors associated with skin movement and marker placement.

Marker positions were tracked within the central 4 m length of the 12 m walkway (50 Hz) by a previously calibrated six-camera motion analysis system (Motus 2000; Vicon, Oxford, UK) for two complete gait cycles (1 right; 1 left). The data were reconstructed using the direct linear transformation (DLT) algorithm[22] and the full body linked-segment model was used to calculate temporospatial gait parameters and angular quantities for the lower limbs. These included stride length, step width, cadence, double support (percent of gait cycle with both

feet on the ground), walking velocity (stride length/stride period), stride timing variability (SD of stride period)[23] and the Gait Stability Ratio (stride frequency/walking velocity)[24]. The position of the centre of mass (COM) relative to the base of support (BOS) was examined in the mediolateral (ML) and anteroposterior (AP) directions and the ML and vertical (VT) displacement of the head and pelvis were assessed to provide a measure of segmental control. Arm swing was calculated as displacement of the wrists in the sagittal plane. These variables were selected because it was believed that older individuals seek to reduce stride length and walking velocity and increase double support time to better control the body and minimise postural instability[25]. Similar compensatory changes in temporospatial gait characteristics have been shown for PD patients[15, 26, 27], but it is unclear whether these changes improve postural stability in this population.

Angular kinematics of the trunk, hip, knee and ankle joints were also examined in the sagittal plane. Trunk flexion angle was defined as the angle formed between the vector joining the markers positioned on the sacrum and C7 spinous process and the vertical axis of the global coordinate system. Hip flexion/extension angle was calculated as the angle formed between the vertical axis of the pelvis segment and the vector joining the hip and knee joints in the sagittal plane. Similarly, knee flexion/extension was measured as the motion between the vectors joining the hip and knee joints and the knee and ankle joints. Ankle plantar- and dorsi-flexion was calculated as the angle formed between the vector joining the ankle joint and the second metatarsal joint, where zero degrees was the point at which the two vectors were perpendicular to each other.

12-Month Prospective Follow-up.

Following testing, the participants were asked to record any falls or injuries that they experienced on a daily falls calendar, which they returned on a monthly basis via a reply-paid envelope over the subsequent 12-month period. When participants reported having a fall, they were asked to provide additional information related to the timing, location and cause of the fall. If participants failed to complete their monthly calendars they were sent reminders by mail and received follow-up phone calls. For the purposes of this study, a fall was defined as "an unintentional coming to the ground or some lower level not as a result of a major intrinsic event (e.g. stroke or syncope) or overwhelming hazard"[28].

Statistical Analysis.

Analysis of variance (ANOVA) was used to determine mean differences between PD patients and controls and the four faller groups for the demographic, temporospatial and joint kinematic variables. To determine where statistically significant differences existed between faller and non-faller groups, the Tukey's Honestly Significant Difference (HSD) post-hoc test was used. The HSD procedure controls for the overall significance level when performing all pairwise comparisons in ANOVA and therefore reduces the likelihood of a Type 1 error. In circumstances where the assumptions of the ANOVA were violated, the non-parametric Kruskal-Wallis Test was used. The degree of association between the categorical variables was assessed with the chi-square (χ^2) test. All statistical procedures were conducted using SPSS 16 and the level of significance was set at $p < 0.05$.

Results

Falls

During the 12-month follow-up, 32 (65%) PD patients and 17 (50%) control participants reported at least one fall, while 21 (43%) PD and 9 (27%) control participants reported falling twice or more. Based on the prospective falls data, participants were divided into four groups; PD Fallers (n = 32); PD Non-Fallers (n = 17); Control Fallers (n = 17); and Control Non-Fallers (n = 17).

