Assessing pre-existing movement and muscular recruitment differences in prolonged standing, transient low back pain developers compared to non-pain developers

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.

Regards,

Jonathan Park

Abstract

Epidemiological studies have reported occupational prolonged standing to be associated with low back pain (LBP). Studies that have conducted simulations of prolonged standing work in healthy individuals have demonstrated a proportion of them will develop transient LBP (termed pain developers or PDs), while others will not (termed non-pain developers or non-PDs). Investigations into differences between pain groups using low-demand tasks have predominantly reported neuromuscular differences involving the hip musculature and have shown capacity to distinguish pain groups. However, misclassification persists. There is little published data on pain groups in response to higher-demand challenges, which may elicit previously unseen or larger differences. Thus, the purpose of this study was to examine movement behavior and muscle recruitment patterns in healthy individuals that are non-PDs or PDs during a variety of tasks with increased functional demand and variety. It was hypothesized that the higher demand challenges will elicit previously unseen or enhanced differences in movement behavior and muscle recruitment in PDs relative to non-PDs.

Healthy university students were recruited to participate in two sessions. The first session involved participants performing a prolonged standing work simulation to determine their pain status. The second session involved participants performing a movement screening protocol involving low and high demand variations of the following tasks: symmetric trunk flexion-extension, symmetric floor-to-knuckle lift, modified star excursion balance test, active hip abduction, and reverse side bridge. Participants were outfitted with 3D motion capture markers and surface electromyography prior to task performance. Depending on the

task, the kinematic data of the trunk and lower limbs were characterized into the following dependent variables: thorax segment angular velocity, peak lumbar spine flexion angle, frontal plane knee excursion, limb length normalized reach distances, and movement arc length. Depending on the task, surface electromyography of the external obliques, lumbar erector spine, gluteus medius, and gluteus maximus muscles were processed into the following dependent variables: phase lags at maximum correlation between muscle pairs and regression slope of median power frequencies for assessment of muscle fatigue.

A total of 39 participants were recruited and categorized, resulting in a subtotal of 22 non-PDs (12 females) and 17 PDs (8 females). Mixed-design analysis of variance analyses revealed no statistically significant main or interaction effects between pain status groups in most of the aforementioned kinematic and surface electromyography dependent variables. Interestingly, performance during the active hip abduction (AHA) revealed a pain status and task difficulty interaction effect ($F_{(1,35)} = 5.22$, $p < 0.05$), with PDs exhibiting larger angular displacement arc length during AHA performance with an external weight relative to no external weight; not observed in non-PDs.

The results of this investigation showed that although task demands demonstrated changes in various kinematic and muscle activation patterns across participants, it did not always coincide with an individual's pain status. Nonetheless, a significant finding to emerge from this study is the potential interaction an external weight has on pain status with their performance during the AHA. Taken together, these results suggest that there is minimal evidence for tasks with increased functional demand and variety to elicit unseen or larger aberrant movement behavior and muscle activation patterns in PDs relative to non-PDs.

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Abbreviations/Symbol

'+'	Denotes the task to be a 'higher demand' challenge or variation if acronyms are identical
AHA	Active Hip Abduction Test
AORN	Association of periOperative Registered Nurses
CC	Cross-Correlation Analysis
CCOHS	Canadian Centre for Occupational Health and Safety
EO	External Oblique
GMED	Gluteus Medius
LBP	Low Back Pain
LES	Lumbar Erector Spinae
SLIFT	Symmetric Floor-to-Knuckle Lift
MCID	Minimally Clinically Important Difference
MdPF	Median Power Frequency
mGAP(s)	Muscle gap(s)
MPF	Mean Power Frequency
mSEBT	modified Star Excursion Balance Test
Non-PD(s)	Non-Pain Developer(s)
PA-M	Pain-Adaptation Model
PD(s)	Pain-Developer(s)
PSP	Prolonged Standing Protocol
PSP-M	Pain-Spasm-Pain Model
RSB	Reverse Side Bridge
STF	Symmetric Trunk Flexion-Extension
VAS	Visual Analogue Scale

Operational Definitions

Functional – "biomechanical movement that is in the realm of normal human activity" (Kelleher & Dickey, 2016)

High Demand – task demands that involve increased load, speed, complexity, completed until exhaustion, or requires high muscular activation (>41% MVIC) (adapted from Escamilla et al., 2016; Frost, Beach, Callaghan, et al., 2015)

Kinematic Compromise – "the deficit of the subject in low back motion characteristics (kinematics) relative to the expected trunk motions (defined by normative database in previous study) and adjusted as a function of gender and age" (Marras et al., 2005)

Low Demand – absence of increased challenges/demands (e.g., low speed, light load, or low-moderate muscular activation) to the task (adapted from Escamilla et al., 2016; Frost, Beach, Callaghan, et al., 2015)

Lumbopelvic Rhythm – "coordination of the movement of the trunk around the pelvis and of the pelvis around the hips during trunk flexion and extension" (McGorry et al., 2001)

Motor Control – how the neuromuscular system works to turn on and coordinate the muscles and body segments to perform a movement or task with a specific goal or purpose (Magill & Anderson, 2011; Rose & Christina, 2006)

Movement Competency – "can be described as an individual's ability to perform a movement pattern in an optimal manner. Optimal movement may be described as movement that occurs without pain or discomfort and involves proper joint alignment, muscle coordination, and posture" (Kritz et al., 2009)

Muscle Fatigue – "loss of the ability to maintain the expected force in static or dynamic exercise" (Vestergaard-Poulsen et al., 1992)

Movement Screen – "a protocol designed for use with apparently healthy, uninjured individuals to primarily assess the 'quality' of a movement(s) rather than objective outcomes such as number of repetitions, distance, or time achieved" (McCunn et al., 2015)

Movement Smoothness – "a quality related to the continuality or non-intermittency of a movement, independent of its amplitude and duration" (Balasubramanian et al., 2015)

Pain Status – belonging to one of two pain groups: pain-developers, or non-pain developers

Chapter 1 – Introduction

Low back pain (LBP) is recognized as an important global health issue that negatively impacts economic, social, and individual health (Hoy et al., 2014; Van Tulder & Koes, 2002). Occupational prolonged standing has been found to be associated with numerous adverse health outcomes, with LBP being one of them (Andersen et al., 2007; Tissot et al., 2009; Waters & Dick, 2015). Epidemiological evidence has demonstrated that prolonged standing is associated with reports of LBP prevalence and is an important work-related predictor of LBP (Sterud & Tynes, 2013).

People from many different occupations perform extensive periods of standing (e.g. peri-operative care providers, industrial workers, etc.) (Gregory & Callaghan, 2008; McCulloch, 2002; Waters & Dick, 2015). In addition, data from several studies suggest that there is an increasing number of people adopting standing work postures with sit-stand workstations in office workplaces (Callaghan et al., 2015; Carr et al., 2016; Chau et al., 2014; MacEwen et al., 2015). Together, the evidence presented thus far indicates a need to understand and prevent LBP development during prolonged standing. Numerous investigations have been carried out on the relationship between prolonged standing and LBP development. However, the underlying mechanisms by which this phenomenon occurs is not well-established and continues to be developed.

In recent years, there has been an increasing amount of literature utilizing a prolonged standing protocol (PSP) to induce LBP in laboratory assessments on healthy, asymptomatic individuals (Bussey et al., 2016; Gallagher et al., 2011; Gregory & Callaghan, 2008; Marshall et

al., 2011; Raftry & Marshall, 2012; Sheahan et al., 2016; Stewart & Gregory, 2016). Specifically, previous research findings have shown that a proportion of healthy individuals (termed pain developers or PDs) will develop LBP throughout the PSP, while others (termed non-pain developers or non-PDs) will not (Figure 1a and Figure 1b). Being categorized as a PD has revealed deleterious implications of future LBP status, as the chance of developing chronic LBP tripled (Figure 1a and Figure 1b) in PDs compared to non-PDs over a 3-year follow up period (Nelson-Wong & Callaghan, 2014).

Several biomechanical investigations have documented specific factors that potentially affect standing LBP development and distinguish PDs from non-PDs. However, many have shown null or mixed prognostic capabilities (Bussey et al., 2016; Gallagher & Callaghan, 2015a; Gallagher et al., 2011, 2016; Gregory & Callaghan, 2008; Gregory et al., 2008; Marshall et al., 2011; Nelson-Wong, Flynn, et al., 2009; Nelson-Wong & Callaghan, 2010b; Nelson-Wong et al., 2008, 2012; Raftry & Marshall, 2012; Sorensen, George, et al., 2016; Sorensen, Norton, et al., 2015).

A recurrent finding in the literature has been the presence of altered muscle activation patterns in the hip musculature, such as the bilateral gluteus medius (GMED) muscles, in PDs compared to non-PDs (Bussey et al., 2016; Gregory et al., 2008; Marshall et al., 2011; Nelson-Wong & Callaghan, 2010b; Nelson-Wong et al., 2008, 2012). For instance, bilateral GMED muscle co-activation level during prolonged standing significantly differed between the two groups, with PDs demonstrating relatively higher or non-reciprocal co-activation levels prior to any pain occurrence (Bussey et al., 2016; Marshall et al., 2011; Nelson-Wong & Callaghan, 2010b; Nelson-Wong et al., 2008). Additionally, a clinical tool termed the active hip abduction

(AHA) test has also been shown to differentiate between the two groups, with PDs exhibiting more difficulty maintaining lumbo-pelvic alignment (Nelson-Wong et al., 2009). These findings have shown capacity to predict individuals into their corresponding pain groups (Marshall et al., 2011; Nelson-Wong et al., 2008, 2009). Furthermore, altered muscle activation and muscle sequencing strategies have been reported during other tasks, such as extension from trunk flexion, or standing perturbation, in PDs relative to non-PDs (Gregory et al., 2008; Nelson-Wong et al., 2012). Altogether, these findings substantiate potential pre-existing movement and muscular recruitment differences between the two groups.

However, misclassification continues to persist with such outcome measures using the above-mentioned variables, indicating other factors that may be involved and not accounted for (Nelson-Wong et al., 2008). It has been suggested that the low-demand tasks (e.g., AHA test) previously used, do not require high levels of muscle activation in the monitored trunk and hip musculature (Nelson-Wong, 2009; Nelson-Wong et al., 2008). There is little published data on the movement behavior and muscular recruitment of PDs and non-PDs in response to higher-demand challenges.

Higher-demand challenges (e.g., increased external task demands such as increased load, speed or both) may elicit previously unseen or larger differences (Figure 2) that were unobservable through low-demand challenges or yet to be observed in other functional activities, such as lifting (Frost, Beach, Callaghan, et al., 2015; Marras & Wongsam, 1986; Winter, 1995). For instance, previously unseen differences are referred to here as ‘risky’ or large sagittal plane spine flexion and frontal plane knee motion. These previously used kinematic variables have not been investigated in pain status groups during symmetric lifting or a single leg balance and reach

task (i.e., the modified star excursion balance test) (Figure 1a and Figure 1b). Given the association with excessive lumbar spine flexion during lifting with LBP (Burgess-Limerick, 2003; Straker, 2003; Van Dieen et al., 1999) or the potential role the hip musculature has in the control of aberrant frontal plane knee motion (Powers, 2010), the presence of such 'risky' movement during activities outside of prolonged standing may suggest PDs to be a "high risk" group for non-contact musculoskeletal injuries. Furthermore, larger differences are referred to here as observing larger kinematic or muscle recruitment differences between pain status groups in previously reported low-demand challenges relative to higher demand variations, such as unloaded or externally loaded AHA test Figure (Figure 1a and Figure 1b). The presence of such differences may further support pre-existing neuromuscular control differences within the lumbopelvic region and hip musculature that were previously observed between pain status groups and enable improved stratification.

Overall, it is possible that additional neuromuscular control differences (characterized as differences in joint kinematics and muscle recruitment patterns) between pain groups may be more apparent with increased functional demand and variety (Nelson-Wong et al., 2008).

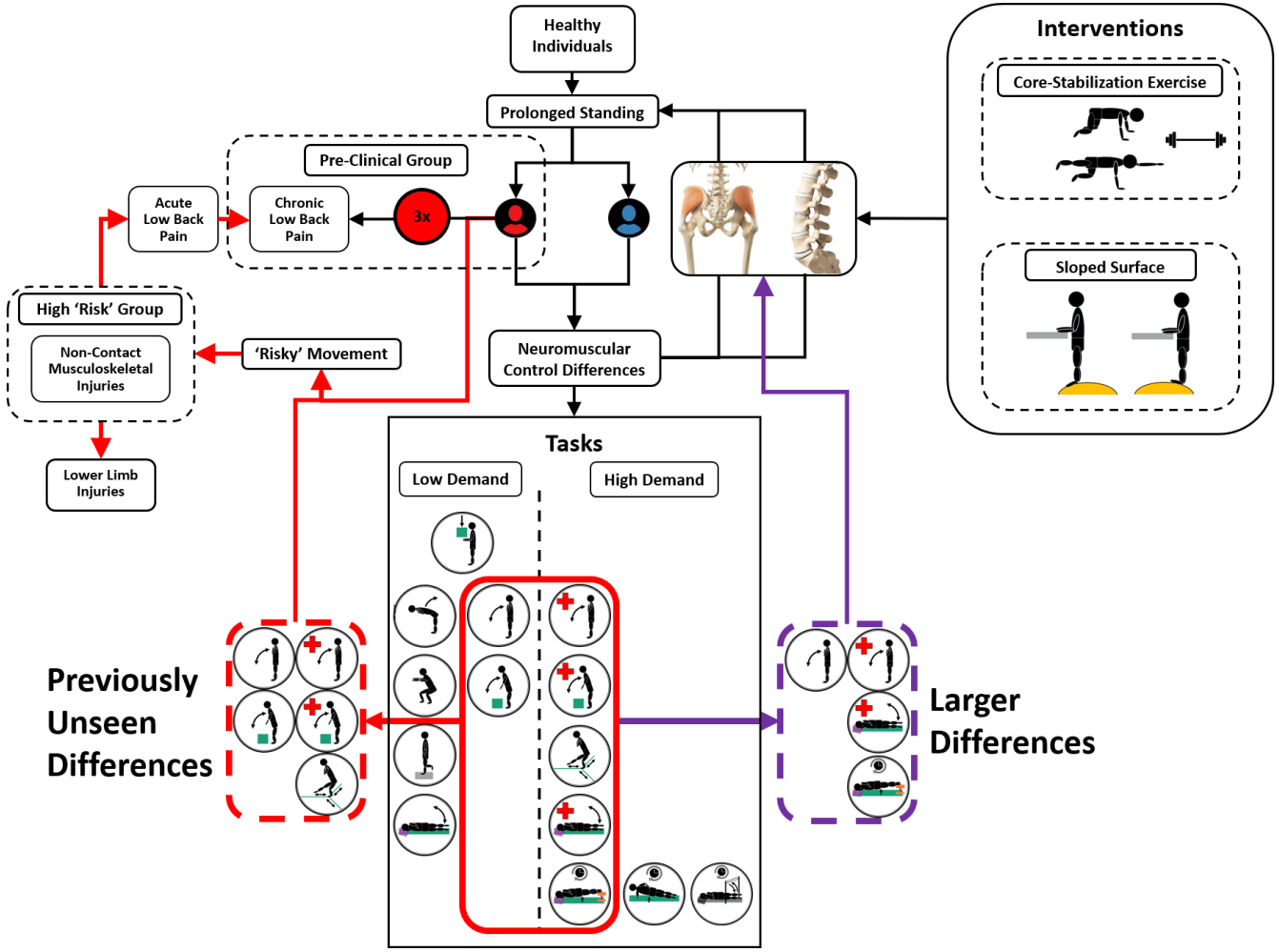


Figure 1a – Overview of anticipated contributions of thesis to previous literature. Refer to Figure 1b for legend. The protocol of tasks implemented in this thesis (outlined in solid red box) can be clustered into two themes to further support pre-existing neuromuscular control differences between pain status groups: 1) previously unseen kinematic differences characterized as 'risky' spine and knee motion that may suggest PDs to be a high risk group for non-contact musculoskeletal injuries; and 2) larger kinematic or muscle recruitment differences between pain status groups in previously reported low-demand challenges relative to higher demand variations

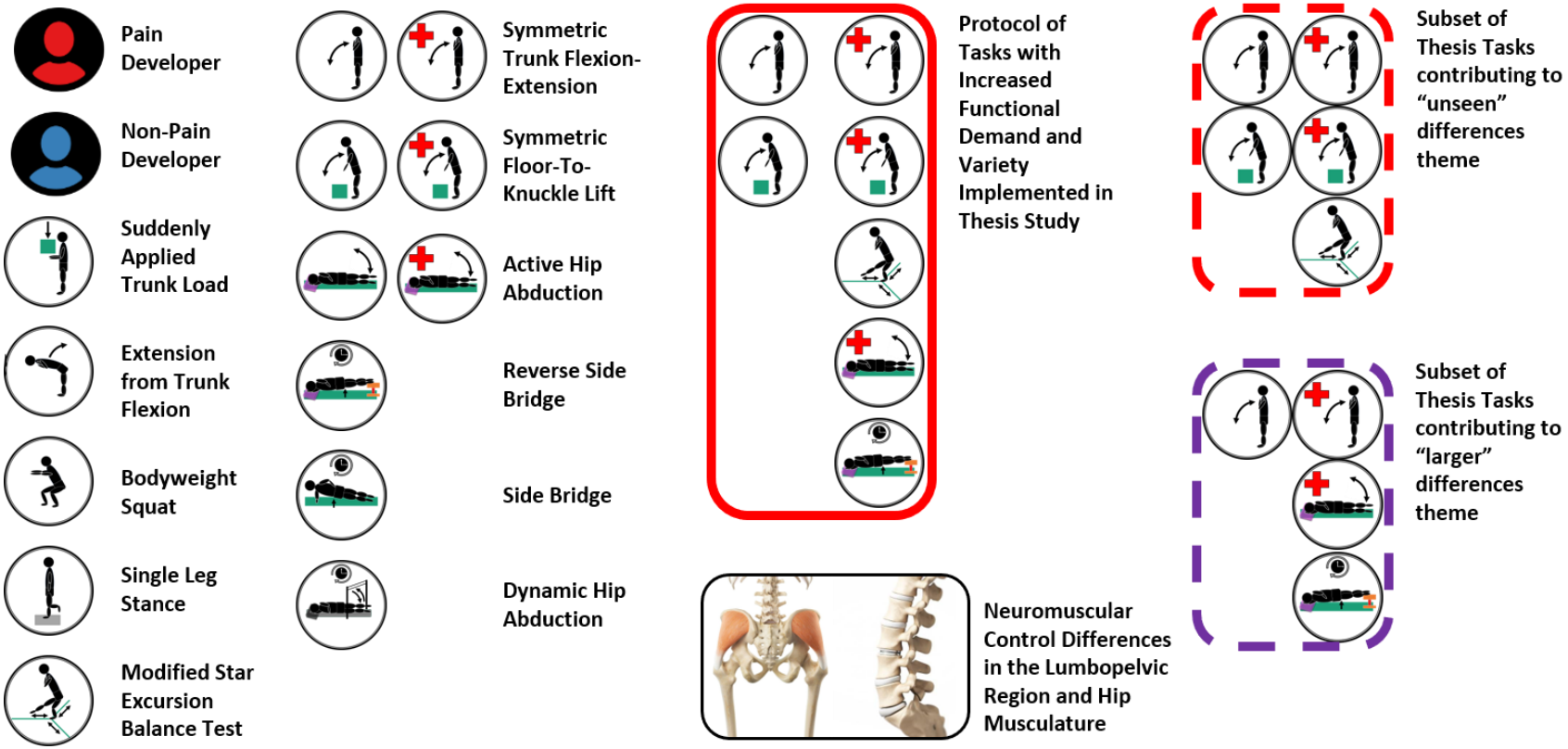


Figure 1b – Legend for symbols used in Figure 1a.

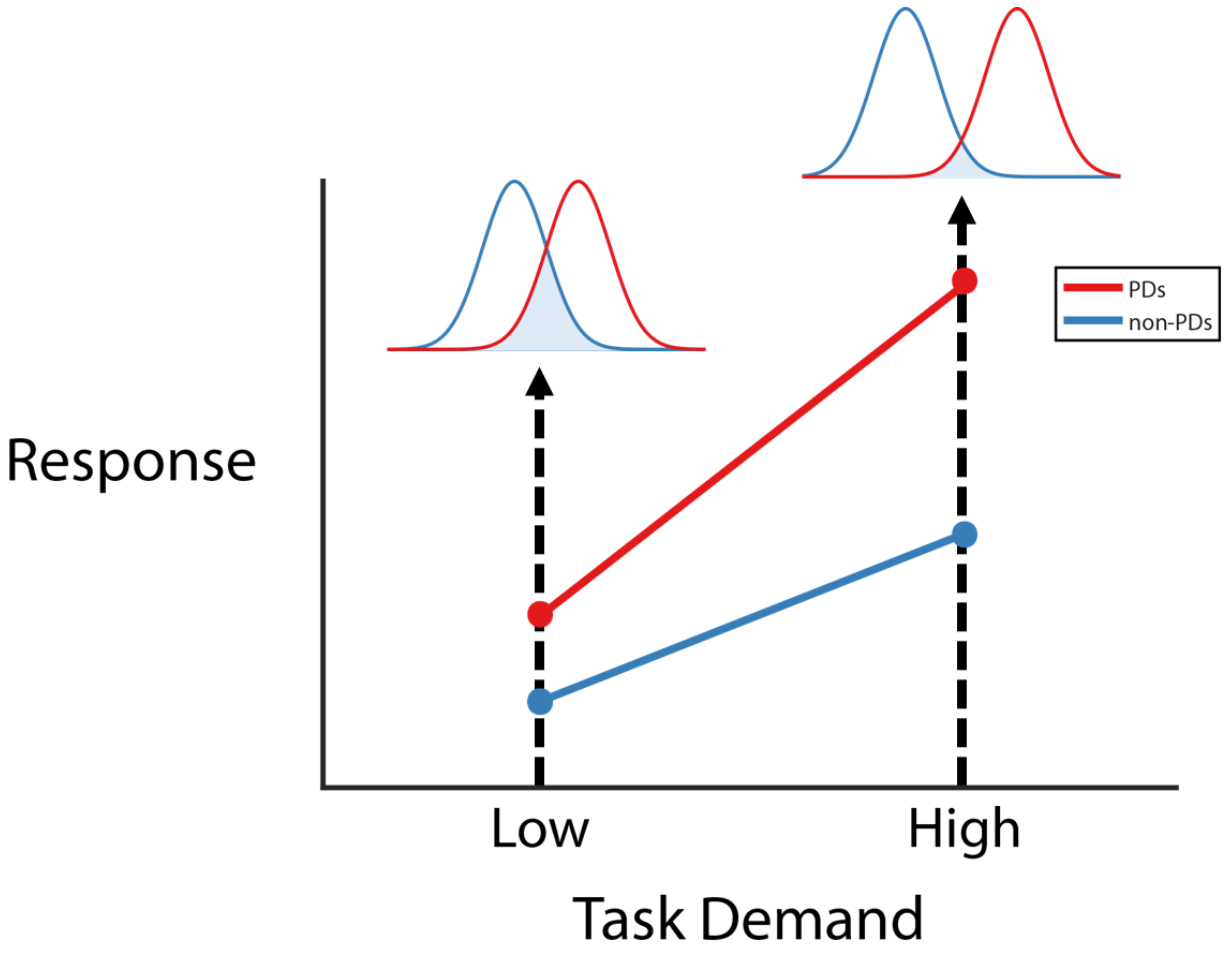


Figure 2 – Conceptual model of the hypothesized response with respect to task demand in PDs compared to non-PDs

1.1 Purpose, Question, and Hypotheses

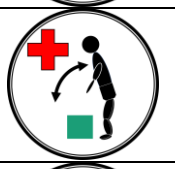
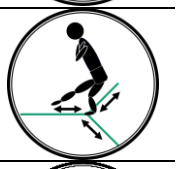
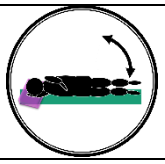
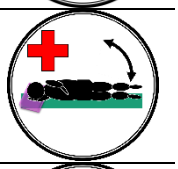
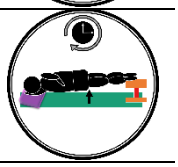
Thus, the purpose of this thesis is to examine movement behavior and muscle recruitment patterns in healthy individuals that are PDs or non-PDs during a protocol of tasks (Table 1) with increased functional demand and variety. This thesis will help elucidate that overarching research question of whether PDs are a 'high risk' group and if standing induced LBP is a by-product of pre-existing or established neuromuscular control, in comparison to non-PDs. It is hypothesized that higher demand challenges will elicit previously unseen or enhanced differences in movement behavior and muscle recruitment in PDs relative to non-PDs.

An overview of primary and secondary research questions is presented in Table 2 and Table 3.

Expanding upon previous findings in PDs and non-PDs (e.g., extension from trunk flexion exertions and AHA performance), a set of tasks with varied external and functional demand was used. These tasks will enable: 1) greater challenge to the individual's ability to coordinate and maintain postures of the trunk and lower limbs in different planes of motion to evaluate movement competency; 2) elicitation of movement patterns which exhibit 'risky' joint kinematics that are associated with increased non-contact musculoskeletal injury risk; 3) elicitation of altered muscle activation patterns that may parallel differences seen in people with LBP, if any; 4) expanded findings on any differences in hip musculature capacity; and 5) potential stratification of individuals as 'high risk' for prolonged standing LBP development.

This research, in turn, will: 1) extend the knowledge of differences in PDs and non-PDs during different tasks and 2) extend the evidence for LBP development during prolonged standing as a by-product of pre-existing movement behavior and muscle recruitment patterns.

Table 1 – Overview of tasks used in this thesis with corresponding levels of challenge

Tasks					
Low-Demand Challenge	**Acronym**	**Symbol**	**High-Demand Challenge (denoted with a '+' if acronyms are identical)**	**Acronym**	**Symbol**
Symmetric Trunk Flexion-Extension	STF		Symmetric Trunk Flexion-Extension Exertion (↑ speed)	STF+	
Symmetric Floor-To-Knuckle Lift and Lower	SLIFT		Symmetric Floor-To-Knuckle Lift and Lower (↑ load, ↑ speed)	SLIFT+	
			Modified Star Excursion Balance Test (↑ "complexity")	mSEBT	
Active Hip Abduction Test	AHA		Active Hip Abduction Test with External Weight (↑ load)	AHA+	
			Reverse Side Bridge (to failure)	RSB	

See Table 12 – Summary of dependent and independent variables for this thesis

Table 2 – Overview of specific primary thesis questions, hypotheses, and corresponding rationale

	Question	Hypothesis	Rationale
1)	Do PDs and non-PDs demonstrate similar trunk angular velocities, lumbopelvic kinematics, and muscle sequencing patterns during submaximal and maximal trunk flexion-extension exertions (STF/STF+)?	PDs compared to non-PDs, will exhibit: a) lower magnitudes of trunk angular velocity during maximal exertions, as seen in LBP patients (Marras & Wongsam, 1986) b) no differences in lumbar and hip joint angle ratios (i.e., lumbopelvic kinematics) during submaximal exertions, but differences will be observed in maximal exertions c) a top-down muscle activation pattern, as seen in a previous study (Nelson-Wong et al., 2012), with larger differences observed in maximal exertions	a) given the high variability characterized in healthy adults, whether there is tendency for some healthy individuals to exhibit trunk kinematics similar to previously reported results of LBP patients is of interest b) previously seen in the literature; unexplored during maximal flexion-extension efforts c) previously seen in the literature; unexplored during maximal flexion-extension efforts
2)	Do PDs and non-PDs exhibit similar spine motion, frontal plane knee motion, and muscle sequencing patterns during symmetric floor-to-knuckle lifting tasks (SLIFT/SLIFT+)?	PDs compared to non-PDs, will exhibit: a) larger sagittal spine motion within all the lifting task conditions, with larger differences in more difficult task conditions b) larger frontal plane knee excursions within all the lifting task conditions, with larger differences in more difficult task conditions c) a top-down muscle activation pattern, with larger differences observed during more difficult task conditions	Given the theory that PDs possess inadequate coordination of trunk musculature, whether this may manifest in other functional activities, such as lifting, has been unexplored
3)	Do PDs and non-PDs exhibit similar dynamic balance control and frontal plane knee excursions during the modified star excursion balance test (mSEBT)?	PDs compared to non-PDs, will exhibit: a) lower limb length normalized reach distances b) greater frontal plane knee motion during the mSEBT	Previously unexplored; given the implications of hip abductor musculature (Powers, 2010) on control of knee motion and aberrant hip muscle activation patterns in PDs
4)	Do PDs and non-PDs exhibit similar lumbopelvic alignment, examiner-rated scores, and movement smoothness during unweighted and weighted variations of the active hip abduction test (AHA/AHA+)?	PDs compared to non-PDs, will exhibit: a) difficulty in maintaining lumbopelvic alignment, be scored worse, and exhibit less smooth movement during the unweighted AHA b) greater difficulty on maintaining lumbopelvic alignment, scored worse than the unweighted AHA, and exhibit lesser smooth movement when exposed to additional external weight on the testing leg (i.e., AHA+)	a) previously reported results b) given that misclassification continues to persist, whether the addition of an external weight may elicit more difficulty to better stratify individuals is of interest; similar to what's been previously reported with added external weight to the Functional Movement Screen (FMS) Test and improved tactical performance prediction (Glass et al. 2015)
5)	Do PDs and non-PDs demonstrate similar time to fatigue and gluteus medius fatigability during the reverse side-bridge (RSB)?	PDs compared to non-PDs, will: a) possess lower holding durations b) exhibit greater gluteus medius fatigability	a) conflicting evidence; previous work (Marshall et al., 2011) suggests potential for GMED endurance to be different b) although previously seen to not be different, whether the reverse side-bridge will provide different results is of interest

Table 3 – Overview of secondary thesis questions, hypotheses, and corresponding rationale

	Question	Hypothesis	Rationale
1)	Do PDs and non-PDs have similar hip abduction strength measures?	PDs compared to non-PDs, will: a) have no differences in their lateral hip strength measures	Previously seen to not be different (Marshall et al., 2011; Viggiani & Callaghan, 2016)
2)	Do PDs and non-PDs have similar ankle function when using a self-reported questionnaire?	PDs compared to non-PDs, will: a) have larger amount of ankle instability	Determine if ankle joint function is related to potential influence up the kinematic chain
3)	Do PDs and non-PDs exhibit similar beliefs and attitudes towards pain when using a self-reported questionnaire?	PDs compared to non-PDs, will: a) have no differences	Previously seen to not be different (Nelson-Wong, 2009)

Chapter 2 – Literature Review

This review begins with an overview of the epidemiology between prolonged standing and LBP development, followed by research on laboratory assessments of standing-induced LBP. Then, the relevant motor control differences found in the laboratory assessments and previous findings in LBP patients compared to healthy controls were examined. Finally, a review on movement screening tools and the different tasks that was used to assess movement behavior and muscle recruitment patterns will be provided.

