Examining the influence of attentional distraction and emotional distress on gait behaviour in Functional Gait Disorders

by

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

Functional Gait Disorders (FGD) are a subgroup of Functional Neurological Disorders (FND) that are characterized by the presence of abnormal postures and movements whose appearance and severity fluctuate, or are inconsistent, over time. These movements appear voluntary but are reported to be involuntary by the patient. FGD symptoms may arise from abnormalities in attentional and emotional regulation, and these dysfunctions lead to loss of agency (control) over movement. These movements may mimic those of other neurological disorders, however sensory and motor testing reveals normal function. This preservation of function despite symptom presentation is referred to as symptom incongruency. Due to the inconsistency and incongruency FGD symptoms, as well as the heterogeneity in phenomenology across individuals with FGD, diagnosis proves a challenge. Individuals with FGD often face delays and excessive costs when pursuing an appropriate diagnosis, ultimately prolonging their disability and delaying access to adequate treatment.

A majority of previous work has utilized qualitative approaches to phenotype FGD and aid in diagnosis. While these approaches provided key foundational information about FGD, they do not capture all aspects of FGD. Therefore, quantitative methods of FGD may provide more insight into its phenomenology. However, there is a lack of work utilizing quantitative approaches in FGD. Existing work has primarily focused on the influence of attentional distraction on symptom presentation and severity during gait, providing mixed evidence addressing the influence of attention on functional gait. Similar to qualitative descriptions, some quantitative evidence shows an improvement in symptom presentation and severity while completing a secondary task. To date, there have been no studies investigating the effect of emotional distress on gait in FGD, and this area would be important to investigate given that emotional dysregulation is a key component of FGD phenomenology. While anxiety during gait has been manipulated with postural threat paradigms, the threat of shock paradigm has also been shown to elicit anxiety in laboratory settings. However, the threat of shock has not yet been utilized in gait research. Investigating its validity for use in gait may provide more insight into how this paradigm provokes anxiety during walking, and how walking may change during this scenario.

As such, the present thesis aims to address several gaps in the literature. The first is that there are few quantitative descriptors of FGD phenomenology, therefore identifying descriptors may complement and augment qualitative observation and subsequent diagnosis. The second is that while the influence of attention has been investigated in FGD, there has been limited work done investigating the influence of emotional distress on gait in this population, despite its self-reported influence on symptom provocation. Understanding or characterizing the influence of emotional distress on gait in this group may provide novel insights for clinical diagnosis. The use of the novel threat of shock paradigm may also provide more insight into the influence of anxiety on walking in FGD. Together, the present study aimed to address these gaps by utilizing the novel threat of shock paradigm to investigate the influence of attentional distraction and emotional distress on gait behavior and symptom severity in individuals with FGD. It was expected that the threat of shock paradigm would elicit anxiety in all participants. Additionally, it was expected that the dual task would lead to normalized gait in the FGD group, and that the threat of shock would yield a worsening of gait in the FGD group. Finally, it was anticipated that greater levels of movement reinvestment in FGD patients would be associated with a greater dual-task effect on gait in this group, meaning that greater reinvesters would show a greater degree of movement normalization when completing a dual task compared to walking in the absence of a dual task.

Eleven FGD patients and 17 age- and sex-matched controls completed 11 walking trials that spanned 4 conditions (neutral, dual task, shock, dual task + shock). All participants self-reported their level of anxiety after each trial, and at the end of the study, completed a battery of questionnaires addressing their movement reinvestment and anxious tendencies. The present study confirmed the utility of the threat of shock during gait, as participants reported greater anxiety when the shock was present. Interestingly, the dual task did not lead to gait normalization in FGD patients. Rather, both patients and matched controls showed worsened gait in the presence of the dual task. Additionally, the threat of shock only impacted step length variability in FGD patients, wherein patients showed greater variability compared to controls in both the presence and absence of shock. Finally, the present study revealed insights into the relationship between reinvestment and symptomology in FGD, wherein patients with a greater degree of reinvestment showed improved gait while dual tasking compared to their baseline gait.

Taken together, the present study not only illustrates the utility of the threat of shock paradigm in gait assessments, but also shows nuances in the relationship between attentional distraction and FGD symptomology. Findings from the present study set the stage for future use of the threat of shock during gait, as well point to the importance of movement reinvestment in the presentation and potential resolution of symptoms in FGD. Future work should continue to investigate reinvestment in the context of FGD and should take a more nuanced and individualistic approach to better encapsulate the heterogeneity inherent in functional gait disorders. Doing so may provide a more complete picture of these disorders and may improve characterization, diagnosis, and treatment of these patients.

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Dedication

Pentru mami și tati, mulțumesc pentru tot. În timp ce stau și îmi scriu mulțumirile, am timp să reflectez. Îmi amintesc când aveam abia zece ani și am descoperit neuroștiința. Mi-ai cumpărat o copie de Scientific American, și am citit-o nesfârșit. Atunci am știut că iubesc creierul si tot ce ține de el. Am scris această teză avându-te în minte – îți mulțmesc că m-ai ajutat să devin savantă și fiica care sunt astăzi. Te iubesc mai mult de cat pot se zic.

Lectură plăcută,
Banii

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List of abbreviations

FND – Functional Neurological Disorders

FMD – Functional Movement Disorders

FGD – Functional Gait Disorders

EEG – Electroencephalography

EMG – Electromyography

EDA – Electrodermal Activity

IMU – Inertial Measurement Unit

pSMA – Pre-Supplementary Motor Area

SMA – Supplementary Motor Area

M1 – Primary Motor Area

TPJ – Temporo-parietal Junction

PFC – Prefrontal Cortex

dlPFC – Dorsolateral Prefrontal Cortex

ROC – Receiver Operating Characteristic

AUC – Area Under Curve

ADHD – Attention Deficit Hyperactivity Disorder

HC – Healthy Controls

DT – Dual Task

S – Shock

WRAP – Waterloo Research in Aging Participants

SAM – Self-Assessment Manikin

MSRS – Movement Specific Reinvestment Scale

G-SAP – Gait-Specific Attentional Profile

STAI – The Spielberger State Trait Anxiety Inventory

HADS – Hospital Anxiety and Depression Scale

DTE – Dual Task Effect

ANOVA – Analysis of Variance

1.0 Literature Review

1.1 Introduction to Functional Neurological, Movement, and Gait Disorders

Functional neurological disorders (FND) are a large group of disorders that do not have a distinct pathology (Hallett, 2016). These disorders encompass a variety of symptoms, such as dizziness, seizures, and abnormal movements that present in a variable nature, ultimately causing a great amount of distress and disability (Carson & Lehn, 2016). Despite the fact that FND is very common, they are a difficult group of disorders to diagnose, subsequently challenging the capacity for appropriate care and treatment. Key factors contributing to these difficulties are the phenomenology of these disorders, challenges with disentangling functional from organic disorders, and concerns around malingering.

As FND encompasses a variety of conditions, phenomenology can be complex. FNDs can be divided into a number of subtypes, such as motor or axial, sensory, speech, and paroxysmal (Espay et al., 2018). Of focus in the present thesis are motor or axial FNDs, also called functional movement disorders (FMDs), and constitute those affecting movement, gait, and posture (Espay et al., 2018). FMDs are typically defined by the inconsistent and incongruent nature of symptom presentation (Espay et al., 2018; Nonnekes et al., 2020). Inconsistency refers to the presentation of symptoms in some instances and not others (Nonnekes et al., 2020). Incongruency refers to symptom presentation that is present in the absence of expected neuropathology, such as ataxic gait in the absence of a brain lesion (Nonnekes et al., 2020). FGDs belong to the broader FMD category and are similarly characterized by abnormal postures and movements during walking which are inconsistent and incongruent in nature (Stone et al., 2005; Espay et al., 2018; Nonnekes et al., 2020). Whilst these movements and postures appear to be voluntary, patients report feeling little control or sense of agency over these movements (Edwards & Bhatia, 2012).

1.1.1 Epidemiology of FND, FMD, and FGD

FNDs account for 15.5 – 30% of referrals to neurologists, having an annual incidence of 4 – 12 cases per 100,000 and a prevalence of 50 per 100,000 cases (Carson et al., 2000; Stone et al., 2010; Carson & Lehn, 2016; O'Mahony et al., 2023). FNDs create large costs to the healthcare

system, as individuals visit the emergency department and specialists more often in order to seek multiple opinions for adequate diagnosis and treatment (Barsky et al., 2005). Additionally, individuals with FND can experience personal financial burden due to seeking appropriate care. The increased rate of emergency department visits and hospital admission yields greater inpatient and outpatient costs, as FND patients can spend anywhere from $578 - $7087 USD ($785 CAD - $9630 CAD) on extra healthcare annually (Barsky et al., 2005; Konnopka et al., 2012). While these costs reflect the burden on the US healthcare system, it is important to note that FND has been documented across the world (Carson & Lehn, 2016), and therefore the costs to the healthcare system and individual may be similar across nations.

Similar to trends seen across multiple FNDs, FMDs also account for significant costs to both the healthcare system and individuals. FMDs account for about 10% of referrals to neurology departments, and FGDs make up approximately 40% of FMD cases (Baik & Lang, 2007; Stone et al., 2010). The average time elapsed between symptom presentation and diagnosis is long, wherein patients can wait up to seven years for proper care (Tinazzi et al., 2021). On average over the course of a year, individuals with FMD make three specialist visits, attend three diagnostic exam sessions, and make seven rehabilitation contacts in order to receive an FMD diagnosis (Tinazzi et al., 2021). Additionally, about ½ of patients are hospitalized before an accurate diagnosis is made (Tinazzi et al., 2021). The cost on the healthcare system due to delays in FMD diagnosis (and subsequent utilization of healthcare services) is €2,300 ($3,300 CAD) per patient, and patients accrue on average €780 ($1,120 CAD) in annual healthcare costs as a result of delayed diagnosis (Tinazzi et al., 2021). While these statistics represent FMD patients as a whole, it is likely that these trends are also seen in FGD, however there is a paucity of evidence.

In addition to financial burden, individuals with FND also experience high levels of distress and disability. FND patients have worse physical and mental health status, and experience difficulties with fulfilling social, physical, and emotional roles and responsibilities compared to individuals with organic disorders (Carson et al., 2011). While FND patients and those without FND experience similar levels of unemployment, patients are much more likely to be unemployed for health reasons and receive governmental disability benefits (Carson et al., 2011). It must also be noted that not every individual with FND is unable to work (Carson et al., 2011), and it is important to consider how working with FND may also increase distress and

worsen patient quality of life. Taken together, it is clear that FND is prevalent and negatively impacts society at both individual and systemic levels. This wide-spread impact is important to mitigate, perhaps through improved diagnosis, in order to reduce burden on patients and the healthcare system.

One key burden on both patients and healthcare system lies in diagnostic delays. These delays may be due to the perception of malingering and potential overlap with organic or other functional movement disorders (Hallett, 2016). FMD were historically seen as factitious or malingering disorders due to the presentation of movements and postures that appear to be voluntary, despite patients reporting these movements to be involuntary (Edwards & Bhatia, 2012; Hallett, 2016). Some individuals with FMD additionally present with other functional disorders, making it difficult for healthcare practitioners to delineate the source of symptoms (Baizabal-Carvallo et al., 2020). Additionally, FMDs themselves are heterogeneous in their presentation, adding another layer of complexity to these disorders. Nonmotor symptoms, such as pain, anxiety, and fatigue may also be present, and these symptoms contribute to disability and may influence motor symptom presentation (Issak et al., 2023).

The complexity of FMD and its diagnosis contributes to FMD being the least preferred clinical group for clinicians to treat (Hallett, 2016). Delays in diagnosis can lead to worsened prognosis (Gupta & Lang, 2009), making early diagnosis and treatment important (Morgante et al., 2013). Therefore, it is critical to improve diagnostic criteria in order to improve the well-being of individuals with FMD, and to lessen the burdens on the healthcare system.

1.1.2 Phenomenology and Diagnosis of FND, FMD, and FGD

Diagnosis of these disorders can be challenging. Firstly, given the history of the descriptor of these disorders, it was thought that psychological distress manifested symptom presentation (Espay et al., 2018). As such, a history of adverse experiences or psychiatric disorders were important in diagnosis (Espay et al., 2018). However, the presence of these factors is not indicative of a FND diagnosis, as affective disorders are present in 2/3 of functional cases and 1/3 of organic cases (Carson et al., 2016). Secondly, there is overlap between functional and organic disorders, with neurologic comorbidities present in 10% of FND cases (Carson & Lehn, 2016). This overlap can create difficulties in delineating which symptoms are functional, and which are organic in nature. Additionally, the emphasis on psychiatric disorders in FND may not be helpful in diagnosis, as not every individual with FND has a psychiatric history. Despite

these challenges, some diagnostic methods have been developed for FND. Those pertaining to FMD and FGD will be of focus for the present thesis.

Some clinical signs have been established in FMD, particularly relating to functional weakness (Espay et al., 2018). Specifically, the Hoover sign (synergistic activation of both the affected and non-affected limb) and difficulty with pronation of outstretched arms are used to identify weakness in the legs and arms, respectively, by demonstrating preserved motor function despite present weakness (Pearce, 2003; Espay et al., 2018). In addition to clinical signs for functional weakness, functional tremor and myoclonus may be diagnosed with electrophysiological evidence following the Gupta-Lang criteria (Gupta & Lang, 2009; Espay et al., 2018). The development of the Gupta-Lang criteria for FMDs allows a stepwise approach for diagnosing FMDs, where clinical features are established and laboratory-based assessments are used to create a definite diagnosis (Gupta & Lang, 2009). Clinicians first take note of a patient's history and symptomology, and then look for the inconsistency and incongruency of presented symptoms to aid in the FMD diagnosis (Gupta & Lang, 2009). Electromyography (EMG) and electroencephalography (EEG) are used in assessment to identify muscle activation patterns and movement planning potentials, where preservation of motor function (e.g., active muscles, normal planning potentials) can be seen in concert with symptoms of interest (Gupta & Lang, 2009; Espay et al., 2018).

The Gupta-Lang criteria help streamline FMD diagnosis by allowing diagnosis to be one that is a positive, or "rule-in", rather than one of exclusion (Gupta & Lang, 2009; Espay et al., 2018). While these criteria aid in diagnosis of certain FMDs, they are not inclusive of all FMDs, subsequently presenting diagnostic challenges for disorders not encompassed by the Gupta-Lang criteria (Espay et al., 2018). Additionally, the heterogeneity in FMD presentation across patients adds extra difficulty to the diagnostic process.

FGDs in particular have been shown to be incredibly heterogenous in nature, with 42 unique features described in the literature (Fung, 2016). A majority of evidence describing the manifestation of FGD symptoms comes from clinical anecdotes. Common clinical descriptors include excessive slowness ("walking on ice" gait), dragging or crouched posture, knee buckling, and fluctuating postures during gait coupled with decent balance control (Stone et al., 2005; Edwards & Bhatia, 2012; Hallett, 2016; Lidstone et al., 2020; Nonnekes et al., 2020;

West & Shah, 2022; Issak et al., 2023). Due to the great number of qualitative descriptions of FGD symptomology, phenotyping FGDs can pose a challenge.

In an attempt to address this challenge, a qualitative sign-based approach has recently been developed to sort FGD into seven broad phenotypes after clinical assessment (Nonnekes et al., 2020). The seven categories are as follows: (1) *ataxic gait*, (2) *spastic gait*, (3) *weak gait*, (4) *antalgic gait*, (5) *parkinsonian (bradykinetic) gait* (6) *hemiparetic gait*, and (7) *dystonic gait* (Nonnekes et al., 2020). A summary of these phenotypes, how they are tested, and interpretation of assessment are presented below in Table 1.

Ataxic gait is characterized by variability in one's base of support and challenges with walking in a straight line, despite having good balance (Nonnekes et al., 2020). This phenotype overlaps with presentation of organic ataxia but can be differentiated through a variety of assessments. Straight line walking reveals swaying of movement from side-to-side and performing a dual task or walk with eyes closed can show and improvement in the gait pattern, demonstrating symptom inconsistency (Nonnekes et al., 2020). Sensory testing reveals normal sensory function, despite poor gait, demonstrating incongruency of symptoms (Nonnekes et al., 2020).

Another phenotype that overlaps with organic disorder presentation is *bradykinetic (excessively slow) gait*. Bradykinetic gait shares similarities with organic Parkinsonian gait and can be evaluated through muscle tone, movement, and balance perturbation testing (Nonnekes et al., 2020). Muscle tone and movement testing demonstrate inconsistency in symptom presentation, where fluctuations in bradykinesia and tremor are seen (Nonnekes et al., 2020). Freezing of gait is not similar to organic Parkinsonian gait, as freezing episodes tend to be longer in this FGD phenotype (Nonnekes et al., 2020). Additionally, balance testing reveals good balance and no balance correcting movements, which is not seen in Parkinsonian gait (Nonnekes et al., 2020).

A third phenotype that shares similarities with an organic movement disorder is *dystonic gait*. This phenotype can be differentiated through muscle tone evaluation, and walking either backward or sideways (Nonnekes et al., 2020). Muscle tone evaluation shows normal results, and dystonia disappears when the individual is walking sideways or backward (Nonnekes et al., 2020).

Spasticity (scissoring) gait can be evaluated through sit-to-stand tests and muscle strength and reflex testing. Strength and reflex testing show symptom incongruency, as results on these tests should be normal (Nonnekes et al., 2020). Similar to ataxic gait, symptom inconsistency can be probed through backward walking, as scissoring disappears (Nonnekes et al., 2020).

Weak gait can be characterized by the buckling of the knees during walking, and *antalgic gait* can be characterized by limping during walking (Nonnekes et al., 2020). Both of these phenotypes can be best assessed through tandem walking, walking while performing a secondary task, and walking with eyes closed (Nonnekes et al., 2020). These different walking conditions show a reduction in knee buckling and limping, highlighting symptom inconsistency (Nonnekes et al., 2020). A method to qualitatively evaluate symptom incongruency in antalgic gait has not yet been established. However, incongruency of symptoms can be evaluated in weak gait, where muscle weakness tests show normal muscle strength. *Dragging* or *hemiparetic gait* can also be assessed in a similar manner. Muscle strength evaluation in hemiparetic gait reveals normal strength, and gait assessment under different cognitive and sensory conditions reveal variability in symptom presentation (Nonnekes et al., 2020).

Table 1. Summary of the seven FGD phenotypes and tests for symptom incongruency and inconsistency. Adapted from Nonnekes et al., 2020.

FGD Phenotype	Symptom Inconsistency Testing	Inconsistency Test Result	Symptom Incongruency Testing	Incongruency Test Result
Ataxic	Walking under various conditions (eyes closed, while completing a dual task)	Reduced side-to-side body movement	Sensory testing for cerebellar ataxia	Normal sensory function despite abnormal gait pattern
Bradykinetic (Parkinsonian)	Muscle tone assessment and movement evaluation	Fluctuations in bradykinesia and tremor	Balance evaluation and observation of freezing of gait episodes	Good balance and no balance corrections; longer freezing episodes
Dystonic	Walking sideways or backward	Disappearance of dystonia	Muscle tone evaluation	Normal muscle tone
Spasticity (Scissoring)	Sit-to-stand testing and walking backward	Fluctuations in postural control; disappearance of scissoring	Muscle strength testing, reflex testing	Normal muscle strength and reflexes

Weak (Knee buckling)	Walking under various conditions (tandem, eyes closed, while completing a dual task)	Reduced knee buckling	Muscle strength testing	Normal muscle strength
Antalgic (Limping)	Walking under various conditions (tandem, eyes closed, while completing a dual task)	Reduced limping	-	-
Hemiparetic	Running or walking under various conditions (tandem, backward, eyes closed, while completing a dual task)	Variability in magnitude of limb dragging when performing walking or running assessments	Muscle strength and tone testing	Normal muscle strength and tone

While this approach delineates appropriate clinical tests to identify various FGD phenotypes, it is important to note that this is a qualitative approach to phenotyping. Qualitative observation may be subject to discrepancies between raters. Additionally, as FGD presents with symptom inconsistency, a qualitative approach may not best capture symptomology, as symptoms may be more obvious at one visit, and less obvious at the next. As such, it is important to consider quantitative approaches to identification of FGD and FGD phenotyping to get a better picture of this disorder. Quantitative approaches to FGD diagnosis, with potential applications to phenotyping, may ameliorate shortcomings with qualitative methods, providing better diagnostic utility. These qualitative approaches also may not completely account for the etiology of FGD (and broadly, FND), which may inform development of improved diagnostic approaches. The combination of the aforementioned factors creates challenges in adequate diagnosis and treatment of these disorders. Therefore, it would be important to further improve FGD identifying and diagnostic criteria to account for these factors.

1.1.3 Etiology of FND, FMD, and FGD

1.1.3.1 Predisposing Factors

Gaining an understanding of the etiology of FND may better inform diagnostic criteria to develop a comprehensive view of proposed pathophysiology of these disorders. While psychological factors, such as trauma and psychiatric disorders, have been thought of as the main predisposing factors in FND, recent evidence suggests a shift from these factors to

neurobiological and psychosocial factors in describing FND etiology (Pick et al., 2019). Five broad categories of FND predisposing factors have been identified, encompassing psychiatric, sensory, and neurobiological domains (Fobian & Elliott, 2019). The five categories are as follows: (1) *trauma/psychiatric symptoms*, (2) *somatic symptoms*, (3) *illness exposure*, (4) *symptom monitoring*, and (5) *neurobiological evidence* (Fobian & Elliott, 2019). The first four categories are supported by the fifth, as a large body of work has found evidence of illness beliefs and expectations, abnormal focus of attention on affected body regions, loss of agency over actions or movements, and functional and structural brain abnormalities in FND such as limbic, sensorimotor, and prefrontal network dysfunction (Fobian & Elliott, 2019). Together, these categories bridge together a complex network of environmental, neurobiological, and other historical factors, as a way of depicting the complexity of etiology and providing a holistic view of FND. Of importance, these categories help explain how one's psychosocial environment can alter nervous system function, ultimately leading to FND presentation.