Clinical Characteristics

PD and control participants were of similar age, height, mass and BMI, and had similar scores for the MMSE and Bailey-Lovie high contrast visual acuity. The modified falls efficacy scale showed that PD fallers had an increased fear of falling compared to PD non-fallers and controls and reported more falls during the previous 12 months than PD and control non-fallers. PD fallers and non-fallers had similar disease severity based on the UPDRS, H&Y and PIGD score, but PD fallers had a significantly greater disease duration and FOG score than non-fallers. Average daily Levodopa dose was not different between the PD fallers and non-fallers (Table 1).

Temporospatial Characteristics

Insert Figure 1 about here.

PD fallers walked significantly more slowly than PD non-fallers and control participants and took significantly shorter strides than controls (Figure 1). PD fallers had higher (poorer) gait stability ratios and spent significantly more time in the stance phase and double support when

compared to controls. Despite these findings, PD non-fallers did not differ significantly from controls for any of the temporospatial measures.

Segmental Motion

Insert Figure 2 about here.

PD fallers had significantly reduced arm swing and did not project their COM as far forward of their BOS compared to the control participants (Figure 2). However, further analysis of the data showed that the position of the COM relative to the BOS was directly proportional to walking speed. The groups did not differ for mediolateral head and pelvis motion (Table 2), but normalisation of these data to walking speed demonstrated that PD fallers had significantly increased mediolateral head motion compared with PD non-fallers and controls (Figure 3). Furthermore, there was a tendency for PD fallers to have increased mediolateral pelvis motion compared with PD non-fallers and controls, but this did not achieve statistical significance. Normalised mediolateral head motion and arm swing were negatively correlated for the whole sample (Spearman's $\rho = -0.383$; $p < 0.001$), indicating that increased arm swing corresponded with reduced mediolateral head motion.

Insert Figure 3 about here.

Joint Kinematics

PD fallers had a reduced range of knee flexion/extension compared to PD non-fallers and controls and had reduced hip flexion/extension compared with the controls. However, there were no differences between the groups for trunk flexion or ankle plantar- and dorsi-flexion

(Table 2). PD non-fallers did not differ significantly from controls for any of the angular measures and normalisation of the joint ranges to stride length yielded similar angular ranges for all four groups.

Insert Table 2 about here.

Discussion

This study is one of the first to fully categorise segmental control during walking in Parkinson's disease patients who reported falling in the ensuing 12 months. The findings demonstrated that PD fallers have very different walking patterns to healthy controls (either fallers or non-fallers) and identified a trend of declining gait performance from the control non-fallers to the PD fallers. The temporospatial findings were in agreement with those presented previously for PD patients with respect to healthy controls[15, 16, 26, 27, 29, 30] and one cross-sectional study that compared PD fallers, non-fallers and controls[11]. However, they were in contrast to those of a recent prospective study, which reported reduced cadence, but no differences in step length or walking velocity for PD fallers compared with PD non-fallers[12].

The joint kinematics confirmed previous reports of a more stooped walking posture[31, 32] and reduced lower limb joint mobility[15, 30] in PD patients. However, expressed relative to stride length, these joint angle differences were negated and were commensurate with the slower walking velocity of PD fallers. Therefore, it was unclear whether the differences observed for the PD fallers were related to reduced joint mobility or the adoption of a more "cautious" gait pattern. Shorter stride length and slower walking velocity have been suggested to result from muscle weakness or postural abnormalities in PD[5, 33] and older adults may adopt these characteristics in an attempt to improve stability by reducing upper body motion[34]. Such stride changes in PD patients are thought to arise from deficits in basal ganglia output to the supplementary motor area and pre-motor cortex[15, 35], which lead to a mismatch between the selected and actual size of well-learned and repetitive movement sequences[15, 35].