2.1 Occupational Prolonged Standing and Low Back Pain

Occupational prolonged standing on a regular basis has been associated with numerous adverse health outcomes, including LBP (McCulloch, 2002; Waters & Dick, 2015). Numerous expert groups and researchers have acknowledged the relationship between prolonged standing with LBP development and other adverse health outcomes (Hughes et al., 2011; Meijsen & Knibbe, 2007; Waters & Dick, 2015). These groups have published guidelines to address the prolonged standing workplace behavior. For instance, in North America, the Association of periOperative Registered Nurses (AORN) implemented a requirement for ergonomic interventions to be set up for perioperative staff members required to perform constrained standing for: 1) ≥ 120 minutes; or 2) > 30% of a working day (Hughes et al., 2011).

Similarly, the Canadian Centre for Occupational Health and Safety (CCOHS) has recommended workplaces to implement ergonomic design strategies, such as standing aids and adjustable workstations (CCOHS, 2016). Additionally, CCOHS and several researchers have recommended workers to frequently change their working positions (e.g., switching between sitting and standing postures), with Callaghan et al. (2015) suggesting an adoption of a 1:1 non-

sedentary activity (e.g., standing, walking, etc.) duration with seated work duration during a typical 8-hour workday.

Lastly, hospitals within the Netherlands have provided standing work guidelines to be limited to no more than 1 hour of continuous standing and 4 hours of total standing time; anything greater requires an ergonomic intervention (Knibbe, Knibbe, & Geuze, 2003; as cited by Meijsen & Knibbe, 2007).

Although various recommendations have been implemented, the relationship between occupational prolonged standing and the prevalence of LBP has been inconsistent in the literature. Several epidemiological investigations into various general working populations have found positive relationships (e.g., higher odds ratios) between prolonged standing and LBP prevalence reports (Andersen et al., 2007; Engels et al., 1996; Sterud & Tynes, 2013; Tissot et al., 2009; Xu et al., 1997). For instance, Sterud et al. (2013) performed a 3-year prospective study in the general working population of 12,550 workers to investigate the relationship of LBP development and psychosocial and physical work exposures experienced in the workplace. Focusing on physical work, they attributed 11.6% of LBP cases to prolonged standing and an odds ratio of 1.48 (95% CI 1.20 to 1.83), suggesting prolonged standing to be an important physical work exposure and a consistent predictor of (Sterud & Tynes, 2013).

Despite the positive findings, there are investigations that have reported no significant relationship between prolonged standing and LBP prevalence (Harkness et al., 2003; Munch Nielsen et al., 2016; Yip, 2004). Additionally, some systematic reviews have concluded that prolonged standing is not an independently causative factor for LBP (Bakker et al., 2009; Roffey

et al., 2010). The systematic reviews and epidemiological studies examined so far, however, were generally exploratory in nature (e.g., cohort studies, case-control studies) (Roffey et al., 2010). Given that some studies and their designs had the outcome and risk factor simultaneously measured, as opposed to documenting it over time, their conclusions are limited in their ability to assert causation (Roffey et al., 2010). Other major limitations and weaknesses, include: 1) the lack of consistent LBP definition or classification (Roffey et al., 2010); and 2) the absence of accuracy and consistency in assessing standing exposures (Roffey et al., 2010; Tissot et al., 2009); and 3) reliance on self-reported exposure data.

Firstly, the ambiguity in defining and classifying LBP in previous studies is synonymous with the ambiguous classification system of specific and non-specific LBP with corresponding general temporal variations (i.e., acute, sub-acute, and chronic). A major assumption with the classification of people with non-specific LBP is the assumption of homogeneous characteristics of the factors causing their LBP, when this is not the case (McCarthy & Arnall, 2004; Van Middelkoop et al., 2011). Additionally, previous studies have shown sub-classifications of non-specific LBP and unique clinical characteristics (Dankaerts & O'Sullivan, 2010; Dankaerts et al., 2009; Delitto et al., 2012; O'Sullivan, 2005). The ineffectiveness of interventions in the literature involving people with non-specific LBP is a result of assuming a homogeneous population. This assumption has led to the emphasis on sub-classification systems based on LBP signs and symptoms (Dankaerts et al., 2009; Delitto et al., 2012; O'Sullivan, 2005; Spitzer et al., 1987). Thus, inconsistencies in findings from epidemiologic studies and systematic reviews may in part arise from the ambiguous definition and classification of LBP.

Second, the standing exposure assessments have been coupled with walking duration for some of the above-mentioned studies (Kopec, Sayre, & Esdaile, 2004; Macfarlane et al., 1997). Conversely, walking has been shown to be a potential strategy for LBP management (Callaghan, Patla, & McGill, 1999; Hendrick et al., 2010) and may be a confounding factor when combined with standing exposure assessment. Additionally, the differences in the types of standing (e.g. constrained vs unconstrained standing) performed by individuals also has differential effects on LBP development (Tissot et al., 2009). Specifically, the freedom to move during unconstrained standing allows for tissue loading to be distributed, as opposed to adopting constrained static postures, which have been shown to be implicated in muscle pain (Veiersted, 1994; Veiersted et al., 1990).

Lastly, the reliance on self-reports to adequately represent time spent standing are vulnerable to 'recall bias', and may contribute to the inconsistency in the results (Roffey et al., 2010). Although, some have found good-to-excellent reproducibility and high agreement with respect to reference methods of exposure measurements of self-reports from workers on physical work demands of standing (Stock et al., 2005).

Despite limitations and ongoing evidence, an overlooked set of novel experimental studies (not included in the systematic reviews) have suggested an important connection between prolonged standing and LBP development. Specifically, studies involving laboratory assessments of healthy, asymptomatic individuals have found a proportion of people will develop LBP during prolonged standing (Nelson-Wong et al., 2010; Sorensen, Johnson, et al., 2015). These studies have enabled extended and prospective understanding of prolonged standing and LBP development.

2.2 Laboratory Assessments of Standing-Induced Low Back Pain

Thus far, several laboratory investigations have conducted occupational simulations of prolonged standing work in healthy, asymptomatic individuals. These studies have demonstrated that 12 - 81% of varying study sample sizes (Table 4) will develop transient LBP (termed pain developers or PDs), while others (termed non-pain developers or non-PDs) will not (Bussey et al., 2016; Gallagher & Callaghan, 2015a, 2016, Gallagher et al., 2011, 2014, 2016; Gregory & Callaghan, 2008; Gregory et al., 2008; Marshall et al., 2011; Nelson-Wong & Callaghan, 2010a, 2010c, 2010d, 2014, Nelson-Wong et al., 2008, 2010, 2012; Nelson-Wong, Flynn, et al., 2009; Nelson-Wong & Callaghan, 2010b; Raftry & Marshall, 2012; Sheahan et al., 2016; Sorensen, George, et al., 2016; Sorensen, Johnson, et al., 2015; Sorensen, Norton, et al., 2015; Stewart & Gregory, 2016).

This wide range of variation seen in proportions of PDs and non-PDs, may be due to: 1) variations in the experimental setup (e.g., the task constraints of foot position and allotted space for standing) (Gregory & Callaghan, 2008; Nelson-Wong et al., 2008; Sorensen, Johnson, et al., 2015); 2) differences in inclusion/exclusion criteria (Nelson-Wong, 2009, p. 147; Sorensen et al., 2014); 3) differences in sample populations studied (e.g., university students or elite female field hockey athletes) (Bussey et al., 2016; Gallagher et al., 2011) and their pain thresholds (e.g., athletes may have higher pain thresholds) (Tesarz et al., 2012); and 4) modifications in the dichotomization process of PDs and non-PDs that was not consistent with a commonly used method of a 10-mm minimally clinical important difference (MCID) threshold (Gregory et al., 2008; Hägg, Fritzell, & Nordwall, 2003; Nelson-Wong & Callaghan, 2010b; Sorensen et al., 2016; Stewart & Gregory, 2016).

Nonetheless, aggregation of the studies participant pools altogether (i.e., without including studies that researchers have explicitly described to have utilized the same pool of participants from a previous investigation or people with LBP and elite athletes as participants), have demonstrated that 44% (195/443) of participants have been classified as PDs, thus far (Table 4).

Table 4 – Compilation of studies and their corresponding proportion of individuals that are pain developers (PDs) and non-pain developers (non-PDs)

Author	Population	Total Sample		Sex of PD		Proportion of PDs from Total Sample (%)
		Female	Male	Female	Male	
(Bussey et al., 2016)	Elite Field Hockey players who are asymptomatic or who have acute/sub-acute LBP	25 14	N/A	3 (healthy) 11 (with LBP)	N/A	3/25 (12) 11/14 (79)
(Gallagher & Callaghan, 2015a)	University	15	17	4	10	14/32 (44)
(Gallagher & Callaghan, 2016; Gallagher et al., 2016)[1]	University	8	9	4	5	9/17 (53)
(Gallagher et al., 2011)	University and Surrounding Community	21	20	9	4	13/41 (32)
(Gallagher et al., 2014)	University*	10	10	5	6	11/20 (55)
(Gregory & Callaghan, 2008)[2]	University	8	8	N/A	N/A	13/16 (81)
(Gregory et al., 2008)	University	7	6	3	4	7/13 (54)
(Marshall et al., 2011)	University	N/A	N/A	11	6	17/24 (71)
(Nelson-Wong et al., 2012, 2009, 2010, Nelson-Wong & Callaghan, 2010a, 2010b)[3]	University and Surrounding Community	21	22	10	7	17/43 (40)
(Nelson-Wong & Callaghan, 2010c)[4]	University and Surrounding Community	12	11	5	3	8/23 (35)
(Nelson-Wong & Callaghan, 2010d)[5]	University and Surrounding Community	8	8	4	4	8/16 (50)

[1] Utilized same participants from a previous investigation

[2] Did not explicitly describe the sub-classification process

[3] Discrepancies in the number of PDs presented within the journal articles exist; the number of PDs were originally 20 but after recalculating VAS with removal of baseline, 3 PDs were categorized into non-PDs (Nelson-Wong, 2009, p. 178-179)

[4] Utilized same participants from a previous investigation

[5] Utilized same participants from a previous investigation

Author	Population	Total Sample		Sex of PD		Proportion of PDs from Total Sample (%)
		Female	Male	Female	Male	
(Nelson-Wong et al., 2008)	University	12	11	N/A	N/A	15/23 (65)
(Raftry & Marshall, 2012)	University	8	12	4	6	10/20 (50)
(Sheahan et al., 2016)	University	10	10	5	3	8/20 (40)
(Sorensen, Norton, et al., 2015)[6]	Universities and Surrounding Community	28	29	15	9	24/57 (42)
(Sorensen, Johnson, et al., 2015)	Universities and Surrounding Community; People without and with LBP (people with LBP were matched with healthy subjects)	N/A	N/A	9 (healthy) 9 (with LBP)	6 (healthy) 6 (with LBP)	15/53 (28)
(Sorensen, George, et al., 2016) [7,8]	Universities and Surrounding Community	28	29	11 (<20 mm) 4 (≥20 mm)	8 (<20 mm) 1 (≥20 mm)	24/57 (42)
(Stewart & Gregory, 2016)[9]	University	8	8	N/A	N/A	12/16 (75)
(Viggiani, 2015, p. 77; Viggiani & Callaghan, 2016)	University*	20	20	8	8	16/40 (40)
TOTAL		**193[10,11]**	**173[10,11]**	**86[10,11]**	**69[16,11]**	**195/443[11] (44)**

[6] Sub-classified PDs reporting any symptoms greater than baseline

[7] Utilized same participants from a previous investigation

[8] Sub-classified PDs either below 20 mm or equal/above 20 mm on VAS

[9] Sub-classified PDs using an 8 mm VAS threshold

[10] Studies that did not report sex were excluded

[11] Did not include people with LBP who were classified as PDs

The importance of this aggregated number stems from the clinically-relevant work by Nelson-Wong et al. (2014), who conducted a 3-year longitudinal investigation to observe whether being a PD is followed by greater likelihood of experiencing clinical LBP (i.e., required a visit to a health practitioner or time off). The researchers demonstrated that more than a third of PDs (35.3%) reported a minimum of one episode of clinical LBP, compared to less than a quarter of non-PDs (23.1%) (Nelson-Wong & Callaghan, 2014). In addition, being a PD tripled their likelihood of experiencing chronic LBP in contrast to non-PDs, suggesting that PDs may be a "pre-clinical group" (Nelson-Wong & Callaghan, 2014).

These findings on the relationships between healthy individuals, LBP development during standing, and clinical LBP, indicates the important need for understanding and addressing this matter. This need is especially valid, due to the increasing adoption of standing work postures by office workers in the workplace to "counteract" the perceived deleterious health effects of sitting (Biswas et al., 2015; Callaghan et al., 2015; Carr et al., 2016; Chau et al., 2014; MacEwen et al., 2015), increasing the potential for exposure to prolonged standing.

In view of all that has been mentioned so far, researchers have been motivated to utilize the prolonged standing protocol (PSP) to: 1) aid in identification of individuals at-risk for LBP (Nelson-Wong & Callaghan, 2010b); 2) extend their knowledge of predictive baseline risk factors (Marshall et al., 2011; Nelson-Wong et al., 2008; Nelson-Wong, Flynn, et al., 2009; Raftry & Marshall, 2012; Sorensen, Johnson, et al., 2016); 3) understand the mechanisms of standing LBP development (Gregory & Callaghan, 2008; Nelson-Wong & Callaghan, 2010b; Nelson-Wong et al., 2008; Sorensen, Norton, et al., 2015); and 4) devise appropriate

interventions to be implemented with preventative and rehabilitative intentions (Gallagher et al., 2014; Nelson-Wong & Callaghan, 2010a; Stewart & Gregory, 2016).

2.2.1 The Utility of the Prolonged Standing Induced Low Back Pain Protocol

The literature on laboratory investigations using the PSP to investigate risk factors and the impact of different interventions has proliferated (Table 4). The PSP usually consists of performing light tasks while simultaneously standing quasi-statically for two hours (Gallagher & Callaghan, 2015b; Marshall et al., 2011; Nelson-Wong et al., 2010; Viggiani, 2015, p.136). However, the repeatability and validity of using the PSP to assess LBP development was limited. As a result, several researchers have investigated the utility of the protocol.

For instance, Nelson-Wong et al. (2010) examined the between-day repeatability of a number of outcome measures (i.e., clinical, biomechanical, and muscle activation patterns) during the PSP in PDs and non-PDs. The researchers indicated that majority of the measures and responses that were observed in PDs and non-PDs were replicated between sessions (Nelson-Wong & Callaghan, 2010c). In addition, individuals generally remained within their corresponding pain groups between days, with 18 out of 22 participants (83%) persisting in their pain status (Nelson-Wong & Callaghan, 2010c). These findings provide confidence in knowing that the outcome measures remain stable between days and any intervention administered will lead to measured changes directly related to it (Nelson-Wong & Callaghan, 2010c).

Additionally, Sorensen et al. (2015) investigated the validity of the PSP by identifying whether the descriptor and location of symptoms in PDs parallel people who have a history of chronic LBP during prolonged standing. Interestingly, symptom descriptors (e.g., aching, cramping stiffening, and tightness) and location of symptoms (e.g., low back, gluteal, and thigh regions) between PDs and people with LBP were similar (Sorensen, et al., 2015). This similarity supports the validity of using the protocol for investigating risk factors for LBP development during prolonged standing (Sorensen, et al., 2015).

2.2.2 Advantages and Disadvantages of the Prolonged Standing Protocol

The existing literature on laboratory investigations using the PSP has revealed several advantages in support of its' use, given that: 1) it involves a functional standing task that is relevant to people and occupations outside the laboratory; 2) PDs and non-PDs are easily dichotomized using the MCID threshold of self-reported pain on the visual analogue scale (Viggiani, 2015, p. 6); 3) PDs and non-PDs retain their pain status and biomechanical responses to prolonged standing between days (Nelson-Wong & Callaghan, 2010c); 4) LBP experienced by PDs are similar to LBP patients (Sorensen, Johnson, et al., 2015); 5) the induced-LBP is transient and subsides once the PSP has elapsed (Callaghan et al., 2015); and 6) the PSP enables investigations into mechanisms that precede LBP development during prolonged standing and may uncover causative factors (Nelson-Wong & Callaghan, 2010b).

However, disadvantages of the PSP also exist, such as the: 1) constrained generalizability of research findings, as much of the work has been done on university populations (Table 4); 2) uncertainty of the psychological role in pain modulation in PDs (Gallagher & Callaghan, 2015; Nelson-Wong, 2009; Sorensen et al., 2016); 3) uncertainty of whether any biomechanical differences among PDs exist (e.g., does a PD who reports 50 mm of pain move the same during standing as a PD who reports 12 mm of pain); and 4) MCID threshold is currently defined based on a chronic LBP population and not an acute or transient LBP population (Gallagher & Callaghan, 2015a; Hägg et al., 2003).

Despite the disadvantages, uncertainty, and basis for specific aspects of the PSP, there is substantial support for the use of the protocol. This suggests the PSP's continued use for prospectively studying standing LBP development.

2.2.3 Classification of Pain Developers versus Non-Pain Developers

As alluded to in section 2.2, healthy, asymptomatic individuals have demonstrated two distinct pain groups during a two hour PSP: transient LBP developers (termed PDs) and non-pain developers (termed non-PDs) (Nelson-Wong et al., 2008).

The method used to assess pain intensity and classify PDs and non-PDs is determined based on subjective reports on a visual analogue scale (VAS) (Gallagher & Callaghan, 2016; Hawker et al., 2011). This scale consists of a line that is 100 mm long and has the ends labelled with "no pain" to "worst pain imaginable" (Ostelo & de Vet, 2005). Participants can indicate what point along the line that best represent their pain intensity at the given time of administration (Ostelo & de Vet, 2005). The VAS has previously been supported to have

excellent validity and reliability (Ostelo & de Vet, 2005; Revill et al., 1976; Von Korff et al., 2000).

Individuals have traditionally been categorized as a PD when they report changes in their low back region VAS score of > 10 mm from baseline, throughout the PSP (Bussey et al., 2016; Gallagher et al., 2014; Gregory & Callaghan, 2008; Marshall et al., 2011; Nelson-Wong & Callaghan, 2010a; Raftry & Marshall, 2012; Sheahan et al., 2016). However, other researchers have used a VAS score of > 0 mm (Sorensen et al., 2016, 2014) or ≥ 8 mm (Hägg et al., 2003; Stewart & Gregory, 2016). Given that the PSP is a low-level pain-inducing protocol (Nelson-Wong et al., 2009), the 10 mm criterion is a conservative threshold that was determined based on: 1) minimal detectable change in a previous study (Nelson-Wong et al., 2009); and 2) minimal clinically important difference (MCID) for deterioration of 8 mm in chronic LBP patients reporting worsening of symptoms/pain with the VAS (Gallagher & Callaghan, 2015a; Hägg et al., 2003).

2.3 Risk Factors for Standing Low Back Pain Development

In the past decade, several studies have investigated baseline differences in PDs and non-PDs in the following factors: anthropometrics, demographics, physical activity levels, psychological factors, and several clinical assessment measures. However, the researchers have reported null findings within the sample sizes that were evaluated (Gallagher & Callaghan, 2015a; Nelson-Wong, 2009; Nelson-Wong et al., 2008; Raftry & Marshall, 2012; Sorensen, George, et al., 2016). Much of the recurrent findings on pre-disposing factors affecting risk for LBP development has been this postulate of motor control differences.

2.3.1 Motor Control Characteristics

Much of the compelling evidence for motor control differences have been from investigations looking at the hip musculature and to a lesser extent, the trunk musculature. Specifically, several researchers have reported that PDs demonstrated co-activation of their bilateral gluteus medius (GMED) muscles during prolonged standing, whereas non-PDs demonstrated reciprocal activation or relatively less co-activation (Bussey et al., 2016; Marshall et al., 2011; Nelson-Wong et al., 2008, 2012; Nelson-Wong & Callaghan, 2010b; Sorensen, Johnson, et al., 2016; Viggiani & Callaghan, 2016). Additionally, PDs have also demonstrated greater trunk flexor-extensor muscle co-activation (Nelson-Wong & Callaghan, 2010b). It has been postulated that PDs demonstrated these co-activation responses as compensatory strategies to an inadequately stabilized trunk during prolonged standing (Nelson-Wong, Flynn, et al., 2009). These co-activation and inadequate trunk stabilization responses are suggested to be a predisposing characteristic to LBP development for several reasons: 1) PDs demonstrated GMED co-activation, trunk flexor-extensor co-activation, and fewer body weight transfers prior

to reaching a clinically important level of LBP during prolonged standing (Gallagher & Callaghan, 2015b; Nelson-Wong & Callaghan, 2010b); 2) PDs demonstrated altered total muscular resting time in the GMED muscles during prolonged standing (Gregory & Callaghan, 2008; Nelson-Wong, 2009; Nelson-Wong & Callaghan, 2010a; Veiersted et al., 1990); 3) prior to prolonged standing, PDs experienced more performance difficulties than non-PDs in maintaining lumbopelvic alignment and exhibited asymmetrical onset of lumbopelvic movement during the AHA test (Nelson-Wong & Callaghan, 2010b, 2010c; Nelson-Wong, Flynn, et al., 2009; Sorensen, Johnson, et al., 2016); and 4) after a core-stabilization exercise intervention, PDs substantially reduced their self-reported LBP during prolonged standing and male PDs showed reductions in GMED co-activation levels concomitantly with reductions in self-reported LBP (Nelson-Wong & Callaghan, 2010a).

These motor control differences have also manifested in PDs relative to non-PDs during different tasks, such as: 1) increased trunk co-activation during suddenly applied hand load trials (Gregory et al., 2008) and 2) “spine-dominant” or “top-down” muscle activation strategy during an extension from trunk flexion exertion (Nelson-Wong et al., 2012). Furthermore, other studies have also demonstrated distinct postural kinematics during prolonged standing in PDs relative to non-PDs, such as: 1) standing in greater lumbar lordosis (Sorensen, Norton, et al., 2015); 2) standing further away from their passive lumbar spine extension neutral zone limit than non-PDs (Gallagher, 2014, p. 106); and 3) performing fewer lumbar spine flexion and extension rotation fidgets (i.e., a fast and large displacement) and overall movement (Gallagher & Callaghan, 2016; Gallagher et al., 2014).

All of these reviewed findings, support the hypothesis that there is a relationship between pre-existing motor control in healthy individuals (e.g., aberrant coordination of the hip and trunk musculature) and their likelihood of developing standing LBP. Consequently, there is evidence to support that PDs perform tasks quite differently from non-PDs.

2.3.2 Muscular Endurance and Strength Measures of the Trunk and Hip Musculature

Several studies on trunk and hip endurance assessments and PD status have shown mixed findings (Bussey et al., 2016; Marshall et al., 2011; Nelson-Wong, 2009; Nelson-Wong & Callaghan, 2010b). Detailed endurance assessments of the gluteus maximus (GMAX), thoracic erector spinae (TES) and lumbar erector spinae (LES) muscles with the Sorensen test (Demoulin et al., 2006) by Nelson-Wong (2009), showed no group differences in trunk extensor muscle fatigability or holding duration (Nelson-Wong, 2009; Nelson-Wong & Callaghan, 2010b). Thus, trunk extensor muscle fatigability may not be a predisposing factor in standing LBP development (Nelson-Wong, 2009, p.114).

Several researchers have found conflicting results of muscular endurance assessment of the GMED muscles (Bussey et al., 2016; Marshall et al., 2011; Nelson-Wong, 2009; Nelson-Wong & Callaghan, 2010b). In a study which set out to assess gluteus medius (GMED) endurance with a side-bridge test (McGill et al., 1999), Nelson-Wong (2009) found no group differences in holding duration. In an analysis of GMED strength and endurance in PDs and non-PDs, Marshall et al. (2011) found no differences in GMED strength between the two groups. In contrast to Nelson-Wong (2009), Marshall et al. (2001) demonstrated that GMED endurance was lower in PDs and that the measured outcome could predict individuals into their corresponding pain group. More recently, a study by Bussey et al. (2016) also used the side-bridge test to assess

GMED endurance in PDs and non-PDs. In support of findings by Nelson-Wong (2009), Bussey et al. (2016) found no differences between PDs and non-PDs. However, the participants in their study were elite field hockey players that were asymptomatic or had a history of acute or sub-acute LBP (Bussey et al., 2016). The evidence presented in this section suggests that there may be a role for GMED endurance to contribute to standing LBP development (Marshall et al., 2011).

2.4 Motor Control Characteristics of People with Low Back Pain

There is a large number of studies describing the relationship between LBP and motor control. Many studies have established that motor control differs between people with or without chronic clinical LBP. For instance, altered trunk muscle activation patterns, kinematics, and lumbo-pelvic rhythm have been a recurrent finding in this population (Esola et al., 1996; Hodges & Moseley, 2003; Laird et al., 2014; Lee & Wong, 2002; Lehman, 2004; Leinonen et al., 2000; Marras & Wongsam, 1986; Marras et al., 1993, 1994, 2000; McGorry et al., 2001; McGregor et al., 1997; Sullivan et al., 2000; Van Dieën et al., 2003; Wong & Lee, 2004). This finding may not be surprising, given the immense complexity required of the motor control system within the lumbopelvic region (Hodges & Moseley, 2003). To illustrate, the factors involved in the dynamic interplay of the subcomponents within the spine stabilizing system in conjunction with generating a coordinated response to produce movement and appropriately control the spine, while concomitantly maintaining a variety of homeostatic function within the trunk (e.g., breathing), is a challenging feat (Hodges & Gandevia, 2000; Hodges & Moseley, 2003; Panjabi, 1992a; Wang & McGill, 2008).

However, it is unclear why these differences manifest. Furthermore, it remains unclear whether these differences are a result of LBP or a cause of LBP, or a combination of both, due to the exploratory (e.g., case-control design) nature of the conducted studies. Findings of both increased and reduced trunk muscle activation responses throughout different tasks and contraction types have been shown in the literature (Van Dieën et al., 2003). The prevailing tenets attempting to explain these responses to LBP are the pain-spasm-pain model (PSP-M) and the pain-adaptation model (PA-M). Briefly, the PSP-M postulates that sustained muscle

hyperactivity (i.e. spasm) manifests as a consequence of pain, resulting in increased muscle activation and subsequently, pain (Travell et al., 1942; Van Dieën et al., 2003). In contrast, the PA-M posits that pain decreases activation of muscles when functioning as agonists and increases activation when active as antagonists, resulting in reduced movement velocity and movement excursion as a means to prevent pain provocation (Lund et al., 1991; Van Dieën et al., 2003). A detailed systematic review of the literature on the effects of clinically (chronic) or experimentally-induced LBP and trunk muscle activation patterns by Van Dieën (2003), showed inconsistent support for either model. Given the inconsistent findings, the author surmised that the muscle activation changes observed with LBP is a means to avoid noxious stimuli in mechanically injured structures and relates to maintaining spinal stability (Panjabi, 1992a). Subsequently, a comprehensive model exploring possible mechanisms of pain on motor control have been proposed (Figure 3) and the reader is directed to Hodges & Moseley (2003).

Finally, Hodges & Tucker (2011) proposed a new theory of motor adaptation to pain, suggesting a more complex model is required. The proposed theory expands upon the concept that the adaptations in response to pain are to reduce pain and protect the painful part with a more adaptable solution. Thus, people with LBP display altered motor control. Largely, the effects of pain on the motor control of the spine appears multifaceted.

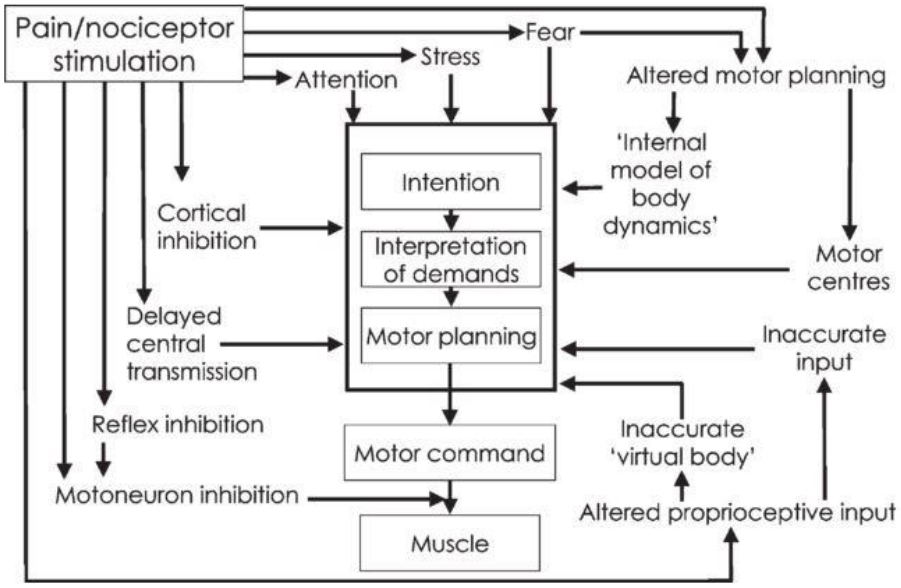


Figure 3 – Proposed mechanisms on how pain can affect the motor control by Hodges & Moseley (2003)

As alluded to in one of the aforementioned sections, the motor control exhibited by people with LBP is dependent on numerous factors, such as the task being performed (Van Dieën et al., 2003). Movement and motor control patterns during lifting have been observed to affect LBP injury risk in athletic, occupational, and non-occupational populations. For instance, an analysis into the mechanics of powerlifters lifting extremely heavy loads, Cholewicki & McGill (1992) found one lifter to report LBP as a result of disproportionately greater rotation at the L4/L5 intervertebral joint, indicating a potentially inappropriate activation sequencing of muscles (e.g., motor control error) (McGill, 1997). This finding falls in line with the theoretical literature that postulates spinal instability to result in injury and pain (Hodges et al., 2003; Panjabi, 1992a, 1992b). In a case-control study (n = 287), Mundt et al. (1993) found that non-occupational activities such as frequent lifting of objects or children weighing ≥ 12 kg with "knees straight

and back bent" was associated with increased risk of lumbar disc herniation (relative risk of 3.95) (Mundt et al., 1993). This is in line with several reviews that have recommended lifting without excessive lumbar spine flexion (e.g. a stooped posture) due to high shear forces (Burgess-Limerick, 2003; Straker, 2003; Van Dieen et al., 1999). The outcomes of a fully flexed lumbar spine can negatively affect the mechanical loading of the spine, increasing the risk of ligament, facet, and intervertebral disc injury (Callaghan & McGill, 2001; McGill et al., 2000; Norman et al., 1998). This notion of avoiding excessive lumbar spine flexion has also been emphasized through the use of a hip hinge in injury prevention, injury management, and performance enhancement endeavors (Giangregorio et al., 2015; Myer et al., 2014).

Another well-studied functional task among this population is trunk flexion-extension. In addition, researchers have analyzed numerous factors pertaining to the task's performance. It is well-established that people with LBP have slower movement performance, reduced range of motion, and altered lumbo-pelvic rhythm (Laird et al., 2014). For instance, data from several studies have identified that range of motion and higher order derivatives of trunk kinematics during trunk flexion-extension exertions are lower in LBP patients (Marras & Wongsam, 1986; Marras et al., 1993, 1994, 2000; McGregor et al., 1997; Sullivan et al., 2000). In addition, the higher order derivatives have demonstrated excellent capability and superiority over range of motion measures for distinguishing people with or without LBP. Additionally, it is well established that the 'normalized' recruitment activation order during extension from trunk flexion involves a sequencing of bottom-up muscles, whereas a top-down strategy is aberrant (Leinonen et al., 2000; McGorry et al., 2001; Nelson-Wong et al., 2012). Lumbar spine and hip contributions to the forward bending motion has also been shown to be different between people

with or without LBP (Esola et al., 1996; Lee & Wong, 2002; Leinonen et al., 2000; McGorry et al., 2001). However, some of these findings are not consistent across LBP patients and may be attributable to the unique characteristics that subgroups of LBP patients may exhibit. Nonetheless, it is recurrently observed that trunk and lumbopelvic kinematics are altered.