This concept is illustrated in Figure 1, which depicts FND and its etiology as a forest (Lidstone et al., 2020). The soil (psychosocial environment) allows for the roots (FND predisposing factors) to grow. The tree trunks (changes in nervous system function) allow for the contents in the roots to be transformed into the leaves (various FND phenotypes) of the trees. This figure also conceptualizes these heterogeneous FND phenotypes as growing from one common set of predisposing factors. This model identifies commonalities between FND phenotypes, contributing to a better understanding of how FND may arise, and how exploring these factors may shed light on salient aspects in diagnosis.

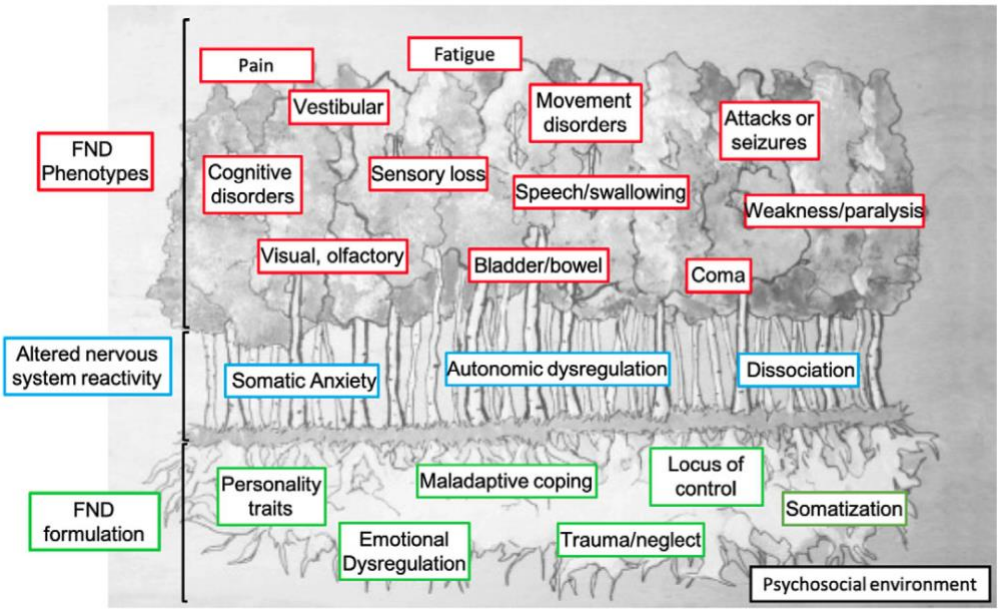


Figure 1. Illustration depicting the biopsychosocial model of FND development. From Lidstone et al., 2020.

1.1.3.2 Reinforcing Factors

Once FND symptoms are formed, their presentation is reinforced through several mechanisms, such as illness beliefs and expectations, comorbid affective disorders, and concurrent psychological stressors (Espay et al., 2018; Fobian & Elliott, 2019; Lidstone et al., 2020). A Bayesian description of FND symptom presentation hinges on the idea that prior beliefs and sensory information are influenced by body-focused attention, symptom expectations, and illness beliefs (Edwards et al., 2012). This framework describes how symptom provocation and maintenance are fueled by attention and expectations toward them, as well as through preconceived beliefs which are constructed through past experience and social contexts (Edwards et al., 2012). The preconceived beliefs in this model are comprised of a combination of empirical knowledge and beliefs about the world and sensory information. This empirical knowledge about the world is utilized in a top-down manner, wherein these beliefs are sent to different levels of information processing hierarchy via predictive backward connections (Edwards et al., 2012). In contrast, sensory evidence is passed to each hierarchical level in a bottom-up manner. This evidence is passed along via forward connections conveying prediction errors to each level until they are rationalized through changes in predictions (Edwards et al., 2012). These two components work together to minimize prediction errors and optimize the model created of the world (Edwards et al., 2012).

In FNDs – specifically FMDs – the relationship between prior expectations (driven by empirical knowledge) and sensory prediction errors is modified by attention (Edwards et al., 2012). This relationship determines how information is perceived and drives movement. Altering the weight of prediction errors via abnormal focus of attention drives FMD symptom presentation, particularly loss of agency (Edwards et al., 2012). False perceptual inferences begin to inform top-down beliefs and contribute to a shift in weight from bottom-up sensory evidence, and the higher levels of the hierarchy now must rationalize these top-down beliefs (Edwards et al., 2012). This rationalization yields a loss in agency over movement as these preferentially weighted top-down processes introduce beliefs into the system, but do not allow for accurate prediction and matching of their contents (Edwards et al., 2012).

This framework is illustrated in Figure 2 (Edwards et al., 2012), which contrasts sensorimotor processing in healthy individuals and those with FMD. The proposed levels of the hierarchy are cerebral areas implicated in movement intention and generation, namely the pre-supplementary motor area (pSMA), the supplementary motor area (SMA), and primary motor cortex (M1). In both cases, attentional processes are represented by the blue arrow, forward motor predictions are represented by the black arrows, and feedback movement and prediction errors are represented by the red arrows. In healthy individuals, movement predictions originate in the pSMA and travel down through the hierarchy. These predictions are compared with errors that arise from the completion of the movement, and these errors are relayed up the hierarchy to be further processed.

However, in individuals with FMD, attention impacts normal processes, particularly through great influence over the SMA. It is thought that the temporo-parietal junction (TPJ) and prefrontal cortex (PFC) are implicated in this influence over the SMA, as patients show decreased functional connectivity between the TPJ, PFC, and the SMA, subsequently reducing the ability to effectively select and plan movements (Conejero et al., 2017; Nahab et al., 2017; Sasikumar & Strafella, 2021). This then leads to an increase in attentional focus (Figure 2; thick blue arrow) mediated through abnormal prior expectations, as the neural areas responsible for mitigating the influence of prior expectations are unable to do so effectively, due to reduced connectivity between attentional and executive control regions. It is important to note that these prior expectations are gathered from previous experiences and beliefs, which may carry inherent emotional attributes. The emotional content of these priors may be magnified due to the

increased activity seen in the amygdala, insula, and posterior cingulate gyrus (Baizabal-Carvallo et al., 2019; Sasikumar & Strafella, 2021). This increased activity in emotional brain networks is coupled with reduced connectivity with the SMA and dorsolateral prefrontal cortex (dlPFC), subsequently leading to impaired allocation of cognitive resources in response to salient stimuli (Boeckle et al., 2016; Conejero et al., 2017; Sasikumar & Strafella, 2021).

Ultimately, this maladaptive increase in attentional focus then alters how top-down information (proprioceptive prediction) is sent (Figure 2; thick black arrows), and how bottom-up movement errors (somatosensory information) are processed (Figure 2; thick red arrows). Specifically, the ambiguity between proprioceptive predictions and somatosensory information is consolidated in the pSMA, where it and other high-level areas attempt to rationalize this ambiguity by attributing it to FMD symptomology or other external factors. As a result, sense of agency over movement is lost, as higher-order regions fail to attribute generated or predicted movement to self-generated sources (Edwards et al., 2012). It is likely that this impaired sense of agency in FMD is driven by decreased connectivity between the TPJ, SMA, motor and sensory cortices, the insula, and the cerebellum (Nahab et al., 2017; Baizabal-Carvallo et al., 2019; Sasikumar & Strafella, 2021). While the afferent and efferent information is mostly preserved in this process – that is, the neural relays carrying this information are intact in FMD – the route this information takes is impacted by the widespread alterations in functional connectivity, ultimately leading to the misattribution of this information and subsequent symptom generation.

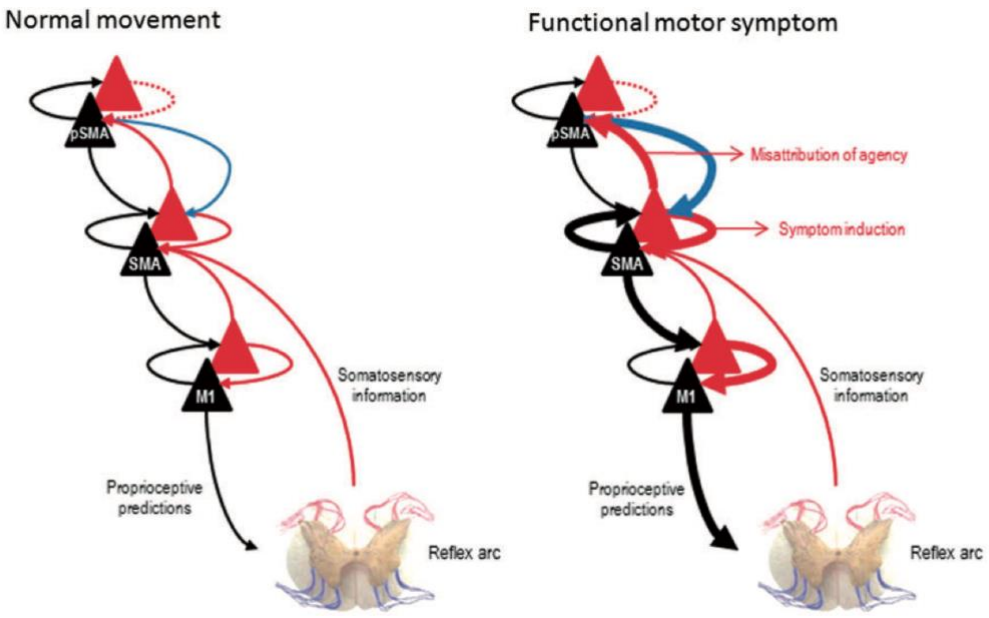


Figure 2. Schematic illustrating the Bayesian model of FMD symptomology. From Edwards et al., 2012.

This framework illustrates how FND etiology is involved in symptom generation and maintenance and attempts to map this to brain regions. Neurophysiological evidence has built on this framework to provide evidence of the pathology of FND.

1.1.4 Proposed pathophysiology of FND, FMD, and FGD

Recent work has also uncovered neurophysiological evidence supporting the theory behind FND symptom presentation and maintenance. As the focus of this thesis is on FMD – specifically functional gait disorders (FGD) – the following sections will mostly touch on pathophysiology of FMD. Recall that FMD is a subset of FND and encompasses a broad variety of phenotypes (Espay et al., 2018). FMD neurophysiology can be explained via the conceptual model presented in Figure 3, wherein limbic system dysfunction influences movement intention and generation, and this increased limbic input facilitates movement (Hallett, 2016). This alteration in movement generation influences sense of agency in a feedforward manner (Hallett, 2016). Much like in the aforementioned Bayesian framework, this alteration in feedforward weighting of information modifies one's sense of control over movement output (Edwards et al., 2012; Hallett, 2016). In parallel, movements are generated due to limbic influences, and the feedback processes comparing predicted movements to completed movements may also contribute to this lack of agency (Hallett, 2016).

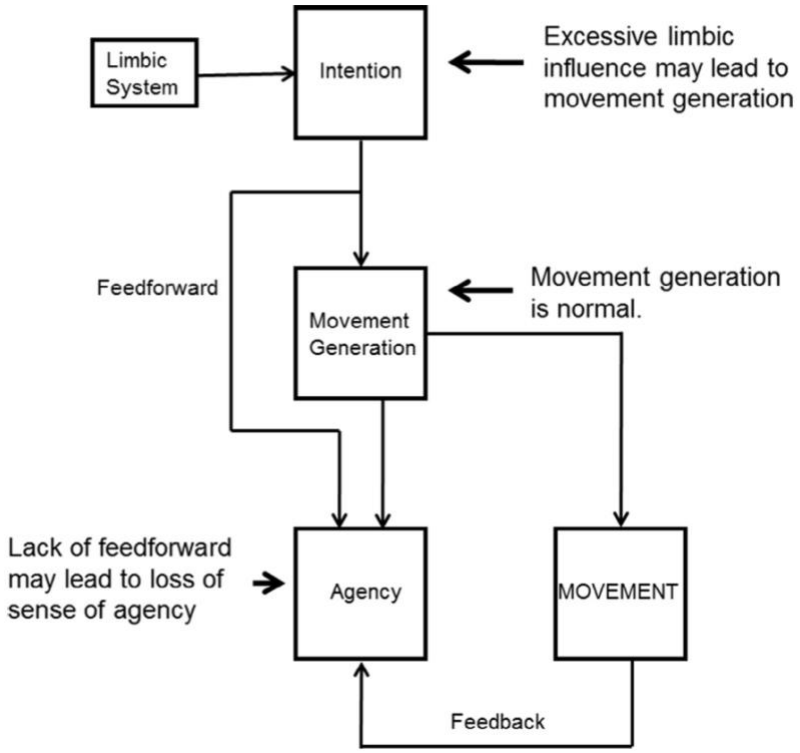


Figure 3. Illustration depicting the proposed pathophysiology of FMD. From Hallett, 2016.

1.1.5.1 Limbic System Influences

A body of evidence has found altered arousal across various FNDs, which includes increased levels of electrodermal activity (EDA) and alterations in startle reflex habituation (Pick et al., 2019). Arousal, specifically physiological arousal, may be defined as the "activation" of an individual which is comprised of several physiological responses, such as increased blood pressure, heart rate, or EDA (Fiorio et al., 2022).

Increased EDA has been found in individuals with functional seizure through facial affect recognition tasks (Pick et al., 2016; 2018). When compared to healthy controls, individuals with functional seizure demonstrated decreased accuracy in identifying facial expressions (Pick et al., 2016). Overall, individuals with functional seizure demonstrated greater levels of EDA when compared to healthy controls (Pick et al., 2016; 2018). However, when compared to controls, some individuals in the functional seizure group showed an attenuation in EDA (Pick et al., 2016; 2018). This finding illustrates the possible differences in emotional processing in FND, where some individuals may show decreased EDA but increased self-reported arousal, and vice versa (Pick et al., 2018). These facial affect studies shed light on emotional processing in FND,

demonstrating the variability in emotional processing between individuals with FND and highlighting clear differences between FND patients and healthy controls.

Regarding FMDs, one study aimed to investigate how startle reflex habituation changed in response to positive and negative affective images, as this reflex has been shown to be modulated by emotional states (Seignourel et al., 2007). 12 FMD patients and 12 age-matched controls were presented with positive, neutral, and negative affective images and a white noise startle probe was played after each image (Seignourel et al., 2007). Participant eye blink responses were recorded to assess startle response and its modulation upon viewing affective images (Seignourel et al., 2007). The researchers found that the age-matched controls demonstrated a typical pattern of startle habituation, where the negative images potentiated the startle response and the positive images attenuated this response (Seignourel et al., 2007). In contrast, individuals in the FMD group demonstrated exaggerated startle potentiation for both negative and positive images (Seignourel et al., 2007). This finding demonstrates clear differences in emotional response between healthy controls and FMD patients. Taken with findings from emotional processing studies conducted in other FNDs, this result points to the commonality of abnormal emotional processing across FNDs.

1.1.5.2 Sense of Agency and Movement Intention

As shown in Figure 3, limbic influences, such as abnormal emotional processing discussed in the previous section, influence movement intention and generation. These modifications in emotional processing influence one's sense of control over movement, and this has been demonstrated in several studies. Several studies have investigated intentional binding – or the time between movement output and related sensory input – in FND (Baizabal-Carvallo et al., 2019). Increased sense of agency results from decreased time between movement output and sensory input and is related to the function of the SMA and other sensory areas (Baizabal-Carvallo et al., 2019). In particular, one study revealed that individuals with FMD demonstrated reduced action-effect binding when compared to healthy controls (Kranick et al., 2013). Action-effect binding can be used as a quantitative measure of sense of agency, measured as the subjective estimation of time between an action and the effect of the action is only present if an individual possesses a sense of agency over the action (Kranick et al., 2013). Therefore, reductions in action-effect binding in FMD reflects lack of agency over movements. This

finding sheds some light on the alterations of agency in FMDs and is supported by the Bayesian framework of FMD symptom presentation (Edwards et al., 2012).

1.1.5.3 Abnormalities in Somatosensation and Cognitive Processing

As sense of agency is related to somatosensation, it is no surprise that some evidence suggests that individuals with FMD experience abnormal somatosensation (Baizabal-Carvallo et al., 2019). FMD patients have demonstrated increased magnitude of sensory-evoked potentials when generating movement (Baizabal-Carvallo et al., 2019). This increase in sensory-evoked potentials may be due to the reduction in agency over movement in this population, as individuals report a lack of voluntary control over their movement (Baizabal-Carvallo et al., 2019). This alteration in somatosensation supports the Bayesian framework describing FND presentation and maintenance in that it highlights the externalization of movement perception in these disorders.

Individuals with FMD have also been found to experience abnormal cognitive processing (Baizabal-Carvallo et al., 2019). These abnormalities in cognitive processing may be driven by abnormal beliefs and feelings around movement, which have been theorized to be important in symptom initiation (Lidstone et al., 2020) and maintenance (Edwards et al., 2012).

Taken together, the evidence presented provides insight into several key aspects that are implicated in the pathophysiology of FND. These aspects are most notably the influence of emotion and attention on FND symptomology. It is important to understand these factors as they are common across all disorders in the FND umbrella. Narrowing the focus on other disorders in the FND umbrella, such as FMDs, or even more specifically, FGDs, may provide insight into how attention and emotion influence movement. In turn, this may be used to compare to our understanding of these influences in healthy movement control, and how these disorders alter movement control.

1.2 Gait and Posture in Functional Movement and Functional Gait Disorders

Currently, there is no quantitative sign-based approach to differentiate FGD phenotypes. However, some work has been done to identify differences in balance outcomes and spatiotemporal gait parameters between FGD patients, patients with organic neurological disorders, and healthy controls.

Regarding balance outcomes, one prospective study assessed the frequency, severity, and outcomes of falls in individuals newly diagnosed with organic (n_{TOTAL} = 283) or functional gait disorders (n =50) (Schneipp et al., 2021). The organic movement disorder subgroups included patients with vestibular, cerebellar, hypokinetic, vascular, and other types of organic disorders. Gait and falls risk were assessed in the laboratory before participants were monitored with inertial measurement units (IMUs) for two weeks. Logistic regressions were done to predict whether an individual would fall, how often they would fall, and how severe falls would be. Regarding FGDs, 81% of individuals reported no past falls, and 58% of those who fell reported a Hopkins fall severity score of one, indicating a non-severe fall. (Schneipp et al., 2021). This finding supports qualitative descriptions of FGD which describe relatively good balance and fewer falls in FGD.

The free-living gait assessment, which used IMUs worn for two weeks, also provided insight into differences in gait patterns between those with FGD and healthy individuals. Participants with FGD demonstrated slower gait velocity, larger base of support, and increased phase synchronization when compared to healthy controls (Schneipp et al., 2021). Increased gait asymmetry (i.e., increased gait asymmetry index) and increased variability (i.e., increased variability in the base of support) were also found in FGD patients (Schneipp et al., 2021). These findings partially support previous work providing a basic overview of gait differences between healthy individuals and those with FGD. Generally, individuals with FGD show significant decreases in gait pace (velocity and stride length) and significant increases in gait variability when compared to healthy individuals (Schneipp et al., 2019). This was shown as a significant difference in gait velocity between controls and FGD patients (Schneipp et al., 2021). Individuals with FGD tend to show increased gait asymmetry compared to healthy individuals (Schneipp et al., 2019), and this was seen as an increase in asymmetry across the two-week monitoring period (Schneipp et al., 2021). Surprisingly, previous work did not find significant differences in stride width and stride width variability (denoted as the postural support domain of gait) between FGD patients and healthy individuals (Schneipp et al., 2019). However, FGD patients demonstrated a significantly larger base of support over the monitoring period (Schneipp et al., 2021). Taken together, these findings point to clear differences in gait behavior between those with and without FGD, providing utility for quantitative approaches to gait assessment in FGD.

1.2.3.1 Heightened attention to movement in FGD

It is important to also consider the aspects of attention and emotion in FGD, as both of these factors are implicated in symptom provocation and maintenance. As such, it is beneficial to incorporate these aspects into quantitative gait assessment in this population. A majority of evidence investigating attention in FGD has come from studies utilizing dual-task paradigms, demonstrating the inconsistency in symptom presentation (Breitkopf et al., 2018; Gandolfi et al., 2021, 2023).

One study assessed gait in FGD and healthy individuals during three walking speeds (preferred, slow, and maximum speed), while completing two sensory tasks (head reclination and eyes closed), and three dual tasks (serial 7 subtraction, spoken words, and carrying an object) (Breitkopf et al., 2018). Participants completed a gait assessment on a pressure-sensor gait carpet, and spatiotemporal gait variables were analyzed using a binary logistic regression, receiver operating characteristic (ROC), and an inversed regression to determine healthy parameters and pathological deviations. Gait variables included were velocity; cadence; base of support area and variability; step/stride length and step/stride time; step/stride length and step/stride time variability; double support, swing, and stance duration; gait asymmetry; and phase synchronization. Step/stride length, time, and variability for step/stride length and time are given for both left and right sides. It is important to note that detailed names of the variables were not provided in this work, so it is unclear whether step or stride length and time were assessed, hence the "step/stride" notation used in the present document. Regardless, these variables measure similar metrics, wherein step data may provide more detail than stride data (Breitkopf et al., 2018).

Gait data from FGD patients and matched controls was assessed using receiver operating characteristic (ROC) curves, wherein area under the curve (AUC) value for each gait metric denotes the magnitude of difference between measures from each participant group. AUC values summarize the ROC output and represent the ability of the analysis to determine participant group membership (Çorbacıoğlu & Aksel, 2023). Values can range from 0 to 1, wherein 1 signifies perfect identification of group membership. In other words, a variable with an AUC of 1 indicates that this variable will always discriminate between healthy individuals and individuals with FGD. An AUC value of 0.80 or greater signifies clinical utility, whereas values lower than 0.80 signify limited clinical utility (Çorbacıoğlu & Aksel, 2023). AUC values

can be interpreted with the supplement of the value's confidence interval, wherein the narrowness of the interval is directly related to the accuracy of the AUC value (Çorbacıoğlu & Aksel, 2023). However, the confidence intervals were not provided for the AUC values in this study, so interpretation of these values is limited.