Reduced arm swing was observed in the PD groups and has been reported extensively in the previous literature[e.g. 36-38] as one of the first presenting features of PD[37, 39]. Unlike lower limb kinematics, this characteristic was not accounted for by differences in walking speed, which suggests it was independent of the other changes. Recent evidence shows that the arms contribute to walking efficiency, by reducing vertical ground reaction moments[40] and/or improving lateral stability[41]. This notion was supported by the finding that, relative to walking speed, PD fallers had significantly increased mediolateral head motion. The negative bivariate relationship between normalised mediolateral head motion and arm swing is consistent with such a mechanism. Conversely, Latt et al.[11] reported no significant differences between PD fallers and non-fallers for mediolateral stability of the head or pelvis, following adjustment for velocity and step timing variability, but reported significantly improved stability in controls. These authors theorised that PD patients might walk with an increased step width to maintain mediolateral stability[11]; however our data did not support this. Our findings, instead, suggest that if patients were to increase their walking speed, mediolateral head motion would likely exceed 'normal' limits. Consequently, their shorter stride lengths may be driven by the need to maintain control of the upper body, which comprises approximately 60 to 70 percent of the body's mass[42]. This notion is supported by the observation that older adults who walked more slowly exhibited improved local and orbital stability[43] and that mediolateral head stability is optimised (higher harmonic ratio) at slower walking velocities in younger participants[44].

It is worth noting, that the PD fallers had an increased fear of falling, which has previously been associated with declines in gait performance[45]. While this fear may have emanated from the greater number of previous falls experienced by these patients, it could also reflect a greater awareness of deficits in walking stability.

A possible limitation of this research is that the PD participants were predominantly early stage patients (H&Y $\leq$ 2). Nonetheless, the results demonstrated that falls are a significant problem even in the early stages of PD and that the observed impairments in postural control could be exacerbated in later stage PD patients who are known to have an increased risk of falling.

This study demonstrates the complexity of gait problems in PD patients who fall. It is suggested that, while it may be possible to improve the efficiency and appearance of gait in PD patients with the use of visual[e.g. 15, 46] or auditory cues[e.g. 47, 48], these improvements may exacerbate mediolateral instability of the head and inherently increase the risk of falling. Therefore, it is important to ensure that these gait characteristics are assessed clinically to facilitate the early identification of PD patients who have a higher propensity to falling. Furthermore, knowledge of such differences in the stride characteristics and segmental control provides scientists and clinicians with information that may aid the development of more effective intervention strategies to assist in preventing falls in this population.

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Figure Captions

Figure 1: Mean (+1 SEM) stride length, walking speed, gait stability ratio and double-support time for the PD fallers, PD non-fallers, control fallers and control non-fallers (* $p < 0.05$).

Figure 2: Average (+1 SEM) arm swing and projection of the centre of mass relative to the base of support in both the anteroposterior (AP) and mediolateral (ML) directions (* $p < 0.05$).

Figure 3: Mean (+1 SEM) mediolateral and vertical displacement of the head and pelvis (a) unadjusted for walking speed and (b) adjusted for walking speed (* $p < 0.05$).

Table Captions

Table 1: Demographic details and disease-specific scores for the Parkinson's disease and Control participants and the faller and non-faller sub-groups.

Table 2: Temporospatial characteristics, segmental coordination and sagittal joint kinematics for the Parkinson's disease and Control fallers and non-fallers. Data represent the mean (and standard error of the mean (SEM)) values.