2.5 Movement Screening as an Approach to Deduce Motor Control and Injury Risk

In recent years, the proliferation of movement screening has occupied the published movement literature, as seen by the numerous screens developed (Cook et al., 2014b; Kritz et al., 2009; McCunn et al., 2015; Mottram & Comerford, 2008). Assessing movement competency through movement screens, has been thought to be an important independent feature to predict injury risk and performance (Chimera & Warren, 2016; Glass, 2015; Kritz et al., 2009; McGill et al., 2015).

This association between specific kinematic features and risk of injury (e.g. non-contact musculoskeletal injury) (Hewett et al., 2005), has led to an increased interest in assessing movement competency in sport athletes (Kritz & Cronin, 2008; Kritz et al., 2009; McCunn et al., 2015) and occupational athletes (e.g. firefighters, police officers, and soldiers) (Frost, Beach, McGill, et al., 2015; McGill et al., 2015) to determine any non-contact musculoskeletal injury risk (Frost, Beach, McGill, et al., 2015).

Movement competency equates to one's ability to perform pain-free movement that encapsulates correct joint alignment, appropriate muscle coordination, and posture (Kritz et al., 2009). The evaluation of movement competency has been done through the use of movement screens, defined as a protocol used on individuals to assess the "quality" of their movement(s) rather than specific performance outcomes (e.g., distance, repetitions, or time) (McCunn et al., 2015). Moreover, the process of movement screening is done through a single or a battery of whole-body movement tasks that may consist predominately of low-demand challenges (Chimera & Warren, 2016; Comerford & Mottram, 2001; Cook et al., 2014a, 2014b; Frost, Beach, McGill, et al., 2015; Kritz, Cronin, & Hume, 2010; Kritz et al., 2009; Plisky et al., 2009).

2.5.1 Limitation of Using Low-Demand Challenges in Healthy Populations

Many different movement screening tools (some more popular than others), exist in the literature (Comerford & Mottram, 2001; Cook et al., 2014a, 2014b; Kritz et al., 2009; McCunn et al., 2015; McGill et al., 2015). Clinicians, coaches, and researchers have been prompted to explore the prognostic capabilities of such popularized tools, to support for or refute against its' function and continued use (McCunn et al., 2015).

The results of a movement screen purportedly enable inferences to be made about an individual's injury risk and performance capabilities (Cook et al., 2014b, 2014a; McCunn et al., 2015). A major drawback postulated with the aforementioned process is the assumption that the individuals' posture and movement expression during a movement screen with low-demand challenges is corroborated with movement performance during athletic, leisure, and occupational activities (i.e. outside the constraints imposed by the testing protocol) (Frost, Beach, McGill, et al., 2015). However, this is not always the case (Frost, Beach, Callaghan, et al., 2015; Scholz & McMillan, 1995; Walsh et al., 2007).

For instance, varied magnitudes of task demands using load and speed have been shown to affect the manifestation of movement during performance of a battery of general tasks (Frost, Beach, Callaghan, et al., 2015; Frost, Beach, McGill, et al., 2015). Whether or not this change in one's movement behavior is perceived to be a safer/effective strategy or an undesirable/compromised strategy, the researchers demonstrated that individuals adapt their movement in response to increased task demands. Thus, there appears to be merit to incorporating elevated task demands into assessing movement competency as it can be more

revealing than low-demand activities of an individual's performance capabilities and risk of injury (Frost, Beach, Callaghan, et al., 2015; Frost, Beach, McGill, et al., 2015).

Likewise, performing the low-demand challenge of quiet standing is known to not be a significantly challenging task to reveal balance mechanisms or deficits within the balance control system (Winter, 1995). Instead, researchers have administered balance tasks with greater challenge (e.g., external perturbations or sensory constrained conditions) to elicit and identify unique balance responses and dysfunctions in the balance control system (Byl & Sinnot, 1991; Mientjes & Frank, 1999; Winter, 1995).

Moreover, low-demand challenges and the movement screening paradigm has been inexplicitly used within research distinguishing motor control in people with LBP and healthy controls. It has previously been mentioned (section 2.4) and demonstrated that although the use of submaximal trunk flexion-extension exertion (TFEE) velocity measures have proven to differ between LBP and healthy people, maximal (i.e., elevated task demand of speed) TFEE velocity differences were much more pronounced between the two groups (Marras & Wongsam, 1986).

Lastly, several researchers have investigated the presence of precarious lower limb kinematics (e.g., dynamic valgus) for potential anterior cruciate ligament (ACL) injury risk during high-demand activities, such as the drop vertical jump task (Hewett et al., 2005; Noyes, 2005). The studies have used high-demand challenges, given that non-contact ACL injuries are often associated with greater knee joint external load demands (such as landing from a jump or change-of-direction maneuvers as seen in sporting movements) (Hewett et al., 2005) and the

potential for the postulated injurious kinematics not being elicited during low-demand challenges (Frost et al., 2016).

Collectively, these studies outline a critical role for elevated external tasks demands to be incorporated into movements screens assessing movement competency to elicit movement behavior reflective of their performance during athletic, leisure, and occupational activities, and, in turn, improved assessment of injury risk and performance capabilities.

2.5.2 What Is 'Risky' Movement?

The literature on movement competency and injury risk has highlighted several movement patterns associated with increased risk of injury. For instance, several reviews have recommended lifting without excessive lumbar spine flexion (e.g. a stooped posture) (Burgess-Limerick, 2003; Straker, 2003; Van Dieen et al., 1999). Outcomes of a fully flexed lumbar spine can negatively affect the mechanical loading of the spine, increasing the risk of ligament, facet, and intervertebral disc injury (Callaghan & McGill, 2001; McGill et al., 2000; Norman et al., 1998). Additionally, the inability to preserve lower limb alignment (i.e., higher knee abduction angles or dynamic knee valgus) during vertical jump landing task (as well as the presence of greater external knee abduction moments) has been postulated to be a key predictive factor with potentially increased risk of non-contact ACL injuries (Hewett et al., 2005; Noyes, 2005). The implication of excessive knee valgus for ACL injuries, has also been demonstrated to be associated with reduced hip musculature strength (Powers, 2010).

With these in mind, Frost et al. (2015) delineated "risky" movement behavior as movements associated with greater risk of injury (Frost, Beach, Callaghan, et al., 2015).

Specifically, the researchers characterized a subject's movement patterns with several different kinematic variables (e.g., 3-D spinal motion, trunk angle, or frontal plane knee motion) chosen to reflect a potential injury mechanism or previously shown to influence the knee, hip, or low back, during a squat or lifting task (Frost, Beach, Callaghan, et al., 2015). Thus, the presence of excessive lumbar flexion and inability to preserve lower limb alignment in various activities suggest it to be movement patterns that can expose an individual to unwarranted passive tissue loads and increased injury risk (McGill et al., 2013).

2.6 Review of Proposed Tasks to Assess Movement Behavior and Muscular Recruitment Patterns

By incorporating the movement-screening paradigm, previous findings in altered motor control differences in people with LBP and previously defined risky/uncontrolled motion variables to elucidate movement competency, a variety of tasks was used to expand upon previous reports on altered motor control differences in PDs and non-PDs. This section provides brief findings and rationale for the tasks that were incorporated in this thesis. The tasks were chosen to: 1) reflect whole-body movements tasks that may be encountered in everyday living (e.g., lifting) (Frost, Beach, McGill, et al., 2015); 2) impose challenge on coordination and maintenance of trunk postures and lower limb alignment throughout different planes of motion and task demands; and 3) elicit movement patterns that may exhibit a lack of control or injurious/risky movement pattern (Frost, Beach, McGill, et al., 2015). Additionally, the rationale for 1) is to measure movement behavior and muscle recruitment patterns that are independent of (or minimize the effect of) practice and learning of the intervention being implemented (Henry et al., 2006).

2.6.1 Symmetric Trunk Flexion-Extension Exertion

Flexion and extension of the trunk in five different positions across the transverse plane is part of the 'functional motion performance' developed by Marras et al. (1986, 1990, 1993, 1994, 1999). This protocol assesses dynamic low back function and has been used as a movement screening tool that allows objective quantification of low back impairment (due to low back pain) through kinematic measures of the trunk (Ferguson & Marras, 2004). For instance, Marras et al. (1986) investigated the practicality of using trunk angular velocity measures over active trunk range of motion (ROM) measures to distinguish people with chronic LBP from healthy controls. All subjects were asked to perform submaximal and maximal trunk flexion-extension in symmetric (0° of twist) trunk positions (Marras & Wongsam, 1986). Focusing on the trunk kinematic measures, the researchers demonstrated that active trunk ROM and angular velocity measures significantly differed between people with LBP and healthy controls. However, differences in trunk angular velocity measures (Figure 4) were more pronounced than ROM measures (Figure 5), especially during maximal effort exertions. Higher order trunk kinematic derivatives have been suggested to be more sensitive than utilizing active trunk ROM measures, as supported by several other studies since (Marras et al., 1993, 1999; Marras & Wongsam, 1986; Sullivan et al., 2000). Interestingly, similar findings of performance differences in the two groups have also been shown during submaximal and maximal asymmetric (15° and 30° of twist in clockwise and counterclockwise trunk positions) trunk flexion-extension (Marras et al., 1990).

Since that time, a considerable amount of research has validated the functional motion performance in conjunction with the corresponding higher order trunk kinematic measures for distinguishing healthy controls from people with LBP and quantifying low back impairment

(Ferguson & Marras, 2004; Ferguson et al., 2003; Marras & Wongsam, 1986; Marras et al., 1993, 1994, 2000; McGregor et al., 1997; Sullivan et al., 2000; Vaisy et al., 2015). Additionally, these measures have been shown to be related to three other outcome measures (i.e., LBP symptoms, activities of daily living, and work status) of improvement when following people with LBP through their recovery process (Ferguson et al., 2000).

However, a drawback from previous research using trunk kinematic measures during TFEE to distinguish healthy controls from people with LBP has been the wide variability in the higher order derivatives of motion found in healthy subjects in one of the studies (Marras & Wongsam, 1986). The variability depicted in Figure 4 reveals that several healthy individuals had similar TFEE velocity measures to LBP patients. This variability suggests potential for differences to be characterized even within healthy subjects that resemble kinematic measures of people with LBP. Thus, whether these differences exist between PDs and non-PDs may further substantiate aberrant motor control strategies and standing LBP development. It has previously been shown that there were no differences in self-selected velocity measures between PDs and non-PDs during extension from trunk flexion exertions (Nelson-Wong et al., 2012). Whether any differences are observed during maximal exertions have been unexplored. A normative database (Table 5) has also been created by previous researchers and was used in conjunction with the data from this thesis (Marras et al., 2000).

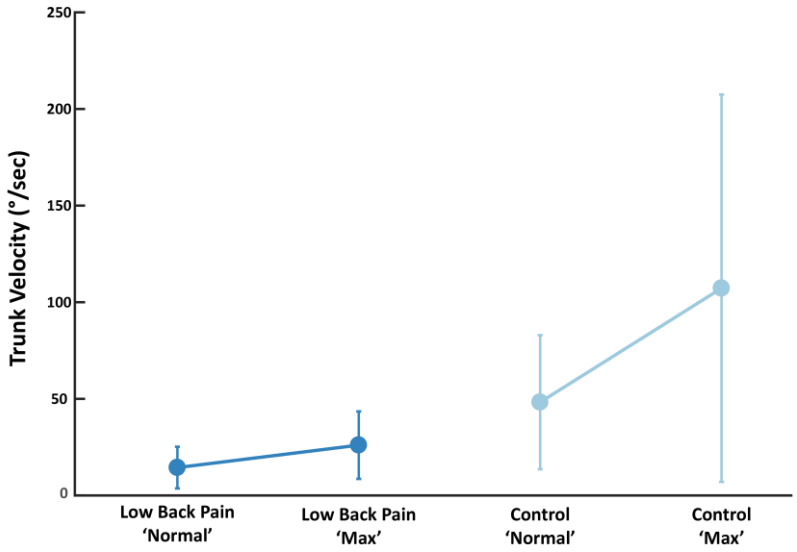


Figure 4 –Trunk velocity measures (mean and standard deviation) during self-selected speed ('normal') and maximal effort ('max') symmetric trunk flexion-extension with knees straight in healthy (control) subjects and (low back pain) patients. Note the standard deviation measures during max efforts (labelled 'Max'). Figure adapted using a web-based digitizer (WebPlotDigitizer v.3.11, Austin, Texas, USA) and originated from Marras et al. (1986).

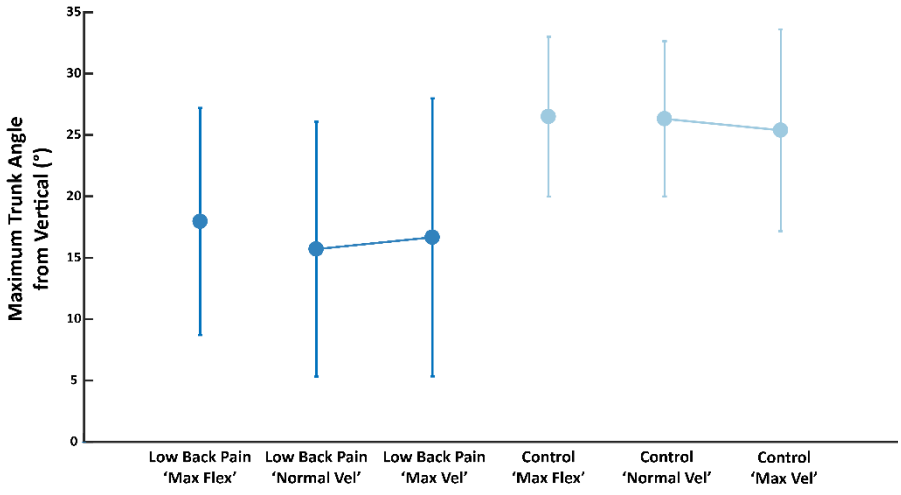


Figure 5 – Absolute trunk range of motion (mean and standard deviation) measures in healthy (control) people and (low back pain) patients during trunk flexion-extension exertions with knees straight. Range of motion during maximum trunk flexion ('max flex'), normal velocity ('normal vel') and maximum velocity ('max vel') depicted. Adapted using a web-based digitizer (WebPlotDigitizer v.3.11, Austin, Texas, USA) and originated from Marras et al. (1986).

Table 5 – Normative database of mean (standard deviation) values for trunk flexion-extension range of motion, velocity, and acceleration measures for males and females 20-60 years of age. Originated from Marras et al. (1993).

PLANE	DIRECTION	MOTION VAR.	AGE									
			MALE					FEMALE				
			20's	30's	40's	50's	60's	20's	30's	40's	50's	60's
SAGITTAL		RANGE (degree)	38.71 (14.41)	41.47 (13.57)	42.75 (14.35)	42.76 (16.58)	37.60 (15.54)	38.64 (17.04)	31.41 (12.82)	29.28 (10.61)	26.47 (7.72)	23.88 (9.46)
	FLEXION	VELOCITY (deg/sec)	104.12 (51.98)	113.88 (49.86)	107.53 (47.15)	101.75 (49.38)	80.25 (45.51)	100.02 (53.74)	82.34 (37.71)	72.45 (28.73)	61.62 (19.54)	47.91 (15.87)
	EXTENSION	VELOCITY (deg/sec)	106.54 (48.09)	120.94 (53.82)	114.84 (44.01)	105.16 (46.26)	81.99 (42.88)	104.50 (53.43)	90.95 (39.96)	78.31 (29.35)	67.79 (22.14)	49.64 (18.38)
	FLEXION	ACC. (deg/sec^2)	475.49 (250.44)	541.90 (287.85)	473.56 (248.38)	425.40 (222.40)	299.02 (181.32)	435.59 (270.85)	354.86 (175.65)	335.70 (144.80)	257.09 (117.98)	194.71 (72.27)
	EXTENSION	ACC. (deg/sec^2)	490.93 (269.25)	552.06 (302.13)	493.27 (248.04)	417.55 (206.49)	322.76 (264.20)	445.10 (248.90)	373.01 (187.90)	318.66 (163.54)	291.78 (146.52)	188.36 (90.72)

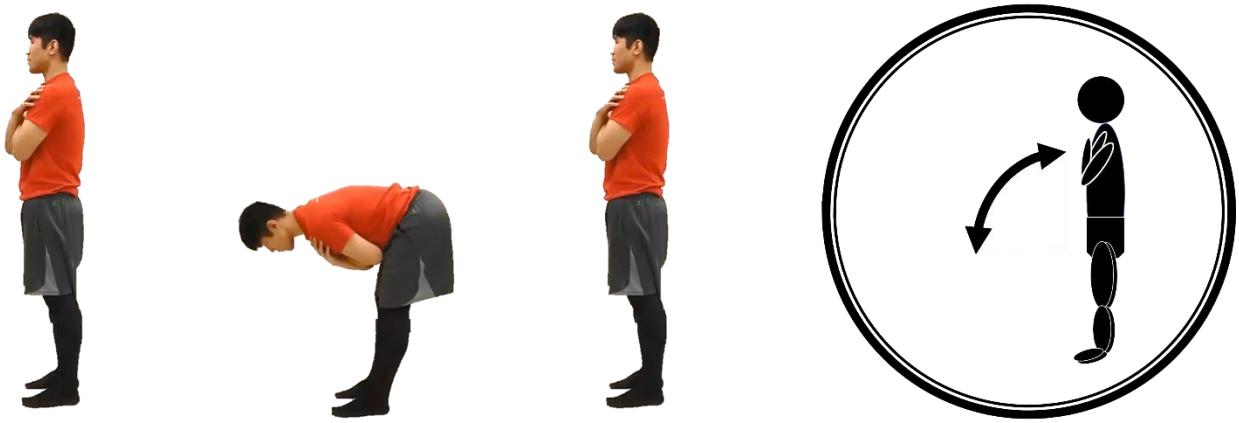


Figure 6 – Depiction of symmetric trunk flexion-extension (STF) exertion

2.6.2 Symmetric Floor-To-Knuckle Lift and Lower Task

The symmetrical floor-to-knuckle lift and lower (SLIFT) is a task that is kinematically similar to activities of daily living (Mundt et al., 1993) and is commonly observed during occupational manual materials handling (Figure 7). This task has been utilized as part of a battery of tests to reflect a whole-body movement pattern commonly used in individuals (Frost, Beach, McGill, et al., 2015). It imposes challenge by demanding the participant to control multiple joints and consequently, elicit movement behavior that may affect musculoskeletal injury risk (e.g., low back or knees) (Beach et al., 2014; Frost, Beach, Callaghan, et al., 2015; Frost, Beach, McGill, et al., 2015; McGill et al., 2013, 2015). In addition, joint kinematics and/or muscle activation has been assessed in response to increased external load demands during the SLIFT (or comparable motion), in populations of athletes (Walsh et al., 2007), occupational athletes (e.g., firefighters) (Frost, Beach, Callaghan, et al., 2015; Frost, Beach, McGill, et al., 2015), industrial workers (Scholz et al., 1995), and university students (Scholz, 1993). Lifting a moderate to heavy object involves numerous neuromuscular constituents, such as controlling and directing the object's trajectory to a target while sustaining balance and minimizing stress on the body (Scholz et al., 1995). It has been previously established that the posture adopted during a lift may not be the same in subsequent lifts with the manipulation of task variables, such as load or speed (Frost, Beach, Callaghan, et al., 2015; Scholz et al., 1995).

To perform the task, the participant stands in front of the crate while awaiting a cue to start. Once they instructed to begin, the individual lifts a crate (0.33 × 0.33 × 0.28 m) (with weight or no weight combined) from the floor to waist/knuckle height and lowers it back down for a specified number of repetitions with a pre-set tempo and rest interval.

Figure 7 – Depiction of lift phase during a sagittal symmetric floor-to-knuckle lift (SLIFT)

2.6.3 Modified Star Excursion Balance Test

Originally a rehabilitative tool, the modified star excursion balance test (mSEBT) is a clinical test that is intended to assess and challenge dynamic postural control, proprioception, range of motion, and strength abilities of an individual (Gribble et al., 2012; Kinzey & Armstrong, 1998). It may be simplified as a "series of unilateral mini-squats" while simultaneously using the non-stance limb to reach as far as possible in a given direction (Earl & Hertel, 2001). The reaching directions involve anterior, posterolateral, and posteromedial, which are named with respect to the specific leg used as the stance limb (Figure 8) (Gribble et al., 2012). These different directions enable challenges to movement control, which requires combinations of sagittal, frontal, and transverse planes of motion.

In addition, based on a Systems Framework for Postural Control (Sibley et al., 2015), the star excursion balance test was proposed to assess the following: anticipatory postural control, functional stability limits, static stability, and underlying motor systems. In contrast to the single leg stance test – assesses static stability and underlying motor systems only (Sibley et al., 2015) – the mSEBT is considered to be more challenging, given that it assesses additional components related to balance control.

The measured performance outcome of the mSEBT is based on the furthest reach distance while adhering to various rules of the task (Gribble et al., 2012). The reach distance values are used as an indicator of their dynamic postural control capability (i.e., a longer reach distance suggests better dynamic postural control) (Gribble et al., 2012). The mSEBT has also demonstrated ability to identify performance inadequacies that are related to lower limb injury (e.g., chronic ankle instability, ACL reconstruction, patellofemoral pain syndrome) (Gribble et

al., 2012) in otherwise, healthy individuals (Gribble et al., 2012; Hertel, 2008; Hertel et al., 2006).

To perform the test, the individual begins by adopting a single leg stance on their stance (testing) limb. While in single leg standing, the participant then uses their non-stance (reaching) limb to reach as far as possible along the direction being tested (Figure 8) (Gribble et al., 2012). The reach portion of the task involves making light contact with the line with their most distal aspect of the reaching limb. Lastly, the individual returns their non-stance limb to the original starting position and reassumes a bilateral stance. Constraints that will not be tolerated include: 1) shifting weight or resting on the reaching limb, 2) 'heavily' making contact with the ground on the reaching limb, 3) making contact with the ground at any point during the test with the reaching limb to maintain balance, or 4) lifts or shifts of any part of the testing limb foot during the trial (Gribble et al., 2012).

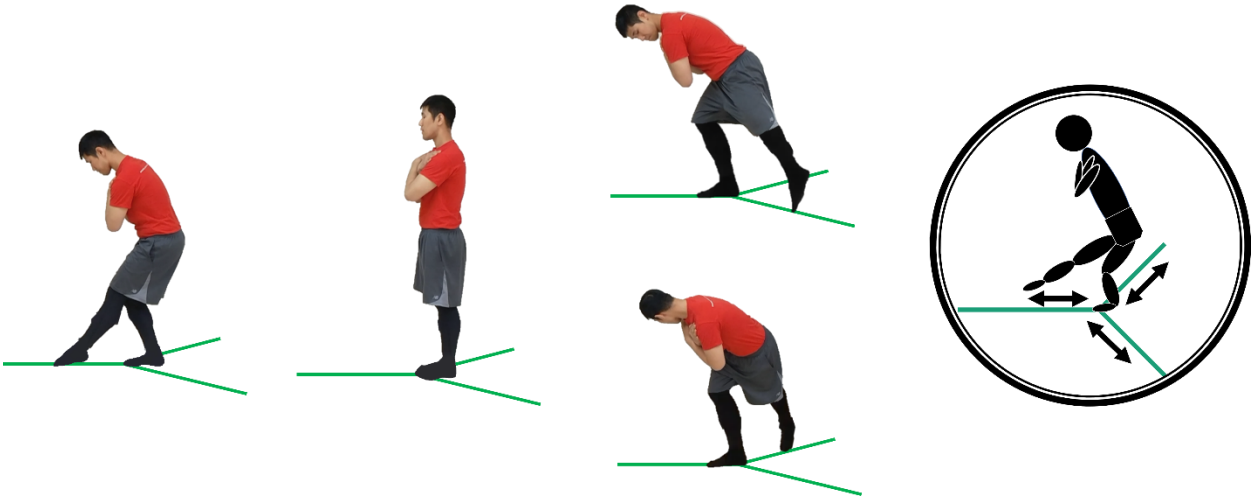


Figure 8 – Depiction of the modified star excursion balance test (mSEBT)

2.6.4 Active Hip Abduction Test

The active hip abduction (AHA) test, initially developed by Nelson-Wong et al. (2009), is a screening tool used to assess an individual's ability to maintain lumbopelvic alignment during the performance of hip abduction in an unstable (side lying) position. This test has been developed to predict which asymptomatic individuals would experience LBP development during standing (Nelson-Wong, Flynn, et al., 2009). The aforementioned purpose is predicated based on the theory that poor performance reflects inadequate trunk musculature stabilization, which translates to muscle recruitment differences observed during prolonged standing and the development of LBP (Nelson-Wong & Callaghan, 2010a; Nelson-Wong et al., 2008; Nelson-Wong, Flynn, et al., 2009). The AHA test is assessed using a set criterion and assigning a performance score ranging from 0-3 (Nelson-Wong, Flynn, et al., 2009). Both self-assessed and examiner-rated AHA test scores (Nelson-Wong, 2009, p. 103) demonstrated potential predictive capabilities of whether an individual is a PD or non-PD, with poor sensitivity (0.35 - 0.41) and high specificity (0.85 – 0.92). These results indicate that PDs experienced greater difficulty performing the AHA test than those who were non-PDs. This similar trend of difficulty has been observed between female PDs and female non-PDs (Viggiani, 2015, p. 82), but not between male PDs and male non-PDs.

This tool has been considered to have a moderate-to-high reliability when scored by practicing physical therapists, with interrater reliability (using the 4-point system) of 0.70 (95% CI: 0.56, 0.94) and intrarater reliability values ranging from 0.53 (95% CI: 0.13, 0.78) to 0.93 (95% CI: 0.82, 0.97) (Davis et al., 2011).

To perform the test, individuals are positioned on a table with their body in side lying position, pelvis perpendicular to the support surface, lower limbs extended, and aligned with their torso (Nelson-Wong, Flynn, et al., 2009). They are then instructed to actively abduct their hip while maintaining the extended knee in line with their trunk and frontal plane pelvic alignment.

Figure 9 – Depiction of Active Hip Abduction (AHA) test performance

Given the numerous studies reporting the effect of load and/or speed on physical performance, a similar paradigm was used to identify whether an additional individualized external load may elicit aberrant movement patterns that may not have been observed during a standard AHA test.

2.6.5 Reverse Side Bridge

The side-bridge is an exercise widely used in core-stabilization programs for prevention and rehabilitation of back pain (McGill, 2010; McGill & Karpowicz, 2009; McGill et al., 1999; Nelson-Wong & Callaghan, 2010a; Youdas et al., 2014). Additionally, it is an assessment tool for evaluating the isometric endurance of the lateral musculature of the core and hip (McGill et al., 1999, 2003, 2013), such as the quadratus lumborum (McGill et al., 1996) and the gluteus medius (Bussey et al., 2016; Ekstrom et al., 2007; Marshall et al., 2011; Nelson-Wong & Callaghan, 2010c).

The traditional side-bridge test position requires being in a side-lying position and supporting the upper body by being held up on the forearm (Figure 10) using the ipsilateral shoulder girdle muscles of the side being tested (e.g., upper body strength and endurance) (Durall et al., 2012; McGill et al., 1999; Musalem et al., 2015). Given this position, individuals may be limited in their performance due to fatigue, pain, or previous injury within their shoulder complex (Durall et al., 2012; Tvrdy, 2012). For instance, comparisons of two trunk flexor endurance tests, the prone bridge (or front plank) and the modified v-sit (or flexor endurance test) revealed weak correlations in their durations (Durall et al., 2012; Musalem et al., 2015). This finding is attributed to the differences in posture of each test, since the prone bridge requires the individual lying prone and propped up on their forearms and toes, whereas the modified v-sit does not involve any use of their upper extremities for support (Durall et al., 2012). Additionally, the performance of the prone bridge is being affected by the performance of the muscles stabilizing the glenohumeral joint (e.g., latissimus dorsi) (Musalem et al., 2015). Inferring upon differences in the prone bridge and the modified v-sit tests, a valid endurance assessment of the

GMED muscles may not have been measured during the traditional side-bridge test in PDs and non-PDs in previous investigations (Bussey et al., 2016; Marshall et al., 2011; McGill et al., 1999; Nelson-Wong, 2009).

The reverse side-bridge (RSB) (Tvrdy, 2012) (also reported as 'feet-elevated side support'; Youdas et al., 2014) is a modified version of the traditional side-bridge test. The main difference is the position of the upper body. The reverse side-bridge absolves the use of the shoulder by having the upper body propped up at the shoulder itself with the use of cushions/pillows (Figure 10). This position potentially possesses improved assessment of isometric endurance in the GMED of PDs and non-PDs by increasing their isometric holding times and subsequently, improved assessment of their muscular isometric endurance capacity (Tvrdy, 2012).

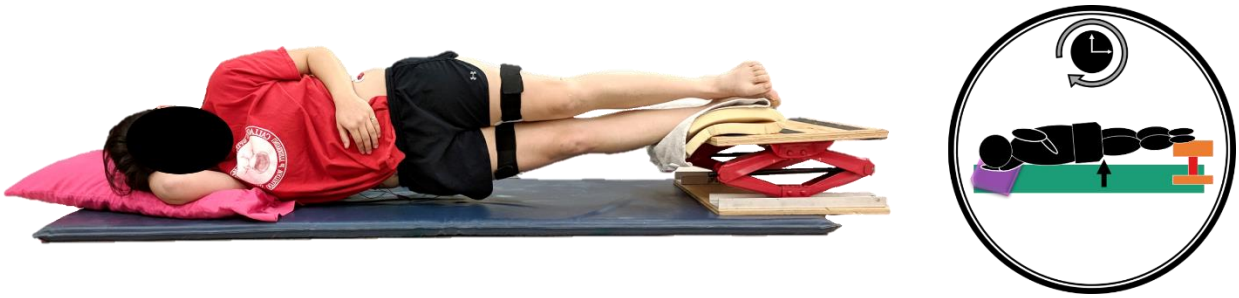


Figure 10 – Depiction of reverse side-bridge (RSB) performance; offsets loading of the ipsilateral shoulder girth muscles relative to a traditional side bridge

Chapter 3 – Methods

3.1 Overview of Study Design

On Day 1, participants underwent an initial screening process and equal counts of PDs and non-PDs were identified. Recruited participants performed a single two-hour standing protocol with minimal equipment setup. Only self-reported pain measures were analyzed from this session, along with questionnaires assessing: attitudes and beliefs towards pain, ankle instability, and physical activity levels.

Once an individual's pain status has been identified, participants were then recruited to participate in the laboratory assessment session. Participants were outfitted with kinematic markers and surface electromyography equipment and asked to perform the set of tasks previously outlined (Table 1). Trunk and lower limb kinematics and muscle activation measures were processed and analyzed.

Prior to participation, all participants read and filled out an informed consent form. The letters of informed consent form were approved by the Office of Research Ethics (#22144) at the University of Waterloo.