At the preferred speed, the area under the curve (AUC) values for all gait variables measured were between 0.66 and 0.85, indicating moderate to great clinical utility of the variables measured (Breitkopf et al., 2018). While not specified in the study of interest, it was likely the case that FGD patients showed slower and more variable walking, based on previous work (Schniepp et al., 2019). In the preferred speed, swing duration and base of support variability showed the lowest AUC (0.66), and step/stride length showed the greatest AUC (0.85). In the serial 7 condition (where participants serially subtracted 7 from a given value whilst walking), the AUC values ranged from 0.33 – 0.78, wherein base of support variability showed the lowest AUC (0.33) and step/stride length showed the greatest AUC (0.78). In the dual task words condition, AUC values ranged from 0.43 – 0.70, wherein stance duration showed the lowest AUC (0.43) and step/stride length showed the greatest AUC (0.70) (Breitkopf et al., 2018).

Taken together, these findings suggest potential differences in gait between FGD patients and healthy controls at baseline. However, the absolute magnitude of these differences is small, therefore the results should be interpreted with caution. Specifically, this work suggests that step/stride length may be the most clinically relevant variable to delineate healthy gait from FGD gait. Although minor, these AUC values shrink when participants complete the cognitive dual task, suggesting that some aspects of FGD gait may normalize with a dual task. In particular, base of support variability and stance duration showed decreased AUC values, meaning that the distinction between cognitive dual task and baseline conditions for these variables was smaller. These findings provide a quantitative description to symptom inconsistency in FGD and highlight the marked influence of attention on gait in this population (Breitkopf et al., 2018).

Following this work, two studies investigated the influence of sensory and cognitive conditions on gait and posture in FMD and FGD patients (Gandolfi et al., 2021; 2023). The first study investigated stationary postural control in 30 FMD patients and 30 healthy controls (Gandolfi et al., 2021). Participants performed a standing balance task with eyes open and eyes

closed. This task was performed while also completing a cognitive dual task, where participants were instructed to subtract backward from 100 by increments of 7. Participants also completed a motor dual task, where they pronated and supinated their right forearm at a frequency of 1 Hz. While completing the single task trials, patients showed greater postural sway than matched controls, in both eyes-open and eyes-closed trials. However, FMD patients showed a reduction in postural sway when completing the motor dual task with their eyes closed, whereas healthy individuals demonstrated greater postural sway. Patients also showed reduced postural sway when completing the cognitive dual task with their eyes open and closed (Gandolfi et al., 2021). These findings not only demonstrate symptom distractibility in FMD, but also allude to some influence of sensory input on symptom presentation.

The second study investigated how different dual task paradigms (motor, cognitive, and visual fixation) influenced spatiotemporal gait parameters to shed light on higher-level gait control mechanisms in FGD (Gandolfi et al., 2023). Twenty-nine FGD patients and 49 healthy controls completed a gait analysis, and outcome measures of interest were the calculated dual task effect on gait speed, stride length, and stride time variability. The researchers selected these variables as they proposed that gait speed and stride length represent overall gait performance, and that stride time variability represents automaticity and steadiness of gait. When compared to healthy controls, individuals with FGD demonstrated decreased gait speed, shorter stride length, and greater stride time variability (Gandolfi et al., 2023). In FGD, dual tasking yielded a further decrease in gait speed and stride length and a further increase in stride time variability when compared to the single task condition. The researchers suggest that this finding implies that dual-tasking worsened gait performance but did not affect automaticity (Gandolfi et al., 2023). This finding is not supported by previous evidence, which demonstrates an improvement in gait performance with attentional distraction (Breitkopf et al., 2018). The authors of the study of interest suggest that the simultaneous execution of the cognitive dual task and walking may have utilized limited shared cognitive resources, ultimately leading to the slowing of movement unexpectedly seen (Gandolfi et al., 2023). While dual task performance accuracy was not shared in the study of interest, its inclusion may have shed light on this line of thinking, as poor performance on the dual task during walking could show the impact on the attentional and motor control brain areas, ultimately showing its impact on gait automaticity (Wu et al., 2015).

It is important to note that the researchers chose a few variables to represent broad categories of spatiotemporal gait variables. This is a large limitation since it is likely that one gait variable is not representative of an entire gait domain (i.e., stride time variability does not represent all aspects of gait automaticity and steadiness). It may be of interest for future work to employ a domain-mapping approach similar to that done in older adults and Parkinson's patients (Lord et al., 2013; Wilson et al., 2019), wherein gait domains (e.g., pace, rhythm, variability, asymmetry, postural control) can be identified and related to a broad range of spatiotemporal gait parameters. These parameters can be subsequently assessed and validated for alignment with the domains of gait and may also be attributed to a variety of involved brain regions, similar to previous work in other older adult populations (Morris et al., 2019). Doing so may provide a more standardized method of gait assessment in FGD. While this process cannot be undertaken with a single study, it is important for future work to contribute to this process by evaluating a broad range of spatiotemporal parameters in FGD, to ensure findings are as complete as possible.

An additional limitation was the lack of neuropsychological assessments and assessments relating to attentional and executive function, as well as any psychiatric or other co-morbidities. It may be possible that certain confounding factors (i.e., combined FGD; presence of anxiety, depression, or other disorder that may influence attention, and degree of movement reinvestment) may not have been accounted for and may have led to a decrement in movement performance in FGD patients. Inclusion of these characteristics may provide a more detailed description of FGD symptomology.

Taken together, the limited evidence from the use of attentional diversion during gait and posture in FMD and FGD demonstrates a clear difference between healthy individuals and those with functional disorders. Dual tasking has been utilized in healthy populations to divert limited attentional processing resources and observe subsequent reductions in task and movement performance to evaluate motor automaticity (Woollacott & Shumway-Cook, 2002; Wu et al., 2015; Stöckel & Mau-Moeller, 2020). Cognitive processing and gait control draw upon similar cognitive resources, which can become limited with increasing secondary task complexity, resulting in the decline in movement performance (Woollacott & Shumway-Cook, 2002; Al-Yahya et al., 2011; Stöckel & Mau-Moeller, 2020). If either gait performance or secondary task performance declines, this demonstrates that gait is not an automatic task since it requires some

(currently unavailable) cognitive resources to maintain optimal performance (Wu et al., 2015). Such decrements in healthy gait performance include decreased velocity, swing time, and stride length, as well as increased stride time and swing and stride time variability (Woollacott & Shumway-Cook, 2002; Al-Yahya et al., 2011; Stöckel & Mau-Moeller, 2020).

Healthy gait performance during dual tasking can be contrasted with that of FGD patients, where dual tasking may actually improve gait performance (Breitkopf et al., 2018), however, this is not always the case (Gandolfi et al., 2023; Sandri et al., 2024). Evidence from qualitative gait assessments also point to a normalization in movement performance when an individual with FGD is distracted (Nonnekes et al., 2018, 2020). This stark difference in performance between healthy individuals and FGD patients points to the involvement of attention and its large influence on motor performance in FGD. When individuals remove attention from their movement, they experience a decrease in symptom presentation, making it clear that attention is implicated in symptom maintenance. This improvement in gait while completing a dual task may suggest that typical or "baseline" FGD walking may not be optimal, as it consumes many cognitive resources due to increased self-monitoring. Therefore, the automaticity of walking is heavily impacted. When attention is diverted from the individual's movement, perhaps this attentional diversion restores previously occupied cognitive resources, allowing for improved and more "automatic" gait. This improvement in gait performance while completing a dual task may possibly relate to the Bayesian framework of FMD symptom maintenance (Edwards et al., 2012) and the etiology of FNDs as a whole, since historical factors such as increased self-focus and monitoring behaviors are shown to be precipitating and maintaining factors in FND (Lidstone et al., 2020).

The idea of increased internal focus of attention leading to decrements in movement performance is also described in healthy individuals through movement reinvestment theory. Movement reinvestment theory states that the inward focus of attention (reinvestment) on movement places more cognitive demands on working memory, and yields decreased movement performance (Masters & Maxwell, 2008; Ellmers & Young, 2018). The relationship between movement reinvestment and movement performance has been found to be mediated by anxiety, wherein increased levels of state anxiety correlate to increased movement reinvestment and subsequent changes in gait behavior (Ellmers & Young, 2018; Ellmers et al., 2020; Young et al., 2020). Such changes in movement performance include increased stance time and gait

velocity, as well as reduced stepping accuracy (Ellmers & Young, 2018; Ellmers et al., 2020). Movement reinvestment theory could be applied to FGD, as it has been demonstrated that increased attention to movement yields movement deficiencies. It is possible that individuals with FGD experience high levels of reinvestment, which may be causing the presentation and maintenance of symptoms.

Increased movement reinvestment has also been shown to alter perceptions of stability in healthy individuals, wherein individuals self-report decreased stability, despite unchanged movement performance, when under postural threat (Ellmers et al., 2021). This finding illuminates the influence of anxiety and attention on movement control, in that they can work together to influence one's perception of movement performance. This finding may be applied to FGD, as beliefs and perceptions about movement are thought to drive the maintenance of symptoms (Edwards et al., 2012). Therefore, work evaluating anxiety and movement reinvestment in individuals with FGD may shed light on its symptomology.

1.2.3.2 Anxiety and movement in FGD

Anxiety-related gait performance in healthy individuals cannot be compared to that of FGD patients, as there is a paucity of work investigating the impact of anxiety on gait behavior in FGD. Only one study to date has investigated the influence of emotion on symptom triggers (Geroin et al., 2022). Triggers are stimuli which worsen or provoke symptoms and are distinct from the initial precipitating factor associated with disease onset. These triggers can include – but are not limited to – exercise/movement, emotional state, photosensitivity, touch to specific body regions, and exposure to certain noises (Geroin et al., 2022). In this study, 100 individuals with FMD underwent a qualitative assessment of presence and type of symptom triggers. Following assessment, it was revealed that 88% of participants reported at least one trigger. The most common triggers in both FMD and FGD were shown to be exercise and movement such as physical exercise and walking forward and backward. The second-most common were emotional stimuli. Emotional triggers encompassed a variety such as anxiety, fear, excitement, agitation, and stress. The presence and common nature of emotional triggers in both FMD and FGD demonstrate the involvement of emotion in symptom presentation and maintenance, supporting theoretical models of FND etiology (Lidstone et al., 2020).

It must also be noted that a majority of work investigating the influence of anxiety on movement performance in healthy individuals has utilized postural threat paradigms. Postural

threat is induced by having the individual walk on an elevated platform, probing at anxiety associated with falling and balance challenges. In general, healthy individuals walk slower, take shorter steps, and spend more time in double support when exposed to postural threat (Gage et al., 2003; Brown et al., 2006). To date, there have not been any studies investigating postural threat during gait in FND.

Another common method of inducing anxiety in laboratory settings is the threat of shock paradigm. This paradigm utilizes electrical shocks (1-1.5 mA intensity) to robustly induce fear and state anxiety in study participants (Grillon & Davis, 1997; Grillon & Ameli, 1998; Schmitz & Grillon, 2012). However, to the best of the author's knowledge, this paradigm has only been utilized in seated paradigms. It may be of use to determine the utility of this paradigm in gait, as it may also effectively provoke anxiety and may demonstrate similar movement decrements seen in postural threat paradigms. This paradigm may also be valuable to use in the FGD population as individuals with FGD show relatively better balance – characterized by less frequent and severe falls – despite their abnormal gait patterns.

1.3 Summary of literature gaps

Attentional and emotional dysregulation are key components of FGD, as these components are thought to influence the presentation and maintenance of symptoms. Despite attentional and emotional dysregulation being common across all FGDs, FGD phenotypes present heterogeneously across individuals. Qualitative methods phenotyping FGD to aid in diagnosis have been developed. However, qualitative methods of diagnosis face several limitations such as the inherent subjective nature of assessment, variability in ratings between and within assessors, and fluctuations in FGD symptom severity and presentation over time. These limitations may be addressed using a quantitative approach to FGD diagnosis.

Few quantitative approaches for FGD characterization and diagnosis are present in the literature. Specifically, there is limited work that has investigated the influences of attentional distraction and emotional distress on gait behavior and symptom severity. Regarding attentional distraction, two studies have assessed dual tasking and its effect on gait behavior in FGD. These studies found mixed evidence surrounding the effect of dual tasking on FGD gait, wherein patients either show slow, more variable gait or fast, less variable gait in the presence of a secondary task (Breitkopf et al., 2018; Gandolfi et al., 2023). This prior evidence partially supports qualitative descriptions of the inconsistency of FGD symptom presentation, suggesting

the relationship between attentional distraction and gait control in FGD is much more nuanced than previously thought, and that other factors (e.g., anxiety, reinvestment) may also contribute to this relationship.

Regarding emotional distress, one study investigated self-reported symptom triggers and found that emotional triggers, such as anxiety and fear, were reported by patients to be very common (Geroin et al., 2022). However, there has not been work investigating the influence of emotion on gait in FGD. The influence of emotion – specifically distress or anxiety – on gait has been evaluated in healthy individuals by utilizing postural threat paradigms. However, the threat of shock paradigm is another robust method of eliciting anxiety, as it creates a general (i.e., not specific to balance or postural disturbances) sense of anxiety. The threat of shock has only been utilized in seated paradigms, and it may be useful in eliciting anxiety during walking as well.

It is clear that there is a paucity of work focused on gait behavior in those with FGD, particularly work aimed at exploring the contributions of emotional triggers (i.e., fear and anxiety) and the interaction with attention to influence gait behavior and severity of FGD symptom expression.

2.0 Study Rationale

Given that emotional and attentional dysregulation are key features of FGD, characterizing both of their influence on gait control in FGD in a comprehensive manner may allow for improved understanding, diagnosis, and treatment of the disorder. Additionally, validation of inducing anxiety in gait with a novel threat of shock paradigm may provide clinical utility, as this paradigm requires minimal equipment and space. A study designed to probe at the influence of attention and anxiety on gait behavior in FGD may provide a novel quantitative approach to FGD diagnosis. Improvement in diagnosis may mitigate distress, disability, and costs accrued by FGD patients, and lessen the burden on the healthcare system.

2.1 Research objectives and hypotheses

The objectives of the present study were multifaceted:

(1) Evaluate whether a threat of shock paradigm is a robust method to induce elevated state anxiety during a clinical gait assessment in FGD patients and healthy controls (HC).

H1: Given that a threat of shock elicits anxiety in seated paradigms, it was expected that all participants will display greater levels of anxiety on walking trials when there is a threat of shock compared to safe trials (where there is no threat of shock). Additionally, given that FGD patients generally report greater anxiety, it was expected that FGD patients will report a higher level of anxiety compared to healthy controls across both threat and safe conditions.

(2) Examine the influence of distraction compared to distress (i.e., anxiety) on spatiotemporal characteristics of gait behaviour (e.g., velocity, step length, step length variability, step width, step width variability, double support duration) in FGD compared to healthy controls.

H2a: Given previous evidence showing movement normalization when dual tasking, it was expected that dual tasking in FGD will yield increased velocity, longer steps, decreased step length variability, decreased step width, decreased step width variability, and less time spent in double support compared to baseline walking. Whereas in healthy controls (HC), it was expected that dual tasking will yield decreased velocity, shorter steps, increased step width, increased step width variability, and more time spent in

double support compared to baseline walking, given that a large body of evidence shows how walking suffers in healthy adults when completing a concurrent dual task.

H2b: Based on previous work showing anxiety-related gait changes, it was expected that threat of shock will yield decreased velocity, shorter steps, increased step length variability, increased step width, increased step width variability, and more time spent in double support in both FGD and HC relative to baseline walking. It was expected that the magnitude of the effect of threat will be greater in FGD compared to HC, given that FGD patients report greater anxiety, and report that anxiety is a prominent symptom trigger.

(3) Evaluate the relationship between dual task cost and movement reinvestment in FGD patients and matched controls.

H3: Given the proposed symptomology in FGD, it was expected that patients with greater levels of movement-specific reinvestment (e.g., greater movement-specific reinvestment [MSRS] scores) would be positively associated with a greater dual task cost on gait behaviour (e.g., more "normalized" gait during a dual task compared to baseline walking). Therefore, it was expected that patients with greater total and subscale MSRS scores would show a relative increase in velocity and step length, as well as a relative decrease in double support duration, step width, step length variability, and step width variability during dual task walking relative to neutral walking.

Conversely, given the detrimental effects of movement reinvestment on gait behaviour in healthy adults, it was expected that greater levels of movement reinvestment in healthy controls would be negatively associated with a greater dual task cost on gait behaviour (e.g., less "effective" gait during a dual task compared to baseline walking). Therefore, it was expected that controls with greater total and subscale MSRS scores would show a relative decrease in velocity and step length, as well as a relative increase in double support duration, step width, step length variability, and step width variability during dual task walking relative to neutral walking.

3.0 Methods

3.1 Participants and recruitment

The present study was in collaboration with the Integrated Functional Movement Disorders Clinic at Toronto Rehabilitation Institute. Eleven FGD patients were recruited through the Integrated Movement Disorders Clinic and were collected onsite at Toronto Rehabilitation Institute. Recruitment was completed between January 2023 and April 2024. FGD patients were eligible to participate in the study if they were between the ages of 18 – 85 years and diagnosed with FMD by a movement disorders neurologist. Additionally, the participants must have been able to walk unassisted for a minimum distance of 10 meters and must not have had any comorbid neurological disease (as diagnosed by a medical practitioner), or significant pain or fatigue that could have interfered with study completion. All FGD patients were recruited and completed the study before the start of the control recruitment process.

Recruitment for the matched controls was completed between May 2024 and May 2025. Age-matched healthy controls were recruited and collected at the University of Waterloo. Recruitment was completed via word-of-mouth and through collaboration with the Waterloo Research in Aging Participants (WRAP) database. To ensure appropriate age- and sex-matching, participants were recruited if they were the same sex as an FGD patient and were within 5 years of age of the FGD patient. Control participants were eligible if they did not have any visual, auditory, or balance impairments, as well as any musculoskeletal, neurological, or cardiovascular conditions. Participants did not have a history of severe upper or lower extremity injuries or severe concussions in the last 6 months. Participants did not have any medical implants – particularly Pacemakers – and must have been able to walk without an assistive device. Additional exclusion criteria included current pregnancy and past Attention Deficit Hyperactivity Disorder (ADHD) diagnosis. Past ADHD diagnosis was determined by responding “yes” or “no” to a question on the eligibility questionnaire asking of history of diagnosis by a medical professional.

3.2 Protocol and Apparatus

3.2.1 Pre-Walk Protocol

Upon arrival to the study session, participants were seated to complete consent and eligibility forms to ensure informed consent was obtained and that the individual met the

study's eligibility criteria. Participants then completed the Spielberger State Trait Anxiety Inventory (STAI)-Y1 (shown in Figure A5) (Spielberger et al., 1983). This questionnaire was used to provide a baseline of how anxious the participant is feeling before beginning the study.

Next, the participants were outfitted with one shock device (Pavlok 2, Behavioral Technology Group, Massachusetts, USA), which was placed on the participant's right wrist. The participant then completed a seated baseline auditory Stroop assessment. The auditory Stroop is an adapted version of the visual Stroop task, comprising of congruent and incongruent stimuli (Morgan & Brandt, 1989). The stimuli in this task are the words "high" and "low" spoken out loud at either high or low pitches. The congruent stimuli are when the spoken word and tone match, and the incongruent stimuli are when there is a mismatch between the spoken word and tone. In this baseline assessment, the auditory Stroop track was played from a portable speaker situated next to the participant. The participant was instructed to listen to the track and verbally identify the pitch of the word being spoken. They responded after each word is spoken, and the task lasted 45 seconds. While the participant completed the task, the researcher noted the number of errors the participant made during this task.

After the completion of the baseline auditory Stroop assessment, the researcher took the participant through the shock level-finding procedure. This level-finding procedure was conducted to find the Pavlok shock intensity that produced a moderately-intense and uncomfortable shock for the participant. The Pavlok 2 device was connected via Bluetooth to the Pavlok mobile app, which was used to administer the shocks. The seated participant was told that the purpose of this procedure was to find the appropriate shock level to use for the study, and that the appropriate shock level corresponds to a target rating of 6 on the Yale Visual Analogue Pain Scale (shown in Figure A1). This scale asks participants to rate their pain from 0 – 10, with 0 representing no pain, and 10 representing the worst pain possible (Correll, 2011; Hawker et al., 2011). The participant was informed that the first shock administered will be almost non-detectable, or at 10% intensity. After the administration of this shock, the participant was asked to rate their pain and discomfort using the Yale Visual Analogue Pain Scale. The researcher noted the participant's response and asked for permission to increase the intensity 10% and administer the next shock. Once permission was given, the shock was administered and the participant rated their pain and discomfort again with the Yale Visual Analogue Pain Scale. This process of shock administration and pain rating continued until the target rating of 6

was reached. The researcher noted and confirmed that this shock intensity would be used during the walking portion of the study. Once this level-finding procedure was complete, the walking trials were ready to begin.

3.2.2 Walk Protocol

The participants completed the walking portion of the study on the Zeno (Zenometrics, New York, USA) gait carpet. The gait carpet is 6 meters in length and is placed in an open area of the research space. There was approximately 1.5 meters of space from either end of the gait carpet and the corners of the research space, to ensure adequate time for gait stabilization and space to complete any turns. There was a camera (Logitech, Lausanne, Switzerland) on a tripod which was situated near the wall at one end of the gait carpet to capture video of the walking trials. The participants were instructed to start at this end of the gait carpet, standing in front of the camera. Data from the video recording was not used in analysis. Rather, the video recordings of each trial served as a back-up in the event that any step processing abnormalities (e.g., erroneous foot side tagging) occurred when cleaning and processing the Zeno data with PKMAS (Protokinetics, Pennsylvania, USA) software, which was especially pertinent when cross-checking the processing of the FGD walking data.