Tables

	PARKINSON'S DISEASE				
	Patients with PD (n = 49)	**Non-Fallers (n = 17)**	**Fallers (n = 32)**	**Test**	***p*-value**
Demographics					
Age (years)	66.4 (1.2)	66.9 (2.1)	66.2 (1.4)	1	0.772
Gender (male)	33 (67.3%)	13 (76.5%)	20 (62.5%)	2	0.321
Height (cm)	167.1 (1.1)	166.6 (1.7)	167.3 (1.4)	1	0.742
Weight (kg)	73.8 (1.9)	69.4 (2.8)	76.1 (2.5)	3	0.231
BMI (kg/m^2)	26.4 (0.6)	24.9 (0.8)	27.1 (0.8)	1	0.068
Falls History and Fear of Falls					
Modified Falls Efficacy Scale	8.7 (0.3)	9.7 (0.1)	8.3 (0.4)	3	**0.005**
Previous Falls	2.9 (2.0)	0.3 (0.1)	4.3 (3.1)	3	**0.013**
Visual and Cognitive Functioning					
High Contrast Visual Acuity (LogMAR)	0.00 (0.01)	-0.02 (0.02)	0.01 (0.02)	3	0.259
Mini-Mental State Exam	27.4 (0.3)	27.8 (0.5)	27.1 (0.4)	1	0.258
Neurological Exam					
Disease Duration (years)	5.4 (0.5)	3.9 (0.6)	6.2 (0.7)	3	**0.044**
Levodopa dose (mg/day)	657.6 (75.7)	598.8 (75.8)	688.8 (109.2)	3	0.736
Freezing of Gait	4.0 (0.6)	2.1 (0.6)	5.0 (0.7)	3	**0.004**
Hoehn & Yahr	1.8 (0.1)	1.6 (0.2)	1.8 (0.1)	3	0.393
UPDRS Total	31.8 (2.3)	26.6 (3.7)	34.5 (2.7)	1	0.097
PIGD	3.9 (0.5)	3.0 (0.6)	4.4 (0.6)	1	0.156
	CONTROLS				
	All Controls (n = 34)	**Non-Fallers (n = 17)**	**Fallers (n = 17)**	**Test**	***p*-value**
Demographics					
Age (years)	67.6 (1.6)	65.1 (2.1)	70.2 (2.3)	1	0.109
Gender (male)	20 (58.8%)	10 (58.8%)	10 (58.8%)	2	1.000
Height (cm)	168.6 (1.5)	169.8 (2.1)	167.5 (2.0)	1	0.437
Weight (kg)	77.6 (2.8)	79.1 (3.9)	76.0 (4.0)	3	0.730
BMI (kg/m^2)	27.1 (0.7)	27.3 (0.9)	26.9 (1.1)	1	0.824
Falls History and Fear of Falls					
Modified Falls Efficacy Scale	9.7 (0.1)	9.7 (0.1)	9.7 (0.2)	3	0.926
Previous Falls	0.4 (0.1)	0.3 (0.2)	0.5 (0.2)	3	0.167
Cognitive Functioning					
High Contrast Visual Acuity (LogMAR)	0.01 (0.01)	0.00 (0.01)	0.02 (0.02)	3	0.357
Mini-Mental State Exam	27.8 (0.4)	27.8 (0.6)	27.7 (0.6)	1	0.890

N.B. Data are mean (+1 SEM) or absolute numbers and percentages. Test 1 = one-way ANOVA; Test 2 = χ^2 test; Test 3 = Kruskal-Wallis Test

Table 1.