3.2 Participants

Participants from the University of Waterloo population and the surrounding community were recruited to partake in this study. Upon successful completion of the categorization session, these participants were selectively recruited into their corresponding pain status groups. This selectivity enabled equal comparisons between PDs and non-PDs, as well as analyzing sex as a factor, since previous studies have shown sex-specific responses throughout the PSP (Gallagher et al., 2011; Nelson-Wong & Callaghan, 2010a, 2010d; Viggiani & Callaghan, 2016).

As outlined in previous studies (Gallagher et al., 2016; Nelson-Wong & Callaghan, 2014; Viggiani & Callaghan, 2016), eligible participants must not have had the following exclusion criteria: 1) any history of LBP throughout their entire life that required seeing a clinical professional or time off from recreation, school, or work, 2) undergone surgical interventions involving the lumbar spine or acetabulofemoral joints, 3) engaged in occupational work that required constrained prolonged standing in the preceding twelve months of study participation, 4) incapable of continuously standing for two hours, and 5) incapable of performing the screening tasks without any pain. An a priori analysis (GPower; Erdfelder, Faul, & Buchner, 1996) ($\alpha = 0.05$, $\beta = 0.80$) using a medium effect size ($f = 0.25$) with a mixed design analysis of variance (ANOVA) (groups = 4; measurements = 4) to simulate analysis for the SLIFT tasks (i.e., 4 conditions) determined that an average of 9 participants per pain status by sex group was needed ($n = 36$). The medium effect size was based on a previous study utilizing a similar muscle sequencing dependent variable.

3.3 Instrumentation

3.3.1 Force Transducer

Prior to each participant entering their LAB session, a strain-gauge force transducer (MLP-250-CO, Transducer Technologies, Temecula, CA) was calibrated using two 5-second trials consisting of no weight attachment and then with a 100.2482 N weight, respectively. The transducer was sampled at 200 Hz and voltage outputs were amplified (Strain Gauge Conditioner 3270, Daytronic Corporation, Miamisburg, OH, USA) and analog-to-digital (AD) converted using a 16-bit AD card with a ±10 volt range.

3.3.2 Surface Electromyography

Before placing any electrodes on the participant, their skin was cleaned through light abrasion with a disposable cloth (Kimwipes, Kimberley-Clark Inc., Irving TX, USA) that was coated with an alcohol solution and shaved with a disposable razor. This procedure was done to minimize skin-electrode impedance and its potential to distort the EMG signals (Clancy et al., 2002).

Disposable silver/silver chloride electrodes (Blue Sensor, Medicotest Inc., Ølstykke, Denmark; Kendall Medi-Trace 130 Foam Electrodes, Medical Mart Supplies Ltd., Ontario, Canada; Dual Electrode #272, Noraxon, Arizona, USA). A bipolar electrode configuration was placed on the skin overlying the middle of the muscle belly of interest, with a 2 cm inter-electrode distance and in parallel with the direction of the muscle fibers. The reference electrodes were placed on top of a bony surface (i.e., lateral aspect of the 11^{th} or 12^{th} rib). All electrode placements were confirmed through palpation and manual resistance. A total of 8 channels of surface EMG was collected from the following bilateral muscles (Table 6): 1)

Lumbar Erector Spinae (LES), 2) External Oblique (EO), 3) Gluteus Medius (GMED), and 4) Gluteus Maximus (GMAX). The EMG signals were differentially amplified with a common-mode rejection ratio (CMRR) of 115 dB at 60 Hz (AMT-16, Bortec, Calgary, Canada; bandwidth = 10 - 1000 Hz; input impedance = 109 Ω). The analog EMG signals were gained by a factor of 500 to 15000 and customized to each participant's muscle activity during maximal voluntary isometric testing contractions (Table 6). Real-time visual feedback was used during this process for purposes of maximizing the input range of the analog signal into the A/D convertor without any signal distortion (Winter, 2009). The gained analog signal was sampled at 2000 Hz using a 16-bit analog-to-digital converter with a ± 2 V range.

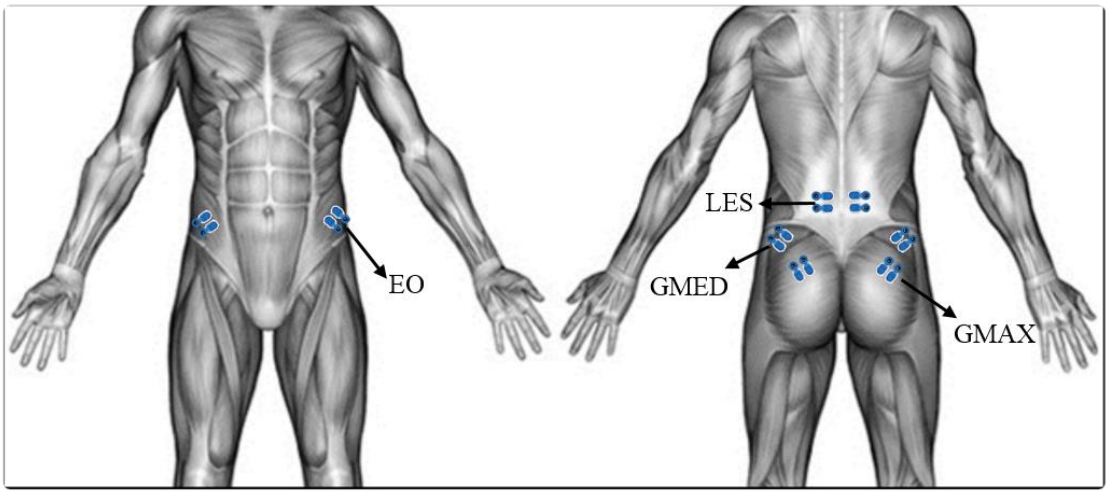


Figure 11 – Visual depiction of surface electrodes placement. For abbreviations, refer to Table 6.

Table 6 – Overview of description of muscles being collected, their corresponding maximal voluntary isometric contraction (MVIC) position, and electrode placement. (Adapted from Viggiani, 2015).

Muscle (Abbreviation)	Maximal Voluntary Isometric Contraction Positions	Electrode Placement
Upper Lumbar Erector Spinae (LES)	Biering-Sorensen position (Dankaerts et al., 2004)	Level of L3 spinous process and over the muscle belly (~3 cm lateral) (McGill, 1991)
External Oblique (EO)	Modified V-sit (Dankaerts et al., 2004; Danneels et al., 2001)	Approximately half the distance from the inferior rib cage and anterior-superior iliac spine, oriented along the line connecting the ipsilateral costal margin to the contralateral pubic tubercle Criswell, 2011; Ng et al., 1998)
Middle Gluteus Medius (GMED)	Clam Shell (Distefano et al., 2009); Side-lying hip abduction (Bolgla et al., 2008)	Approximately 1/3 the distance from the iliac crest (highest point) and greater trochanter, over the muscle belly (Bussey et al., 2016; Nelson-Wong & Callaghan, 2010b; O'Sullivan et al., 2010; Otten et al., 2014)
Gluteus Maximus (GMAX)	Biering-Sorensen position (Dankaerts et al., 2004) and prone hip extension with 90° knee flexion (McGill & Marshall, 2012)	Approximately half the distance from the sacrum and the greater trochanter (SENIAM, 1999); a location that does not overlap the innervation zone (Rainoldi et al., 2004)

To facilitate comparison of data across subjects and experimental conditions, the EMG signal for each muscle was normalized to their corresponding maximal voluntary isometric contraction (MVIC) (De Luca, 1997). Specifically, each MVIC for the corresponding muscle involved a five-second contraction. The initial three seconds involved an effortful ramp up to maximum perceived exertion, followed by maintaining their maximum perceived exertion of contraction for two seconds. A self-selected resting period or researcher-imposed resting period was allotted in between each MVIC for recovery (De Luca, 1997). The following tasks was used to elicit MVIC in the corresponding muscle(s) (also see Table 6):

1) Biering-Sorensen Test – The participant laid prone on top of a massage table. Their anterior superior iliac crests were positioned at the edge of the table. Their legs were secured, and their trunk was suspended over the edge of the table. With their arms crossed, the participant was asked to position their trunk in a flexed position. They were then instructed to begin extending their torso upwards and informed to continue extending once they encounter resistance. Once the participant's torso reached a parallel position, the experimenter applied resistance downwards onto the participant while they continued to extend with maximal effort.

2) Clam Shell – The participant was position in a side-lying position with their knees flexed to 90° and hips flexed to approximately 60°. They were then instructed to abduct their knees away from each other while keeping their feet together. The experimenter then applied resistance downwards onto the participant's knee at approximately 10-15° of abduction, while they continued to exert maximal effort.

3) Modified V-sit Test – The participant was positioned in a supine sitting position on top of a table with the trunk held in a 45° angle, knees flexed to 90°, and hands placed across their chest. They were then left unsupported and required to maintain their position and exert trunk rotation with manual resistance applied to their shoulders for maximal external oblique activation (Danneels et al., 2001).

4) Prone Hip Extension with 90° Knee Flexion – The participant performed separate trials for each leg. They were instructed to adopt a prone lying position with their knee bent to approximately 90 degrees. They were then instructed to "reach their foot towards the ceiling" while a trained researcher applied resistance to restrict further movement.

5) Maximum Side Lying Hip Abduction Strength Test – The participant was positioned on their side with their head relaxed on the hand of their supporting arm (Figure 12). Their uninvolved leg was fully extended and parallel to the leg being tested. The "test" leg remained extended and minimally abducted from horizontal. A strain-gauge force transducer (MLP-250-CO, Transducer Technologies, Temecula, CA) was tethered to the ground and connected to a strap that was fastened around their leg, positioned approximately 2 cm proximal from their lateral femoral condyle (Bolgla & Uhl, 2007; Marshall et al., 2011). The participant had their back and pelvis positioned against a solid wall to minimize any trunk or pelvic rotation. In addition, their bottom hand was positioned to "cup" their head and their top hand was placed flat on their stomach to avoid any compensations using their hand.

Figure 12 – Participant setup for performing Maximum Side Lying Hip Abduction Strength Test (left). Bird's eye view of participant's back and pelvis against the wall to minimize any pelvic rotation (right).

Lastly, a resting trial was collected with participants laying prone on a table to allow for removal of resting bias in EMG activity if required.

Regardless of the task performed, the highest measured voltage in any of the MVIC trials was used as a maximal value for the corresponding muscle after visual examination to ensure that the signal was not attributable to noise.

3.3.3 Motion Capture System

The 3-D kinematic data were sampled at 50 Hz, using an Optotrak® Certus optoelectronic motion capture system (Northern Digital Inc. (NDI), Waterloo ON, Canada). The motion capture system was composed of Optotrak® Certus and Optotrak® 3020 position sensors that were in a daisy-chained configuration and connected to the System Control Unit (NDI, Waterloo, ON, Canada). Each position sensor contains a 'bank' of three (McDowell et al., 2005) infrared detecting cameras to track the position of Optotrak® Smart Markers (termed IREDs or infrared emitting diodes) (NDI, Waterloo, ON, Canada). The operational

measurement volume of the multiple position sensors was calibrated prior to each collection with a 'cubic reference emitter' tool that is instrumented with sixteen IREDs on four sides of a rigid cube. The calibration process involved two components: 1) registration – a dynamic registration trial used for aligning the position sensors to a single global coordinate system (GCS), and 2) alignment – a static registration trial for establishing the origin of the GCS. The axes convention was in alignment with standards established by the International Society of Biomechanics (ISB) (Wu & Cavanagh, 1995), such that: 1) +X axis was directed anteriorly, 2) +Y axis was directed superiorly, and 3) +Z axis was directed laterally (to the right).

Following calibration procedures, motion of the trunk, pelvis, thighs, shanks, and feet were measured. This motion tracking was done by using clusters of three to six IREDs affixed to custom 3-D printed (Cubicon Single Plus; Hyvision System, Seongnam-si, Korea) thermoplastic (termed rigid bodies).

The rigid bodies were secured to the participant's skin overlaying the thoracic spine (level of T9), lumbar spine (level of L1), sacrum (level of S1), thighs (lateral aspect of femur), shanks (lateral aspect of tibia/fibula), and feet (anterolateral aspect of talus) (Figure 13). To minimize motion that occurs separately from the segment motion, the rigid bodies were secured to the participant with the use of double-sided tape (Scotch, St. Paul MN, USA; Roberts 50-605, Roberts Consolidated Industries Inc., Florida, USA), medical tape (Hypafix, BSN Medical, Hamburg, Germany), and Velcro® straps. The skin was covered with a layer of medical tape and then a layer of double-sided tape, to minimize effects of sweat altering the interface between skin and tape throughout the experimental protocol. The rigid bodies

were used to track the transformation of the body segment of interest. Additionally, by use of a four-marker probe, anatomically-meaningful segment endpoints (externally palpated by the researcher) were digitized to establish imaginary markers (NDI, Waterloo, ON, Canada). The rigid bodies were used to enable position measurement of imaginary markers (Table 7). This digitization process took place with the participant in a quiet standing posture.

Body segment definitions of proximal and distal endpoints for the rigid bodies are displayed in Table 7. The same researcher palpated the locations of anatomical landmarks of interest on each participant.

Table 7 – Segment name location of rigid body digitized landmarks. Adapted from Viggiani (2015).

Body Segment	Rigid Body Location	Anatomically Meaningful Segment Endpoints
Thoracic Spine (THX)	T9 Spinous Process	• Bilateral Acromion Processes • Lateral aspects of bilateral 12th Rib
Lumbar Spine (LUM)	L1 Spinous Process	• Lateral aspects of bilateral 12th Rib • Lateral aspects of bilateral Iliac Crests
Pelvis (PEL)	S1 Spinous Process	• Bilateral Anterior Superior Iliac Spine • Bilateral Posterior Superior Iliac Spine
Left Thigh (LTH)	Lateral Aspect of Femur	• Left Greater Trochanter • Medial and Lateral Femoral Condyles of Left Femur
Right Thigh (RTH)	Lateral Aspect of Femur	• Right Greater Trochanter • Medial and Lateral Femoral Condyles of Right Femur
Left Shank (LSH)	Lateral Aspect of Tibia/Fibula	• Medial and Lateral Tibial Condyles of Left Tibia • Medial Malleolus • Lateral Malleolus
Right Shank (RSH)	Lateral Aspect of Tibia/Fibula	• Medial and Lateral Tibial Condyles of Right Tibia • Medial Malleolus • Lateral Malleolus
Left Foot (LFT)	Anterolateral Aspect of Talus	• Medial Malleolus • Lateral Malleolus • Calcaneal Tuberosity • 5th Metatarsal • 1st Metatarsal • Anterior Aspect of 1st Distal Phalanx (Big Toe)
Right Foot (RFT)	Anterolateral Aspect of Talus	• Medial Malleolus • Lateral Malleolus • Calcaneal Tuberosity • 5th Metatarsal • 1st Metatarsal • Anterior Aspect of 1st Distal Phalanx (Big Toe)

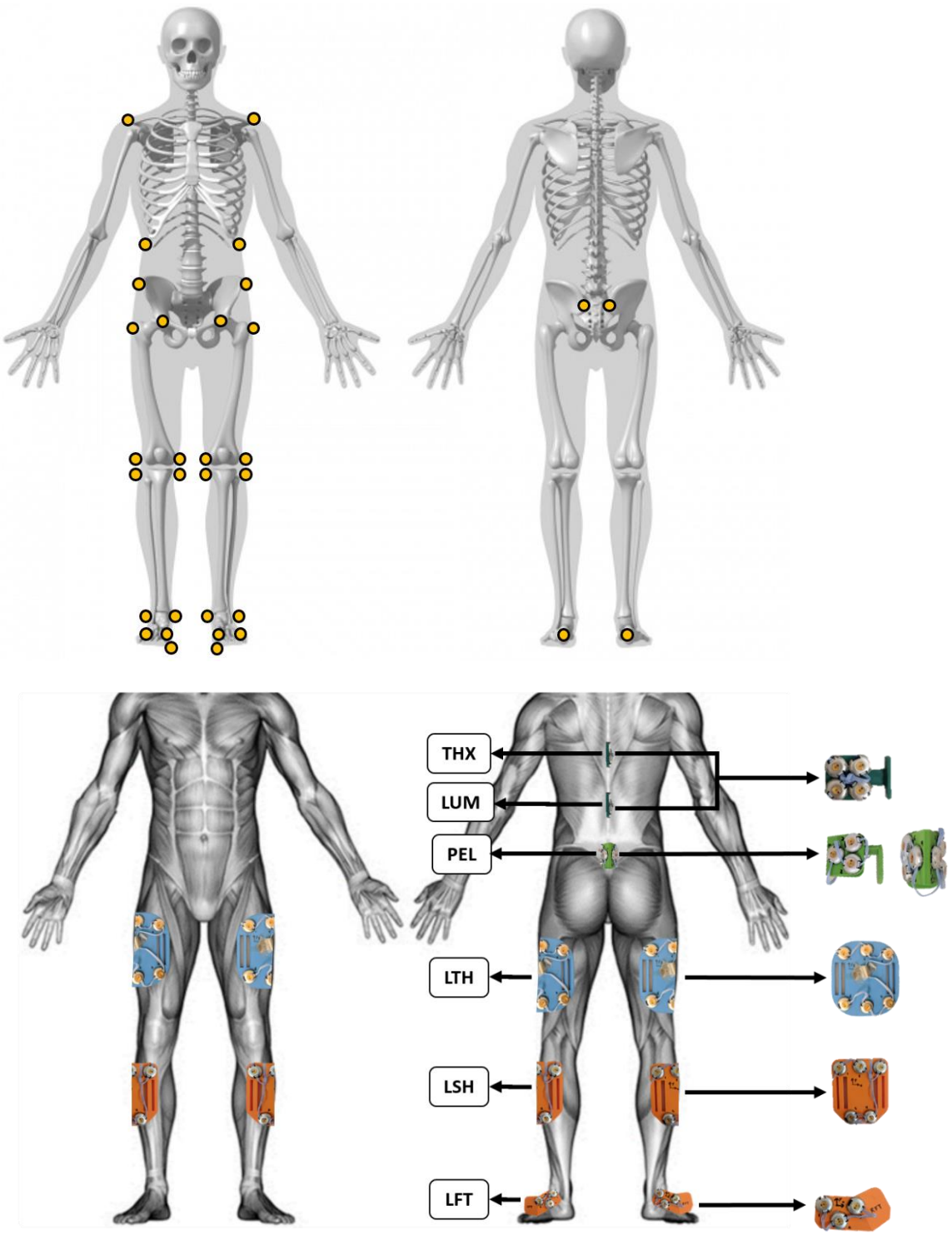


Figure 13 – Visual depiction of: 1) imaginary marker locations (top) and 2) rigid body cluster placements for the first part of the LAB session (bottom). For abbreviations, refer to Table 7.

Once instrumentation was complete, a static standing trial of each participant was collected to define 'neutral' joint angles (i.e. zero degree). This static standing trial involved participants being instructed to "stand quietly and face forward". Additionally, participants performed a series of maximal range of motion trials for the following planes of motion of the lumbar spine: flexion, extension, lateral bending, and twisting. Furthermore, participants performed a series of dynamic rhythmic movement trials with moderate ranges (Camomilla et al., 2006; Kainz et al., 2015) about their hip joint in the following planes of motion: flexion/extension, abduction/adduction, clockwise circumduction, and counter-clockwise circumduction. These dynamic movements enabled predictive calculations of individual hip joint centers of location with respect to their pelvis to enable calculation of the femoral coordinate system (Wu et al., 2002). This process was done in Visual3D™ Professional (ver. 6.0.24, C-Motion Inc., Germantown MD, USA) using a "functional" approach (Schwartz & Rozumalski, 2005; Wu et al., 2002). Sampling rate was set at 50 Hz for the motion capture system.

3.3.4 Video Camera

An action camera (EKEN H9R 4K, Shenzhen, China) was used to record the performance of participants' active hip abduction. The action camera was positioned on a pole above the participant to capture their frontal plane with focus on the lumbopelvic region of the participant.

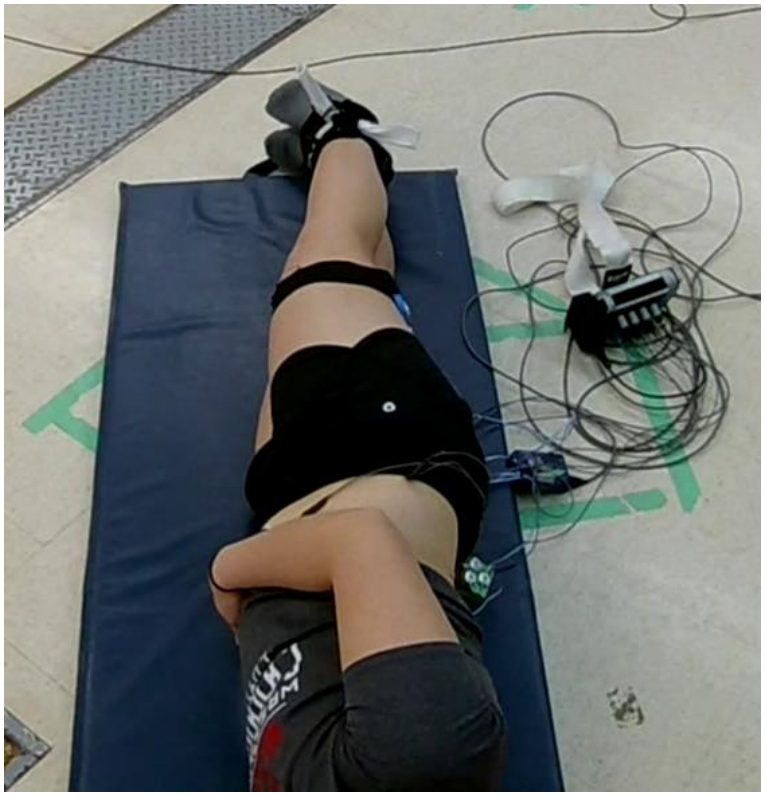


Figure 14 – The action camera's visual depiction of a participants' starting position during the active hip abduction

3.4 Experimental Protocol

Each participant was invited to go through two sessions (Figure 15) in a span of two nonconsecutive days: 1) a pain status categorization (CAT) session (Figure 16), and 2) a laboratory assessment (LAB) session (Figure 17). The CAT session involved the participant performing a single bout of prolonged standing for two consecutive hours with minimal instrumentation. Participants then underwent the laboratory assessment protocol (LAB) with full instrumentation on a different day.

3.4.1 Categorization Session

The first session involved participants being introduced to the prolonged standing protocol (PSP) by the researcher. Once informed consent was provided by each participant, they were given a brief orientation to rules during the PSP and asked to fill out a baseline rating of their all the body regions (outlined in 3.4.1.1) on a 100-mm VAS. Participants then filled out a series of questionnaires related to their general physical health, physical activity levels (3.4.1.1), psychological beliefs regarding pain (3.4.1.3, 3.4.1.4), and ankle instability (3.4.1.5).

Once the questionnaires were completed, participants then performed prolonged standing for two continuous hours. The standing workstation was adjusted to 5 cm below the underside of the olecranon when their elbows were placed at 90 degrees, which is the position most favorable for handwork while standing (Kroemer & Grandjean, 1997, p.46-47). They were then instructed to stand “in their usual manner as if they were standing for an extended period” (Nelson-Wong & Callaghan, 2010a) and then began to perform a two-hour PSP.

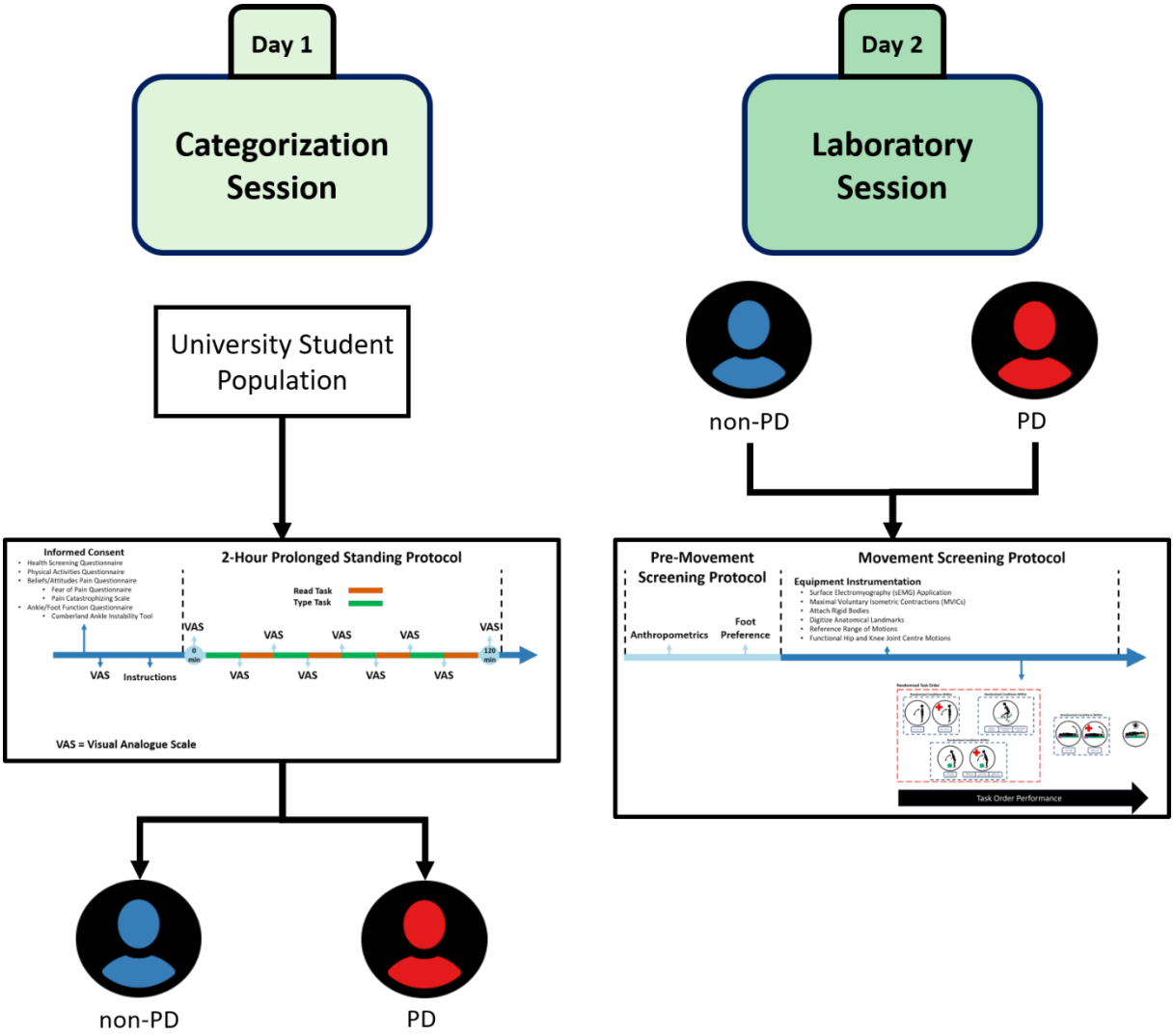


Figure 15 – Outline of experimental protocol. Participants underwent two different sessions on separate days. The first session, categorization session (CAT), consisted of participants performing a prolonged standing protocol with minimal equipment and only self-reports of VAS being collected. The second session, laboratory assessment (LAB), had participants perform the various tasks with instrumentation.

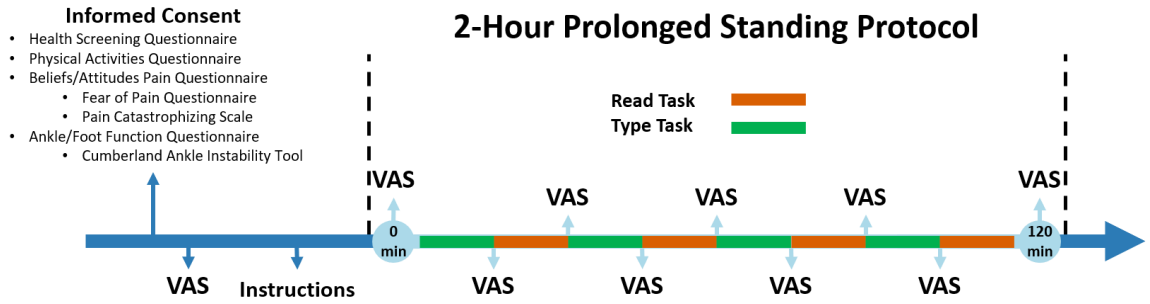


Figure 16 – Timeline and corresponding components during the categorization session. VAS = Visual Analogue Scale

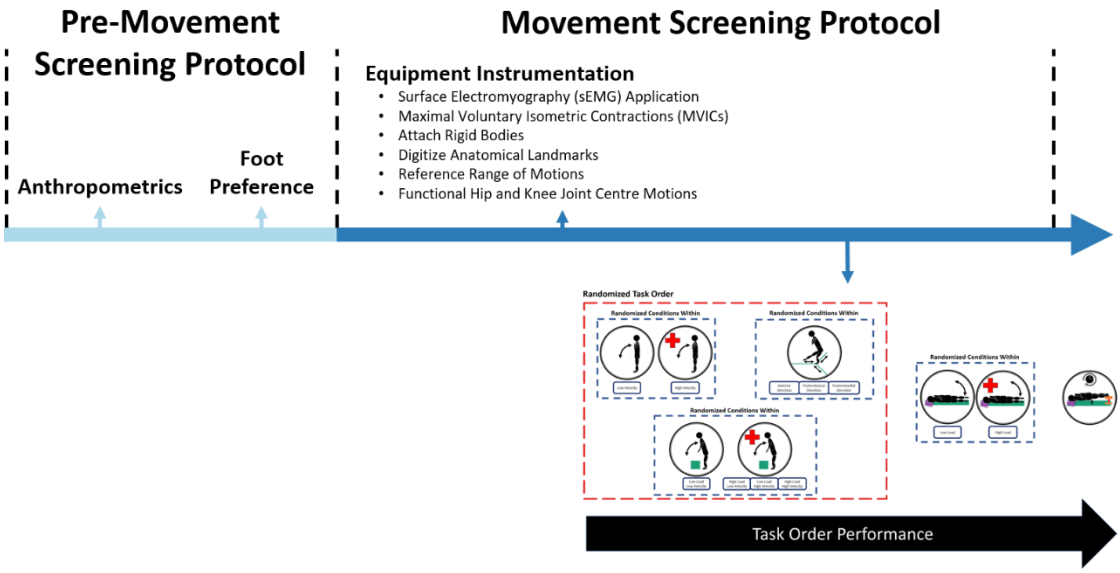


Figure 17 – Timeline and corresponding components during the laboratory session

The brief orientation consisted of the participants to perform and adhere to the following guidelines:

1) Stand in the confined working area (0.50 m x 0.46 m) (Gregory & Callaghan, 2008; Marshall et al., 2011) marked on a thin plastic film that is adhered to the ground and do not let your feet leave the area
2) Not allowed to lean or distribute/support their weight on the workstation with their upper or lower extremities (Nelson-Wong & Callaghan, 2010a)
3) Not allowed to cross your legs or feet during the PSP
4) No bathroom breaks during the PSP. Participants required to go to the bathroom during the PSP will restart the PSP from the beginning or be asked to return another day if timing does not permit
5) No social media or smartphone use
6) Perform reading, typing, and form filling tasks only throughout the PSP
7) Rate their level of pain for a corresponding bodily region on the 100-mm VAS every 15 minutes throughout the PSP and at the end of the PSP (Nelson-Wong et al., 2008)

A total of 10 VAS scores for each participant was accumulated. Participants were classified into PD or non-PD groups based on their maximum reported VAS scores in the depicted body regions (Figure 18). Participants were categorized into PDs if they reported LBP VAS scores of $\geq$ 10 mm. This tool and threshold have been used previously by

laboratory investigations on prolonged standing and LBP development (Nelson-Wong et al., 2008; Viggiani & Callaghan, 2016). Once their pain status was determined, they were recruited to take part in the LAB session.