The participants were then informed of the process of the walking protocol. They were told that each trial consisted of one pass on the gait carpet. One pass is equivalent to a 7.5 m straight-line walk from the start point to the other end of the gait carpet, a 180-degree turn in the space off the gait carpet, and a 7.5 m straight-line walk back to the start point. They were also told a spotter would walk beside them if needed, to ensure safety in the event of postural instability.

The study consisted of 11 walking trials, which were comprised of different dual task (DT) and shock (S) manipulations. The trials spanned 4 conditions: (i) *-DT, -S*; (ii) *+DT, -S*; (iii) *-DT, +S*; (iv) *+DT, +S* (Table 2). Trial order was pseudorandomized, wherein the first and last trials were always baseline (-DT, -S) trials. The remaining order of the 9 trials were randomized across the dual task (+DT, -S), shock (-DT, +S), and dual task + shock (+DT, +S) conditions.

Table 2. Summary of the four different walking trial types

	Shock absent	**Shock present**
Dual Task absent	*-DT, -S* Baseline (Condition i)	*-DT, +S* Shock (Condition iii)
Dual Task present	*+DT, -S* Dual Task (Condition ii)	*+DT, +S* Dual Task + Shock (Condition iv)

In the *-DT, -S* (baseline) condition, the participants were asked to walk at their normal pace without completing the dual task (-DT) and while safe from shock (-S). In the *+DT, -S* condition, the participants walked at their normal pace and completed the dual task (+DT) and while safe from shock (-S). In the *-DT, +S* condition, the participants walked at their normal pace without completing the dual task (-DT) and with a 50% chance of experiencing a shock during the trial (+S). In the *+DT,+S* condition, the participants walked at their normal pace while completing the dual task (+DT) and with a 50% chance of experiencing a shock during the trial. (+S).

Trial order was pseudorandomized, where one -DT, -S trial as the first walk trial served as a baseline, and the second -DT, -S trial at the end served as a post-baseline. Before each trial, participants were informed if the trial entailed a dual task (+DT), potential to receive a shock (+S), or both (+DT, +S). In the +DT trials, participants were asked to verbally respond to the auditory Stroop task while walking. The audio track played from a portable speaker next to the walking area. While the participant completed the task, the researcher recorded the number of errors, total responses, and the audio track start and stop time.

Shock administration only occurred in 3 of the +S trials (during one -DT, +S trial, and during two +DT, +S trials). As the Pavlok 2 device was connected via Bluetooth to its mobile app, shocks were applied without providing any notice to the participant, preserving the anticipatory anxiety component of the threat of shock paradigm. Participants were not told or given a countdown before shock administration, and only one shock was delivered during the selected trial. Shocks were always administered when the participant is turning to avoid fully disrupting the gait cycle and gait carpet data acquisition. Before starting the first trial, participants were asked to rate their feeling of anxiety at the current moment using the arousal subscale of the Self-Assessment Manikin (SAM; shown in Figure A2). This subscale which asked participants to rate their level of "anxiety" (arousal) from 1 – 9, with 1 representing low

anxiety and 9 representing the high anxiety (Bradley & Lang, 1994). The term "anxiety" was used when asking participants to respond to ensure the question was not misinterpreted by the participant. This rating provided insight into the participant's baseline level of arousal immediately before walking. After this rating was given, the first trial began. The participant was told that the current trial does not contain a dual task or threat of shock and was instructed to walk after hearing a "beep" from the gait carpet. After this noise, they completed the pass on the gait carpet and rated their post-trial anxiety using the SAM. This post-trial SAM provided a measure of arousal during the walking trial. After this, the next trial began. This procedure repeated for all 11 trials as described above.

3.2.3 Post-Walk Protocol

After the walking trials were complete, the Pavlok device was removed and returned to the researcher. The participants then were seated to complete the post-assessment questionnaires. The first questionnaire used was the Movement Specific Reinvestment Scale (MSRS; shown in Figure A3), which asked participants to characterize the degree of movement reinvestment they experience in daily life (Masters & Maxwell, 2008). The next questionnaire administered was the Gait-Specific Attentional Profile (G-SAP; shown in Figure A4), which asked similar information to the MSRS, but was specific to walking (Young et al., 2020). These questionnaires were completed after the walking portion to ensure participants were not paying attention to their movement reinvestment tendencies while completing the walking portion of the study. Next, the Spielberger State Trait Anxiety Inventory (STAI)-Y2 (shown in Figure A6) measured trait anxiety, and thus was used to understand how anxious the participant was overall (Spielberger et al., 1983). Finally, the Hospital Anxiety and Depression Scale (HADS; shown in Figure A8) was used to gain a general understanding of participants' anxiety and depression symptoms. The HADS provided different information than the STAI-Y2, as the HADS focused on taking inventory of clinical descriptors of common anxiety and depression symptoms (Zigmond & Snaith, 1983). Once the questionnaires were completed, the participants were thanked for their time and provided remuneration for their participation, marking, the conclusion of the study session. A summary of the events in one study session are depicted below in Figure 4.

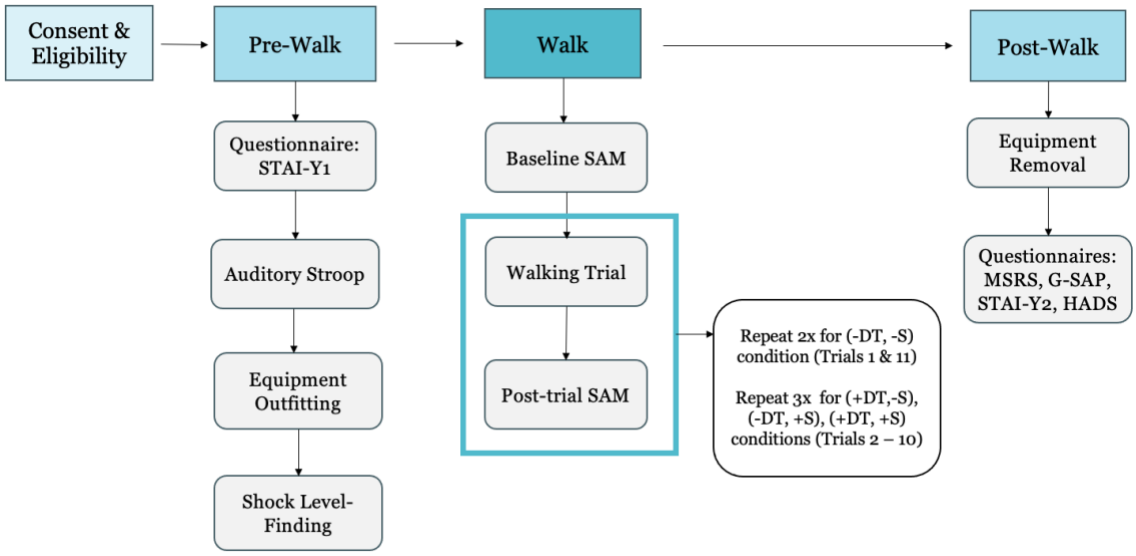


Figure 4. Schematic illustrating proposed study procedure. STAI-Y1: Spielberger State-Trait Anxiety Inventory (State anxiety measure); SAM: Self-Assessment Manikin; DT: Dual-Task; S: Shock; MSRS: Movement Specific Reinvestment Scale; G-SAP: Gait-Specific Attentional Profile; STAI-Y2: Spielberger State-Trait Anxiety Inventory (Trait anxiety measure); HADS: Hospital Anxiety and Depression Scale.

3.3 Outcome Measures

3.3.1 Gait Variables of Interest

Gait variables of interest were collected using the Zeno pressure sensor gait carpet, and output using the PKMAS software. These variables were included in the analysis for all study objectives and comprised of velocity, step length, step length variability, step width, step width variability, and time spent in double support. These variables were selected for the present study given their use in previous literature investigating the effects of dual tasking and anxiety on walking in a multitude of populations (Woollacott & Shumway-Cook, 2002; Gage et al., 2003; Brown et al., 2006; Al-Yahya et al., 2011; Hall et al., 2011; Stöckel & Mau-Moeller, 2020; Norouzian et al., 2024). Additionally, some of these variables have been utilized in previous quantitative approaches to FGD, therefore replication of previous findings and addition of novel evidence contributes valuable information to the growing field of quantitative gait analysis in FGD (Breitkopf et al., 2018; Gandolfi et al., 2023; Sandri et al., 2024).

Velocity (centimeters/second) is calculated as the sum of all stride length measurements divided by the sum of all stride time measurements for each trial (Chang., n.d.). Step length (centimeters) is measured as the distance between the successive heel points of the left and right

foot and is given in centimeters. Step width (called "Stride width" in PKMAS; measured in centimeters) is calculated as the distance perpendicular to the line drawn from two heel points of the same foot. Step length and step width variability (percent) is the coefficient of variation of the step length and step width, respectively. Time spent in double support (double support duration; given in seconds) is calculated as the sum all time periods where both feet were in contact with the ground in stance phase (Chang., n.d.).

3.3.2 Cognitive Dual Task

The auditory Stroop was chosen for this study since it assesses executive function and can be completed regardless of participant education level (Janssen et al., 2019; Kestens et al., 2021). It also is a task which requires active participant involvement since they are required to verbally respond. The active nature of this task was thought to have pulled attentional focus away from movement, subsequently preventing individuals in the FGD group from quitting the task and redirecting attention to their movement. Additionally, as the task is spoken, it was clear to see the level of task adherence and when participants made errors or stopped completely. During the baseline assessment and each +DT trial, the researcher recorded the number of errors and total responses, as well as the audio track start and stop time. Dual task performance for each trial was quantified by the equation below:

$$\text{Dual Task Accuracy (\%)} = (\text{Number of Errors} / \text{Total Number of Responses}) * 100$$

3.3.3 MSRS Questionnaire Scoring

As described in Section 3.2, the present study utilized a variety of questionnaires to collect data regarding participant emotional disturbance and movement reinvestment. A majority of these questionnaires remained solely for the purpose of demographic description, however, the MSRS was utilized for further analysis in Objective 3. To provide context for the use of this questionnaire for the analysis, it is important to describe its use and scoring. For reference, an image of the questionnaire is provided in Appendix A (Figure A3).

The MSRS is split into two subscales which are the Conscious Movement Processing (CMP) and Movement Self-Consciousness (MSC) subscales (Masters & Maxwell, 2008). There are five questions in each subsection, and responses can be scored on a scale of 1 ("Strongly Disagree") to 6 ("Strongly Agree"). These subscales are scored individually to determine the degree of CMP and MSC a participant possesses, and the maximum score for each subscale is 30. These subscale scores may be summed to gain a general overview of a participant's

movement reinvestment tendencies, wherein the maximum sum of both subscales is 60. The greater the score on either subscale or the sum of both indicates a greater degree of either specific tendencies (subscale), and/or general tendencies (subscale sums) (Masters & Maxwell, 2008).

Questions for each subsection may address a similar issue but are worded in a way that aligns with their respective subsection. For example, CMP question 4 asks “I am aware of the way my body works when I am carrying out a movement” and MSC question 5 asks “I am concerned about what people think about me when I am moving”. While both of these questions address the topic of awareness around body movement, the CMP question targets the pure mechanical process of body movement in contrast to the MSC question which addresses the social or worry component regarding movement (Masters & Maxwell, 2008). Therefore, both subscale scores and total scores were included in analysis of Objective 3 to determine if specific or general movement reinvestment tendencies influence gait behaviour, particularly in comparison between baseline and dual-task walking.

4.0 Statistical Analysis

The present section will detail the statistical analyses completed for the present thesis. All statistical testing was carried out in R (v 4.2.1, R core team 2022). A list of libraries utilized is included in Appendix B (Table B1).

4.1 Participant Characteristics

To evaluate differences in participant demographics, all demographic measurements (excluding sex) were compared between groups with independent t-tests. If data were not normally distributed, Mann-Whitney U tests were utilized instead. It was expected that participants would be matched in age (as described in Section 3.1), and that FGD patients would score higher on all the questionnaires (STAI, MSRS, G-SAP, HADS). Sex was compared between groups using a Chi-Squared test, where no significant differences were expected (e.g., both groups were matched by sex).

Dual task performance was calculated using the following equation: Dual Task Accuracy (%) = (Number of Errors / Total Number of Responses) * 100. To evaluate whether dual task performance differed between groups or dual task conditions, a two-way mixed analysis of variance (ANOVA) [Condition (B, DT, DTS) x Group (HC, FGD)] was conducted. If data were not normally distributed (via Shapiro-Wilks testing), an aligned-rank transform (ART) analysis was conducted instead, as ARTs are a robust nonparametric equivalent to a factorial ANOVA (Wobbrock et al., 2011). It was expected that all participants would perform similarly at seated baseline and would show performance decrements during walking.

4.2 Objective 1

To evaluate whether a threat of shock paradigm is a robust method of inducing elevated state anxiety during a clinical gait assessment, a two-way mixed ANOVA [S (+/-) x Group (HC/FGD)] was conducted for each post-trial SAM ratings to determine whether threat of shock elicited elevated state anxiety in both participant groups. Data from three FGD were excluded, as P05 and P08 did not complete all trial types and did not have S trial SAM scores, and SAM data was not collected for P06. Therefore the ANOVA was conducted on 25 total participants ($n_{FMD} = 8$, $n_{HC} = 17$). Data were normally distributed, sphericity was not violated, and Bonferroni corrections were utilized for significant post-hoc tests.

4.3 Objective 2

To examine the influence of distraction compared to anxiety on gait behaviour in FGD compared to healthy controls, a three-way mixed ANOVA [DT (+/-) x S (+/-) x Group (HC/FGD)] was conducted for each primary gait variable to determine the changes in gait behavior due to dual tasking and threat of shock, both in isolation and in combination. The outcome variables included in this analysis were velocity, step length, step length variability, step width, step width variability, time spent in double support from each trial. Normality testing determined that data for step length, step width variability, and double support duration were not normally distributed, therefore ART ANOVAs were conducted instead. The data for all variables did not violate sphericity. Post-hoc tests with Bonferroni corrections, or contrast tests were conducted on significant interaction effects found in the three-way mixed or ART ANOVAs, respectively.

It was expected that there would not be any group or condition effects for the gait variables of interest when comparing baseline and dual task conditions. However, it was expected that there would be a two-way interaction effect between group and condition. It was likely that FGD would demonstrate increases in all gait variables in the dual task condition compared to baseline, and HC would demonstrate decreases in all gait variables in the dual task condition compared to baseline.

It was expected that there would be group and condition effects for gait variables of interest when comparing baseline to shock conditions. It was also expected that there would be a two-way interaction effect between group and condition, wherein both FGD and HC would demonstrate decreases in the gait variables of interest, but the FGD would show this change to a greater extent. Finally, it was also expected that there would be a three-way interaction effect. When comparing the change from baseline to dual task with change from baseline to shock, it was expected that FGD would demonstrate a greater change in gait variables compared to HC.

4.4 Objective 3

To evaluate the relationship between movement reinvestment and dual task cost on gait in FGD and healthy individuals, a Kendall correlation was conducted for each participant group to understand the degree to which MSRS scores (total, CMP, and MSC) are associated with changes in gait variables of interest across dual task and single task conditions in both participant groups ($n_{FMD} = 11$, $n_{HC} = 17$). The gait variables of interest were velocity, step

length, step length variability, step width, step width variability, and time spent in double support. In total, 7 associations for each MSRS score were conducted for each participant group, yielding 42 total correlations conducted. Normality was assessed for each variable and each group by using Shaprio-Wilk tests. However, given that each participant group was small, Kendall correlations were conducted for all 42 tests.

It was expected that in FGD, greater levels of movement specific reinvestment would be positively associated with a greater change in gait behaviour during dual task compared to baseline. In HC, it was expected that greater levels of movement-specific reinvestment would be negatively associated with a greater change in gait behaviour in dual task compared to baseline.

5.0 Results

Due to the magnitude of analyses and subsequent results comprising the present study, the following section will only report significant results. All results for the analysis of each objective are included at the end of the present document in Appendices C1 – C3.

5.1 Participant Characteristics

5.1.1 Demographics

Participant demographics are presented below in Table 3. Individuals in the FGD group scored higher on both STAI subscales ($t_{26} = 3.4$, $p_{State} = 0.002$; $W = 157.5$, $p_{Trait} < 0.001$) and HADS subscales ($W = 139$, $p_{Anxiety} = 0.03$; $W = 163$, $p_{Depression} = 0.001$). FGD patients also scored higher on the total MSRS ($t_{26} = 5.24$, $p < 0.001$) and the conscious movement processing ($t_{26} = 4.11$, $p < 0.001$) and movement self-consciousness ($W = 167.5$, $p < 0.001$) subscales. Individuals with FGD scored higher on the total G-SAP ($t_{25} = 4.7$, $p < 0.001$), as well as on all the subscales ($W = 166$, $p_{Anxiety} < 0.001$; $W = 126$, $p_{CMP} = 0.04$; $W = 126.5$, $p_{Task} = 0.04$; $W = 154$, $p_{Processing} < 0.001$).

Table 3. Participant characteristics.

	HC	**FGD**	**p-value**
Sex	12F; 5M	9F; 2M	0.14
Age (years)	69 (26 – 82)	50 (30 – 75)	0.21
STAI (State)	28 (20 – 53)	44 (26 – 66)	**0.002** **
STAI (Trait)	29 (20 – 61)	47.5 (42 – 54)	**< 0.001** **
MSRS			
Total	21 (12 – 35)	41 (21 – 56)	**< 0.001** ***
CMP	11 (6 – 22)	19 (11 – 27)	**< 0.001** ***
MSC	8 (5 – 23)	23 (10 – 29)	**< 0.001** ***
G-SAP			
Total	16 (11 – 44)	35.5 (19 – 49)	**< 0.001** ***
Anxiety	4 (3 – 11)	12 (6 – 14)	**< 0.001** ***
CMP	5 (3 – 14)	8.5 (5 – 15)	**0.04** *
Task Irrelevant Ruminations/Thoughts	4 (3 – 12)	6 (3 – 15)	**0.04** *
Processing Inefficiencies	2 (2 – 9)	7.5 (3 – 17)	**< 0.001** ***
HADS			
Anxiety	6 (0 – 20)	10 (0 – 18)	**0.03** *
Depression	1 (0 – 14)	9 (1 – 17)	**0.001** **

Data is presented as median (range), with the exception of Sex. Abbreviations: HC = Healthy Controls, FGD = Functional Gait Disorders, STAI = State-Trait Anxiety Inventory, MSRS = Movement-Specific Reinvestment Scale, CMP = Conscious Movement Processing, MSC = Movement Self-Consciousness, G-SAP = Gait-Specific Attentional Profile, HADS = Hospital Anxiety and Depression Scale.

FGD phenotypes as characterized by the diagnosing movement disorders physiotherapist are presented for each participant below in Table 4. P06 demonstrated an intermittent dystonic gait pattern wherein symptoms fluctuated significantly and were not fully present during the gait assessment.

Table 4. List of FGD participant phenotypes as described by the diagnosing physiotherapist.

Participant	FGD Phenotype
P01	Cautious gait
P02	Buckling gait
P03	Dragging/Weak gait
P04	Buckling/Dragging gait
P05	Dystonic gait
P06	Dystonic gait (intermittent)
P07	Weak gait
P08	Cautious gait
P09	Dragging/Weak gait
P10	Tremulous gait
P11	Cautious gait

5.1.2 Dual task performance is similar between groups and conditions

Auditory Stroop baseline performance between the groups was compared with a Student's t-test to account for any baseline differences in future analyses. Data from 2 FGD participants (P05 and P08) were removed from analysis, as these participants did not complete all trials and did not have any DT+S data. The baseline seated accuracy comparison revealed no significant differences in baseline performance between the two groups ($t_{24} = 0.20$, $p = 0.84$). Descriptive statistics for dual task performance are listed below in Table 5.

Table 5. Descriptive statistics for dual task performance.

	Baseline		**DT**		**DT+S**	
	HC	FGD	HC	FGD	HC	FGD
Dual Task Accuracy (%)	88 (52 – 100)	80 (64 – 100)	100 (50 – 100)	76.9 (30 – 100)	100 (50 – 100)	86.7 (33.3 – 100)

Data is presented as median (range). Abbreviations: DT = Dual Task walking condition, DT+S = Dual Task + Shock walking condition, HC = Healthy Controls, FGD = Functional Gait Disorders.

A two-way ANOVA [Group (HC, FGD) x Condition (B, DT, DT+S)] was conducted on calculated auditory Stroop accuracy scores from B, DT, and DT+S trials to evaluate whether there were differences in task performance between groups and across conditions. Analysis revealed no significant effects of group or condition (Table C1-1 in Appendix C). Task accuracy is displayed below in Figure 5.

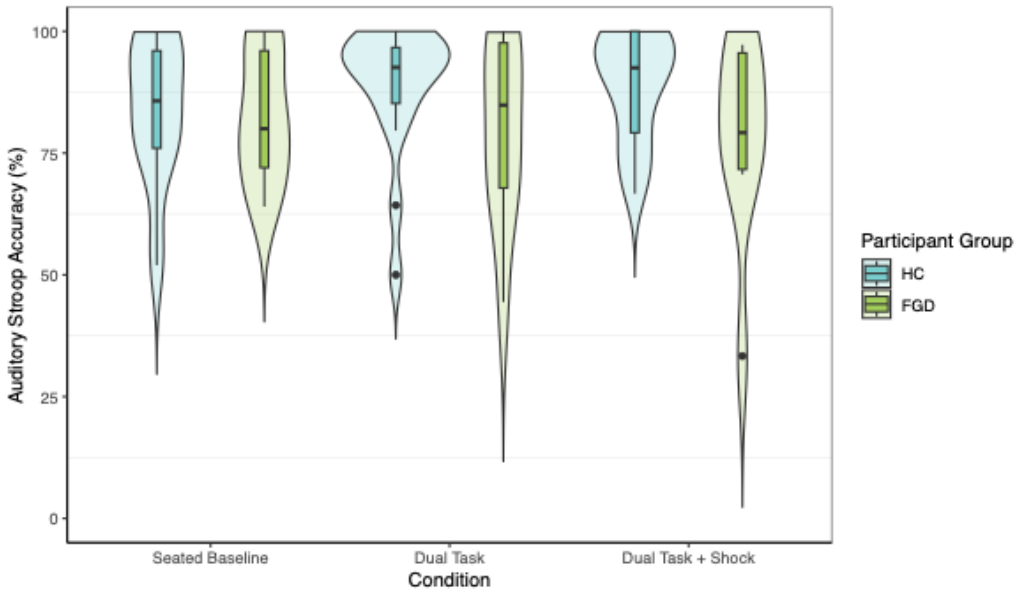


Figure 5. Box and violin plots showing accuracy on the auditory Stroop task between groups and across conditions. Data from 11 FGD patients and 17 HC are shown.