	PD Faller (n = 32)		PD Non-Faller (n = 17)		Control Faller (n = 17)		Control Non-Faller (n = 17)		
	Mean	**SEM**	**Mean**	**SEM**	**Mean**	**SEM**	**Mean**	**SEM**	**Sig.**
Temporospatial									
Stride Length (m)	1.10	0.03	1.21	0.04	1.25	0.03	1.30	0.04	**a, c, d**
Step Width (cm)	8.41	0.50	8.03	0.65	8.17	0.80	9.23	0.75	**ns**
Cadence (steps/s)	1.86	0.04	1.90	0.03	1.95	0.02	1.97	0.05	**ns**
Stance Phase (%)	62.64	0.40	61.68	0.27	60.87	0.50	60.46	0.49	**a, c, d**
Swing Phase (%)	37.36	0.40	38.32	0.27	39.13	0.50	39.54	0.49	**a, c, d**
Double Support (%)	25.54	0.77	23.20	0.55	21.76	1.06	21.12	1.04	**a, c, d**
Single Support (%)	74.75	0.79	76.68	0.54	78.29	1.01	79.11	0.99	**a, c, d**
Velocity (m/s)	1.03	0.04	1.15	0.04	1.22	0.04	1.28	0.05	**a, b, c, d**
Stride Timing Variability	29.87	2.27	28.65	2.58	22.39	1.59	24.64	2.04	**a**
Gait Stability Ratio	1.87	0.06	1.68	0.05	1.62	0.04	1.57	0.04	**a, c, d**
Segmental Motion (cm)									
Avg Arm Swing	21.55	2.33	25.39	2.16	28.54	1.66	34.24	2.64	**a, c, d, f**
COM to BOS - AP	27.16	0.94	30.72	0.99	31.30	1.10	32.33	1.35	**a, c, d**
COM to BOS - ML	-4.05	0.23	-3.86	0.27	-3.84	0.29	-4.36	0.24	**ns**
Head Motion - VT	2.95	0.17	3.22	0.17	3.49	0.20	3.79	0.31	**a**
Head Motion - ML	5.34	0.30	4.53	0.26	4.88	0.26	5.22	0.37	**ns**
Pelvis Motion - VT	2.95	0.16	3.23	0.17	3.45	0.19	3.71	0.30	**a**
Pelvis Motion - ML	4.42	0.25	4.12	0.21	4.44	0.26	4.65	0.19	**ns**
Norm Head Motion - VT	2.86	0.12	2.80	0.11	2.85	0.12	2.96	0.18	**ns**
Norm Head Motion - ML	5.43	0.35	4.01	0.27	4.13	0.34	4.19	0.39	**a, b, c, d**
Norm Pelvis Motion - VT	2.87	0.11	2.81	0.10	2.82	0.12	2.91	0.18	**ns**
Norm Pelvis Motion - ML	4.44	0.26	3.65	0.22	3.67	0.21	3.69	0.23	**ns**
Joint Kinematics (°)									
Trunk Flexion Angle	13.55	0.81	11.56	0.83	10.77	0.61	11.47	0.72	**a**
Trunk Flexion Range	3.18	0.19	3.17	0.17	3.42	0.21	4.02	0.44	**ns**
Hip Flx/Ext Range	35.75	0.97	39.64	1.56	41.08	1.03	43.54	1.70	**a, c, d**
Knee Flx/Ext Range	47.65	1.13	52.12	1.15	52.52	1.12	53.86	1.41	**a, b, c, d**
Ankle Dor/Pln Range	23.76	0.71	26.98	0.88	25.53	1.04	25.69	1.12	**ns**
Norm Hip Flx/Ext Range	32.73	0.67	32.93	1.00	32.97	0.65	33.46	0.48	**ns**
Norm Knee Flx/Ext Range	43.98	1.24	43.64	1.24	42.25	0.99	41.72	0.90	**ns**
Norm Ankle Dor/Pln Range	22.02	0.81	22.53	0.75	20.45	0.69	20.09	1.09	**a**

ns. No significant differences between the groups ($p > 0.05$)
a. PD significantly different to Controls ($p < 0.05$)
b. PD Fallers significantly different to PD Non-Fallers ($p < 0.05$)
c. PD Fallers significantly different to Control Fallers ($p < 0.05$)
d. PD Fallers significantly different to Control Non-Fallers ($p < 0.05$)
e. PD Non-Fallers significantly different to Control Fallers ($p < 0.05$)
f. PD Non-Fallers significantly different to Control Non-Fallers ($p < 0.05$)
g. Control Fallers significantly different to Control Non-Fallers ($p < 0.05$)

Table 2.

Author Roles

1. **Research project:** **A.** Conception **B.** Organization **C.** Execution
2. **Statistical Analysis:** **A.** Design **B.** Execution **C.** Review and Critique
3. **Manuscript:** **A.** Writing of first draft **B.** Review and Critique

Dr Michael H. Cole: 1C, 2, 3

Professor Peter A. Silburn: 1, 2C, 3B

Professor Joanne M. Wood: 1B, 1C, 2C, 3B

Dr Charles J. Worringham: 1A, 1B, 2C, 3B

Associate Professor Graham K. Kerr: 1, 2A, 2C, 3B

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