3.4.1.1 Visual Analogue Scale

A visual analog scale (VAS) was used to assess subjective pain reports by the participants. The VAS consisted of a 100 mm horizontally oriented line (Scott & Huskisson, 1979), with ends labelled "no pain" (located at 0 mm) and "worst pain imaginable" (located at 100 mm) (Hägg et al., 2003; Kelly, 1998). Body regions that were assessed included the following: low back, right gluteal, and left gluteal (Figure 18). Participants were required to indicate their perceived level of pain on the 100 mm line for each body region of interest.

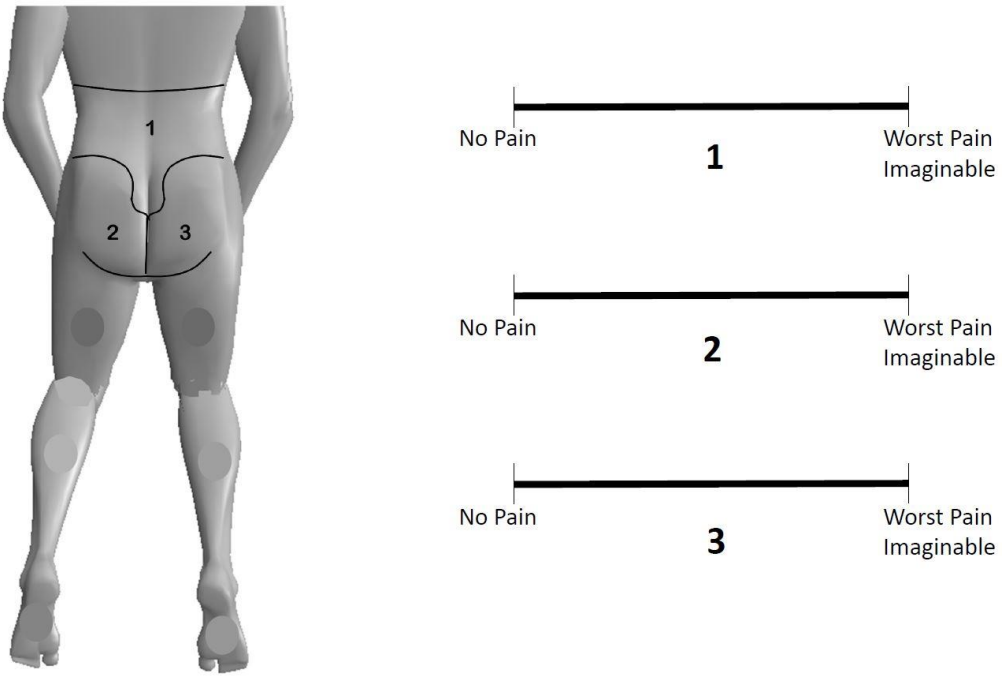


Figure 18 – An example visual analogue scale (VAS) with the body regions assessed (VAS lines not printed to scale)

3.4.1.2 Modified Minnesota Leisure-Time Physical Activity Questionnaire

Originally based on the longitudinal Minnesota Leisure-Time Physical Activity Questionnaire (MPAQ) (Taylor et al., 1978) that assessed physical activity in North American adults, the modified Minnesota Leisure-Time Physical Activity Questionnaire (mMPAQ) was used to assess an individual's self-reported leisure time physical activity in the preceding 4-months from their first collection date (Nelson-Wong, 2009). Briefly, the individual indicated which physical activity they participated in on the questionnaire within the past 4 weeks. Then the primary investigator further inquired about the frequency and duration of each activity (Taylor et al., 1978). Each activity possessed a corresponding metabolic rate. Using the aforementioned rates, an activity metabolic index was calculated for each participant to reflect their estimated total energy expenditure.

3.4.1.3 Fear of Pain Questionnaire III

The Fear of Pain Questionnaire III (FPQ-III) was curated to assess an individual's self-reported pain and fear relationships associated with potentially confronting various types of clinical and non-clinically relevant painful stimuluses (McNeil & Rainwater, 1998). The FPQ-III involved 30 questions with 5 optional ratings for the amount of fear one would experience when faced with a specific situation. Each response corresponded to a number between 1 ("Not at All") and 5 ("Extreme"). The FPQ-III produced a total score lying between 30 to 150, with higher scores indicating higher fear of pain (McNeil & Rainwater, 1998). Despite subscales (i.e., minor, severe, and medical pain subscales) present in the FPQ-III, only the total score was initially analyzed for this study.

3.4.1.4 Pain Catastrophizing Scale

The Pain Catastrophizing Scale (PCS) was used to assess an individual's self-reported cognitive state in response to real or imagined painful stimuli that they may or may not have experienced (Sullivan, 2009; Sullivan et al., 1995). The PCS required the individual to indicate the intensity of one of the 13 thoughts or feelings experienced during pain with 5 optional ratings ranging from 0 ("Not at All") to 4 ("All the Time") (Sullivan, 2009; Sullivan et al., 1995). The PCS produced a total score ranging from 0 to 52, with higher scores reflecting greater catastrophizing thoughts (Sullivan, 2009; Sullivan et al., 1995). Despite, subscales (i.e., helplessness, magnification, and rumination) present in the PCS, only the total score was initially analyzed for this study.

3.4.1.5 Cumberland Ankle Instability Tool

One of the recommended questionnaires for assessing self-reported chronic ankle instability (Gribble, Delahunt, et al., 2013), the Cumberland Ankle Instability Tool (CAIT) was developed to assess an individual's functional ankle instability (Hiller et al., 2006). The CAIT consists of nine questions that assesses one's difficulty with a specific physical activity by using a range of 3-6 responses for each question. The CAIT produces a total score ranging from 0 to 30, with a lower score suggesting a greater degree of ankle instability (Hiller et al., 2006).

3.4.2 Laboratory Assessment Session

The laboratory assessment session (LAB) assessed a single participant at a time. The participant was provided a brief orientation of the procedures during the LAB.

3.4.2.1 Pre-Movement Screening Protocol

Prior to movement screening, the participant's height, mass, and shoulder width (acromion to acromion) were measured in a quiet standing position.

Upon completing the measurements, the participant underwent an inventory of adapted tasks from Chapman et al. (1987) to determine their foot preference. The tasks consisted of the following: 1) kick a soccer ball, 2) write their name "in sand" on the floor, and 3) after writing their name, try to erase it or smooth the "sand" (Chapman et al., 1987). For 1), the soccer ball was placed in the center of the distance between their feet to minimize any potential bias of limb choice based on proximity (Chapman et al., 1987; Viggiani, 2015). The leg used for two of the three tasks was determined as the participant's foot preference.

3.4.2.2 Movement Screening Protocol

The participants were then instrumented with surface EMG electrodes and rigid bodies. They underwent a series of MVICs (3.3.2), maximal range of motion trials (3.3.3), and dynamic rhythmic movement trials (3.3.3). Given the logistic constraints of the tasks, a completely randomized design was not used. Instead, participants performed the first part of tasks (Table 8) in a restricted randomized order (Figure 19). Briefly, the Symmetric Trunk Flexion-Extension (STF), Symmetric Floor-to-Knuckle Lift (SLIFT), and Modified Star Excursion Balance Test (mSEBT) were performed in a randomized order. Furthermore, the conditions within each task was also randomized (Figure 19).

After the first part was completed, the lumbar and thigh clusters were reoriented. The thorax, shank, and foot clusters were removed (Figure 20). The participant then underwent a second digitization process, followed by another set of functional hip joint trials. The Active Hip Abduction (AHA) test and then the Reverse Side Bridge (RSB) were performed (Figure 19).

The tasks chosen were based on two themes (refer to Chapter 1): 1) to implement tasks that have not been investigated in pain status groups and to assess their movement competency by characterizing differences in 'risky' kinematic variables that are associated with non-contact musculoskeletal injuries; and 2) to expand upon previous reports of neuromuscular control differences in the lumbopelvic and hip regions and to impose varied and/or greater challenge within these regions in pain status groups. The presence of these differences may suggest PDs to be a 'high risk' group for non-contact musculoskeletal injury, enable improved stratification, and further support pre-existing neuromuscular control differences within the lumbopelvic region and hip musculature that were previously observed between pain status groups.

The task descriptions are located in Table 8 and Table 9 and the task instructions are presented in Appendix B – Task Instructions. Briefly, feedback was provided after each trial on a need-to-know basis for the purpose of standardized task performance across participants (e.g., lifting the heel of the stance limb during the mSEBT is not allowed). The amount of feedback was limited to a single error at a time. This feedback method was used, as prior research has shown that novice performers have difficulty understanding and recalling greater than five to nine verbal instruction items (Williams & Hodges, 2012). In addition, the

feedback was also prioritized with respect to importance of task performance, if applicable (Williams & Hodges, 2012). Although not entirely feasible, many of the provided cues relied on an external focus as opposed to an internal focus of attention in order to facilitate the participants' use of their "unconscious or automatic processes" rather than using an internally focused cue that may lead to "more conscious type of control" that may disturb the aforementioned automatic processes (Williams & Hodges, 2012; Wulf et al., 2010).

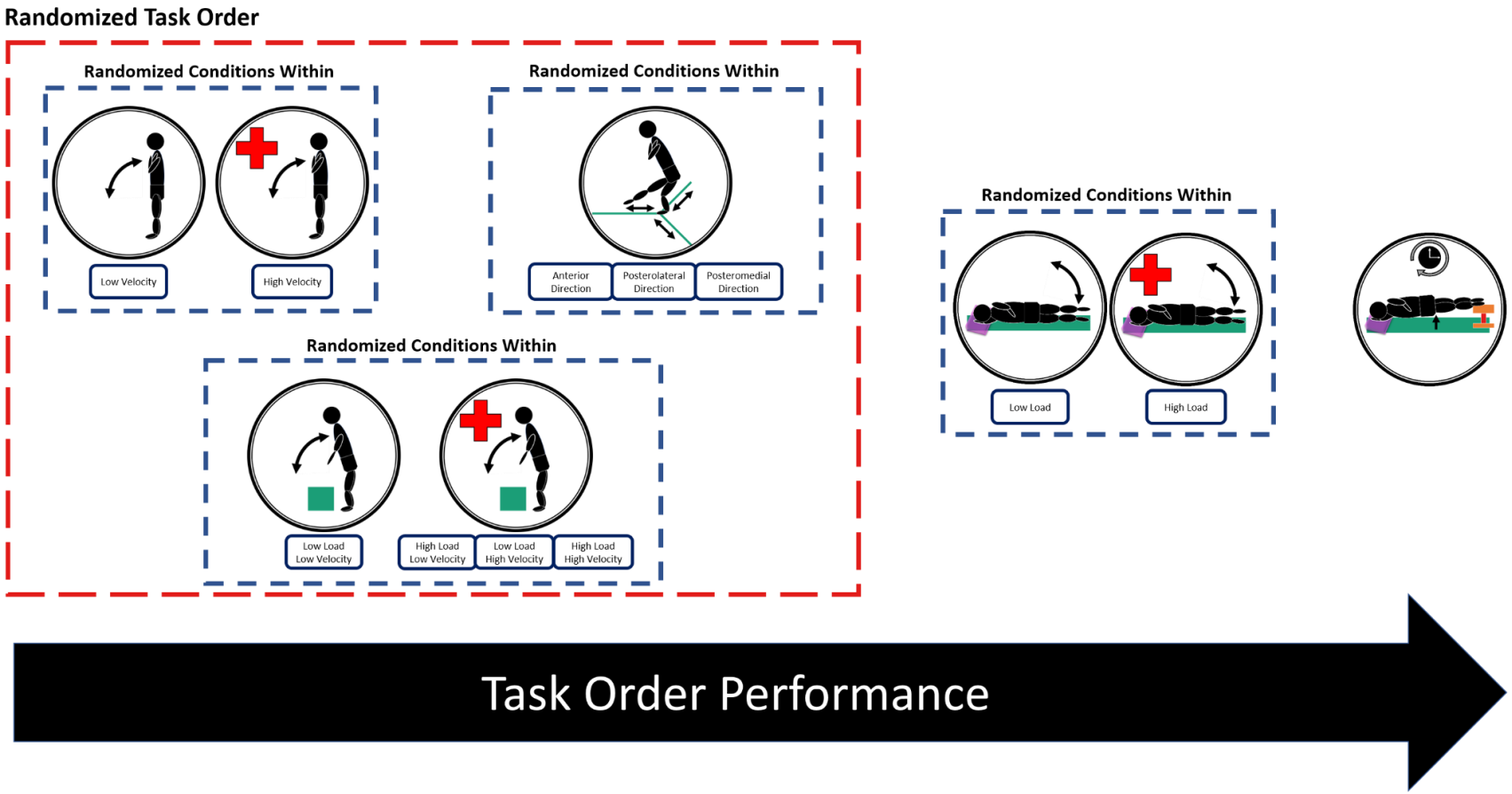


Figure 19 – Overview of task order performance with depiction of task order and randomization during the laboratory session.

Note: Although it was not depicted, whether the task began with the left or right side was also randomized within each task.
LV = Low Velocity (i.e., self-selected speed); HV = High Velocity (i.e., maximum speed)

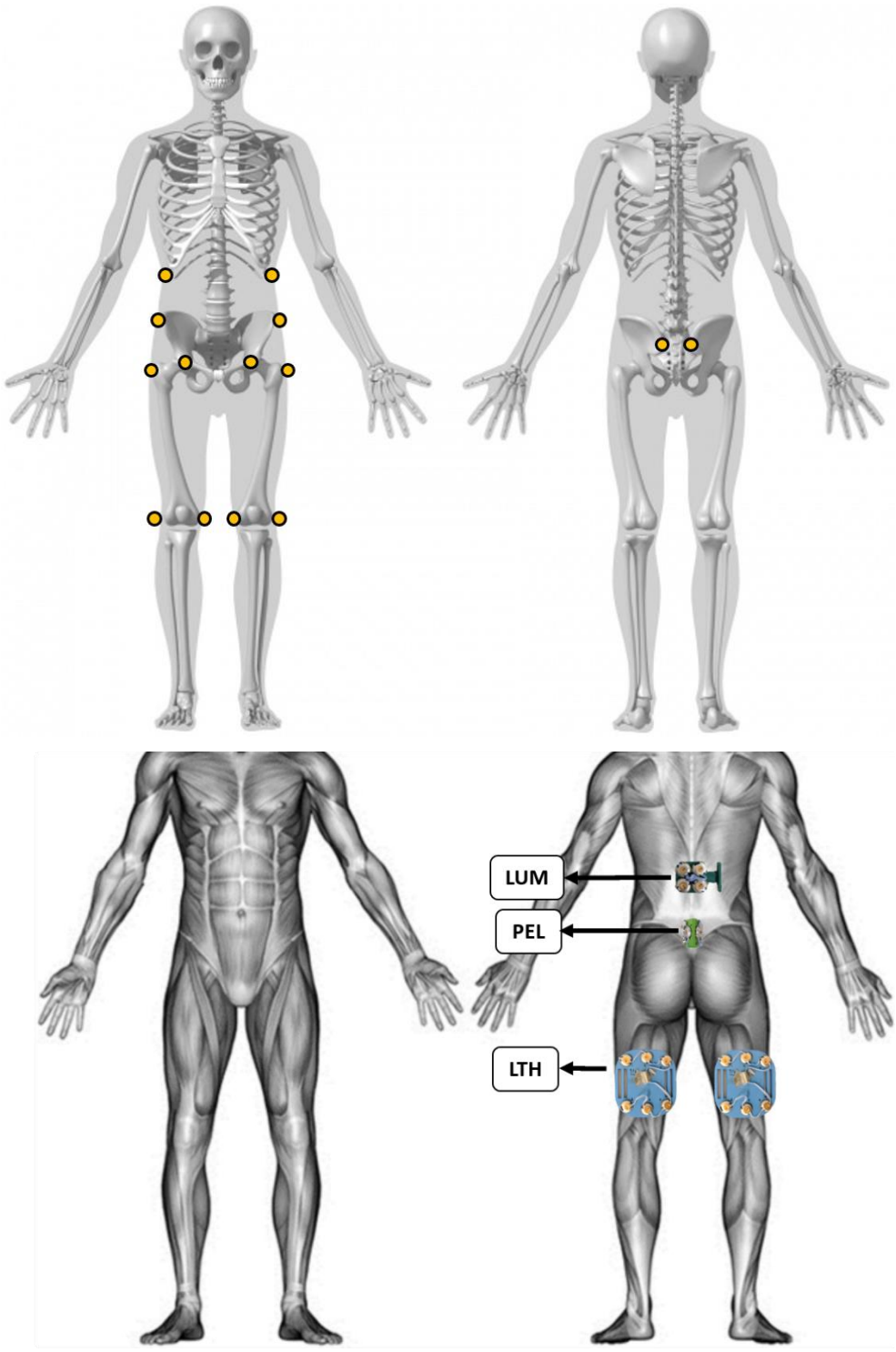


Figure 20 – Visual depiction of: 1) imaginary marker locations (top) and 2) rigid body cluster placements for part 2 of movement tasks during the LAB session (bottom). For abbreviations, refer to Table 7.

Table 8 – List of low-demand challenges and their corresponding task descriptions. SS = Self-selected; RI = Researcher-imposed

Low-Demand Challenge	Task Description	Number of Repetitions	Number of Practice Trials	Resting Time Provision
AHA	Each participant began in a side-lying position on a 1.5-inch vinyl-covered foam mat with lower extremities straight and aligned with the torso (Nelson-Wong et al., 2009). Their performance was video recorded using an action camera. The pelvis was positioned so that it was in the frontal plane and perpendicular to their support surface. They were then instructed to perform a single active abduction of the top thigh (i.e., the testing limb) towards the ceiling and up to a certain height, while maintaining the knee in extension and the lower limb aligned with the trunk and pelvis.	1 on each side	None; testing limb was passively raised to approximate desired height	SS or RI
SLIFT	Each participant was standing in front of an empty crate (33 cm x 33 cm x 28 cm). They will then be instructed to grasp the crate, lift it off the ground, pause, and then place it back down on the ground. Participants were instructed to utilize their "natural lifting technique" or their preferred strategy to perform the lifting task.	3	SS	SS or RI
STF	Each participant was instructed to stand with their feet shoulder width apart and their arms across their chest. They were then instructed to flex and extend their trunk at a self-selected speed in the sagittal plane with their knees straight throughout (Ferguson & Marras, 2004).	3	SS	SS or RI

Table 9 – List of high-demand challenges and their corresponding task descriptions. SS = Self-selected; RI = Researcher-imposed

High-Demand Challenge	Task Description	Number of Repetitions	Number of Practice Trials	Resting Time Provision
AHA+	Identical to AHA, along with 10 pounds strapped to their ankle of the testing limb.	1 on each side	None; testing limb was passively raised to approximate desired height	SS or RI
SLIFT+	Similar to the SLIFT, along with performing the task with their maximum speed that can be comfortably managed and/or with increased mass of the crate.	3	SS	SS or RI
mSEBT	Each participant stood at the center of an intersection of three lines that resemble the letter "Y". The three lines are positioned relative to the testing leg and corresponded to three reach directions: anterior, posteromedial, and posterolateral. Participants were instructed to position their hands across their chest and to reach as far as they possibly can with their non-stance leg in the direction they are being tested in. They were asked to lightly touch the line with their big toe and return their non-stance leg back to the center while continuing to maintain their balance (Lieshout et al., 2016).	3 in each direction	4 in each direction; given its learning effect (Hertel et al., 2000)	SS or RI
RSB	Each participant began in a side-lying position (Tvrdy, 2012). A pillow was used to rest their head and shoulder. For standardizing purposes, their feet (level of the malleolus) was placed on top of a board that has been set to half of the participant's shoulder width. The end of the test was designated with when the participant's hip returned to contact the floor (McGill et al., 1999).	1 on each side	None; just familiarization with position was enabled	$\geq$ 5 min
STF+	Similar to the STF, but with their maximum speed that can be comfortably managed.	3	SS	SS or RI

3.5 Data Analysis and Signal Processing Procedures

All signal and data processing were performed with custom-written functions/scripts within MATLAB software (version 2016a, The Mathworks Inc., Natick MA, USA) and Visual3D™ Professional (ver. 6.0.24, C-Motion Inc., Germantown MD, USA).

3.5.1 Visual Analogue Scale

Participants who reported a non-zero Visual Analogue Scale (VAS) score immediately prior to beginning the PSP had this value removed as a bias from their remaining VAS scores collected in order to ensure that VAS score changes were a result of the standing protocol (Nelson-Wong, 2009). The peak VAS score from each of the three body regions was extracted for each time point in each subject. The peak VAS score from the entire prolonged standing protocol was used to categorize PDs and non-PDs.

3.5.2 Questionnaires

The group mean scores for PDs and non-PDs in each of the questionnaires administered were compiled and analyzed.

3.5.3 Force Transducer

Force transducer data collected were digitally low-pass filtered (Butterworth, 2nd order, dual-pass) with a cut-off frequency of 6 Hz (Viggiani, 2015; Winter, 2009).

3.5.3.1 Hip Abductor Strength

Strength was represented by mean peak torque normalized to body mass for each participant. Specifically, the mean of each participant's maximal isometric hip abduction force trials for left and right side was multiplied by their limb's femur length (i.e., calculated from functional hip joint centre to digitized lateral femoral condyle during standing

calibration trial; only right femur length was used for both sides) to obtain hip abductor torque (N·m) and then divided by their body mass (kg) to determine their body mass normalized hip abductor torque (Bolgla et al., 2008).

3.5.4 Surface Electromyography

The maximal amplitude measured during the MVIC trials for any given muscle was used as the reference peak amplitude for normalization. The digital EMG signal was processed in the following order to enable further analyses:

1) Systematic bias was removed (i.e., detrended)
2) Electromagnetic noise component (60 Hz) was removed using a 59-61 Hz band-stop filter (Mello et al., 2007; Nelson-Wong et al., 2012)
3) Heart muscle electrical activity (ECG) contamination removed from EMG trials by applying a digital high-pass filter (Butterworth, 4^{th} order, zero-lag filter; dual-pass creates a fourth-order filter with zero phase shift) at a 30 Hz cut-off frequency (Drake & Callaghan, 2006; Redfern et al., 1993)
4) Full-wave rectified and application of a digital low-pass filter (Butterworth, 4^{th} order, dual-pass filter) at a cut-off frequency of 2.5 Hz (Appendix E – Previous Study EMG Frequency Cutoffs) (Brereton & McGill, 1998). A 6 Hz cut-off was used for analyses on EMG trials for percent MVIC analyses.

3.5.4.1 Cross Correlation

Cross-Correlation (CC) was used to identify the spatial and temporal similarity between two time-varying signals, x(t) and y(t) (Nelson-Wong, Howarth, et al., 2009;

Winter, 2009). This method has previously been performed by numerous studies (Nelson-Wong & Callaghan, 2010b; Nelson-Wong et al., 2008, 2012; Nelson-Wong, Howarth, et al., 2009). Specifically, CC determined the relative sequencing/timing information between two physiological (i.e., EMG) signals from two different muscle groups. Concisely, this process involves having one signal held stationary while the second signal is incrementally shifted forwards and backwards in time against the stationary signal (Nelson-Wong, Howarth, et al., 2009). This is completed along the entire length of the signal. Each increment produced a spatial correlation value (Rxy) of the input signals at each time shift (denoted by symbol τ) (Nelson-Wong et al., 2012). The resulting outcome is a cross correlation function Rxy(τ) and a third signal that consists of time series data of correlation values that corresponds at each unit of time or phase shift.

The digital implementation of the cross-correlation function is:

$$R_{xy}(\tau) = \frac{\frac{1}{N}\sum_{i=1}^{N}(x_i - \bar{x})(y_{i+\tau} - \bar{y})}{\frac{1}{N}\sqrt{\sum_{i=1}^{N}(x_i - \bar{x})^2 \sum_{i=1}^{N}(y_i - \bar{y})^2}}$$

Equation 1 – Cross-Correlation Digital Implementation (Nelson-Wong, Howarth, et al., 2009)

Where N is the number of data points in the input signals, the numerator is the sum of the product of the deviations of the time-varying signals, τ is the discrete temporal phase shift, and the denominator is the square root of the product of the sum of squared deviations of the two signals. The phase lag between two signals is represented by the τ value with maximum spatial correlation (Nelson-Wong et al., 2012; Nelson-Wong, Howarth, et al., 2009).

3.5.4.1.1 Symmetric Trunk Flexion-Extension and Symmetric Floor-To-Knuckle Lifting

Cross-correlation was used to determine relative muscle sequencing relationships between the ipsilateral (i.e., right and left sides) LES and GMAX muscles during extension from terminal torso flexion (Nelson-Wong et al., 2012). This analysis was done on both the STF and SLIFT tasks. The cross-correlation in the STF started from the participant's terminal trunk flexion position to their upright position. The cross-correlation in the SLIFT started from the participant's terminal trunk flexion position to their upright position with the crate in their hands. For each of the muscle pairings, the phase lag corresponding to the maximum Rxy calculated was recorded for further analysis (Nelson-Wong et al., 2012). The maximum τ value permissible was within a window of -500 ms $\geq \tau \leq$ 500 ms, as 500 ms was the assumed threshold based on previously observed activation timing between paraspinal muscles during gait (Nelson-Wong, 2009; Nelson-Wong et al., 2012; Nelson-Wong, Howarth, et al., 2009).

3.5.4.2 Median Power Frequency

Many different EMG indices have been used to determine the development of fatigue (Mannion & O'Riordan, 2012). However, of the EMG indices, the decrease in mean power frequency (or centroid frequency) (MPF) and median power frequency (MdPF) slopes of the power spectrum is highly correlated with sustained isometric contraction endurance time to exhaustion (Hagberg, 1981) and with metabolite build-up in development of muscle fatigue (Bouissou et al., 1989; Mannion & O'Riordan, 2012; Vestergaard-Poulsen et al., 1992). Some have found MPF to be the "best estimator" of spectral EMG changes since it was the most reliable measure of spectral shifts with low variability (Hary et al., 1982). In contrast,

MdPF has been preferred because it is less sensitive to noise, signal aliasing, and more sensitive to the fatigue-related physiological and biochemical changes (De Luca, 1997). A neutral view has been described to find "virtually no difference in these two frequency measures and their correlations with independent measures of fatigue" (Kerr and Callaghan, 1999; as cited by Winter, 2009). Despite conflicting views on which measure is best, MdPF was used in this study to enable comparisons with work by Marshall et al. (2011).

3.5.4.2.1 Reverse Side Bridge

Start and end of the trials were determined using the motion capture system. The raw digital EMG signal from the ipsilateral muscles of the side being tested during the reverse side bridge was directly inputted into a Discrete Fourier Transform (DFT) after the signal was conditioned to remove the bias and any ECG contamination. The MdPFs were calculated by using a Hamming Window function over 500 millisecond windows throughout the trial. The calculated MdPFs were then used in a linear regression analysis to predict the slope of the regression line (i.e., rate of muscle fatigue) over the entire trial (Marshall et al., 2011).

3.5.5 Motion Capture System

Kinematic data from Optotrak Certus® were imported into and processed using Visual3D™ software (Version 6.0.24, C-Motion, Inc., Germantown, MD, USA). Missing data points within collected data were cubic spline interpolated (if need be, up to 200 ms and then visually inspected; Howarth & Callaghan, 2010) and digitally low-pass filtered (Butterworth, 2nd order, dual-pass) with a cut-off frequency of 6 Hz for all the trials in the upright position and 3 Hz for all the trials in the side lying position (i.e., for active hip abduction trials).

3.5.5.1 Movement Characterization

Computation of Cardan joint angles for all tasks (except AHA trials) was performed in Visual3D™, with a Z-X-Y Cardan rotation sequence (i.e. flexion-extension about the local z-axis, abduction/adduction about the x-axis, and axial twist about the y-axis). Joint angles were calculated using the orientation of the distal segment (e.g., lumbar) with respect to the proximal segment (e.g., pelvis).

Frost et al. (2015) delineated "risky" movement behavior as 'uncontrolled' (e.g., larger) spinal and frontal plane knee motions (Frost, Beach, Campbell, et al., 2015). These risky kinematic features throughout various whole-body movement patterns have been quantitatively assessed and adapted for use in this study.

3.5.5.1.1 Symmetric Trunk Flexion-Extension

Computational event detection commands were generated using custom-written MATLAB™ scripts. Specifically, motion of the thorax marker cluster's center of mass vertical position was used to indicate the frame number at which terminal trunk flexion occurred by computing the minimum value of the cluster position. Lumbar spine angles were computed with the lumbar marker cluster relative to the pelvis. Hip joint angles were computed with the thigh marker cluster relative to the pelvis. Knee frontal plane motion was computed relative to a body-fixed plane made using the corresponding hip joint, ankle joint and distal foot (Frost, Beach, Campbell, et al., 2015). Using the aforementioned methods, lumbar spine and hip joint angles were computed at terminal flexion to identify their contributions to terminal torso flexion range of motion (i.e., lumbar and hip joint angle

ratios) (Nelson-Wong et al., 2012). These angles were computed by direct subtraction of joint angles during the standing calibration trial relative to their terminal torso flexion.

Lastly, angular velocity was calculated in Visual3D throughout the trial. The peak thorax relative to pelvis angular velocity during the extension phase of each trunk flexion-extension trial was determined (Nelson-Wong et al., 2012).

3.5.5.1.2 Symmetric Floor-To-Knuckle Lifting

Computational event detection commands were generated using custom-written MATLAB™ scripts. Specifically, motion of the thorax marker cluster's center of mass vertical position was used to indicate the frame number at which terminal trunk flexion occurred by computing the minimum value of the cluster position. This value was assumed to be the moment prior to the participant picking up the crate. Sagittal plane lumbar spine angles were computed with the lumbar marker cluster relative to the pelvis. Knee frontal plane motion was computed relative to a body-fixed plane made using the corresponding hip joint, ankle joint and distal foot (Frost, Beach, Campbell, et al., 2015). Using the aforementioned methods, lumbar spine angles were computed at terminal flexion to identify their contributions to terminal torso flexion range of motion. This angle was computed by direct subtraction of joint angles during the standing calibration trial relative to their terminal torso flexion.

Peak frontal plane knee excursion was quantified from upright standing to lifting the crate from the floor-to-knuckle height.