5.2 Self-reported anxiety is greater in the shock conditions

The two-way ANOVA revealed a main effect of group ($F_{1,23} = 12.77$, $p = 0.002$, $\eta^2 = 0.35$), and a main effect of shock ($F_{1,23} = 22.18$, $p < 0.001$, $\eta^2 = 0.04$). However, there was no significant interaction effect ($F_{1,23} = 1.03$, $p = 0.32$, $\eta^2 = 0.002$). Main effect post-hoc testing revealed that FGD patients generally reported greater anxiety than matched controls ($p = 0.003$, Figure 6), and that all participants reported greater anxiety when a threat of shock was present ($p < 0.001$, Figure 6). Descriptive statistics form SAM scores are shown below in Table 6, and SAM scores between groups and conditions are visualized below in Figure 6.

Table 6. Descriptive statistics for self-reported anxiety.

	Neutral		**Shock**	
	HC	FGD	HC	FGD
SAM Score	1 (1 – 3)	3 (1 – 9)	1 (1 – 4)	3.25 (1 – 9)

Data is presented as median (range). Abbreviations: SAM = Self-Assessment Manikin, HC = Healthy Controls, FGD = Functional Gait Disorders.

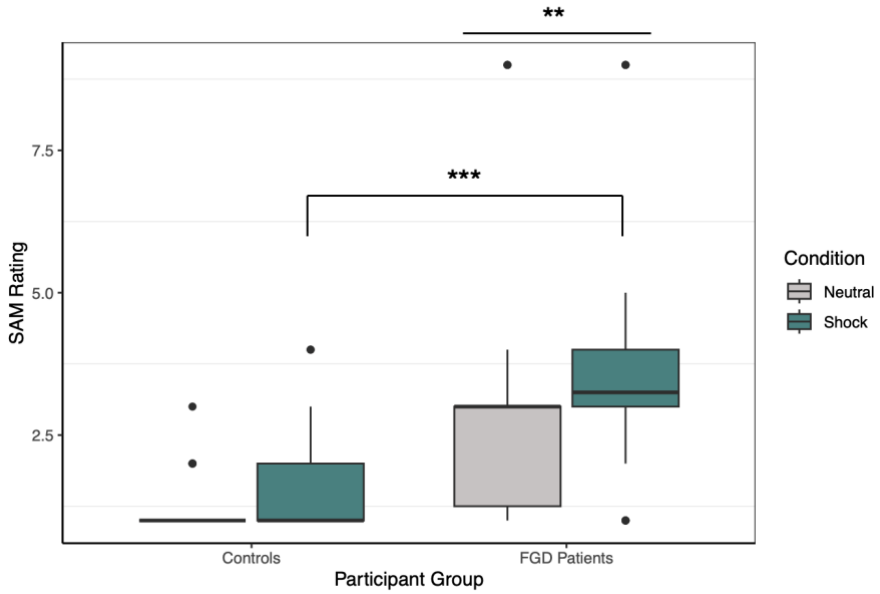


Figure 6. SAM ratings for age-matched controls and FGD patients across Neutral and Shock conditions. Data from 8 FGD patients and 17 HC are shown.

5.3 Walking behaviour

Descriptive statistics for the gait variables of interest are presented below in Table 7. Details regarding subsequent analyses are presented below in the following sections.

Table 7. Descriptive statistics for gait metrics.

	N		**DT**		**S**		**DT+S**	
	HC	FGD	HC	FGD	HC	FGD	HC	FGD
Step Width (cm)	7.4 (2.2-15.5)	14.6 (4.8-27.3)	7.6 (0.9-16.2)	15 (8.2-27.8)	6.6 (2.5-16.5)	13.3 (3.5-27.7)	7.7 (1.4-16.4)	15.3 (9.1-27.3)
Double Support Duration (% gait cycle)	28.4 (23.9-31.9)	30 (26.1-54.5)	30.2 (24.7-34.1)	39.5 (27.5-68)	28.9 (23.6-31.1)	29.9 (25.7-62.4)	29.9 (24.4-32.5)	36.1 (27.7 - 71.8)
Velocity (cm/s)	111.2 (90.4-134.8)	84.6 (29.8-118.8)	98 (67.9-122.8)	64.8 (13.5-112)	111.1 (86.3-131.7)	83.2 (19.3-122.8)	101.7 (73.3-127.9)	64.4 (13.2-112.4)
Step Length (cm)	60.9 (51.4-69.7)	48 (20.1-69.7)	45 (48.3-66.8)	57.4 (15.8-66.6)	61.4 (52.2-71)	46.9 (22.4-70.4)	57 (48.8-68.3)	45.3 (21.2-65.8)
Step Length Variability (%CV)	5 (2.7-24.4)	6.8 (3.4-162.6)	4.4 (2.3-23.8)	11.2 (3.3-222.6)	4.1 (2.3-18.2)	6.4 (3.2-149.9)	4.9 (3.5-18.3)	9.4 (5.2-162)
Step Width Variability (%CV)	29.3 (10.7-69.2)	21.4 (4.9-188.7)	22.6 (12-176.2)	16.7 (4.8-282.4)	27.6 (10.7-78.7)	15.3 (3.4-475.6)	26.3 (11.3-167.6)	16.7 (4.7-114.4)

Data is presented as median (range). Abbreviations: N = Neutral walking condition, DT = Dual Task walking condition, S = Shock walking condition, DT+S = Dual Task + Shock walking condition, HC = Healthy Controls, FGD = Functional Gait Disorders.

5.3.1 There are clear differences in gait between patients and matched controls at baseline

Analysis revealed a main effect of group ($F_{1,92} = 66.46$, $p < 0.001$, $\eta_p^2 = 0.42$; Figure 7A) for step width, wherein patients walked with wider steps compared to matched controls. A main effect of group was also found for double support duration ($F_{1,92} = 15.30$, $p < 0.001$, $\eta_p^2 = 0.15$; Figure 7B), as patients spent a greater time in double support versus matched controls.

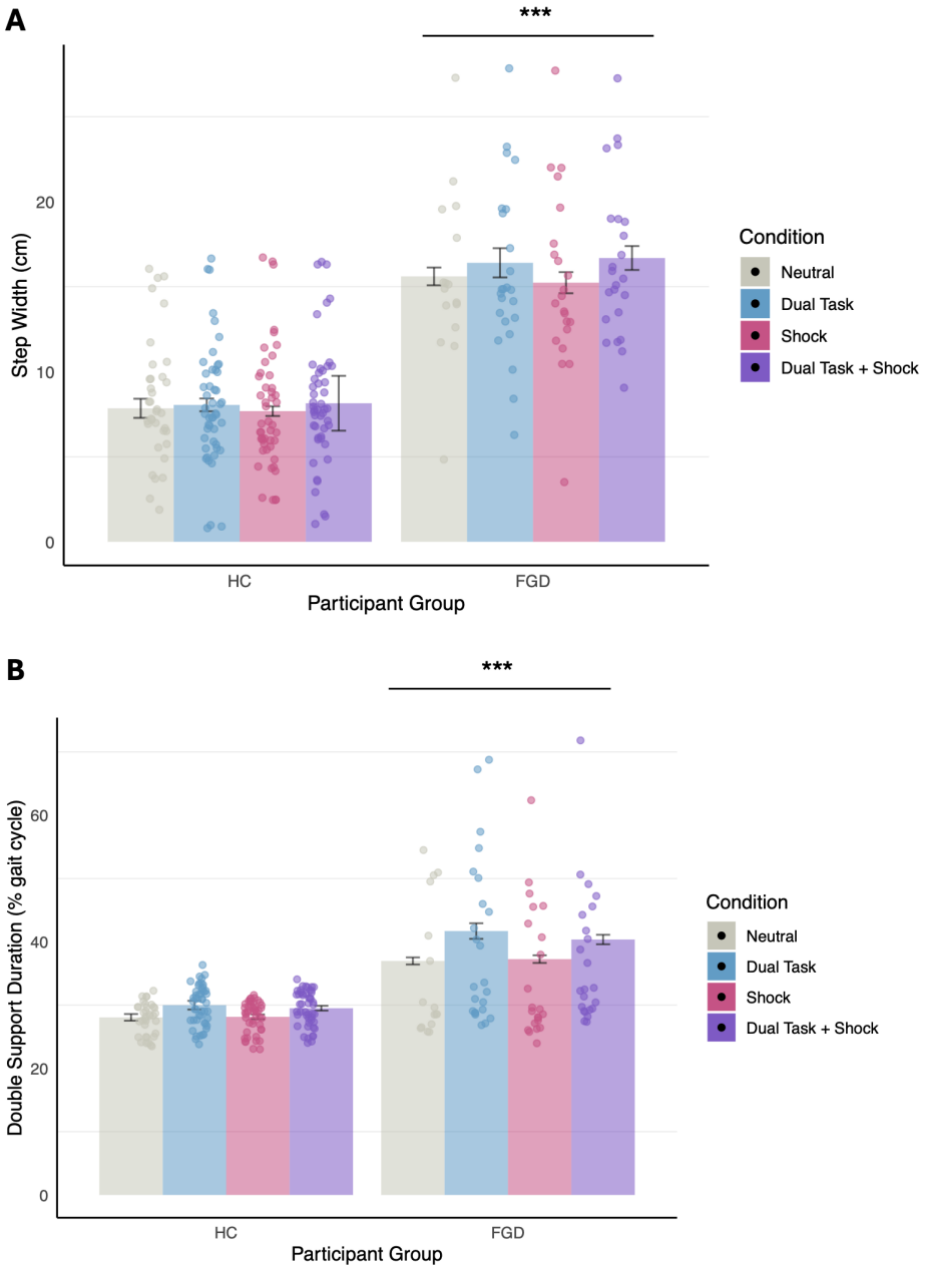


Figure 7. Bar graphs showing average step width (A) and double support duration (B) in matched controls (HC) and patients (FGD) across the four walking conditions. Individual datapoints for each condition are plotted on top of the bars. Data from 11 FGD patients and 17 HC are shown.

A main effect of group was also found for step length ($F_{1,23} = 12.94$, $p = 0.002$, $\eta^2 = 0.35$), where patients adopt shorter steps compared to matched controls ($p < 0.001$). Similarly, a main effect of group was found for velocity ($F_{1,23} = 20.35$, $p < 0.001$, $\eta^2 = 0.46$), wherein FGD patients demonstrated slower velocity compared to matched controls ($p < 0.001$).

5.3.2 Both groups adopt a slower and shorter steps when a dual task is present

Analysis revealed a significant main effect of dual task for step length ($F_{1,23} = 44.19$, $p < 0.001$, $\eta_p^2 = 0.03$). Similarly, a main effect of task was found for velocity ($F_{1,23} = 62.14$, $p < 0.001$, $\eta^2 = 0.05$). Post-hoc testing revealed that all participants walked slower and adopted shorter steps when a dual task was present ($p < 0.001$, Figure 8).

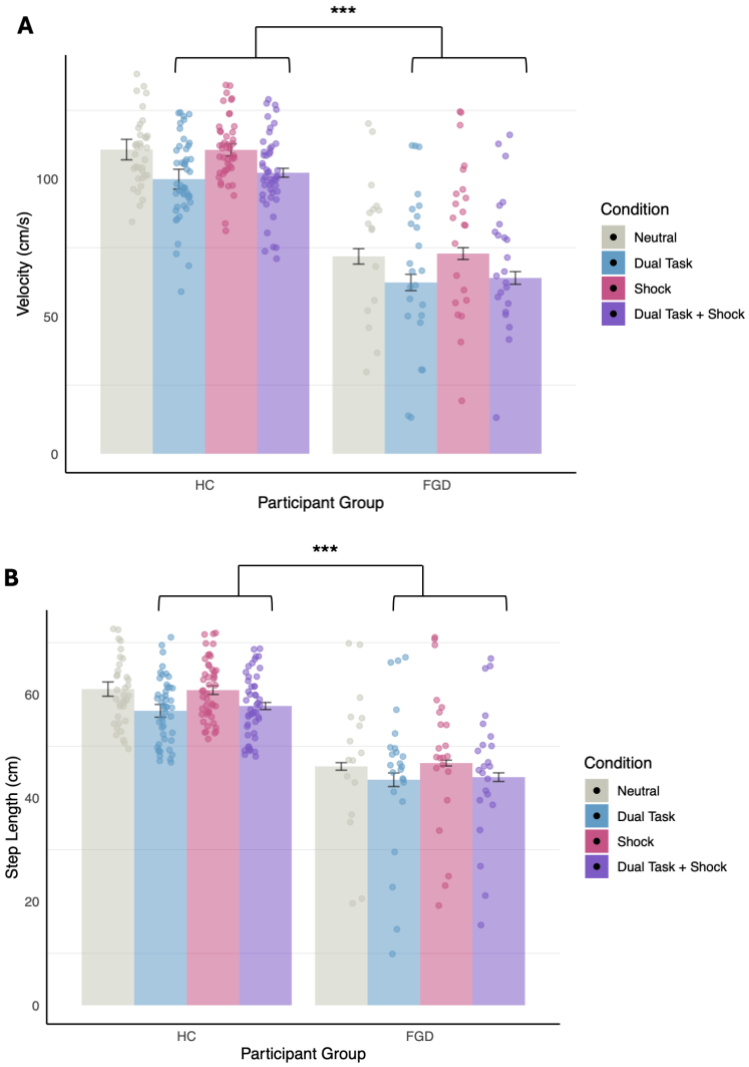


Figure 8. Bar graphs showing average velocity (A) and step length(B) in matched controls (HC) and patients (FGD) across the four walking conditions. Individual datapoints for each condition are plotted on top of the bars. Data from 11 FGD patients and 17 HC are shown.

5.3.3 Step length variability in FGD is impacted by shock

Analysis revealed a significant interaction effect between group and shock for step length variability ($F_{1,92} = 6.06$, $p = 0.02$, $\eta_p^2 = 0.06$). ART contrast testing revealed that FGD demonstrated greater step length variability compared to matched controls when shock was absent ($p = 0.002$, Figure 9) and present ($p = 0.001$, Figure 9).

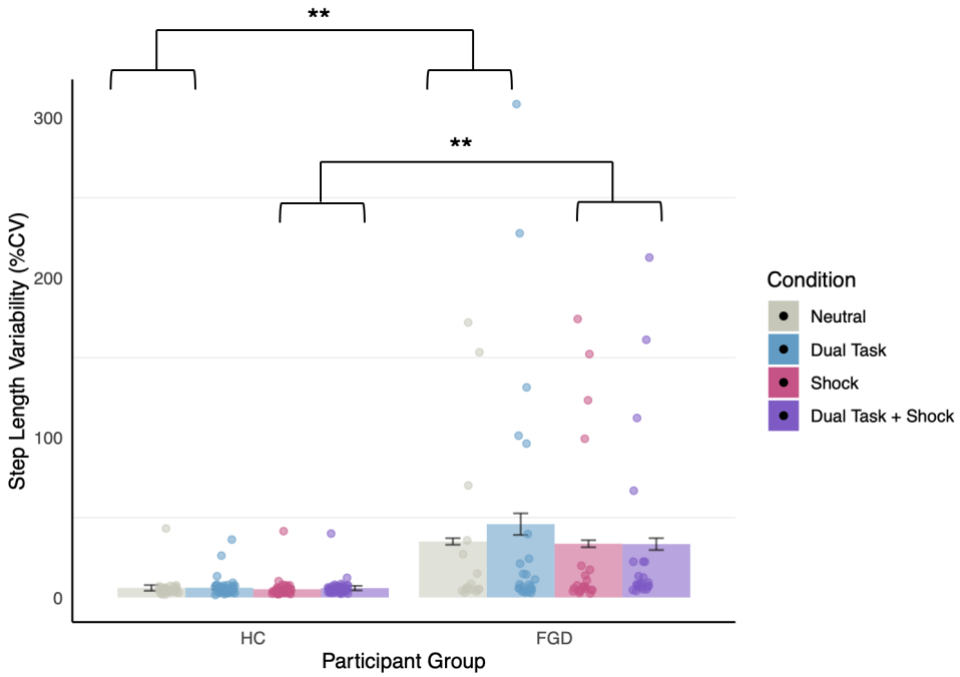


Figure 9. Bar graph showing average step length variability in matched controls (HC) and patients (FGD) across the four walking conditions. Individual datapoints for each condition are plotted on top of the bars. Data from 11 FGD patients and 17 HC are shown.

5.4 Clear relationships between movement reinvestment and dual-task gait behaviour in FGD

Analysis to address the third objective included total MSRS and subscale (CMP and MSC) scores, which were gathered for individuals in both participant groups. These scores denoted the magnitude of movement reinvestment possessed by study participants and were correlated with the dual task effect (DTE) on the primary gait variables of interest. DTE on the gait variables of interest was calculated as a change between dual task and neutral conditions. The equation used is shown below:

$$DTE(Variable) = Variable_{DT} - Variable_{N}$$

It is important to note that these change scores are calculated relative to each participant's baseline (neutral) walking, therefore interpretations of significant associations are in relative terms (rather than absolute). Below is a sample calculation of the dual task effect (change score) on velocity:

$$DTE(Velocity) = Velocity_{DT} - Velocity_{N}$$

$$DTE(Velocity) = 90\ cm/s - 100\ cm/s$$

$$DTE(Velocity) = -10\ cm/s$$

Given that step width and velocity yielded strong associations with MSRS scores in FGD patients, interpretation of the dual task effects are listed below in Table 8.

Table 8. Interpretation of calculated dual task effects (i.e., direction and magnitude of gait variable change scores).

Variable of interest	Direction and magnitude of DTE	Interpretation
Step Width (cm)	$Step\ Width_{DT} > Step\ Width_{N} = +DTE$	DTE is **positive**, therefore step width is *larger* in dual task relative to neutral.
	$Step\ Width_{DT} < Step\ Width_{N} = -DTE$	DTE is **negative**, therefore step width is *smaller* in dual task relative to neutral.
Velocity (cm/s)	$Velocity_{DT} > Velocity_{N} = +DTE$	DTE is **positive**, therefore velocity is *faster* in dual task relative to neutral.
	$Velocity_{DT} < Velocity_{N} = -DTE$	DTE is **negative**, therefore velocity is *slower* in dual task relative to neutral.

Kendall correlations revealed that FGD patients with greater total MSRS scores showed a relative reduction in step width during dual task walking compared to baseline walking ($p = 0.007$, $\tau = -0.67$, Figure 14A). A similar relationship was found with MSRS-MSC scores, wherein patients with greater MSC scores also showed a relative reduction in step width during dual task walking compared to baseline walking ($p = 0.009$, $\tau = -0.66$, Figure 14B). Additionally, Kendall correlations also showed that FGFD patients with greater MSRS-CMP scores showed relative increase in velocity during dual task walking compared to baseline ($p = 0.04$, $\tau = 0.54$, Figure 14C). Complete results are displayed in Table C3-1, Appendix C3. Kendall correlations revealed no significant associations between primary gait variables and MSRS scores. Complete results are displayed in Table C3-2, Appendix C3.

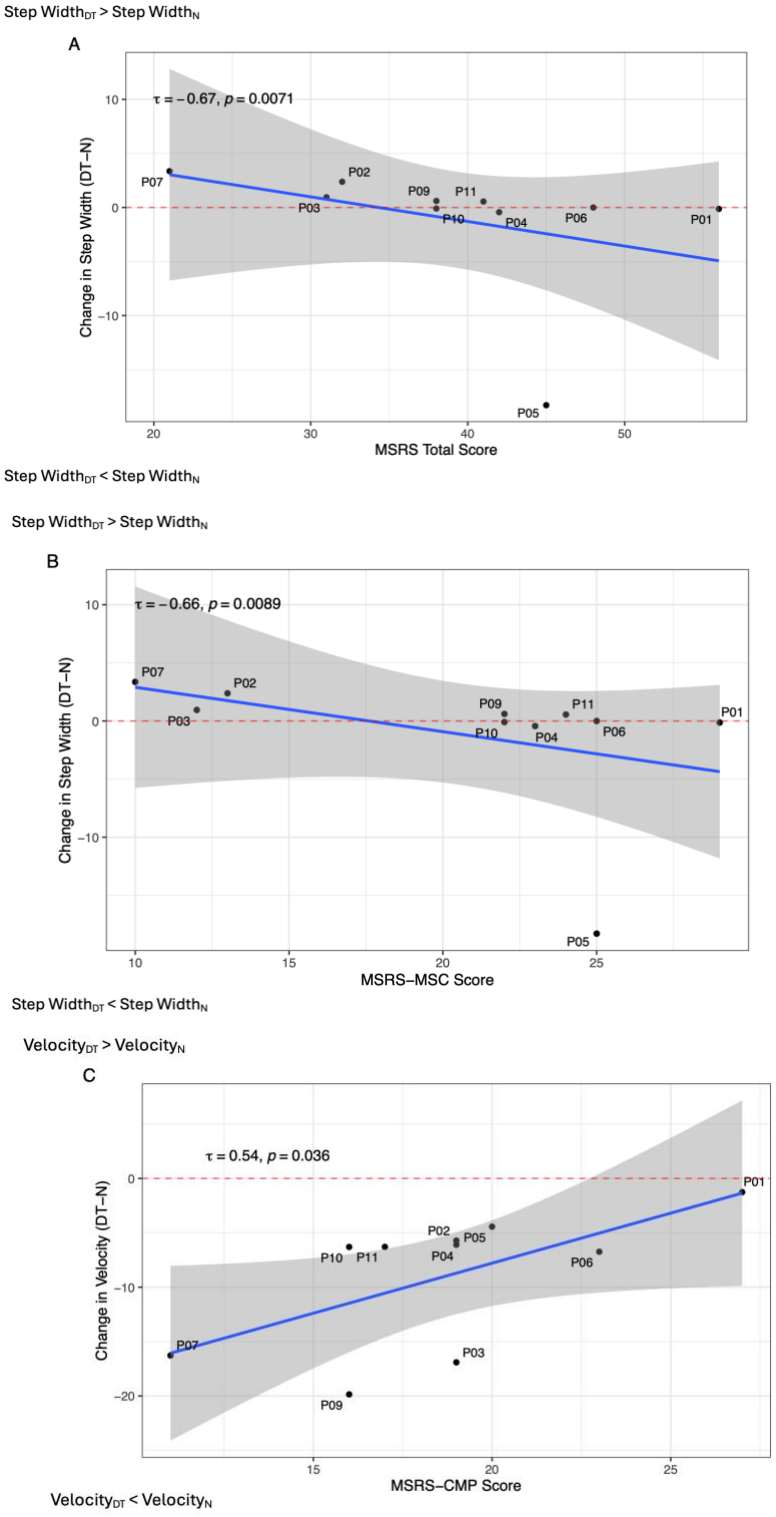


Figure 10. Significant correlations between MSRS scores and dual task effect (change between DT and N) for primary gait variables in the FGD group. Red dashed horizontal line indicates no change between conditions. Direction and magnitude of the DTE is shown on the positive and negative y-axes. Data from 10 FGD patients are shown.