3.5.5.1.3 Modified Star Excursion Balance Test Reach Distances

The reach distance for a trial was quantified at the frame by which the big toe of the reaching limb made contact with the ground (Figure 21 and Figure 22). The ground contact was visually determined for each trial in each direction for each subject using the aforementioned method (Figure 22) and then visually inspected using a 3-D scatterplot (Figure 23). The 3-D vector length was then calculated in the following manner (Gribble, Kelly, et al., 2013):

a) Anterior (ANT) Reach Direction: the distance from left 1st metatarsal to the right 1st metatarsal was calculated (Figure 23)

b) Posterolateral (PLAT) and Posteromedial (PMED) Reach Directions: the distance from the stance limb calcaneal tuberosity to the reaching limb 1st metatarsal was calculated

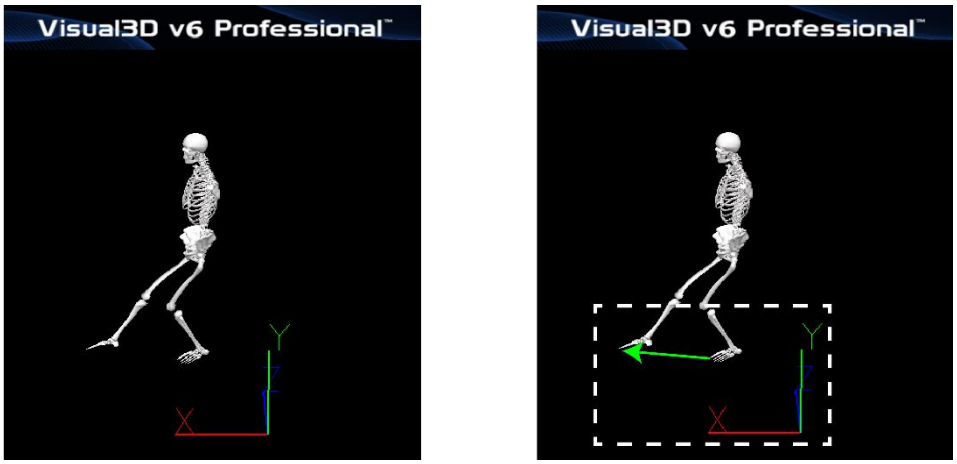


Figure 21 – Visual representation of segment link model for subject 36 making contact with the ground with the big toe of their reaching limb (i.e., right foot) during the anterior reach of the mSEBT. Image on the right represents the reference for the 3-D scatterplot constructed in Figure 23.

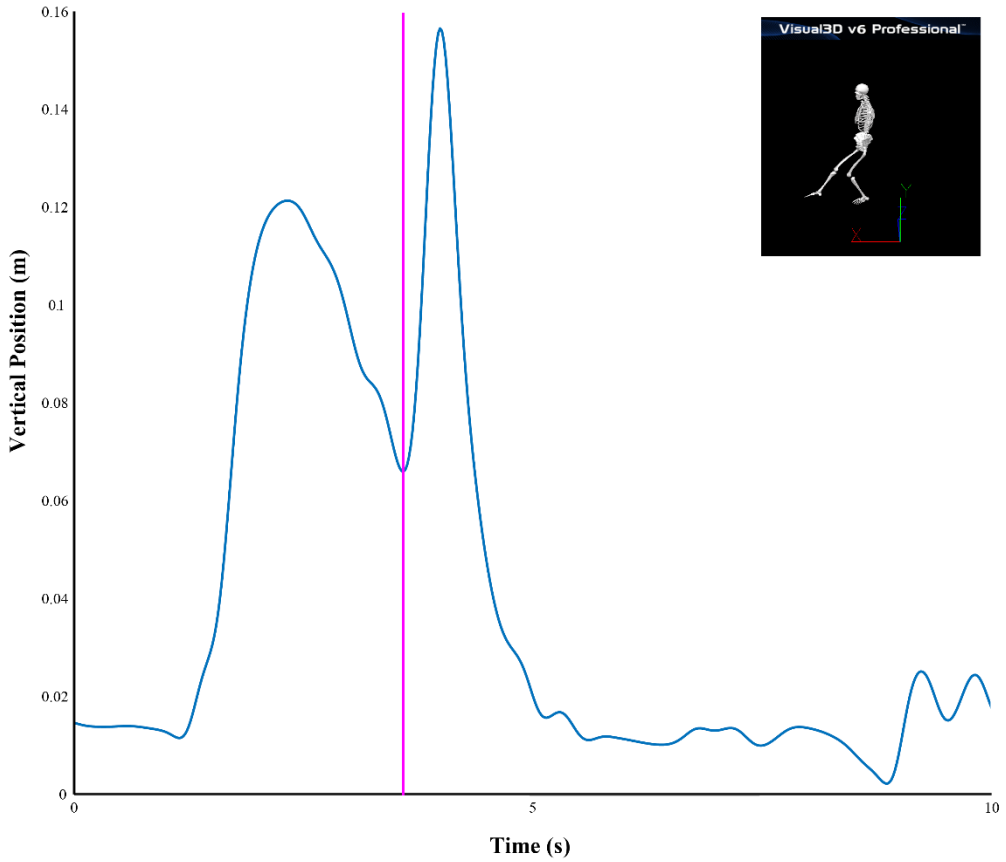


Figure 22 – Visual representation of the vertical position of subject 36's big toe of the reaching limb during the anterior reach of the mSEBT. The vertical line represents the manually selected local minimum representing the big toe making contact with the ground.

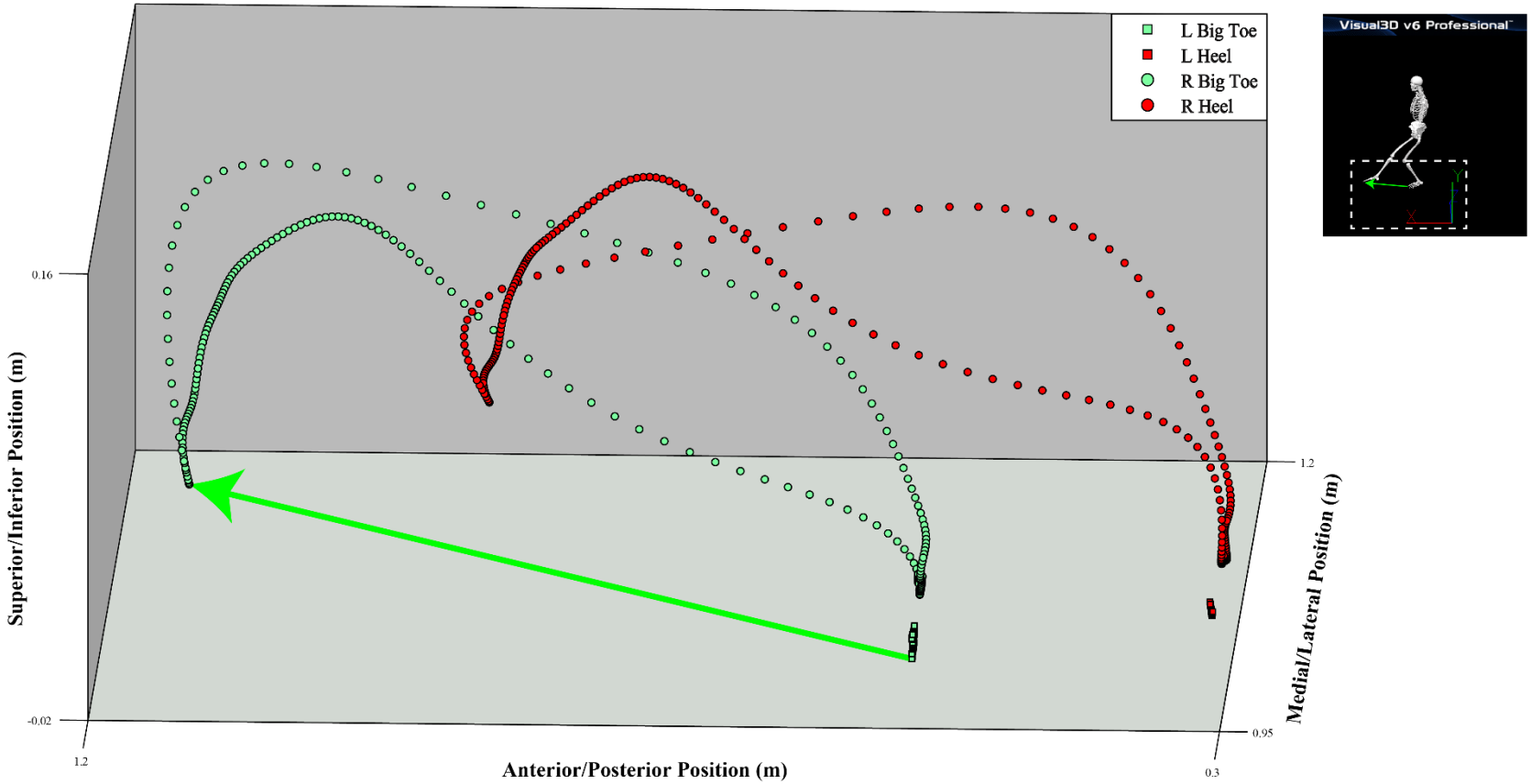


Figure 23 – 3-D scatter plot of Figure 16 with the heel and big toe digitized markers during the anterior reach with the reaching limb being the right and stance limb being the left. The green arrow represents the 3-D vector calculated as the reach distance. L = Left; R = Right

Using previously outlined methods, the participant's limb length (measured from their digitized anterior superior iliac spine to their digitized medial malleolus; both from the right side only) was used to normalize reach distances obtained during the mSEBT. Using this method of allocating the two bony landmarks for limb length measurement has been shown to be a valid measure (Gogia & Braatz, 1986; Sabharwal & Kumar, 2008). The reach distance for all trials in a single direction were collapsed into a composite mean reach distance for each reaching limb. The composite reach distance was then expressed as a ratio of the participant's limb length (Gribble et al., 2012; Plisky et al., 2009).

Knee frontal plane motion was computed relative to a body-fixed plane made using the corresponding hip joint, ankle joint and distal foot (Frost, Beach, Campbell, et al., 2015). The frontal plane knee excursion for analysis was computed from the point the participant reached their maximum distance.

3.5.5.1.4 Active Hip Abduction Test

Computation of Cardan joint angles for the AHA trials was performed with an X-Y-Z Cardan rotation sequence (i.e. abduction/adduction about the x-axis, axial twist about the y-axis, and flexion-extension about the local z-axis) (Table 12; Sorensen, Johnson, et al., 2016).

The AHA trials were divided into an ascending and descending phase (Figure 24). Initially, the beginning of the ascending hip abduction motion of the testing limb was calculated to be the minimum frame number that satisfied either of the following (Sorensen, Johnson, et al., 2016; Van Dillen et al., 2007): 1) an angular displacement increase of 1 degree from baseline or 2) angular velocity exceeded 5% of maximum ascending hip

abduction velocity. However, upon visual inspection, if neither threshold adequately captured the individual's start, a new frame was selected manually. Upon review, a new set of thresholds was selected to accommodate these trials using the following: 1) an angular displacement increase OR decrease of 1 degree from baseline or 2) an increase OR decrease in hip abduction angular velocity exceeding the maximum magnitude of 5% of ascending hip abduction velocity. The decrease in angular displacement and/or angular velocity represented an initial adduction/external rotation of the testing limb prior to initiating abduction (Figure 24).

The ending of the ascending hip abduction and beginning of descending hip abduction motion frame numbers of the testing limb was calculated to be the following: 1) maximum hip abduction.

The ending of the descending hip abduction motion of the testing limb was calculated to be the frame number that satisfied either of the following: 1) an angular displacement increase OR decrease of 1 degree from baseline or 2) an increase OR decrease in hip abduction angular velocity exceeding the maximum magnitude of 5% of descending hip abduction velocity and 3) a stabilization of hip abduction angular displacement and angular velocity to reflect the end of the movement (i.e., approximately '0') upon visual inspection.

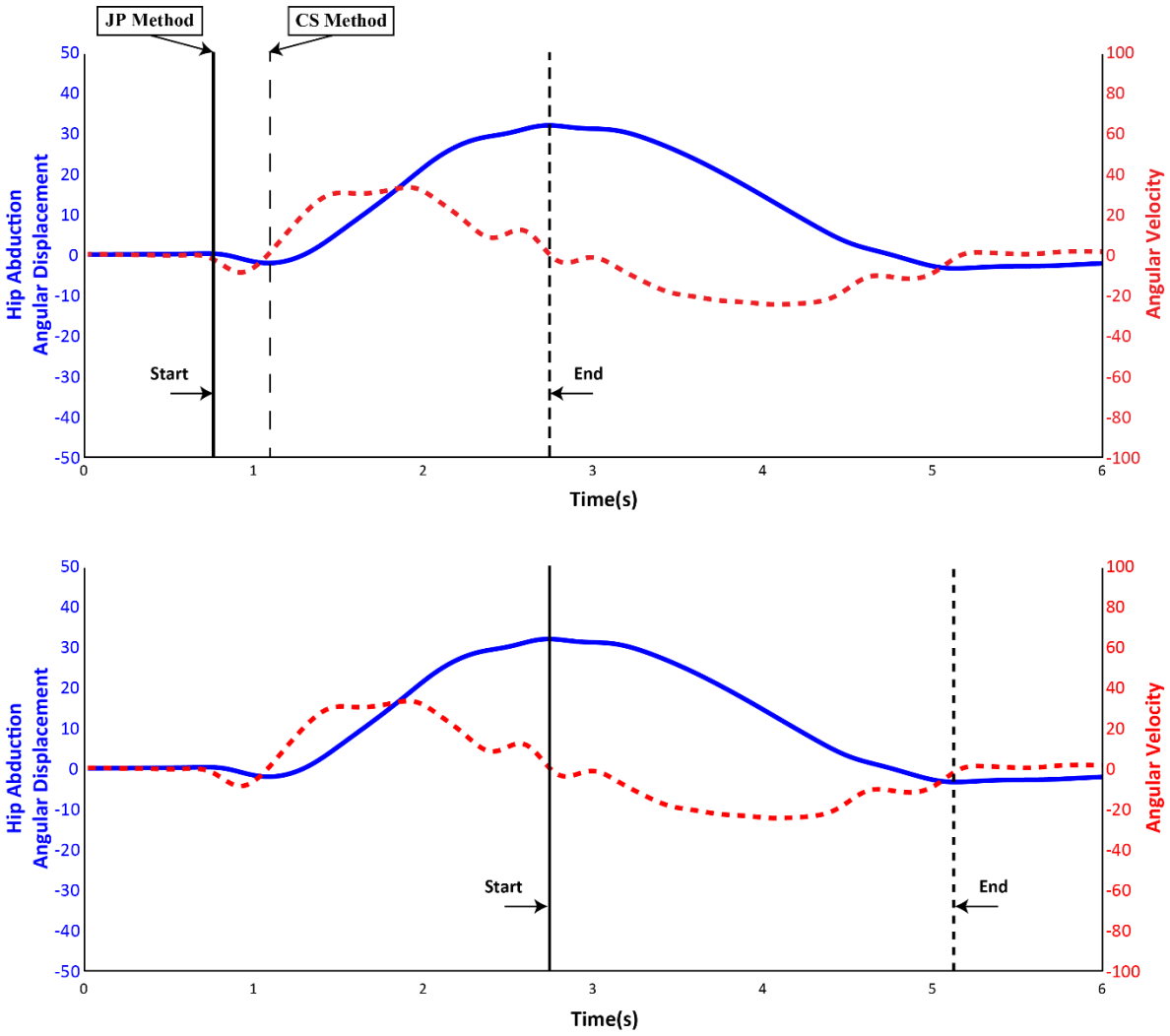


Figure 24 – Depiction of ascending start and endpoint (top) and descending start and endpoint (bottom) for a participant's active hip abduction of the left limb with no load; truncated from a 10-second trial. Differences in threshold selection depicted for the two different methods (top). JP Method = threshold used for this thesis; CS Method = threshold used in Sorensen et al., (2016). Blue curve = angular displacement; red dashed curve = angular velocity. Solid vertical line = start; Dotted vertical line = end

Once the start and end frames were established, the ascending and descending phases were partitioned and separately processed. The hip abduction angle in the frontal plane

angular displacement and angular velocity from each phase was extracted and linearly spaced to 100 data points and then cubic spline interpolated to time normalize the length of the trial (i.e., ascending phase was 100 frames long and descending phase was 100 frames long).

Arc length of each phase was calculated by taking the integral of approximated hypotenuses of adjacent data points and summing it all together (Equation 2). The summed value was then divided by the range of motion or range of speed (i.e., ascending phase's range was used for ascending phase and descending phase's range was used for descending phase) and the absolute values were taken to ignore polarity (Equation 3). Lastly, the ascending and descending arc lengths were then summed together to retrieve the total normalized arc length in arbitrary units.

Given a curve $f(x)$, where x = trial length and $y = f(x)$:

$$\text{Arc Length of } f(x) = \int_a^b \sqrt{(d_x)^2 + (d_y)^2} = \int_a^b \sqrt{1 + \left(\frac{d_y}{d_x}\right)^2}\, d_x$$

Equation 2 – Arc length is the integral of approximated hypotenuses of adjacent data points along curve from a range of $x = a$ (the starting point of the curve) to $x = b$ (the endpoint of the curve).

$$\text{Normalized Arc Length of } f(x) = \left| \frac{\int_1^{200} \sqrt{1+\left(\frac{d_y}{d_x}\right)^2}\, d_x}{\max(f(x)) - \min(f(x))} \right|$$

Equation 3 – Normalized arc length is the integral of approximated hypotenuses of adjacent data points along the curve that was time normalized to 200 data points and then divided by the range of the curve.

3.5.5.1.5 Reverse Side Bridge

The start and end frames numbers of posture maintenance during the RSB trials were visually determined by using the vertical center of mass position of any visible marker cluster during the trial. The frame numbers were then used to objectively determine the holding duration in seconds.

Using the previously identified start and end frames, the surface electromyography data was appropriately truncated for the muscles on the side of the body being tested. Maximum percent of muscle voluntary contraction during the trial was compiled for each muscle in each participant. Additionally, the MdPF was calculated.

3.5.6 Video Camera

3.5.6.1 Active Hip Abduction Peak-Examiner Rated Score

All the videos of every participant's performance from this thesis data collection were compiled and each video was then relabeled with a randomly generated 3-letter code using an adaptation of a previously generated Python script (Roja, 2012). Each video was then rated by the same researcher on a single occasion, using the performance criteria described in Table 10. The scores for each participant was reduced to a single value for each task (i.e., during the unweighted (AHA) or weighted (AHA+) by taking the peak-examiner rated score from the left and right side. The peak-examiner rated scores used for the proportional odds logistic regression model. In addition, the participants arc lengths corresponding to the peak-examiner rated score were used for parametric statistical testing.

Table 10 – Examiner/Rater Guide Criteria for Scoring the Active Hip Abduction Test. Adapted from Davis et al. (2011), Nelson-Wong, Flynn, et al. (2009).

Score	Performance Capability	Performance Summary (in frontal plane)
0	• Movement is done easily and smooth • Maintains alignment of shoulders, trunk, pelvis, and lower extremities	Sufficient Lumbopelvic alignment
1	• 'Slight' wobble at the start or during movement but then regains control • Noticeable effortful exertion or "ratcheting" of testing limb	Minimal loss in Lumbopelvic alignment
2	• Demonstrates a minimum of two of the following cues: a) noticeable wobble through movement, b) tipping of pelvis, c) rotations of shoulders/trunk, d) hip flexion, or e) internal rotation of the testing limb • Rapid movement resulting in loss of control and may or may not be able to regain control	Moderate loss in Lumbopelvic alignment

3	• Demonstrates similar characteristics as in score 2, but with greater severity. • Loses balance and control of movement; requires use of hand or arm to maintain balance	Severe loss in Lumbopelvic alignment

3.5.6.2 Active Hip Abduction Intra-rater Reliability Calculation

Prior to rating the participant's AHA performance from this study, a brief instructional video to the AHA test was viewed (obtained from Dr. Erika Nelson-Wong; similar to the one used in Davis et al., 2011). Then, the researcher's intra-rater reliability was assessed. Briefly, 38 videos of AHA performances from 19 different subjects were obtained from Dr. Erika Nelson-Wong (Davis et al., 2011). These videos were relabeled on each occasion with a randomly generated 3-letter code and assessed on three different occasions: Day 1, Day 2, and Day 8. Using the Intraclass Correlation Coefficient (ICC) model (3, 1), intra-rater reliability was quantified (Vincent & Weir, 2012).

An intraclass correlation of the AHA performance scores (Table 11) for practice videos across three different days (Day 1, Day 2, Day 8) resulted in a $ICC_{(3,1)} = 0.72$.

Table 11 – Overview of scores given on each day of assessment of practice video trials that were not collected from this thesis study

Subject	Side	Day 1	Day 2	Day 8	Subject	Side	Day 1	Day 2	Day 8
2	L	0	0	0	**11**	R	1	1	1
2	R	0	0	0	**12**	L	1	0	0
3	L	0	0	0	**12**	R	1	1	1
3	R	0	0	0	**13**	L	0	0	0
4	L	0	0	0	**13**	R	1	1	1
4	R	0	0	0	**16**	L	1	0	0
5	L	1	1	1	**16**	R	0	0	0
5	R	0	0	0	**17**	L	3	3	3
6	L	1	0	0	**17**	R	1	0	0
6	R	1	1	0	**18**	L	1	0	1
7	L	0	0	0	**18**	R	0	0	0
7	R	0	0	0	**19**	L	1	1	1
8	L	1	1	1	**19**	R	2	2	2
8	R	1	1	1	**20**	L	2	2	2
9	L	0	0	0	**20**	R	0	0	0
9	R	3	3	3	**21**	L	0	0	0
10	L	0	0	0	**21**	R	0	0	0
10	R	0	0	0	**22**	L	0	1	1
11	L	1	0	0	**22**	R	2	1	1

3.6 Statistical Analyses

All statistical analyses were conducted using R (ver. 3.2.0, R Development Team, Vienna, Austria). Independent t-tests between pain status groups were conducted on participant characteristics (i.e., body mass index or BMI, age, physical activity levels, pain attitudes and beliefs, ankle instability) (Nelson-Wong & Callaghan, 2010b). The within-subject factor of SIDE was excluded from the analyses if it presented no significant/meaningful main or interaction effect. Data from both sides were collapsed if results indicated non-significance. Similarly, between-subject factor of SEX was excluded from the analyses if it involved no significant main or interaction effect. Residuals were reviewed for violations to normality and homoscedasticity with normal probability and residual plots, respectively. Outliers that posed violations to normality homoscedasticity were removed.

The dependent variables outlined in Table 12 were analyzed with a mixed-design ANOVA in R using the ezANOVA function from the ez package (Lawrence, 2016). The corresponding independent between and within factors outlined in Table 12 were used. Briefly, between group factors included PAIN (PD/non-PD), SEX (female/male), and along with within-subject factors of SIDE (left/right), TASK (low/high demand variants; refer to Table 1) or a task's specific conditions (e.g., direction within the mSEBT).

The significance level to be used for all statistical analyses was set at an alpha level of 0.05. However, any observed trend towards significance ($0.05 < p < 0.10$) for effects involving PAIN were also reported. Additionally, Mauchly's test was performed on datasets to test if the assumption of sphericity (i.e., variance of the differences of scores between all

combinations of conditions) was violated. If violated, Greenhouse-Geisser Adjustment or Huynh-Feldt adjusted p-values in those cases were utilized to determine significance of the F ratio (Glezos, 2012). The lmer function from the lme4 package (Bates et al., 2015) was used to replicate the results from ezANOVA and used for post-hoc testing. For significant main effects with more than two levels or significant interaction effects, a multiple comparison test was performed using Tukey's Honestly Significant Difference method on proportional weighted least square means using the lsmeans package (Lenth, 2016). In addition, a simple effects analysis approach was used for deciphering significant interaction effects.

Lastly, the proportional odds logistic regression was implemented by using the polr function from the MASS package (Venables & Ripley, 2002).

3.6.1 Dependent and Independent Variables Overview

Table 12 – Summary of dependent and independent variables for this thesis

	Dependent	Independent	Analysis
STF/STF+	• Thorax Segment Angular Velocity • Lumbar/Hip Ratios • Phase Lags from Cross Correlation Analysis	Pain Status (b/n) Sex (b/n) Task (w/n)	Mixed Model ANOVA
SLIFT/SLIFT+	• Lumbar Spine Angles • Frontal Plane Knee Excursion • Phase Lags from Cross Correlation Analysis	Pain Status (b/n) Sex (b/n) Task (w/n)	Mixed Model ANOVA
mSEBT	• Limb Length Normalized Reach Distances • Frontal Plane Knee Excursion	Pain Status (b/n) Sex (b/n) Side (w/n) Direction (w/n)	Mixed Model ANOVA
AHA/AHA+	• Peak Examiner-Rated Scores • Arc Length – Angular Displacement • Arc Length – Angular Velocity	Pain Status (b/n) Sex (b/n) Side (w/n)	Intraclass Correlation Coefficient (3,1) Proportional Odds Ordinal Logistic Regression Mixed Model ANOVA
RSB	• Time to fatigue (i.e., holding duration) • Rate of fatigue (i.e., MdPF regression line slopes)	Pain Status (b/n) Sex (b/n) Side (w/n)	Mixed Model ANOVA
Hip Abductor Strength	• Body mass normalized hip abductor torque (N·m/kg)	Pain Status (b/n) Sex (b/n) Side (w/n)	Mixed Model ANOVA
Participant Characteristics/ Questionnaires	• Scores	Pain Status (b/n)	Independent t-tests

b/n = between-subject factor; w/n = within-subject factor; MdPF = median power frequency

Chapter 4 – Results

All values in brackets and error bars in figures presented are standard deviations, unless indicated otherwise. An overview of the hypotheses and their statuses are presented at the of this section.

4.1 Visual Analogue Scale

A total of 41 participants completed the categorization and laboratory assessment sessions. However, data from a female non-PD was removed due to logistic constraint leading to an incomplete dataset. In addition, data from a male participant was removed due to concerns for confounding factors during their categorization session. These removals resulted in 39 participants for further analyses. Out of the 39 participants (20 females), a total of 22 non-PDs (12 females) and 17 PDs (8 females) were categorized. Independent t-tests with pooled variances found on average, no significant differences between pain status groups with respect to age $t_{(37)} = 0.72$, $p = 0.47$; or Body Mass Index (BMI) $t_{(37)} = 0.69$, $p = 0.49$.

Table 13 – Participant characteristics of non-PDs and PDs. Values presented are non-adjusted averages and standard deviations.

Pain Status	non-PDs	PDs
Count	22	17
Age (years)	21.4 (3.29)	20.7 (2.02)
BMI (kg/m^2)	23.6 (2.65)	23.0 (3.25)
Height (m)	1.68 (0.08)	1.70 (0.11)
Mass (kg)	66.82 (12.31)	66.28 (9.56)

Sex	Female	Male	Female	Male
Count	12	10	8	9

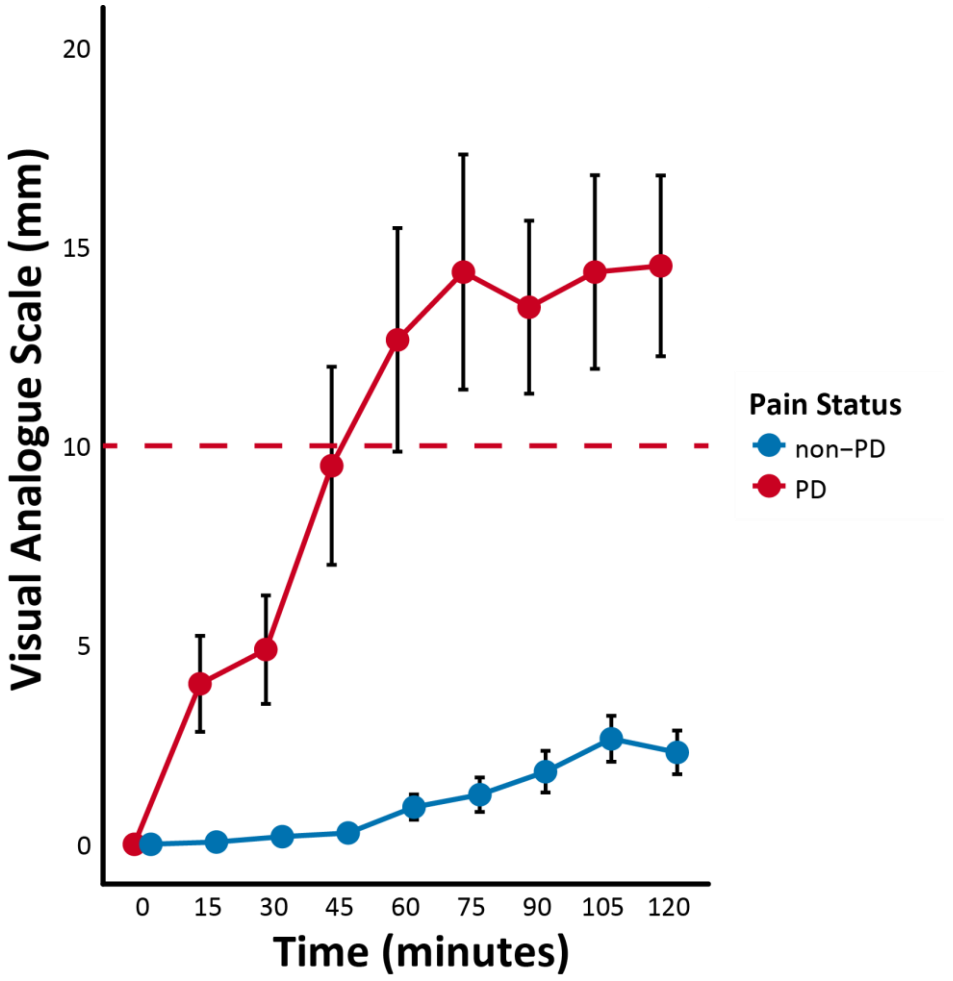


Figure 25 – Mean of peak visual analogue scale scores throughout the prolonged standing protocol within each pain status group with standard error bars presented.

4.2 Symmetric Trunk Flexion-Extension

4.2.1 Trunk Segment Angular Velocity

A mixed-design ANOVA with between-subject factors of PAIN, SEX and within-subject factor of TASK for angular velocity revealed a significant main effect of TASK, $F_{(1, 35)} = 160.7$, $p < .001$, with participants exhibiting higher angular velocity during the STF+ (M = 160.5, SD = 45.3) relative to STF (M = 89.4, SD = 36.6).

There was a significant interaction effect between PAIN and TASK, $F_{(1, 35)} = 6.5$, $p < .015$. This result indicates that non-PDs and PDs were affected differently by the TASK condition. Specifically, non-PDs performed faster during the STF+ (M = 158.39, SD = 40.58) than the STF (M = 94.12, SD = 33.69) condition. However, although PDs had similar performances during the STF+ (M = 167.98, SD = 48.64) compared to the STF (M = 80.16, SD = 36.65), their difference was much greater. All other main effects and interaction effects were not statistically significant $F \leq 1.26$, $p \geq 0.26$.

Table 14 – Non-adjusted mean of peak sagittal plane angular velocity (degrees/s) of thorax segment relative to pelvis during the extension phase from trunk flexion overview for pain status groups, sex, and task condition

Pain Status	Sex	Task	Mean	SD	SE
non-PD	F	STF	89.5	32.4	9.4
	M		105.0	39.2	12.4
PD	F		89.1	50.9	18.0
	M		72.2	16.3	5.4
non-PD	F	STF+	145.5	43.1	12.4
	M		165.7	42.2	13.4
PD	F		175.3	54.0	19.1
	M		161.5	45.6	15.2

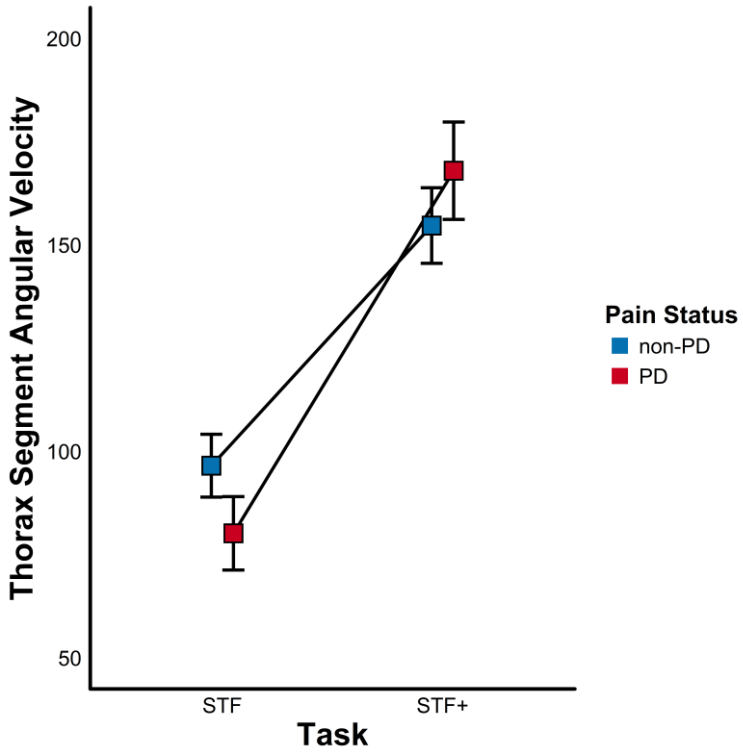


Figure 26 – Unadjusted means interaction plot of thorax segment angular velocity organized by pain status and task condition. Error bars represent standard error.

4.2.2 Lumbar and Hip Joint Angle Ratios

A paired samples t-tests showed no significant difference between the left (M = 61.28 – 69.60, SD = 16.05 – 15.31) and right hip joint angles (M = 62.27 – 69.46, SD = 16.17 – 15.27) during the STF, $t_{(38)} = 0.03$, $p = 0.98$, or during the STF+, $t_{(37)} = 1.61$, $p = 0.12$. As a result, the hip joint angle was averaged between both sides prior to lumbar-hip joint ratio calculation.

A mixed-design ANOVA with between-subject factors of PAIN, SEX and within-subject factor of TASK for lumbar-hip joint angle ratios revealed a significant main effect of TASK, $F_{(1, 35)} = 23.39$, $p < .001$, with participants having higher lumbar-hip joint motion ratios during the STF (M = 0.88, SD = 0.38) relative to STF+ (M = 0.73, SD = 0.28). All other main effects and interaction effects were not statistically significant $F \leq 2.73$, $p \geq 0.11$.

Table 15 – Non-adjusted mean of lumbar and hip joint angle ratios (unitless) at maximum trunk flexion organized by pain status groups, sex, and task condition

Pain Status	Sex	Task	Mean	SD	SE
non-PD	F	STF	0.81	0.24	0.07
	M		0.93	0.56	0.18
PD	F		0.91	0.36	0.13
	M		0.87	0.37	0.12
non-PD	F	STF+	0.73	0.21	0.06
	M		0.73	0.40	0.13
PD	F		0.79	0.30	0.10
	M		0.66	0.19	0.06

4.2.3 Cross-correlation Analysis

Upon visual observation of raw surface electromyography for all subjects during STF and STF+ exertions, 67 trials were discarded due to data issue (i.e., noise) (i.e., out of 468 trials) or 86% of trials were preserved. A male and female PD were removed during cross-correlation analyses for STF+ due to discarded trials. As a data imputation and reduction method, all trials and sides were averaged prior to statistical analyses.

A mixed-design ANOVA with between-subject factors of PAIN, SEX and within-subject factor of TASK revealed a significant main effect of TASK, $F_{(1, 33)} = 5.62$, $p < .05$, with participants experiencing longer phase lags during the STF (M = 0.098, SD = 0.18) relative to STF+ (M = 0.035, SD = 0.090). All other main effects and interaction effects were not statistically significant $F \leq 1.31$, $p \geq 0.26$.

Table 16 – Non-adjusted mean of phase lag values (seconds) with peak correlation between lumbar erector spinae and gluteus maximus overview for pain status groups, sex, and task condition

Pain Status	Sex	Task	Mean	SD	SE
non-PD	F	STF	0.085	0.165	0.048
	M		0.086	0.156	0.049
PD	F		0.049	0.122	0.043
	M		0.172	0.249	0.083
non-PD	F	STF+	0.051	0.102	0.030
	M		0.035	0.079	0.025
PD	F		-0.001	0.014	0.005
	M		0.043	0.122	0.041

4.3 Symmetric Floor-To-Knuckle Lift and Lower Task

4.3.1 Sagittal Plane Lumbar Spine Angles

4.3.1.1 Peak Lumbar Spine Angles

Data from a female PD was removed from analysis due to incomplete dataset across conditions. A mixed-design ANOVA with between factors of PAIN, SEX and within-subject factor of TASK revealed no main or significant interactions with SEX. Thus, SEX was removed from the analysis.

A final mixed-design ANOVA with between factors of PAIN and within-subject factor of TASK revealed no significant main or interaction effects $F < 2.13$, $p > 0.10$.

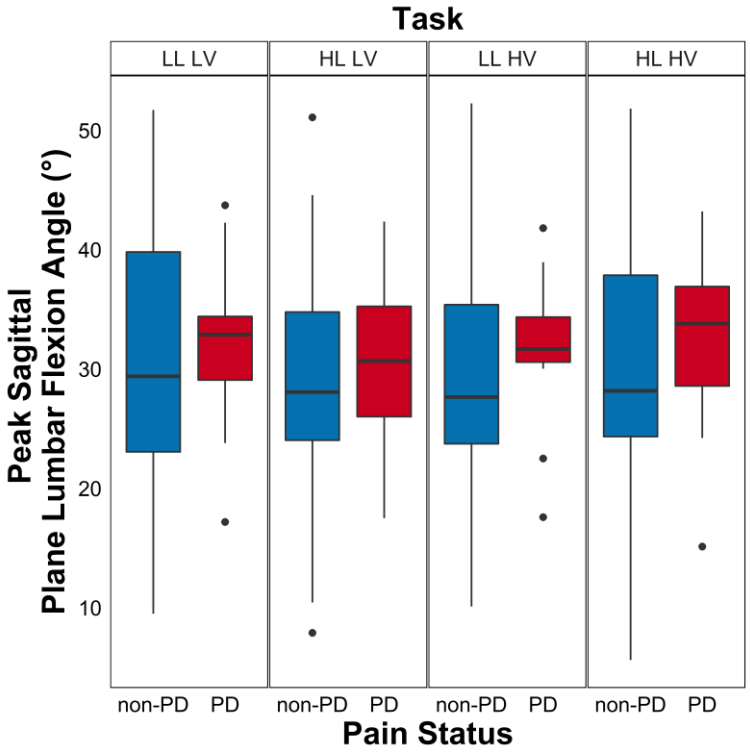


Figure 27 – Boxplot of peak lumbar spine flexion angle (degrees) organized by pain status groups and facetted by lifting task conditions. Dots represent outliers. LL = Low Load; HL = High Load; LV = Low Velocity (i.e., self-selected speed); HV = High Velocity (i.e., maximum speed);

4.3.1.2 Normalized Lumbar Spine Angles

Data from a female PD and male PD were removed from analysis due to incomplete dataset across conditions. A mixed-design ANOVA with between factors of PAIN, SEX and within-subject factor of TASK revealed no main or significant interactions with SEX. Thus, SEX was removed from the analysis.

A final mixed-design ANOVA with between factors of PAIN and within-subject factor of TASK revealed no significant main or interaction effects $F < 2.0$, $p > 0.12$.

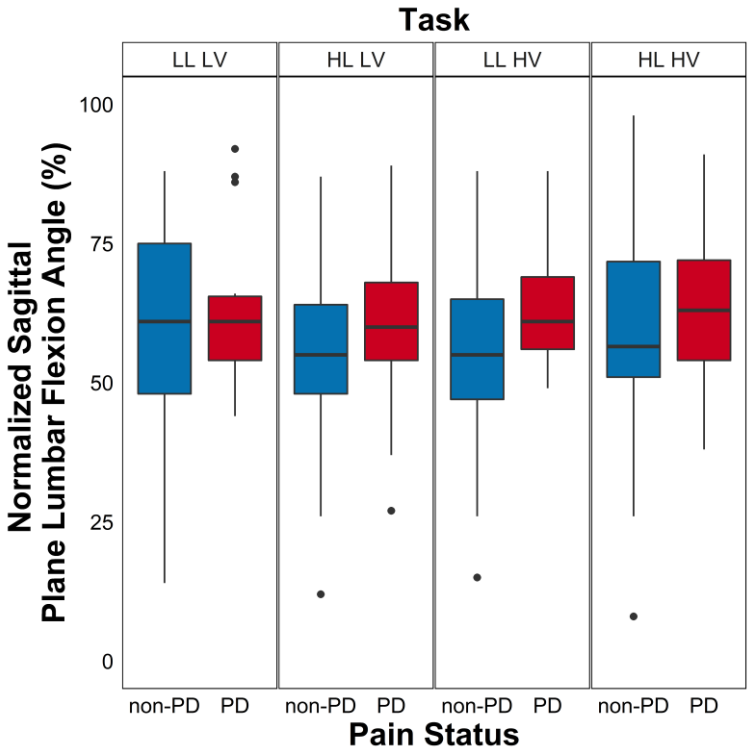


Figure 28 – Boxplot of normalized peak lumbar spine flexion angles (percent max) organized by pain status groups and facetted by lifting task conditions. Dots represent outliers. LL = Low

Load; HL = High Load; LV = Low Velocity (i.e., self-selected speed); HV = High Velocity (i.e., maximum speed);

4.3.2 Frontal Plane Knee Excursion

Data from a male PD was removed from analysis due to statistical reason (i.e., outlier). A mixed-design ANOVA with between factors of PAIN, SEX and within-subject factor of SIDE and TASK revealed a significant main effect of TASK, $F_{(3, 102)} = 3.80$, $p < .05$ and an interaction effect of SEX:TASK, $F_{(3, 102)} = 2.91$, $p < .05$. However, violations to sphericity were observed, $W = 0.52$, $p < 0.001$. Sphericity corrected p-values using Greenhouse-Geisser Adjustment $\varepsilon = 0.71$, revealed a significant main effect of TASK, $F_{(2.1, 72.4)} = 3.80$, $p < .05$ persisted. Knee excursions during HL LV was greater than all other lifting conditions. Upon correction, there was no longer a significant interaction effect of SEX:TASK $F_{(2.1, 72.4)} = 2.91$, $p = 0.058$.

A significant interaction effect of SIDE:TASK, $F_{(3, 102)} = 3.25$, $p < .05$, revealed the right knee excursion during the HL LV was greater than both the LL LV and LL HV; but not the HL HV. The left knee excursions were not different between task conditions. No other significant main or interaction effects were observed, $F < 2.6$, $p > 0.06$.

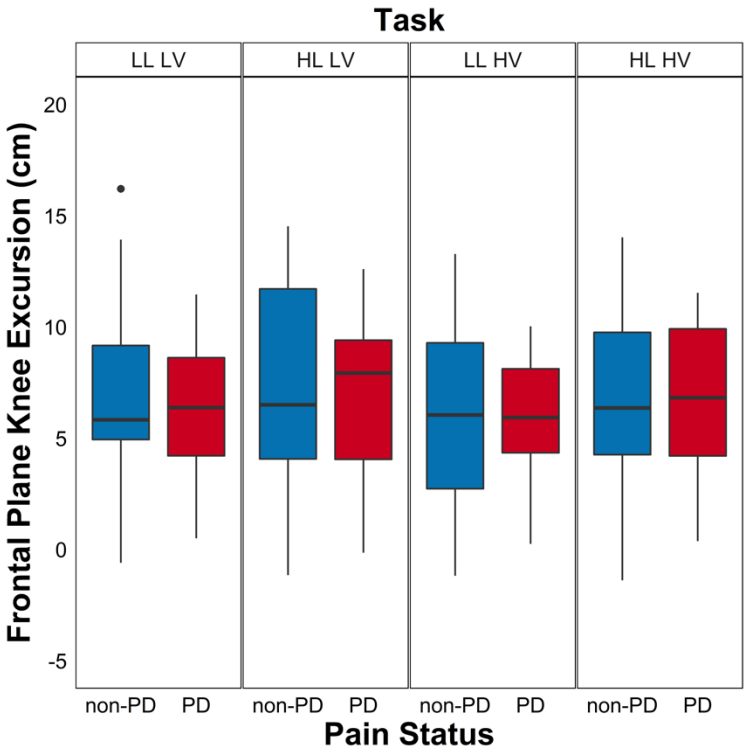


Figure 29 – Boxplot of frontal plane knee excursion organized by pain status groups and facetted by lifting task conditions. Dots represent outliers. LL = Low Load; HL = High Load; LV = Low Velocity (i.e., self-selected speed); HV = High Velocity (i.e., maximum speed);

4.3.3 Cross-correlation Analysis

Upon visual observation of raw surface electromyography for all subjects during all lifting exertions, 120 trials were discarded due to data issue (i.e., noise) (i.e., out of 1404 trials) or 91% of trials were preserved. Data from a total of 3 participants (2 male non-PDs, 1 male PD) were removed during cross-correlation analyses due to discarded trials and subsequent incomplete dataset. This resulted in a final number of 12 female non-PDs, 8 male non-PDs, 8 female PDs, and 8 male PDs. As a data imputation and reduction method, the average of all trials and sides were extracted prior to statistical analyses.

A mixed-design ANOVA with between-subject factors of PAIN, SEX and within-subject factor of TASK revealed a significant main effect of TASK, $F_{(3, 96)} = 18.21$, $p < .001$. Phase lags during LL LV and HL LV are longer compared to LL HV and HL HV. In addition, there was a significant interaction effect of SEX:TASK, $F_{(3, 96)} = 5.29$, $p < .01$. For females, phase lags during the HL LV were longer than the LL HV. However, for males, LL LV and HL LV were both longer than the LL HV and HL HV.

There was a trend towards the main effect of PAIN, $F_{(1, 32)} = 3.78$, $p = .061$, with non-PDs having longer phase lags than PDs. In addition, an observed trend towards an interaction effect of PAIN:TASK, $F_{(3, 96)} = 2.18$, $p = .095$, indicated phase lags during LL LV and HL LV were both longer than the LL HV and HL HV for non-PDs. For PDs, all lifting conditions had similar phase lags. All other main effects and interaction effects were not statistically significant $F \leq 1.09$, $p \geq 0.36$. No violations to sphericity were observed, $W = 0.81$, $p = 0.26$.

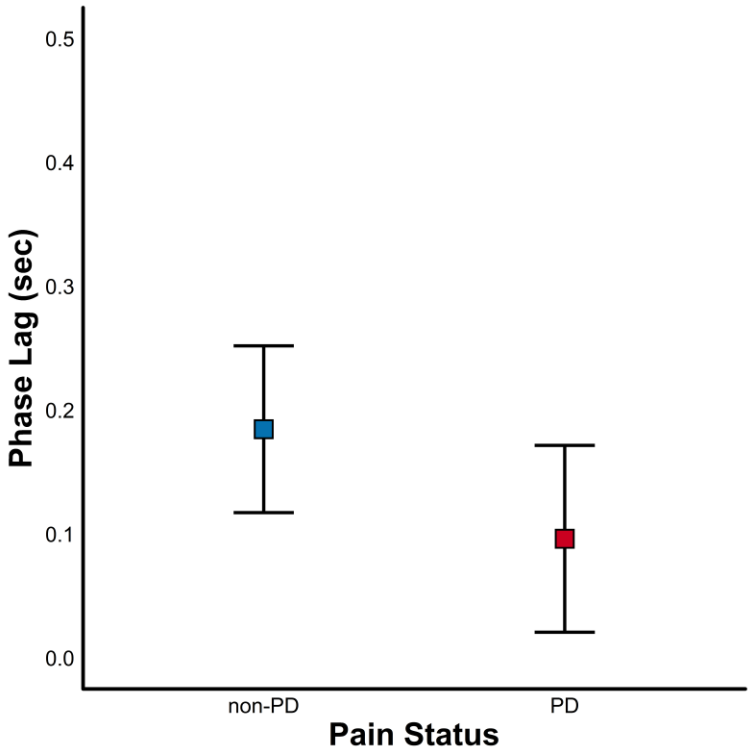


Figure 30 – Least square means plot of phase lag collapsed across lifting conditions and organized by pain status groups; approaching a trend towards statistical significance. Error bars represent 95% confidence intervals.

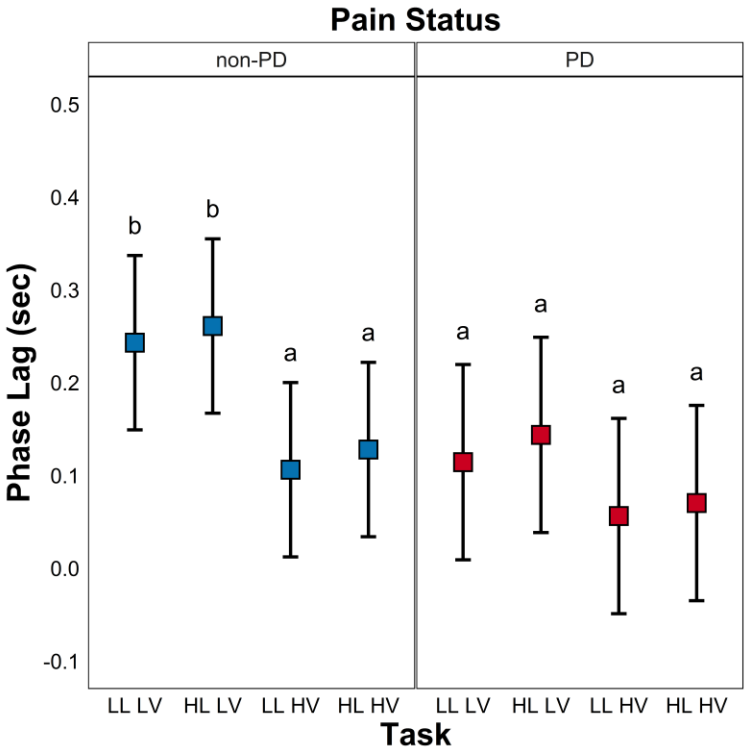


Figure 31 – Least square means plot of phase lag organized by pain status and facetted by lifting task conditions; approaching a trend towards statistical significance. Means sharing a letter are not significantly different from each other (Tukey-adjusted pairwise comparisons). Error bars represent 95% confidence intervals. LL = Low Load; HL = High Load; LV = Low Velocity (i.e., self-selected speed); HV = High Velocity (i.e., maximum speed);

4.4 Modified Star Excursion Balance Test

4.4.1 Normalized Reach Distances

A mixed-design ANOVA with between-subject factors of PAIN, SEX and within-subject factors of SIDE and DIRECTION revealed a significant main effect of SIDE, $F_{(1,35)} = 4.7$, $p < 0.05$. However, given the mean limb length of participants were 85.8 cm and that the difference between left (M = 0.69, SD = 0.11) and right (M = 0.68, SD = 0.09) sides were 0.013 (i.e., 1.3% of one's limb length or an average of 1.1 cm, below a 4 cm cut-off previously established; Ness et al. 2015) and no other interaction effect with SIDE was present, SIDE was removed as a factor.

A second mixed-design ANOVA with between-subject factors of PAIN, SEX and within-subject factors of DIRECTION revealed no main or significant interactions with SEX. Thus, SEX was also removed from the analysis.

A final mixed-design ANOVA with between-subject factor of PAIN and within-subject factor of DIRECTION revealed a main effect of DIRECTION, $F_{(2, 74)} = 30.6$, $p < .001$. However, violations to sphericity were observed, $W = 0.51$, $p < 0.001$. Sphericity corrected p-values using Greenhouse-Geisser Adjustment $\varepsilon = 0.67$, revealed a significant main effect of DIRECTION, $F_{(1.3,49.6)} = 30.9$, $p < .001$ persisted. Reach distances in the PMED were greater relative to the ANT and PLAT directions. No other significant main or interaction effects were observed, $F < 2.5$, $p > 0.12$.

Table 17 – Normalized to limb length non-adjusted mean (unitless) reach distance overview for pain status groups, sex, and direction

Pain Status	Sex	Direction	Mean	SD	SE
non-PD	F	ANT	0.69	0.05	0.01
	M		0.64	0.05	0.01
PD	F		0.66	0.06	0.02
	M		0.63	0.07	0.02
non-PD	F	PLAT	0.70	0.11	0.02
	M		0.68	0.09	0.02
PD	F		0.61	0.09	0.02
	M		0.65	0.11	0.03
non-PD	F	PMED	0.78	0.09	0.02
	M		0.73	0.12	0.03
PD	F		0.70	0.08	0.02
	M		0.74	0.10	0.02

4.4.2 Frontal Plane Knee Excursion

A mixed-design ANOVA with between-subject factors of PAIN, SEX and within-subject factors of SIDE and DIRECTION revealed no main or interaction effect with SIDE. As a result, SIDE was removed as a factor.

A final mixed-design ANOVA with between-subject factors of PAIN, SEX and within-subject factor of DIRECTION revealed a significant main effect of DIRECTION, $F_{(2, 70)} = 53.6$, $p < .001$. Frontal plane knee excursion was largest in the PMED direction and smallest in the PLAT direction.

A significant interaction effect of SEX:DIRECTION, $F_{(2, 70)} = 5.2$, $p < .01$, revealed females exhibited largest excursion in the PMED direction and the smallest in the PLAT direction. Similarly, males exhibited lowest frontal plane knee excursion in the PLAT

direction and the most in the PMED direction. However, they exhibited similar amounts in the PLAT and ANT directions. No differences were observed within each specific direction between females and males. Violations to sphericity was not observed, W = 0.91, p = 0.22.

Table 18 – Non-adjusted frontal plane knee excursion (cm) mean for pain status groups, sex, and direction

Pain Status	Sex	Direction	Mean	SD	SE
non-PD	F	ANT	7.72	3.06	0.62
	M		6.70	3.18	0.71
PD	F		5.38	2.56	0.64
	M		5.93	4.16	0.98
non-PD	F	PLAT	5.29	2.39	0.49
	M		5.10	2.76	0.62
PD	F		2.95	2.72	0.68
	M		4.03	3.38	0.80
non-PD	F	PMED	9.25	3.38	0.69
	M		6.24	3.19	0.71
PD	F		7.22	2.99	0.75
	M		7.20	3.86	0.91

4.5 Active Hip Abduction

4.5.1 Peak Examiner-Rated Scores

A proportional odds logistic regression model was used to analyze the main and interaction effect of PAIN, SEX, and LOAD on peak examiner-rated ordinal scores (Table 20). Given that significant main or interaction effects of SEX were absent on a previous iteration, the factor was removed, and the model was reduced to PAIN and LOAD.

There was a significant main effect of LOAD, $p < 0.05$. with participants 3.76 times more likely to score higher on the AHA test within the high load condition compared to the low load, given that all the other variables in the model are held constant (Table 19). There was no main effect of PAIN, $p = 0.48$, or significant interaction effect of PAIN:LOAD , $p = 0.26$. Probabilities of being scored 0 or 1 compared to 2 or 3 were much higher for both non-PDs (91%) and PDs (86%) in the low load condition (Figure 32). The proportions scored 0 or 1 changed during the high load condition, with non-PDs (73%) persisting in the lower categories compared to PDs (37%).

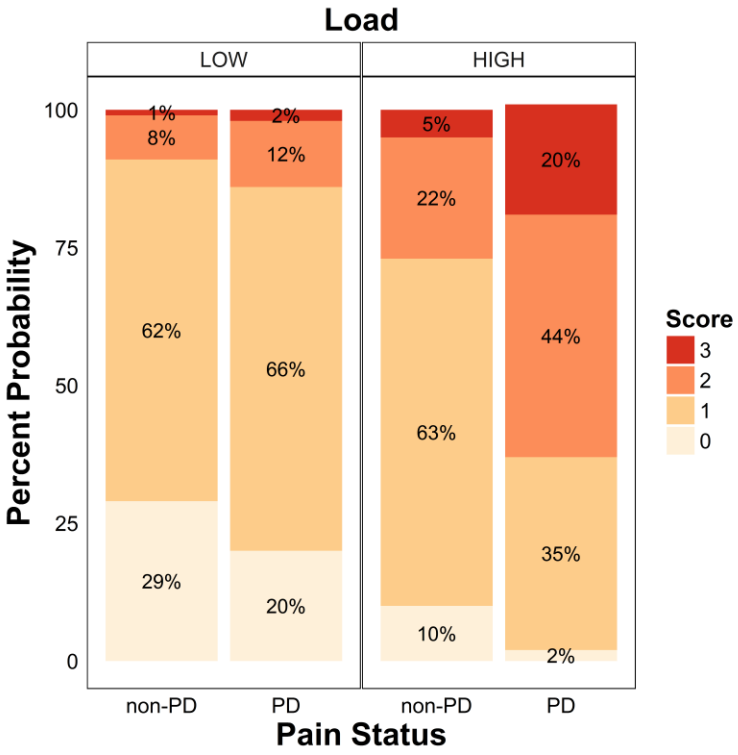


Figure 32 – Stacked bar graph representing percent probability of obtaining a specific score for pain status and load, as predicted by the proportional odds logistic regression model

Table 19 – Intercepts and regression coefficients for the proportional odds logistic regression model

Variable	Regression coefficient	Standard error	p-value	Odds ratio	95% CI of OR
Intercept 0 | 1:3	-0.919	0.454			
Intercept 0:1 | 2:3	2.292	0.551			
Intercept 0:2 | 3	4.24	0.714			
PAIN	0.470	0.665	0.48	1.60	0.44 – 6.03
LOAD	1.324	0.652	0.04	3.76	1.08 – 4.14
PAIN:LOAD	1.036	0.920	0.26	2.82	0.47 – 7.53

Table 20 – Peak examiner-rated scores for pain status groups and load condition

Pain Status	Load	Score	Count
non-PD	LOW	0	7
		1	12
		2	3
		3	-
PD		0	3
		1	12
		2	2
		3	-
non-PD	HIGH	0	2
		1	14
		2	5
		3	1
PD		0	-
		1	7
		2	6
		3	4

However, due to laboratory/equipment constraints and incomplete kinematic visibility during collection trials, the arclength values calculated do not correspond with the peak examiner-rated scores. As a result, the calculable arclength values analyzed correspond with the examiner-rated scores outlined in Table 21.

4.5.2 Calculable Arc Length Analysis

4.5.2.1 Angular Displacement Arc Length

Data from a male non-PD and female non-PD were removed from the analysis as outliers. A mixed-design ANOVA on frontal plane angular displacement range of motion arc length with between-subject factors of PAIN, SEX and within-subject factor of LOAD

revealed a significant main effect of PAIN, $F_{(1, 33)} = 7.94$, $p < .01$. PDs had higher arc length values compared to non-PDs. A main effect of LOAD, $F_{(1, 33)} = 14.57$, $p < .001$, indicated higher angular displacement during the high loading condition compared to low load. There was a significant interaction effect with PAIN:LOAD, $F_{(1,33)} = 5.01$, $p < 0.05$. PDs exhibited larger angular displacement arc length during the high load condition relative to the low load condition, but this was not visible in non-PDs. No other main or interaction effects were observed, $F < 1.24$, $p > .27$.

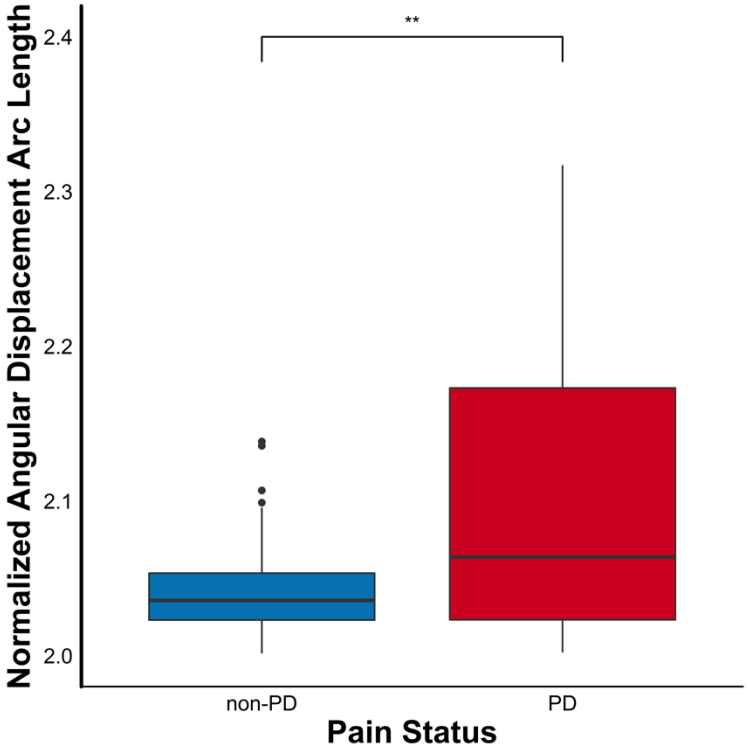


Figure 33 – Boxplot of angular displacement arc length for pain status groups. ** indicates significance at p < .01. Dots represent outliers.

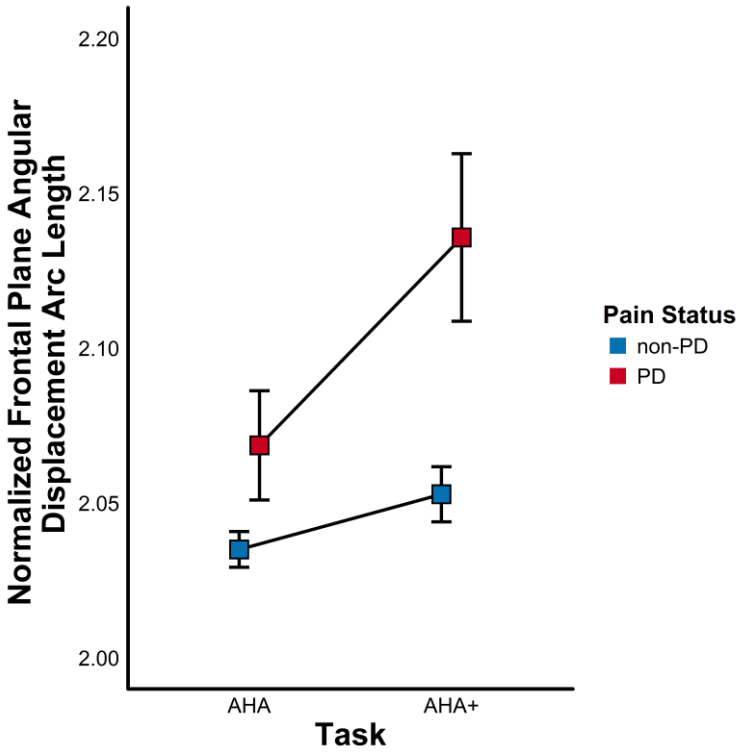


Figure 34 – Unadjusted means interaction plot of angular displacement arc length organized by load condition and pain status group. Error bars represent standard error.