6.0 Discussion

The aim of the present study was threefold: (i) validate the use of the threat of shock paradigm during walking in FGD patients and matched controls; (ii) evaluate the influence of attentional distraction and emotional distress on gait behaviour in FGD patients in comparison to matched controls; and (iii) examine the relationship between movement reinvestment and dual task effect on FGD and HC walking behaviour. As such, it was expected that the threat of shock would increase state anxiety during walking. The present study did indeed find that all participants report greater anxiety when the threat of shock is present, therefore confirming the effectiveness of the use of this paradigm in walking studies aiming to provoke a state of anxiety.

Additionally, it was anticipated that dual tasking would yield gait improvement in FGD patients and the threat of shock would worsen gait in both groups. The present study found baseline gait differences between patients and matched controls, wherein patients walk slower, take shorter and wider steps, and spend more time in double support, supporting previous work showing similar differences. Surprisingly, the present study found that FGD gait worsens, rather than improves, in the presence of the cognitive dual task. Both patients and matched controls adopted slower and shorter steps when completing the auditory Stroop task. The threat of shock yielded greater step length variability in patients compared to matched controls, but did not impact the variables that were found to be different at baseline (e.g., step length, step width, velocity, double support duration). The influence of the threat of shock on step length variability in FGD provides novel evidence showing altered gait in the presence of emotional distress.

Finally, it was expected that the degree of movement reinvestment would be strongly related to the impact of dual tasking on movement normalization. The MSRS contributed to a more nuanced understanding of the changes of gait based on attention which were found in the present study. In particular, greater reinvestment tendencies in FGD patients were associated with a speeding and narrowing of their steps when completing the auditory Stroop when compared to their baseline walking.

6.1 Validation of the novel threat of shock paradigm

The present study found that overall, FGD patients self-report greater anxiety. This aligns with previous work and aforementioned findings demonstrating greater affective disturbance present in patients (Carson et al., 2016; Huys et al., 2020). In addition, when compared to

baseline, all participants reported greater anxiety when a threat of shock was present during walking. This finding was expected given that a threat of shock has been shown to be incredibly anxiogenic in seated paradigms, as evidenced by measures of self-reported and physiological arousal (Grillon & Davis, 1997; Grillon & Ameli, 1998; Schmitz & Grillon, 2012).

Taken together, greater self-reported anxiety across groups due to the presence of shock indicates the effectiveness of the threat paradigm, thereby providing support for use of this paradigm in future anxiogenic studies. Given that the FGD patients in the present study reported greater movement reinvestment and anxiety, it is of importance to explore how these factors impact walking behaviour in these patients.

6.2 Gait behaviour in FGD and matched controls during attentional distraction and emotional distress

6.2.1 Gait differences between groups at baseline

The present study found that at baseline, FGD patients demonstrated slower velocity, shorter and wider steps, greater step length variability when compared to matched controls. These findings align with previous work investigating baseline differences between patients and individuals without FGD (Schneipp et al., 2019; 2021, Gandolfi et al., 2023, Sandri et al., 2024). The present study also found that at baseline, FGD patients spend more time in double support. While this finding has not been reported in the literature to date, it mirrors the wider step width seen in the present study and in previous work (Schneipp et al., 2019; 2021). Like step width, double support time is a gait metric that can indirectly demonstrate the efficacy of dynamic gait stability. Specifically, adopting a narrower base of support and reducing double support duration indicates adoption of a less cautious gait pattern and low likelihood of balance disruptions, wherein the converse is also true, especially within the context of fear of falling (Gage et al., 2003; Brown et al., 2006). While FGD patients tend to fall less frequently and severely compared to patients with organic movement disorders, individuals with FGD still adopt this cautious gait pattern (Schniepp et al., 2021). Taken together, the present findings contribute to a growing body of knowledge surrounding FGD, underscoring the clear differences in baseline walking patterns between patients and matched controls.

6.2.2 Both groups show gait decrements in the presence of a secondary task

The present study found that both FGD patients and matched controls demonstrated shorter steps and slower velocity when completing a cognitive dual task while walking. In the context of gait behaviour in healthy adults, this finding aligns with a large body of evidence showing decrements in step/stride length and velocity related to dual tasking (Al-Yahya et al., 2011; Hall et al., 2011; Stöckel & Mau-Moeller, 2020). These gait decrements illustrate the complexity of gait control and magnitude of cognitive resources required to allow gait control to seem automatic, wherein disruptions to walking and/or dual task performance demonstrates the shifting of already limited cognitive resources towards two demanding tasks (Woollacott & Shumway-Cook, 2002; Wu, 2015). Therefore, the present study provides evidence that completion of an auditory Stroop task is another valuable tool to use to investigate alterations in attention and gait control in healthy adults.

While the slowing of velocity and shortening of steps in the presence of a secondary cognitive task was expected for matched controls in the present study, the same result was not expected for the FGD group. Movement normalization was anticipated in FGD patients, as this was shown in a large number of previous qualitative and quantitative assessments (Stone et al., 2005; Espay et al., 2018; Breitkopf et al., 2018; Nonnekes et al., 2020) which subsequently informed the hypotheses of the present study. However, more recent quantitative FGD work did not shown movement normalization during dual tasking, wherein greater deficits in gait speed and stride length (e.g., slower speed and shorter steps) were seen in FGD patients when completing a cognitive dual task (Gandolfi et al., 2023, Sandri et al., 2024). These gait changes were also seen in the present study, as patients slowed their velocity and shortened their steps when completing the auditory Stroop task. While this finding does not support the work which informed the present hypothesis, it aligns with more recent work (Gandolfi et al., 2023; Sandri et al., 2024). Rather than use of an auditory Stroop, previous studies employed a serial-7s subtraction task, wherein participants had to subtract 7 backward from a given integer whilst walking. Given the complexity of the task, it may be possible that higher-order brain regions were concurrently recruited for completion of the task and gait control, which subsequently yielded the gait decrements seen (Gandolfi et al., 2023, Sandri et al., 2024).

Although the present study utilized the auditory Stroop – which primarily targets inhibition rather than working memory capacity – it may be the case that the auditory Stroop also recruited

higher-order brain regions that were also being used for effective gait control. This may have been the reason why FGD patients in the present study demonstrated gait "decrements" (e.g., slower velocity, shorter steps) in the presence of the auditory Stroop, as limited cognitive resources were concurrently recruited and subsequently impacted movement performance. Rather than redirecting cognitive resources elsewhere to elicit movement normalization, the auditory Stroop (and similar complex cognitive tasks) may not be beneficial to probe symptom resolution in this clinical population. Thus, it may be of interest to investigate the impact of dual tasks of increasing difficulty on gait behaviour in FGD patients.

While specific gait metrics were impacted by dual tasking, previous work found some metrics of gait variability (stride time variability and standard deviation of swing time) were unchanged when dual task walking relative to single task walking, suggesting preservation of gait automaticity in patients when a dual task is present (Gandolfi et al., 2023; Sandri et al., 2024). As the present study did not investigate the impact of dual tasking on stride/step time variability or swing time variability in FGD patients, it is not certain that the decrements found in the present study mirrored any preservation of automaticity as indicated by these specific variables. These variables were not selected for analysis in the present study as the current variables of interest closely mirror those seen in a majority of dual task work (Al-Yahya et al., 2011; Hall et al., 2011; Stöckel & Mau-Moeller, 2020; Gandolfi et al., 2023; Sandri et al., 2024), which was used to support the rationale behind the present study aims and hypotheses.

Additionally, previous quantitative approaches to FGD did not provide clear rationale for the importance in selection of stride time variability and/or standard deviation of swing time; rather broadly stating that these variables measure gait automaticity and steadiness (Gandolfi et al., 2023; Sandri et al., 2024) without providing nuance. However, previous gait and dual task work suggests that metrics of variability are indicative of fall risk, wherein greater variability reflects poorer rhythmicity and increased susceptibility to falls (Maki, 1997; Yogev at al., 2005). While investigation of fear of falling has merit, it was not the main focus of the current study, given that a majority of FGD patients do not experience frequent or severe falls (Schneipp et al., 2021). As such, stride/step time variability and standard deviation of swing time were excluded from the present study.

It is important to note that these variability metrics were measured and analyzed in the context of dual task effect, where dual task effect was calculated below (Gandolfi et al., 2023; Sandri et al., 2024):

Dual Task Effect (DTE) [%] = [(Dual Task performance – Single Task performance) / Single Task performance)]*100

It is also important to note that this equation is distinct from the one utilized to calculate dual task accuracy in the present thesis. The dual task effect of each variable was calculated and subsequently analyzed with ANOVAs, yielding a lack of change in the dual task effect on stride time variability and standard deviation of swing time present (Gandolfi et al., 2023; Sandri et al., 2024). While utilizing a metric quantifying dual task effect contains merit, previous findings regarding gait variability should be regarded with caution, as the raw data should also be inspected and analyzed. While previous work shows that the raw gait speed and stride length are decreased during a cognitive dual task – along with their DTE counterparts – the same relationship is not as clear in the variability metrics (Gandolfi et al., 2023; Sandri et al., 2024). Instead, it appears that the raw stride time variability and standard deviation of swing time values during dual task walking are greater than those in single task walking (i.e., variability is increased during a dual task). Therefore, future work should specify which variables are analyzed, and that interpretations are adequately operationalized in alignment with the variable format.

Moreover, it is imperative that future work aims to clearly describe automaticity in the context of FGD. It may be of interest to conduct a study with the sole purpose of curating and validating a set of variables which describe automaticity (and other domains of gait) in FGD, similar to previous work conducted in older adults (Lord et al., 2013; Wilson et al., 2019). This approach would clearly outline how the traditional domains of gait map onto functional gait and may provide a clearer framework for interpretation in future research. This framework may be used in a similar manner to work in Parkinson's, wherein these domains may be mapped onto neural regions and functional networks encompassing gait control and cognitive function (Morris et al., 2019). This approach would not only bridge the gap between existing neurobiological evidence and knowledge of gait behaviour in FGD, but would also provide a clearer, more integrative framework for future implementation, thereby substantiating arguments in previous work.

While stride time variability and standard deviation of swing time were not included in the current study, step width was analyzed. Although stride/step width was not included in previous work (Gandolfi et al., 2023; Sandri et al., 2024), this metric provides vital information regarding balance control and subsequent fall risk by directly indicating the magnitude of the base of support. Limited work has investigated step width in FGD, and previous and current evidence shows that patients adopt wider steps during single task walking compared to matched controls (Breitkopf et al., 2018). However, when completing a cognitive and motor dual task, patients did not show altered step width (i.e., base of support) when a dual task was present, as all AUC values for the base of support measurement during a dual task were between 0.68 – 0.70, indicating little difference between patients and controls (Breitkopf et al., 2018). While the present study did not conduct an ROC analysis, similar results were found, as there was no main effect of task or interaction between group and task on step width. Therefore, it is possible that step width is not sensitive to the effects of dual task in this population, however, step width can still delineate healthy and functional gait, given the clear differences found at baseline in the present study.

Additionally, it is important to consider how dual task performance – specifically performance on the auditory Stroop – may have impacted gait in FGD patients in the present study. Patients demonstrated similar performance to matched controls during the seated (baseline) Stroop task, as well as during walking. This finding suggests that cognitive disturbance is not seen in FGD – or not specifically captured by the auditory Stroop task. Interestingly, this finding aligns with previous work showing that FGD patients may report greater cognitive disturbance, but do not show altered performance on cognitive tests compared to matched controls (Heintz et al., 2013). However, it is important to consider the capacity of the auditory Stroop in completely evaluating cognitive function, as its main purpose is to test inhibition. Stroop task accuracy was the only metric of cognition assessed in the current study, and both response rate and response time may have provided more information surrounding cognitive capacity in FGD. It may have also been the case that the auditory Stroop was not adequately challenging of cognition, wherein participants may have found the task too easy or too difficult. While perception of difficulty varies by individual, overall, the task may have been too easy and thus not sufficiently taxing on cognitive resources. Taken together, future work

should aim to either collect more auditory Stroop metrics or include a variety of cognitive assessments measuring other aspects of executive function.

Perhaps when individuals with FGD walk, this walking in combination with the dual task may serve as somewhat of a distraction from their movement patterns, potentially freeing up previously occupied cognitive resources and therefore allowing improved DT performance. It may be the case that the auditory Stroop task may not be adequately distracting to see an "improvement" in walking behaviour (hence no "improvement" seen in variables of interest), but the walking in combination with the additional task may demonstrate attentional diversion to some extent. This may be contrasted with the finding from the present study that matched controls appear to worsen their dual task performance when walking. This result is expected in the matched controls, given that cognitive dual tasks are utilized to disrupt the automaticity of movement by drawing upon shared cognitive resources (Wu et al., 2015).

Additionally, the discrepancy in findings provides an intriguing point of discussion surrounding the operationalization of the terms "deficits", "gait decrements", and "automaticity" within the context of FGD. The present study hypothesized that the addition of a cognitive dual task would contribute to movement normalization in patients, by allowing redirection of inwardly-focused attention toward an external task subsequently yielding "improved" or more "automatic" gait due to the freeing of previously-occupied cognitive resources. The redirection of these cognitive resources, by the function of movement reinvestment ceases the breakdown of a highly-automatized movement (i.e., gait) and allows this "automaticity" to return, wherein this new gait pattern resembles that of an individual without FGD.

The following concept is illustrated in Figure 11. Matched controls and patients have the same critical threshold for effective performance, wherein a level of "water" (cognitive resources) below or above this threshold results in a degradation of movement performance. At baseline (part A), resources dedicated to walking and cognitive tasks sit at the appropriate level in their respective "cups" in matched controls, resulting in effective movement. However, FGD patients have an excess of "water" in their "cup" dedicated to gait control, wherein this excess is due to movement reinvestment. This difference between the two groups was seen at baseline in the present study, wherein patients demonstrated shorter steps, slower velocity, greater double support time, and wider steps compared to matched controls.

During a dual task (part B), resources dedicated to walking are now moved to the cognitive task "cup" in both participant groups, however, yielding contrasting results. This movement of "water" (attentional redirection) in matched controls leads to the decrement of movement performance when completing a secondary cognitive task, which was clearly seen in the present study. However, this movement of water has a restorative effect on movement performance in FGD patients, wherein the resources dedicated to walking are now at the appropriate level, allowing for improved or more automatic gait in patients during a dual task. While this restorative effect was not seen at a group level in the present study (e.g., the group effects seen showed decrements in gait behaviour whilst dual tasking), this effect is uncovered when accounting for the degree of movement reinvestment present in patients.

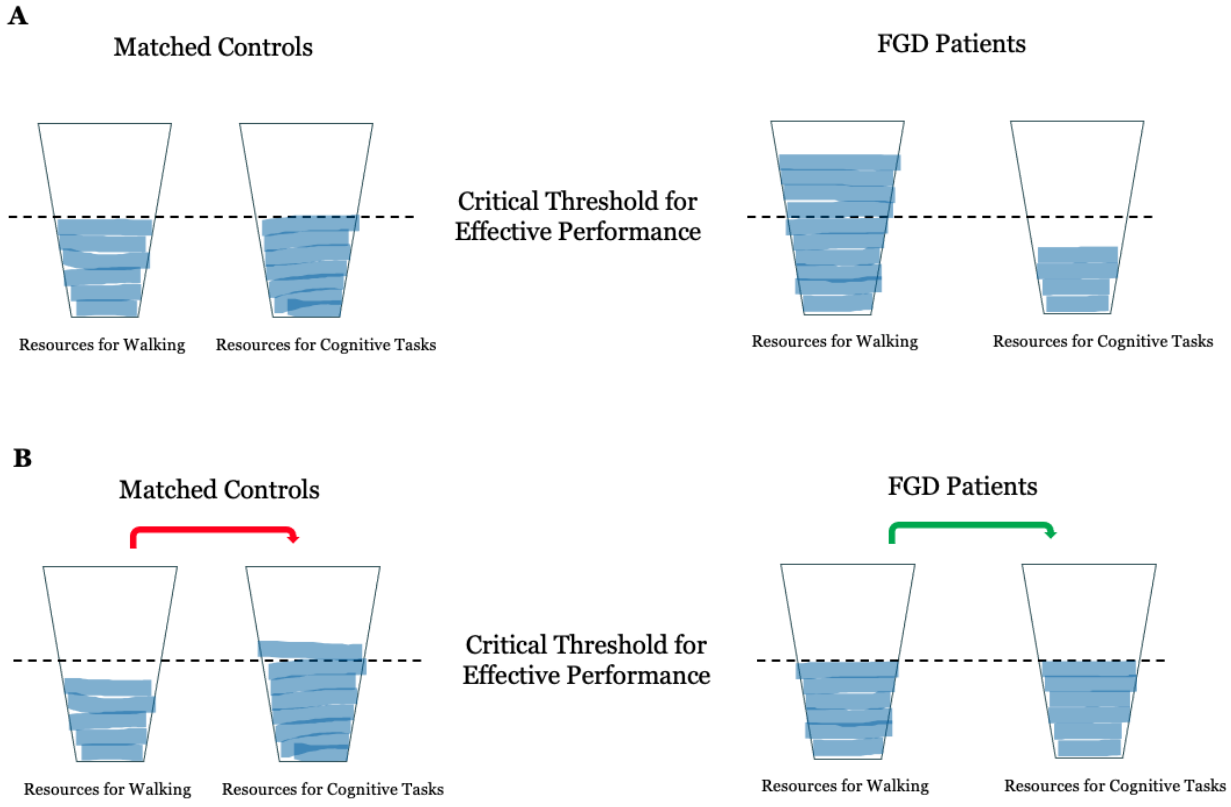


Figure 11. Illustration of hypothesized sharing of cognitive resources between walking and cognitive tasks in matched controls and FGD patients during single task (A) and during cognitive dual task walking (B).

6.2.3 Patients show greater step length variability while under threat of shock

Finally, the present study provided novel findings regarding gait alterations in FGD under anxiogenic conditions, wherein the presence of the threat of shock yielded increased step length variability in FGD. To date, this is the first metric of gait shown to be sensitive to anxiety in FGD. However, this finding partially supports the present study hypothesis, which expected that FGD patients would demonstrate gait deficits (e.g., decreased speed, shorter steps, and increased variability) when anxiety is present. This hypothesis was based on previous evidence reporting that individuals with FMD and/or FGD more commonly experience concurrent affective disorders, and that emotions such as fear and anxiety are symptom triggers (Geroin et al., 2022). Therefore, it would be expected that walking performance would suffer in situations provoking fear and anxiety.

Despite the paucity of work investigating the effect of anxiety on walking behaviour in FGD, the results from the present study align with previous work investigating postural threat in young adults, wherein younger adults showed greater step length variability in high-threat conditions (Norouzian et al., 2024). Additionally, unlike the FGD group, the matched controls did not show the same gait alterations when shock was present, which does not support the present study hypothesis. It was expected that matched controls would show similar gait alterations during anxiogenic conditions, wherein these changes (e.g., decreased speed, shorter steps, increased variability) would be present and parallel to those seen in FGD, but not as exaggerated in nature. This hypothesis was based on evidence from postural threat paradigms demonstrating that younger and older adults adopt a more cautious gait pattern, characterized by slower velocity, shorter steps, and increased step length variability (Norouzian et al., 2024). This adoption of a cautious gait pattern reflects the alterations in walking to preserve dynamic stability during postural threat to address fear of falling and subsequent injury.

It may be the case that since the anxiogenic paradigm in the present study utilized a threat of shock, rather than an elevated plank, the paradigm did not elicit a postural threat response in either group, and subsequently did not yield the hypothesized results. Therefore, it is important to consider why these hypothesized results were not seen. The present study sufficiently induced anxiety with the presence of shock, as shown by elevated self-reported anxiety in both groups when under a threat of shock. While anxiety was present, this anxiety may not have been present to a large enough magnitude to significantly alter walking patterns in either population.

Additionally, the present anxiety manipulation may not have yielded gait alterations specific to postural threat and may have instead yielded shock-related gait alterations, as participants may not have been as directly concerned about falling and related injury. In other words, the results seen in the present study may be indicative of gait behaviours humans exhibit when experiencing the threat of a moderately uncomfortable shock. However, future work is needed to clearly delineate differences between walking while under postural threat and walking while under threat of shock.

For example, the threat of shock and plank paradigms (either virtual or real-world environments) could be combined in one study, wherein some trials only utilize the threat of shock, some only utilize the plank paradigm, and other trials combine the two. This method may provide a more direct way of isolating and identifying which gait alterations correspond to which paradigm. Healthy adults, as well as patients from clinical groups of interest, could partake in this study as a way of further characterizing paradigm-related gait changes in the context of participant population. Undertaking of this work would provide further detail regarding the utility of the threat of shock during walking, as well as whether its effects are distinct from those in plank paradigms. This delineation would ultimately provide additional nuance to the relationship between anxiety and human gait control.

6.3 Reinvestment, affect, and their ties to walking in FGD

The present study found that when compared to matched controls, individuals with FGD demonstrated greater movement reinvestment and affective disturbance, as evidenced by greater MSRS, GSAP, and HADS scores. This finding is in line with previous work demonstrating that individuals with FMD score higher on the total, subscale, and item scores of the MSRS and HADS (Huys et al., 2020). The current study also found that individuals with FGD also showed greater trait anxiety compared to matched controls. While there is a lack of work investigating the use of the trait anxiety component of the STAI in FGD, the heightened trait anxiety found offers additional support to previous evidence showing the prevalence of anxiety and comorbid affective disorders in this population (Carson et al., 2016). Together, these findings highlight greater conscious motor processing, movement self-consciousness, and emotion experienced by patients. These characteristics may be a key factor involved in symptom presentation, wherein greater trait anxiety and movement reinvestment may play a role in pathogenic gait in FGD, as patients in the present study with greater reinvestment tendencies showed a relative

improvement in their gait (e.g., greater velocity and shorter steps) whilst dual tasking relative to their single task walking. This finding complements the body of work showing that these qualities lead to gait decrements in individuals without FGD (Gage et al., 2003; Brown et al., 2006; Ellmers et al., 2016; Young et al., 2016; Ellmers & Young, 2018; Ellmers et al., 2020; Norouzian et al., 2024).

6.3.1 Patients with greater reinvestment tendencies show faster and narrower steps during a dual task relative to baseline

It was expected that there would be a positive association between MSRS scores and effect of dual task on gait in FGD, wherein patients who were greater reinvesters would show a relative "improvement" of their pathogenic gait when dual tasking compared to single tasking. This "improvement" or distractibility refers to the lessening or resolution of symptom appearance, which has been seen in clinical examinations employing attentional distraction (Hallett, 2016; Nonnekes et al., 2020). Within the context of the present study, symptom distractibility refers to a relative "improvement" in velocity, step length, step width, step length variability, step width variability, and double support time during the dual task condition compared to the neutral condition. Relative "improvement" (symptom distractibility) is characterized by faster velocity, shorter and narrower steps, and decreased variability and double support duration in a dual task compared to neutral. Therefore, analyses yielding these findings would indicate symptom distractibility in high reinvesters. Indeed, the current study provided evidence to show that patients with greater reinvestment tendencies demonstrated symptom distractibility, specifically in velocity and step length. Patients with greater general reinvestment and conscious movement processing tendencies showed a relative increase in velocity in dual task walking compared single task walking. Additionally, patients with greater movement self-consciousness showed a relative narrowing of their steps when completing the dual task compared to walking without a dual task (i.e., altered gait behaviour between conditions).

It may be the case that for these high reinvesters, the addition of the cognitive dual task may evoke some symptom distractibility, which manifests as increased speed and a narrower base of support when completing a concurrent task during walking. This distractibility may be caused in part by the potential beneficial effect movement reinvestment has on restoring or supplementing automaticity of movement in FMD (Huys et al., 2020). This increased conscious motor

processing may be important as it allows for relatively "effective" movement and compensations in movement to supplement any automatic motor processes that may be affected by FMD (Huys et al., 2020). This hypothesis complements movement reinvestment theory, where generally, excessively directing attention inward decreases the efficacy of movement performance as a result of sharing limited cognitive resources between movement control and working memory (Masters & Maxwell, 2008; Ellmers & Young, 2018). In the case of the present study, FGD patients who demonstrate high levels of reinvestment may have a decreased ability to share cognitive resources between movement control and working memory processes, potentially resulting in the pathogenic gait seen at baseline. However, when this cycle is interrupted by completing a cognitive dual task, the limits on these cognitive resources have been removed via attentional redirection, allowing for more efficient movement performance (i.e., movement normalization and symptom distractibility).

The association between reinvestment and distractibility found in the present study supports the Bayesian framework of FMD symptom maintenance (Edwards et al., 2012; Fiorio et al., 2022). The Bayesian model suggests that symptom maintenance is driven by extreme focus and anxiety surrounding the appearance of motor symptoms, wherein this attention toward symptom presentation creates a vicious cycle that further perpetuates symptomology (Edwards et al., 2012; Fiorio et al., 2022). This extreme focus and anxiety regarding the internal body state in these patients is driven in part by historical factors (e.g., self-focus and monitoring behaviors) as they are shown to be precipitating and maintaining factors in FND symptom presentation (Lidstone et al., 2020; Fiorio et al., 2022). Subsequently, the introduction of a secondary task during movement may disrupt this vicious cycle of symptomology. As greater reinvestment drives greater attention toward movement in FGD, dual-tasking may allow for a greater propensity to shift attention away from movement toward the secondary task, yielding improved gait performance. This effect is most likely prominent in the greatest movement reinvesters, which may explain why the FGD group as a whole did not show improved gait performance whilst dual-tasking, but patients with greater MSRS scores did show these performance improvements.

The present concept is described below in Figure 12. At baseline, the excess reinvestment present in FGD patients fuels a vicious cycle of symptomology (green arrow). However, it may

be the case that the presence of a dual task (DT) interrupts this vicious cycle (red dashed arrow), perhaps as a function of reallocation of cognitive resources as illustrated in Figure 11.

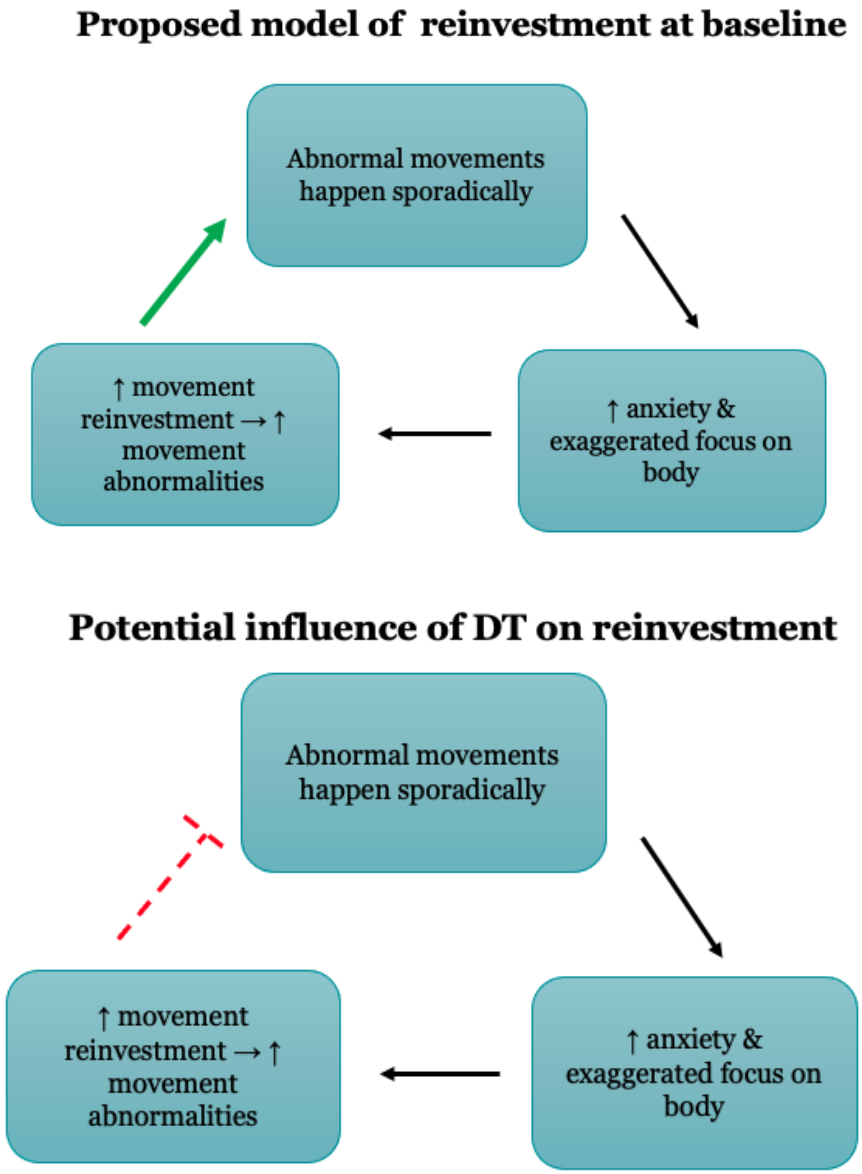


Figure 12. Illustration of the hypothesized model of reinvestment on FGD symptomology, as well as the influence of a cognitive dual task (DT) on this symptomology cycle. Adapted from Edwards et al., 2012 and Fiorio et al., 2022.

Therefore, it may be of value to target reinvestment tendencies when treating patients with FGD, wherein dual-task or distractibility strategies may be more effective when used with patients who demonstrate large magnitudes of reinvestment. These strategies may be in added

into therapies which are already standard of care for FGD patients, such as physiotherapy and cognitive behavioural therapy (Fiorio et al., 2022; Bhatt et al., 2025). Future work should look to investigate the feasibility of these strategies by clearly delineating the magnitude of influence of reinvestment on walking patterns in FGD patients.

6.3.2 Matched controls do not show altered gait behaviour during a dual task as a function of movement reinvestment

Conversely, it is expected that greater levels of movement-specific reinvestment in matched controls would be negatively associated with the dual task effect on gait behaviour (e.g., matched controls with greater MSRS scores would show worse walking during a dual task compared to neutral). However, the present study did not find any significant associations between MSRS scores and gait behaviour change in matched controls. This finding contradicts prior work showing clear movement decrements during completion of a cognitive dual task in high-reinvestment healthy individuals (Ellmers et al., 2016; Ellmers & Young, 2018). While these specific studies did not provide details regarding participant MSRS scores, additional work showed similar gait decrements in high reinvesters (Ellmers et al., 2019; Young et al., 2020). This work also specified the stratification of low and high reinvesters, wherein low reinvesters scored on average 4.6/40 and high reinvesters scored on average 21.5/40 on the MSRS (Young et al., 2020). Following this definition, the matched controls in the present study showed high levels of reinvestment, where the average MSRS score for the group was 22.8. Therefore, it is possible that the discrepancy in results between the present study and previous work may be due to other factors.

One prominent factor is age, where participants in previous studies were on average in their seventies, and controls in the current study were on average in their fifties. It may be the case that age may have influenced reinvestment and subsequent gait behaviour in previous work, given that older individuals are more susceptible to age-related gait alterations. This susceptibility is of interest given its potential relationship to fear of falling, wherein age-related gait changes may trigger fear of falling in older individuals who develop greater reinvestment tendencies as a strategy to combat the fear of falling. As such, it would be of interest for future work to gather a larger sample with a greater range of middle aged and older adults. Doing so would allow the sample to be stratified by age, where reinvestment tendencies and their relationship to age and gait behaviour may be more clearly identified.

7.0 Final remarks

7.1 Study strengths, limitations, and future directions

The primary strength of the present study is that it is among the first to characterize the influence of common FGD symptom triggers (i.e., fear and anxiety) on FGD gait behaviour. Despite the ubiquity of these symptom triggers in FGD, previous work has not quantified the impact of emotional distress on FGD symptomology. While the current study only identified that patients adopt greater step length variability under anxiogenic conditions, the identification of this marker adds to a growing body of literature surrounding quantitative approaches in FGD. In particular, addressing these symptom triggers in the context of gait behaviour sets the stage for future work to further consider emotional symptom triggers in various methodologies. As previously discussed, future work could aim to investigate the impact of other anxiogenic paradigms (e.g., postural threat, social anxiety) on gait in FGD as a method of delineating the impact of various anxiogenic paradigms on gait in this population. Findings from these studies may better inform the particularity of the influence of anxiety on symptom presentation in functional gait, and could inform potential diagnostic criteria (e.g., gait metric alterations specific to anxiety) or therapeutic strategies (e.g., scenarios or topics to target with various therapeutic modalities).

Similarly, another strength of the present study is that it is also among the first to utilize the threat of shock paradigm during walking. Given the present study is among few utilizing this paradigm. It would be important for future work to replicate findings from the present study in FGD, in order to validate its utility in FGD. Additionally, it would be of interest for future work to establish how this paradigm impacts walking in other populations (e.g., young adults, clinically-anxious people, people with Parkinson's). Results from this work may better describe the utility of this paradigm in a multitude of populations and may lead to the discovery of its effectiveness in research conducted in these fields. Additionally, findings from threat of shock studies may be contrasted with those from other paradigms (e.g., postural threat) to complement existing work and develop an increasingly nuanced understanding of the population of interest.

A third strength of the present study is the underscoring of the influence of movement reinvestment on FGD symptom presentation. While this influence has been theorized, the present study is one of the first to apply this theory to movement and see expected results. This evidence provides a path for future work to expand upon this evidence, and perhaps cement a

portion of knowledge surrounding the mystery of FGD symptomology and phenomenology. Subsequently, this may improve diagnosis and treatment of these disorders, ultimately lessening the burden on systems and individuals.

While the current study has many strengths, inherent limitations are also present. The primary limitation concerns sample size, particularly in the FGD group. Given the heterogeneity present across and within FGD phenotypes, findings from 11 study participants are not generalizable to the larger FGD population. Indeed, a majority of the three-way interactions were underpowered in the present study, suggesting that results from the present study – both significant or not – may be partially explained by the heterogeneity in the FGD group, wherein the unique phenotypic features may have driven the results seen. Therefore, it is imperative for future studies to recruit greater numbers of FGD patients, ensuring that the main FGD phenotypes are represented in the sample. Not only would this allow for generalizability of results, but this would also strengthen the evidence being added to the growing body of FGD literature. Additionally, better accounting for phenotypic variability may also provide evidence surrounding phenotype-specific gait deficits, and in turn, may inform more tailored rehabilitation strategies.

A similar limitation may have been present within the control group, given the greater range in participant age compared to the FGD group. While controls do not show the same degree of heterogeneity in walking as FGD patients, it is possible that age-related changes in gait were seen in matched controls and not accounted for. Given the slow progression of mobility alterations across the life span, there may have been slight differences in walking among the healthy controls, as participants in their fifties may adopt different gait patterns than those in their seventies. Therefore, it is critical for future studies to not only gather a larger sample of participants to yield more generalizable results, but to ensure any potential covariates are considered.

Additional limitations fall within the category of experimental design. The first concerns the lack of physiological arousal measures in the present study. While self-reported metrics have their own merit, they are not without reporting bias. Collection of physiological arousal measures (e.g., electrodermal activity, heart rate, respiration rate) whilst walking would further confirm the effectiveness and validity of the threat of shock paradigm. Similarly, use of physiological measures could confirm the presence or absence of trial carryover effects. Given

that the trial order in the current study was pseudorandomized (rather than blocked and counterbalanced), it is possible that anxiety and related gait changes could have influenced non-anxiogenic conditions. Therefore, it is important for future work to employ a counterbalanced block design to mitigate the potential carryover effects, wherein the magnitude of these effects could be quantified through measures of physiological arousal.

An additional limitation regarding experimental design is the lack of measurement of cognitive performance, as auditory Stroop accuracy at baseline served as a proxy for cognitive performance. As a result, the true nature of cognitive performance among the FGD patients may not have been captured. Given the lack of work investigating cognition in FGD, it may be of interest for future studies to include true cognitive measures (e.g., MoCA) to gain a clearer picture of cognitive abilities in FGD. This would not only inform researchers of the influence baseline cognition has on cognitive task performance in this population but would provide more evidence surrounding the relationship between cognitive abilities and FGD. Additionally, while the auditory Stroop was a secondary task which required active participation, its use was not without limitations. Given the task requires the participant to distinguish between tones of spoken words, some patients reported the task used did not distinguish enough between the low and high tones, which subsequently led to stimulus ambiguity and potential erroneous responses. As such, it is integral for future studies to utilize versions of the task which mitigate ambiguity of responses. Finally, the auditory Stroop task solely captures one aspect of cognition (inhibition) and therefore fails to capture other aspects, such as working memory capacity and cognitive flexibility. Therefore, it may be of interest to employ a battery of cognitive assessments that widely capture executive functions. In particular, working memory assessments may provide further insight into FGD symptomology, given the proposed phenomenology and clear involvement of movement reinvestment.

The final limitation concerns the specifics of the walking assessment. Firstly, the conditions of the walking assessment were not ideal, especially for the FGD setup. The space allotted at the UHN site did not allow for 1.5 m on each side of the gait carpet, which may have impacted the true representation of steady-state gait on the carpet. This was controlled for in data processing for the FGD group, where the first 4 footsteps from each pass were removed before the data was processed. These 4 footsteps were the ones most likely to represent gait deceleration rather than steady state. Despite these controls, future work utilizing a pressure-sensor carpet must ensure

adequate space for gait acceleration and deceleration in order to capture steady-state gait. Additionally, while pressure sensor data has been used in a large body of gait assessment work, it only captures lower limb gait metrics. Utilizing IMUs – especially those placed on the trunk and upper limb – allows for a more complete understanding of postural changes during walking. This may be especially of use in a heterogeneous clinical group like FGD, where IMU data can better characterize the various phenotypes at baseline and while distracted and/or distressed. The use of IMUs may also allow for ease of integration with clinical practice or home-monitoring settings, given the limited equipment needed and non-invasive nature of IMU data collection. Ultimately, future work should continue to strive toward implementation in clinical and home settings, given that FGD symptoms do not appear solely during a laboratory visit.

7.2 Conclusion

The present study provides evidence underscoring clear baseline differences in walking between FGD patients and matched controls. While the addition of a cognitive task did not result in clear movement normalization in the FGD group, patients with a greater degree of movement reinvestment demonstrated this normalization with concurrent performance of an auditory Stroop task. The present study also provides evidence illustrating the impact of the novel threat of shock paradigm on FGD symptomology, laying the foundation for this line of thought to continue through future work.

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Appendix A: Study Materials

Yale Visual Analogue Pain Scale

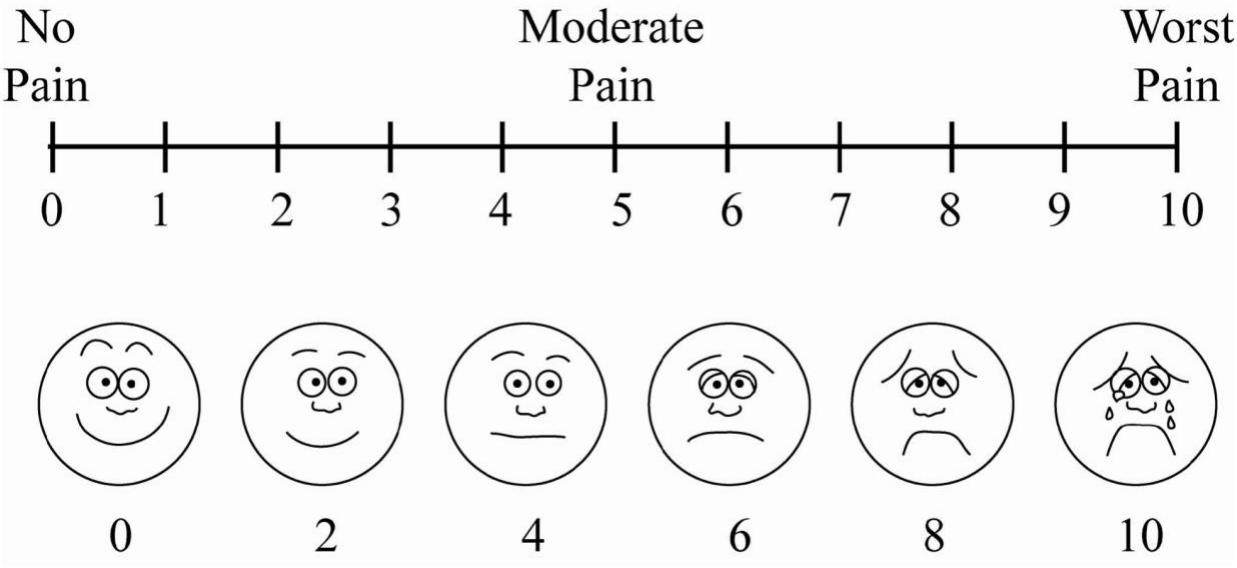


Figure A1. Yale Visual Analogue Pain Scale. This scale will be utilized during the shock level-finding procedure prior to the walking portion of the study. After each shock is administered, participants are instructed to rate their level of pain on a scale of 0 – 10 using the number line above. The target pain level for the study is moderate pain (6 on the scale). The shock level-finding procedure will continue until this target rating is reached, and then the corresponding shock intensity will be used for the walking portion of the study.

Self-Assessment Manikin – Arousal Subscale (SAM)

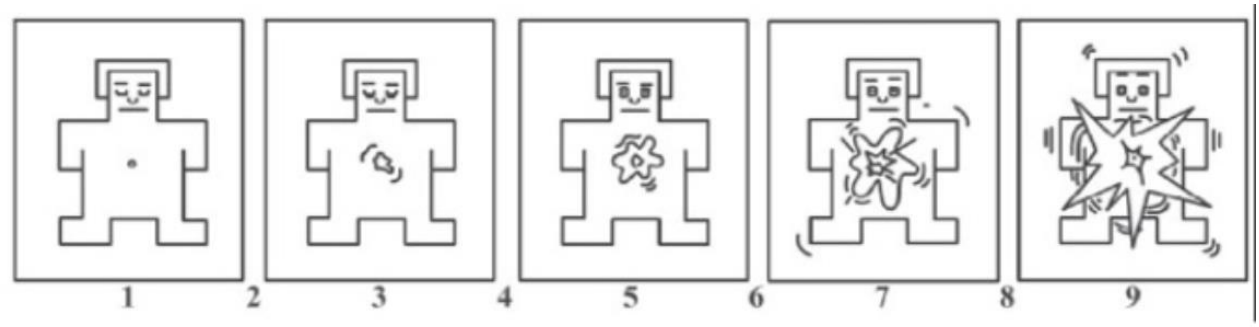


Figure A2. Self-Assessment Manikin (SAM) – Arousal subscale. This will be utilized before the walking portion of the study to gain a baseline level of arousal, as well as after each walking trial to assess post-trial arousal. Participants are asked to rate their level of "anxiety" (used as a proxy for arousal to avoid misinterpretation) from the scale of 1 – 9 (low arousal – high arousal).

Movement Specific Reinvestment Scale (MSRS)

Participant ID:_____ Date:_____

☐ Screening Questionnaire

Age:_____
Sex: Male Female
Height: _____cm
Leg Length: _____ cm
Weight:_____ lbs

The Movement Specific Reinvestment Scale (MSRS)

Instructions: Circle the answer that best describes how they feel.

	Strongly Disagree					Strongly Agree
Conscious Motor Processing						
I am always trying to think about my movements when I carry them out	1	2	3	4	5	6
I reflect about my movement a lot	1	2	3	4	5	6
I am always trying to figure out why my actions failed	1	2	3	4	5	6
I am aware of the way my body works when I am carrying out a movement	1	2	3	4	5	6
I rarely forget the times when my movements have failed me	1	2	3	4	5	6
Movement Self-Consciousness						
I am concerned about my style of moving	1	2	3	4	5	6
I am self-conscious about the way I look when I am moving	1	2	3	4	5	6
If I see my reflection in a shop window, I will examine my movements	1	2	3	4	5	6
I sometimes have the feeling that I am watching myself move	1	2	3	4	5	6
I am concerned about what people think about me when I am moving	1	2	3	4	5	6

Figure A3. Movement Specific Reinvestment Scale (MSRS). This is the first questionnaire to be administered in the post-walk portion. Participants will be instructed to respond to the statements and circle their response based on their magnitude of agreement or disagreement with the statement. These questions are to be answered in the context of their general, day-to-day behavior and attitudes. Each subscale (Conscious Motor Processing and Movement Self-Consciousness) is scored by obtaining the sum of their respective responses. The total questionnaire score can also be obtained by adding the subscale scores together. Either the total or subscale scores may be reported.

Gait-Specific Attentional Profile (G-SAP)

Gait-Specific Attentional Profile©

Mark the appropriate circle to indicate how you feel when you walk	NOT AT ALL	NOT VERY MUCH	MODERATELY SO	OFTEN	VERY MUCH SO
A1. I feel strained.....	①	②	③	④	⑤
A2. I am concerned about what people think about my movements	①	②	③	④	⑤
A3. I think about previous occasions when I lost my balance	①	②	③	④	⑤
A4. I think about what would happen if I fell.....	①	②	③	④	⑤
A5. I get confused and make illogical decisions.....	①	②	③	④	⑤
A6. Worrisome thoughts about falling run through my mind	①	②	③	④	⑤
A7. I try to think about the way I walk/move.....	①	②	③	④	⑤
A8. I consciously try to control my movements.....	①	②	③	④	⑤
A9. I examine the way I walk/move.....	①	②	③	④	⑤
A10. I feel tense.....	①	②	③	④	⑤
A11. I find it difficult to concentrate on two things at once	①	②	③	④	⑤

To be completed by researcher/clinician

Calculate the total score from each item relating to the following four categories: -

Anxiety (sum of A1, A2, A10)	=	.....
Conscious movement processing (sum of A7, A8, A9)	=	.....
Task-irrelevant ruminations/thoughts (sum of A3, A4, A6)	=	.....
Processing inefficiencies (sum of A5, A11)	=	.....

Figure A4. Gait-Specific Attentional Profile (G-SAP). This is the second questionnaire to be administered in the post-walk portion. Participants will be instructed to respond to the statements and circle their response based on their magnitude of agreement or disagreement with the statement. These questions are to be answered in the context of their general, day-to-day behavior and attitudes. Each subscale (Anxiety, Conscious Movement Processing, Task-irrelevant Ruminations, and Processing inefficiencies) is scored by obtaining the sum of the responses listed in the scoring box above.

Spielberger State Trait Anxiety Inventory (STAI) Y-1

Form Y-1 STAI State Anxiety: ____

DIRECTIONS:

A number of statements which people have used to describe themselves are given below. Read each statement and then circle the appropriate number to the right of the statement to indicate how you feel *right* now, that is, *at this moment*. There are no right or wrong answers. Do not spend too much time on any one statement but give the answer which seems to describe your present feelings best.

	NOT AT ALL	SOMEWHAT	MODERATELY SO	VERY MUCH SO
1. I feel calm	1	2	3	4
2. I feel secure	1	2	3	4
3. I am tense	1	2	3	4
4. I feel strained	1	2	3	4
5. I feel at ease	1	2	3	4
6. I feel upset	1	2	3	4
7. I am presently worrying over possible misfortunes	1	2	3	4
8. I feel satisfied	1	2	3	4
9. I feel frightened	1	2	3	4
10. I feel comfortable	1	2	3	4
11. I feel self-confident	1	2	3	4
12. I feel nervous	1	2	3	4
13. I am jittery	1	2	3	4
14. I feel indecisive	1	2	3	4
15. I am relaxed	1	2	3	4
16. I feel content	1	2	3	4
17. I am worried	1	2	3	4
18. I feel confused	1	2	3	4
19. I feel steady	1	2	3	4
20. I feel pleasant	1	2	3	4

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STAIP-AD Test Form Y
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Figure A5. Spielberger State Trait Anxiety Inventory (STAI) Y1. This is the only questionnaire to be administered in the pre-walk portion. Participants will be instructed to respond to the statements and circle their response based on their magnitude of agreement or disagreement with the statement. These questions are to be answered in the context of how the individual is feeling at that current moment. Scoring is done by using the scoring sheet shown in Figure A7.

Spielberger State Trait Anxiety Inventory (STAI) Y-2

For use by Kaylena Ehgoetz Martens only. Received from Mind Garden, Inc. on October 21, 2021

SELF-EVALUATION QUESTIONNAIRE

STAI Form Y-2

_____Date_____

DIRECTIONS

A number of statements which people have used to describe themselves are given below. Read each statement and then circle the appropriate number to the right of the statement to indicate how you *generally* feel.

	ALMOST NEVER	SOMETIMES	OFTEN	ALMOST ALWAYS
21. I feel pleasant	1	2	3	4
22. I feel nervous and restless	1	2	3	4
23. I feel satisfied with myself	1	2	3	4
24. I wish I could be as happy as others seem to be	1	2	3	4
25. I feel like a failure	1	2	3	4
26. I feel rested	1	2	3	4
27. I am "calm, cool, and collected"	1	2	3	4
28. I feel that difficulties are piling up so that I cannot overcome them	1	2	3	4
29. I worry too much over something that really doesn't matter	1	2	3	4
30. I am happy	1	2	3	4
31. I have disturbing thoughts	1	2	3	4
32. I lack self-confidence	1	2	3	4
33. I feel secure	1	2	3	4
34. I make decisions easily	1	2	3	4
35. I feel inadequate	1	2	3	4
36. I am content	1	2	3	4
37. Some unimportant thought runs through my mind and bothers me	1	2	3	4
38. I take disappointments so keenly that I can't put them out of my mind	1	2	3	4
39. I am a steady person	1	2	3	4
40. I get in a state of tension or turmoil as I think over my recent concerns and interests	1	2	3	4

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Figure A6. Spielberger State Trait Anxiety Inventory (STAI) Y2. This is the third questionnaire to be administered in the post-walk portion. Participants will be instructed to respond to the statements and circle their response based on their magnitude of agreement or disagreement with the statement. These questions are to be answered in the context of how the individual generally feels. Scoring is done by using the scoring sheet shown in Figure A7.

Spielberger State Trait Anxiety Inventory (STAI) Scoring Key

State-Trait Anxiety Inventory for Adults Scoring Key (Form Y-1, Y-2)

Developed by Charles D. Spielberger in collaboration with R.L. Gorsuch, R. Lushene, P.R. Vagg, and G.A. Jacobs

To use this stencil, fold this sheet in half and line up with the appropriate test side, either Form Y-1 or Form Y-2. Simply total the scoring **weights** shown on the stencil for each response category. For example, for question # 1, if the respondent marked 3, then the **weight** would be **2**. Refer to the manual for appropriate normative data.

Form Y-1	NOT AT ALL	SOMEWHAT	MODERATELY SO	VERY MUCH SO
1.	4	3	2	1
2.	4	3	2	1
3.	1	2	3	4
4.	1	2	3	4
5.	4	3	2	1
6.	1	2	3	4
7.	1	2	3	4
8.	4	3	2	1
9.	1	2	3	4
10.	4	3	2	1
11.	4	3	2	1
12.	1	2	3	4
13.	1	2	3	4
14.	1	2	3	4
15.	4	3	2	1
16.	4	3	2	1
17.	1	2	3	4
18.	1	2	3	4
19.	4	3	2	1
20.	4	3	2	1

Form Y-2	ALMOST NEVER	SOMETIMES	OFTEN	ALMOST ALWAYS
21.	4	3	2	1
22.	1	2	3	4
23.	4	3	2	1
24.	1	2	3	4
25.	1	2	3	4
26.	4	3	2	1
27.	4	3	2	1
28.	1	2	3	4
29.	1	2	3	4
30.	4	3	2	1
31.	1	2	3	4
32.	1	2	3	4
33.	4	3	2	1
34.	4	3	2	1
35.	1	2	3	4
36.	4	3	2	1
37.	1	2	3	4
38.	1	2	3	4
39.	4	3	2	1
40.	1	2	3	4

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STAIP-AD Scoring Key
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Scoring:

BFI scale scoring ("R" denotes reverse-scored items):

Extraversion: 1, 6R, 11, 16, 21R, 26, 31R, 36
Agreeableness: 2R, 7, 12R, 17, 22, 27R, 32, 37R, 42
Conscientiousness: 3, 8R, 13, 18R, 23R, 28, 33, 38, 43R
Neuroticism: 4, 9R, 14, 19, 24R, 29, 34R, 39
Openness: 5, 10, 15, 20, 25, 30, 35R, 40, 41R, 44

Figure A7. Spielberger State Trait Anxiety Inventory (STAI) Scoring Key. Responses from the Y-1 and Y-2 forms are transferred by circling the response on the scoring key corresponding to the participant's questionnaire response. These responses on the scoring key are then summed together to get the total state anxiety (Y-1) and trait anxiety (Y-2) scores.

Hospital Anxiety and Depression Scale (HADS)

Hospital Anxiety and Depression Scale (HADS)

Tick the box beside the reply that is closest to how you have been feeling in the past week.
Don't take too long over you replies: your immediate is best.

D	A		D	A	
		I feel tense or 'wound up':			**I feel as if I am slowed down:**
	3	Most of the time	3		Nearly all the time
	2	A lot of the time	2		Very often
	1	From time to time, occasionally	1		Sometimes
	0	Not at all	0		Not at all
		I still enjoy the things I used to enjoy:			**I get a sort of frightened feeling like 'butterflies' in the stomach:**
0		Definitely as much		0	Not at all
1		Not quite so much		1	Occasionally
2		Only a little		2	Quite Often
3		Hardly at all		3	Very Often
		I get a sort of frightened feeling as if something awful is about to happen:			**I have lost interest in my appearance:**
	3	Very definitely and quite badly	3		Definitely
	2	Yes, but not too badly	2		I don't take as much care as I should
	1	A little, but it doesn't worry me	1		I may not take quite as much care
	0	Not at all	0		I take just as much care as ever
		I can laugh and see the funny side of things:			**I feel restless as I have to be on the move:**
0		As much as I always could		3	Very much indeed
1		Not quite so much now		2	Quite a lot
2		Definitely not so much now		1	Not very much
3		Not at all		0	Not at all
		Worrying thoughts go through my mind:			**I look forward with enjoyment to things:**
	3	A great deal of the time	0		As much as I ever did
	2	A lot of the time	1		Rather less than I used to
	1	From time to time, but not too often	2		Definitely less than I used to
	0	Only occasionally	3		Hardly at all
		I feel cheerful:			**I get sudden feelings of panic:**
3		Not at all		3	Very often indeed
2		Not often		2	Quite often
1		Sometimes		1	Not very often
0		Most of the time		0	Not at all
		I can sit at ease and feel relaxed:			**I can enjoy a good book or radio or TV program:**
	0	Definitely	0		Often
	1	Usually	1		Sometimes
	2	Not Often	2		Not often
	3	Not at all	3		Very seldom

Please check you have answered all the questions

Figure A8. Hospital Anxiety and Depression Scale (HADS). This is the last questionnaire administered in the post-walk portion of the study. Participants will be instructed to respond to the statements and circle their response based on their magnitude of agreement or disagreement with the statement. These questions are to be answered in the context of how the individual has felt in the past week. Scoring is done by adding the responses to the "A" questions to get the anxiety score, and by adding the responses to the "D" questions to get the depression score. These two values are reported.

Appendix B: List of R libraries utilized in analysis

Table B1. List of R libraries used in analysis

Library	Use
tidyverse	General data wrangling and organization
gridExtra	Organizing multiple plots on one page
ggplot2	Creating customizable and publishable plots
cowplot	ggplot add-on to create publishable plots
dplyr	Allows work with dataframes
rstatix	Allows parametric and non-parametric statistical testing (e.g., t-tests; ANOVAs); works in tandem with tidyverse
ggstatsplot	Adds statistical output details onto plots (e.g., F values, degrees of freedom, p values, effect sizes)
ggpubr	Adds regression coefficients to plots
patchwork	Multiple figure alignment
ez	ANOVA testing
e1071	Covers additional statistical tests not encompassed in aforementioned packages
car	"Companion to Applied Regression"; assists with linear regressions and related analyses
ggrepel	Labelling points on scatterplots
ARTool	ART ANOVA testing
Hmisc	Provides rcorr function

Appendix C: Supplementary Data and Figures

C1: Analysis outputs for participant characteristics

Table C1-1. ANOVA results for dual task accuracy

Effect	F value	p-value	Effect Size (η^2)
Group	$F_{(1,24)} = 1.63$	0.21	0.05
Condition	$F_{(2, 48)} = 0.07$	0.93	0.0007
Group*Condition	$F_{(2, 48)} = 2.01$	0.14	0.02

Table C1-2. ANOVA results for SAM score

Effect	F value	p-value	Effect Size (η^2)
Group	$F_{(1,23)} = 12.77$	**0.002**	**0.35**
Shock	$F_{(1, 23)} = 22.18$	**< 0.001**	**0.04**
Group*Shock	$F_{(1, 23)} = 1.03$	0.32	0.002

C2: Analysis outputs for primary gait variables

Table C2-1. ANOVA results for step length

Effect	F value	p-value	Effect Size (η^2)
Group	$F_{(1, 23)} = 12.94$	**0.002**	**0.36**
DT	$F_{(1, 23)} = 44.19$	**< 0.001**	**0.03**
S	$F_{(1, 23)} = 4.07$	0.06	0.0006
Group*DT	$F_{(1, 23)} = 1.09$	0.31	0.007
Group*S	$F_{(1, 23)} = 0.19$	0.66	0.0003
DT*S	$F_{(1, 23)} = 0.73$	0.40	0.0002
Group*DT*S	$F_{(1, 23)} = 1.23$	0.28	0.0003

Table C2-2. ART ANOVA results for step length variability

Effect	F value	p-value	Effect Size (η_p^2)
Group	$F_{(1, 92)} = 40.81$	**< 0.001**	**0.38**
DT	$F_{(1, 92)} = 3.23$	0.07	0.04
S	$F_{(1, 92)} = 4.99$	**0.03**	**0.06**
Group*DT	$F_{(1, 92)} = 2.58$	0.10	0.03
Group*S	$F_{(1, 92)} = 6.06$	**0.03**	**0.06**
DT*S	$F_{(1, 92)} = 1.81$	0.18	0.02
Group*DT*S	$F_{(1, 92)} = 3.05$	0.08	0.03

Table C2-2a. Group*S contrast test results for step length variability

Comparison (Group,S)	t value	p-value
FGD,N – FGD,Y	$t_{(92)} = -0.39$	0.98
FGD,N – HC,N	$t_{(92)} = 3.37$	**0.006**
FGD,N – HC,Y	$t_{(92)} = 3.72$	**0.002**
FGD,Y – HC,N	$t_{(92)} = 3.81$	**0.001**
FGD,Y – HC,Y	$t_{(92)} = 4.16$	**0.0004**
HC,N – HC,Y	$t_{(92)} = 0.41$	0.98

Table C2-3. ANOVA results for velocity

Effect	F value	p-value	Effect Size (η^2)
Group	$F_{(1, 23)} = 20.35$	**< 0.001**	**0.46**
DT	$F_{(1, 23)} = 62.14$	**< 0.001**	**0.05**
S	$F_{(1, 23)} = 3.06$	0.10	0.0009
Group*DT	$F_{(1, 23)} = 0.02$	0.88	0.00002
Group*S	$F_{(1, 23)} = 0.02$	0.88	0.000007
DT*S	$F_{(1, 23)} = 1.76$	0.20	0.0003
Group*DT*S	$F_{(1, 23)} = 0.62$	0.44	0.0001

Table C2-4. ANOVA results for step width

Effect	F value	p-value	Effect Size (η^2)
Group	$F_{(1, 92)} = 66.46$	**< 0.001**	**0.42**
DT	$F_{(1, 92)} = 0.46$	0.50	0.005
S	$F_{(1, 92)} = 0.11$	0.74	0.001
Group*DT	$F_{(1, 92)} = 0.07$	0.80	0.0007
Group*S	$F_{(1, 92)} = 0.002$	0.96	0.00002
DT*S	$F_{(1, 92)} = 0.19$	0.66	0.002
Group*DT*S	$F_{(1, 92)} = 0.004$	0.95	0.00005

Table C2-5. ART ANOVA results for step width variability

Effect	F value	p-value	Effect Size (η_p^2)
Group	$F_{(1, 92)} = 0.61$	0.44	0.007
DT	$F_{(1, 92)} = 0.22$	0.64	0.002
S	$F_{(1, 92)} = 0.08$	0.78	0.0008
Group*DT	$F_{(1, 92)} = 0.01$	0.92	0.0001
Group*S	$F_{(1, 92)} = 0.13$	0.72	0.001
DT*S	$F_{(1, 92)} = 0.20$	0.66	0.002
Group*DT*S	$F_{(1, 92)} = 0.53$	0.47	0.006

Table C2-6. ART ANOVA results for double support duration

Effect	F value	p-value	Effect Size (η_p^2)
Group	$F_{(1, 92)} = 16.30$	**< 0.001**	**0.15**
DT	$F_{(1, 92)} = 3.13$	0.08	0.03
S	$F_{(1, 92)} = 0.06$	0.81	0.0006
Group*DT	$F_{(1, 92)} = 2.91$	0.59	0.003
Group*S	$F_{(1, 92)} = 1.51$	0.99	0.000002
DT*S	$F_{(1, 92)} = 1.89$	0.66	0.002
Group*DT*S	$F_{(1, 92)} = 0.03$	0.86	0.0003

C3: Analysis outputs for primary gait variable and MSRS correlations

Table C3-1. Correlation coefficients and p-values for Kendall correlations examining the relationship between MSRS subscale and change in gait between DT and N conditions in FGD patients.

Variable (Variable$_{DT}$- Variable$_{N}$)	**Correlation Coefficient (τ)**	**p-value**
MSRS-Total and DT-N		
Step Length	0	1
Step Length Variability	-0.18	0.47
Velocity	0.45	0.07
Step Width	**-0.67**	**0.007 ****
Step Width Variability	-0.22	0.37
Double Support Duration	-0.45	0.07
MSRS-CMP and DT-N		
Step Length	0.16	0.52
Step Length Variability	-0.21	0.41
Velocity	**0.54**	**0.04 ***
Step Width	-0.4	0.12
Step Width Variability	0.02	0.93
Double Support Duration	-0.35	0.17
MSRS-MSC and DT-N		
Step Length	-0.02	0.93
Step Length Variability	-0.2	0.42
Velocity	0.43	0.09
Step Width	**-0.66**	**0.009 ****
Step Width Variability	-0.25	0.32
Double Support Duration	-0.39	0.13

Table C3-2. Correlation coefficients and p-values for Kendall correlations examining the relationship between MSRS subscale and change in gait between DT and N conditions in healthy controls.

Variable (Variable$_{DT}$- Variable$_{N}$)	**Correlation Coefficient (τ)**	**p-value**
MSRS-Total and DT-N		
Step Length	0.53	0.19
Step Length Variability	-0.14	0.47
Velocity	-0.08	0.65
Step Width	-0.03	0.86
Step Width Variability	-0.05	0.79
Double Support Duration	-0.17	0.37
MSRS-CMP and DT-N		
Step Length	-0.06	0.75
Step Length Variability	-0.13	0.49
Velocity	-0.04	0.82
Step Width	-0.24	0.22
Step Width Variability	0.25	0.19
Double Support Duration	-0.17	0.39
MSRS-MSC and DT-N		
Step Length	0.09	0.65
Step Length Variability	-0.02	0.93
Velocity	-0.03	0.86
Step Width	0.14	0.47
Step Width Variability	-0.16	0.41
Double Support Duration	-0.19	0.32