4.5.2.2 Angular Velocity Arc Length

A mixed-design ANOVA on frontal plane angular velocity arc length with between-subject factors of PAIN, SEX and within-subject factor of LOAD revealed a significant main effect of LOAD, $F_{(1, 35)} = 21.4$, $p < .001$, indicated higher angular velocities during the high loading condition compared to low load. No other main or interaction effects were observed, $F < 2.35$, $p > .13$.

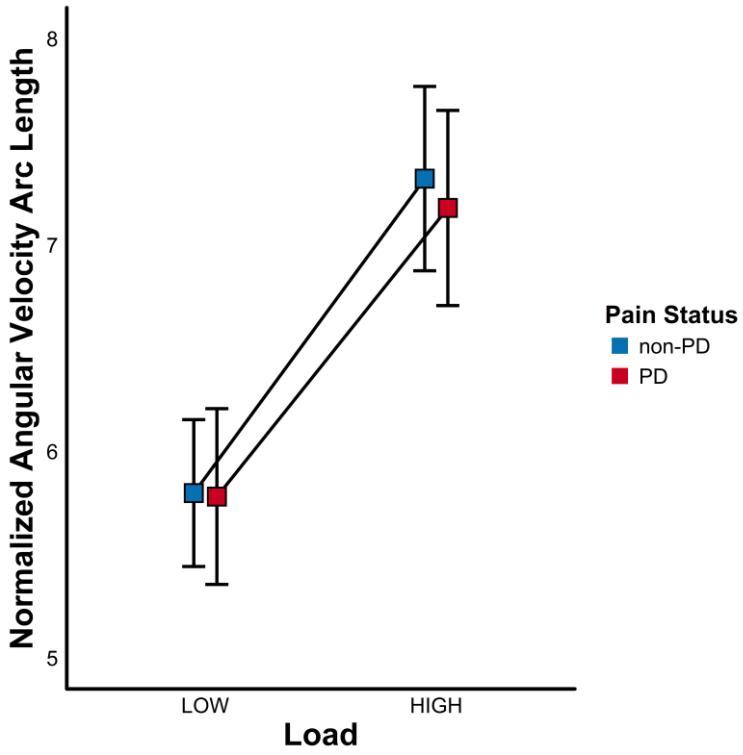


Figure 35 – Unadjusted means interaction plot of angular velocity arc length organized by load condition and pain status group. Error bars represent standard error.

Table 21 – Calculable Arc Length (AL) non-adjusted means (unitless) and their corresponding examiner-rated scores for pain status groups and load conditions

Pain Status	Load	Score	Count	Position AL Mean	Position AL SD	Position AL SE	Velocity AL Mean	Velocity AL SD	Velocity AL SE
non-PD	LOW	0	7	2.02	0.02	0.01	4.78	0.68	0.26
		1	12	2.05	0.03	0.01	5.83	1.19	0.34
		2	3	2.04	0.01	0.00	8.05	2.98	1.72
		3	-	-	-	-	-	-	-
PD		0	3	2.03	0.02	0.01	4.95	0.94	0.54
		1	12	2.07	0.08	0.02	5.62	1.09	0.31
		2	2	2.12	0.04	0.03	7.97	4.74	3.35
		3	-	-	-	-	-	-	-
non-PD	HIGH	0	2	2.04	0.05	0.04	6.24	0.56	0.39
		1	14	2.08	0.15	0.04	6.98	2.27	0.61
		2	6	2.20	0.27	0.11	8.47	1.63	0.66
		3	-	-	-	-	-	-	-
PD		0	1	2.00	-	-	6.48	-	-
		1	8	2.11	0.10	0.04	6.57	1.88	0.66
		2	6	2.14	0.12	0.05	7.77	2.12	0.87
		3	2	2.27	0.03	0.02	8.21	2.42	1.71

4.6 Reverse Side Bridge

4.6.1 Holding Duration

A mixed-design ANOVA with between factors of PAIN, SEX and within factor of SIDE on time to fatigue (i.e., holding duration) revealed no main or interaction effects involving SIDE. Therefore, SIDE was removed.

A final two-way ANOVA between PAIN and SEX was performed. A main effect of SEX was statistically significant, $F_{(1, 35)} = 15.2$, $p < .001$. On average, males held the reverse side-bridge position longer than females. No other main or interaction effect was present, $F < 1.4$, $p > 0.25$.

Table 22 – Holding duration non-adjusted mean overview in seconds

Pain Status	Sex	Mean	SD	SE
non-PD	F	75	32	9
	M	106	43	14
PD	F	49	16	6
	M	105	38	13

4.6.2 Median Power Frequency Regression Analysis

Upon visual observation of raw surface electromyography for all subjects during the reverse side-bridge, data from a male PD's surface EMG data was discarded due to data issue (i.e., noise). In addition, 21 separate muscle surface EMG data were discarded due to data issue (i.e., noise) (i.e., out of 234 surface EMG data signals) or 90% of trials were preserved for median power frequency analyses. However, data from a total of 11 participants were removed due to the incomplete datasets. This resulted in a final number of 7 female non-PDs, 9 male non-PDs, 5 female PDs, and 6 male PDs.

A mixed-design ANOVA on slopes of the regression line with between-subject factors of PAIN, SEX and within-subject factors of SIDE and MUSCLE revealed no significant main or interaction effect of SIDE. Thus, SIDE was removed from the analysis.

A final mixed-design ANOVA with between-subject factors of PAIN, SEX and within-subject factor of MUSCLE revealed a significant main effect of MUSCLE, $F_{(2, 46)} = 4.90$, $p < .05$. The EO muscles exhibited significantly larger negative slope relative to the GMED muscles. However, the LES muscles exhibited similar slopes to both EO and GMED muscles. In addition, a significant main effect of SEX, $F_{(1, 23)} = 6.4$, $p < .05$, revealed females exhibited larger negatives relative to males. No other significant main or interaction effect were observed, $F < 1.2$, $p > 0.31$.

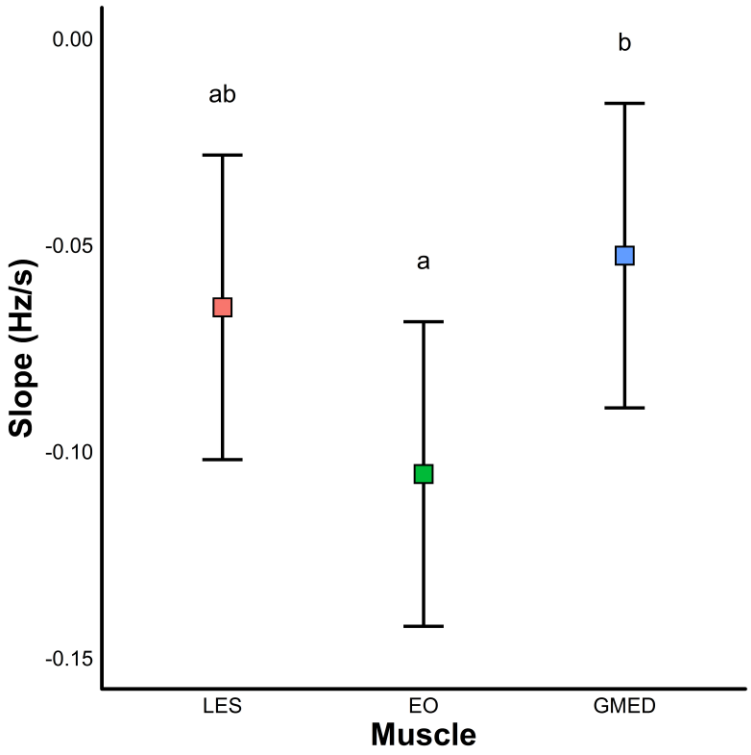


Figure 36 – Least square means plot of regression line slope organized by muscle. Means sharing a letter are not significantly different from each other (Tukey-adjusted pairwise comparisons). Error bars represent 95% confidence intervals.

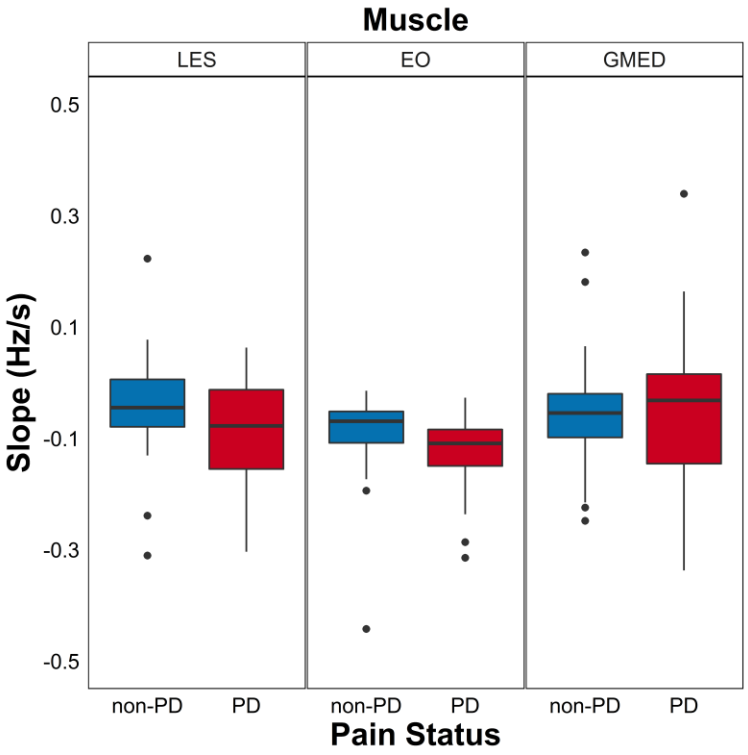


Figure 37 – Boxplot of regression line slope for pain status groups facetted by muscle group.

Dots represent outliers.

4.7 Questionnaires

There were no significant differences between pain status groups for the modified Minnesota Physical Activity Questionnaire (mMPAQ) scores, $t_{(37)} = 0.13$, $p = 0.89$ or the Cumberland Ankle Instability Tool (CAIT) scores, $t_{(37)} = 1.35$, $p = 0.18$. However, a significant difference were found for Fear of Pain (FOP) scores, $t_{(37)} = -2.09$, $p = 0.043$, with PDs exhibiting higher FOP scores than non-PDs (Table 23). In addition, a significant difference were found for Pain Catastrophizing Scale (PCS) scores, $t_{(37)} = -2.24$, $p = 0.030$, with PDs exhibiting higher PCS scores than non-PDs (Table 23).

Table 23 – Overview of total non-adjusted mean (standard deviation) questionnaire scores for each pain status group.

	non-PDs	PDs	p-values
CAIT Total	27.04 (2.89)	25.71 (3.31)	0.18
FOP Total	71.72 (22.77)	85.82 (18.17)	0.04
mMPAQ Total	10206.32 (6892.18)	9927.76 (6044.78)	0.89
PCS Total	13.27 (8.36)	19.53 (8.98)	0.03

4.8 Hip Abductor Strength

A mixed-model ANOVA with between-subject factors of PAIN, SEX and within-subject factor of SIDE revealed no main or interaction effect with SIDE. As a result, SIDE was removed as a factor.

A final two-way ANOVA with between-subject factors of PAIN and SEX revealed a significant main effect of SEX, $F_{(1, 35)} = 27.43$, $p < .001$, with females ($M = 1.56$, $SD = 0.24$)

producing less torque per body mass compared to males (M = 2.06, SD = 0.38). Other main and interaction effect were not statistically significant $F \leq 0.87$, $p \geq 0.36$.

Table 24 – Overview of non-adjusted mean of body mass normalized hip torque (N·m/kg) organized by pain status groups and sex.

Pain Status	Sex	Mean	SD	SE
non-PD	F	1.62	0.22	0.05
	M	2.04	0.44	0.10
PD	F	1.47	0.25	0.06
	M	2.07	0.31	0.07

Chapter 5 – Discussion

This study sought to investigate the pre-existing movement behavior and muscle recruitment patterns in healthy individuals that are PDs or non-PDs during a protocol of tasks with increased functional demand and variety. As mentioned in the literature review, several studies have noted importance of specific kinematic and surface electromyography variables for differentiating PDs from non-PDs among the healthy population. However, little information was found in the literature on the question of whether these defining features are more apparent with higher demand challenges and/or present using other specific variables in other functional activities that have not been implemented in these groups. It was hypothesized that a protocol of tasks with increased functional demand and variety may elicit previously unseen or larger differences between PDs and non-PDs in movement behavior and muscle recruitment patterns.

The investigation of low and/or high-demand challenges in the symmetric trunk flexion-extension (STF) exertions, symmetric floor-to-knuckle lifting (SLIFT), modified star excursion balance test (mSEBT) and the reverse side bridge (RSB), did not exhibit any significant performance differences in trunk angular segment velocities, lumbar/hip joint angle ratios, frontal plane knee excursions, muscle sequencing, sagittal plane spine motion, reach distances, holding duration, and muscle fatigability (refer to overview in Table 25 and Table 26). These findings are contrary to previous studies which have suggested that differences exist in the lumbopelvic region and hip musculature between pain status groups. For instance, lumbopelvic kinematics and muscle recruitment patterns have been shown to vary between pain status groups throughout prolonged standing (Bussey et al.,

2016; Marshall et al., 2011; Nelson-Wong & Callaghan, 2010b; Nelson-Wong et al., 2008) and various low demand tasks PDs (Gregory et al., 2008; Nelson-Wong et al., 2012). A possible explanation for unobserved differences may be that task performance indicators emphasized creating movement involving other bodily regions besides the lumbopelvic region and hip musculature for coordination. For instance, differential loading demands imposed in the mSEBT or RSB were observed to emphasize muscles of the thigh or torso, respectively (elaborated upon in Section 5.1 and onwards). A note of caution is due here since methodological differences across studies, such as the task instructions used and processing methods, may have influenced study results comparisons (elaborated upon in Section 5.1 and onwards).

Interestingly, the active hip abduction test (AHA) revealed PDs performed similarly during the low demand condition compared to non-PDs. However, PDs performed worse during the high demand variation (AHA+) than the unloaded AHA, whereas this result was not visible in non-PDs. These results reinforce previously reported lumbopelvic region neuromuscular control differences between pain status groups, with potential facilitation for larger differences to be observed and improved capacity to stratify pain status groups using the AHA+.

Taken together, the results of the tasks from this thesis and their corresponding investigated kinematic and muscle recruitment variables suggest that there is minimal evidence for tasks with increased functional demand and variety to elicit previously unseen or larger differences in movement behavior and muscle recruitment patterns between pain status groups.

Specific findings within each task will be presented and discussed in the subsequent sections. The overview of thesis questions, hypotheses, and corresponding status of acceptance/rejection are outlined in Table 25 and Table 26. Inherent to each of the hypothesis was that adding increased challenge to a task by increased speed and/or load would result in larger differences between PDs and non-PDs. Although sex differences were present during a number of tasks, they were not elaborated on unless an interaction with pain status was involved. Lastly, a posteriori analyses results are located in the Appendix section.

Table 25 – Overview of specific primary thesis questions, hypotheses, and corresponding accept/reject status

	Question	Hypothesis	Status
1)	Do PDs and non-PDs demonstrate similar trunk angular velocities, lumbopelvic kinematics, and muscle sequencing patterns during submaximal and maximal trunk flexion-extension exertions (STF/STF+)?	PDs compared to non-PDs, will exhibit: a) lower magnitudes of trunk angular velocity during maximal exertions, as seen in LBP patients (Marras & Wongsam, 1986) b) no differences in lumbar and hip joint angle ratios (i.e., lumbopelvic kinematics) during submaximal exertions, but differences will be observed in maximal exertions c) a top-down muscle activation pattern, as seen in a previous study (Nelson-Wong et al., 2012), with larger differences observed in maximal exertions	Reject: Although there is potential for partial acceptance due to the observed interaction effect with pain status and task condition using trunk angular velocity, validity of results are of concern and elaborated upon in 5.1
2)	Do PDs and non-PDs exhibit similar spine motion, frontal plane knee motion, and muscle sequencing patterns during symmetric floor-to-knuckle lifting tasks (SLIFT/SLIFT+)?	PDs compared to non-PDs, will exhibit: a) larger sagittal spine motion within all the lifting task conditions, with larger differences in more difficult task conditions b) larger frontal plane knee excursions within all the lifting task conditions, with larger differences in more difficult task conditions c) a top-down muscle activation pattern, with larger differences observed during more difficult task conditions	Reject: No differences were observed
3)	Do PDs and non-PDs exhibit similar dynamic balance control and frontal plane knee excursions during the modified star excursion balance test (mSEBT)?	PDs compared to non-PDs, will exhibit: a) lower limb length normalized reach distances b) greater frontal plane knee motion during the mSEBT	Reject: No differences were observed
4)	Do PDs and non-PDs exhibit similar lumbopelvic alignment, examiner-rated scores, and movement smoothness during unweighted and weighted variations of the active hip abduction test (AHA/AHA+)?	PDs compared to non-PDs, will exhibit: a) difficulty in maintaining lumbopelvic alignment, be scored worse, and exhibit less smooth movement during the unweighted AHA b) greater difficulty on maintaining lumbopelvic alignment, scored worse than the unweighted AHA, and exhibit lesser smooth movement when exposed to additional external weight on the testing leg (i.e., AHA+)	Partially Accept: Interaction effect with pain status and load condition was observed with angular displacement arc length (i.e., movement smoothness)
5)	Do PDs and non-PDs demonstrate similar time to fatigue and gluteus medius fatigability during the reverse side-bridge (RSB)?	PDs compared to non-PDs, will: a) possess lower holding durations b) exhibit greater gluteus medius fatigability	Reject: No differences were observed

Table 26 – Overview of secondary thesis questions, hypotheses, and accept/reject status

	Question	Hypothesis	Status
1)	Do PDs and non-PDs have similar hip abduction strength measures?	PDs compared to non-PDs, will: a) have no differences in their lateral hip strength measures	Accept: No differences were observed
2)	Do PDs and non-PDs have similar ankle function when using a self-reported questionnaire?	PDs compared to non-PDs, will: a) have larger amount of ankle instability	Reject: No differences were observed
3)	Do PDs and non-PDs exhibit similar beliefs and attitudes towards pain when using a self-reported questionnaire?	PDs compared to non-PDs, will: a) have no differences	Reject: Differences were observed in fear of pain and pain catastrophizing scores between PDs and non-PDs

5.1 Symmetric Trunk Flexion-Extension Exertion

It was initially hypothesized that PDs compared to non-PDs, would demonstrate lower trunk angular velocity magnitudes, larger lumbar/hip joint ratios, and a top-down muscle activation pattern during submaximal and maximal trunk flexion-extension exertions and that differences would be more pronounced when comparing submaximal and maximal exertions. The results of this study did not show any significant differences between PDs and non-PDs in any of the outcome variables for submaximal and maximal exertions. These results reflect those of Nelson-Wong et al. (2012) who also found no differences in trunk angular velocity magnitudes and lumbar/hip ratios during submaximal trunk flexion-extension exertions. However, the authors showed that PDs exhibited a top-down muscle activation pattern during submaximal trunk flexion-extension exertion during cross-correlation analyses of the lumbar erector spinae and gluteus maximus muscles (Nelson-Wong et al., 2012). In contrast to the previous finding, no evidence of a top-down muscle activation was detected in PDs for either submaximal or maximal exertions. A possible explanation for this might be the differences in instructions given to participants for performing the task (Nelson-Wong, 2009, p. 65). Participants were previously instructed to maximally bend forward and then hold that position for a few seconds prior to returning back to a standing position, whereas this study employed an attempt to minimize restrictions and capture a participant's usual movement by making the exertion continuous throughout.

One unanticipated finding was the significant interaction effect indicating larger differences observed in trunk angular velocity magnitudes between STF and STF+ in PDs compared to non-PDs. This result has not previously been described in such a stratified

population. It is difficult to explain this result, but it might be related to task order effect (elaborated upon in the next paragraph). When the current trunk angular velocity study results are compared to previous studies (Figure 38) that used submaximal and maximal STF exertions to separate healthy controls from low back patients, PDs and non-PDs from this study resembled previous trunk angular velocity values from healthy controls. In addition, this study did not find a significant difference between PDs and non-PDs trunk angular velocity magnitudes during maximal exertions. Previous studies showed higher order kinematic derivatives separated low back patients from healthy individuals (Marras & Wongsam, 1986; Marras et al., 1993, 1999). It has been theorized that PDs be considered a pre-clinical group due to their increased likelihood for becoming low back patients in the future. The magnitudes observed in this investigation does not support any potential underlying difference during trunk flexion-extension exertions. This result may be explained by the fact that Marras & Wongsam (1986) theorized the low back patient's movement behavior (i.e., slower movement during maximal exertions) were a by-product of minimizing loads to the spine to prevent pain due to their previous history/experiences. However, PDs experienced pain only during prolonged standing and were otherwise, able to move pain-free with no apprehension of experiencing pain in their lumbar spine in trunk flexion-extension.

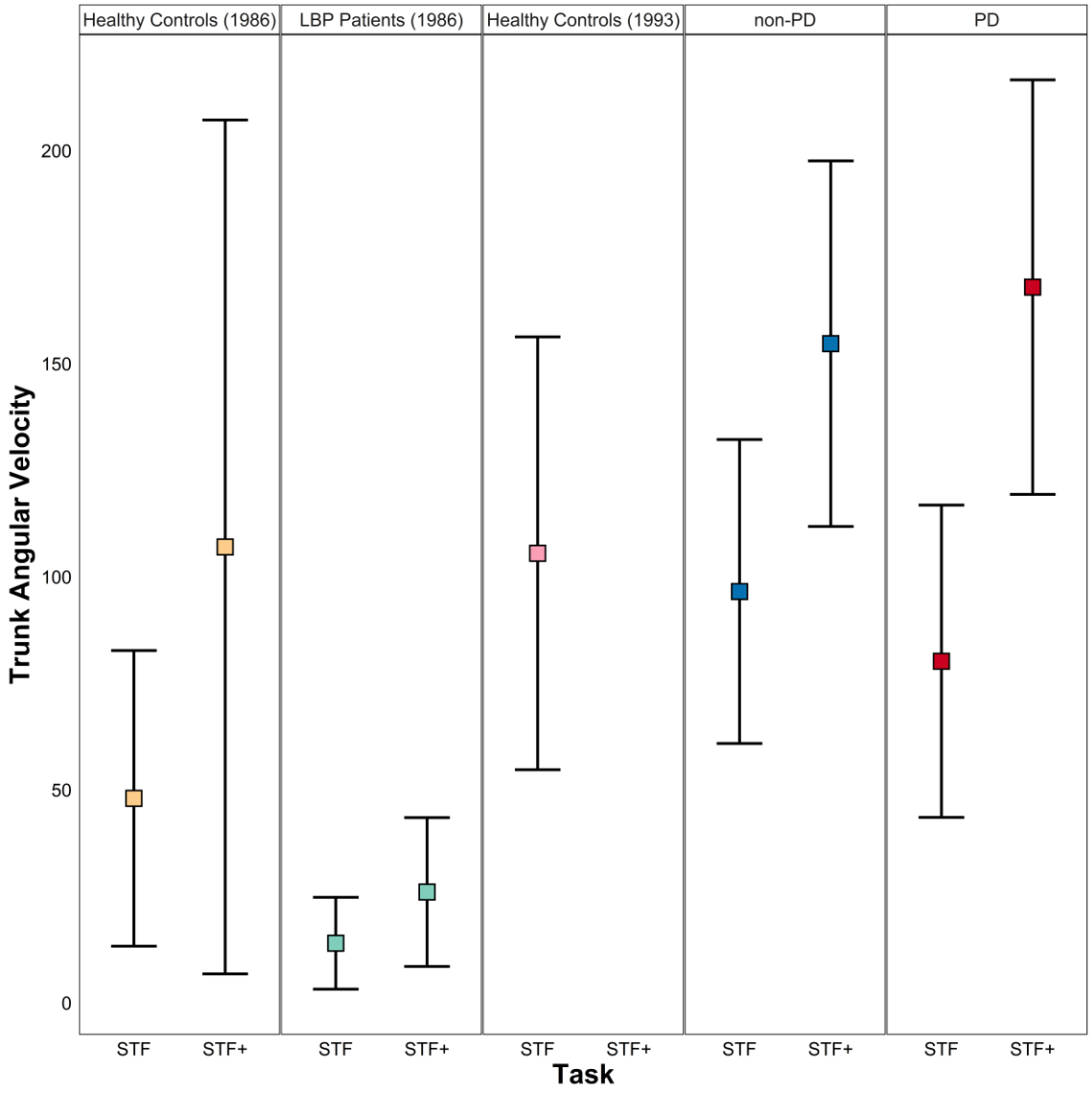


Figure 38 – Overview of trunk angular velocity from healthy controls and low back pain (LBP) patients from Marras & Wongsam (1986), Marras et al. (1993) and current study results (non-PD/PD). Square points represent mean and error bars represent standard deviation.

A note of caution is due here since one unanticipated finding was that an a posteriori analysis of task order effect ($p < 0.05$) revealed participants who performed the submaximal

trunk flexion-extension exertion after the maximal exertion possessed significantly higher angular velocity magnitudes (M = 101.8, SD = 38.8) relative to participants who performed in the order of submaximal then maximal exertion (M = 67.3, SD = 17.7) (Section 6.4.4.1). This discrepancy could be attributed to misjudging the actual speed of performance as a result of exposure to high speeds. This phenomenon is adapted from ‘velocitization’, in which prolonged driving exposure to high speeds (e.g., highway) can affect judgement on their true speed (Glezos, 2012).

5.2 Symmetric Floor-To-Knuckle Lifting

The second question in this study sought to determine whether PDs would exhibit a larger spinal and frontal plane knee motion and top-down muscular recruitment strategy during symmetrical lifting tasks. In contrast to earlier findings in healthy individuals (Frost, Beach, Callaghan, et al., 2015; Scholz et al., 1995), however, evidence for PDs and non-PDs differing in spine and knee motion with any of the lifting conditions were not detected. There are several possible explanations for this result. For instance, the outcome variables do not account for potential inter-joint coordination differences that may have been apparent throughout (Scholz et al., 1995). The height of the lift was not standardized with respect to participant's anthropometric, as it has been previously shown that the height of the lift can influence the strategy adopted to perform the lift (Burgess-Limerick et al., 2001). Lastly, given the standardized masses used for males and females, the increased task demands with heavier loads may not have been adequately challenging participants, as previous studies used a percent maximum lifting capacity (Scholz et al., 1995).

Despite the observed trends toward differences in muscle sequencing for pain status groups, this must be interpreted with caution. Given that the minimum trunk flexion was assumed to be the start of the lift (i.e., lifting the crate off the ground), the results may largely be influenced by the aforementioned assumption and the 500 ms boundary conditions for which maximum delay in muscle sequence would be anticipated.

5.3 Modified Star Excursion Balance Test

The third question in this study sought to determine whether PDs would exhibit smaller reach distances and larger frontal plane knee excursions in all the reaching directions. Contrary to expectations, this study did not show any significant differences in normalized reach distances or frontal plane knee excursion of the stance limb between PDs and non-PDs in any of the directions. This finding broadly supports the work of other studies in this area investigating balance control with standing LBP development. For instance, Nelson-Wong (2009) showed no differences in a single leg stance balance task using total center-of-pressure excursion. The kinematic attributes support an absence of these differences, given that a posteriori analyses of joint angles (ankle, knee, and hip) revealed no significant differences between pain status groups (Section 6.4.4.2). It is difficult to explain this result, given that a previous investigation of hip and thigh muscle activation during the mSEBT (i.e., anterior and posteromedial directions) revealed an enduring stabilization role for the gluteus medius (GMED) muscle and gluteus maximus (GMAX) muscles relative to vastus medialis (VM) (Norris & Trudelle-Jackson, 2011). This discrepancy could be attributed to the short duration of the trial and the high-level recruitment of the VM muscle needed to perform the reaches, despite the challenge observed in the hip musculature. The latter may also explain no differences being observed in the frontal plane knee excursions.

Interestingly, these results corroborate the ideas described by Ness et al. (2015), who investigated the relationship between movement pattern faults and mSEBT reach performance. Specifically, clinicians adopted a predetermined movement criterion – previously used to indicate increased risk for lower-limb injury – and rated participants for

having a presence or absence of those movement pattern faults (Ness et al., 2015). In addition, participants were dichotomized as being at-risk for lower-limb injury or not, based on the amount of discrepancy between their left and right sides and/or their composite reach distance performance (Ness et al., 2015). Contrary to their hypothesis, the authors found participants that were designated at-risk exhibited fewer movement faults (i.e., movement behavior was inversely related to risky mSEBT performance) (Ness et al., 2015). The authors adapted the concept of an individual's "cone of stability" – an internalized construction of one's limits of stability to maintain balance, shaped as a cone – and postulated that participants who exhibited less aberrant movement while encapsulating at-risk mSEBT performance measures may be aversive or unable to move towards their stability boundaries (Horak, 2006; Ness et al., 2015). This averseness or inability to maneuver within their boundaries may be a reflection of an inaccurate internal construction of one's stability limits (Horak, 2006; Ness et al., 2015). It is unclear why this may be the case, although one's cone is a by-product of their base of support (i.e., feet), joint ranges of motion, muscle strength, and sensory information integration (Horak, 2006). The authors reasoned that if the aforementioned participants performed further toward their stability boundaries, more movement faults might have been apparent (Ness et al., 2015).

Although not statistically significant, the frontal plane knee excursions and joint angles observed in this study revealed a select number of PDs exhibited less frontal plane knee motion and hip, knee, and ankle flexion angles, relative to non-PDs. The inaccurate cone of stability construction postulation may be hypothesized to contribute to these results. This supposition corroborates previous research on PDs exhibiting bilateral GMED co-contraction

(Bussey et al., 2016; Marshall et al., 2011; Nelson-Wong et al., 2008, 2012; Nelson-Wong & Callaghan, 2010b; Sorensen, Johnson, et al., 2016; Viggiani & Callaghan, 2016) during prolonged standing.

In accordance with the present results, previous studies have generally exhibited larger normalized reach distances in their healthy participants. This discrepancy may largely be attributed to differences in methodologies, given that this is the third study to utilize an optoelectronic system for reach distances as opposed to a measuring tape and concomitant intra/interrater dependency. The mSEBT reach distances in this study were calculated from the 3-dimensional vector as opposed to the 2-dimensional vector along the plane of the ground in previous assessments. As a result, values may not be directly comparable.

Table 27 – Overview of studies of their reported mean (standard deviation) normalized reach distances (in percentages) using the (modified) star excursion balance test in healthy control or patient groups

Study	Population	Direction	Distance
Current Study	non-PD	ANT	66.6 (5.0)
	PD		64.4 (6.3)
	non-PD	PLAT	68.9 (9.9)
	PD		62.9 (10.0)
	non-PD	PMED	75.4 (9.6)
	PD		72.4 (8.5)
Ganesh et al. (2015)	Control	ANT	82.4 (5.1)
	CLBP		72.6 (6.9)
	Control	PLAT	76.3 (9.3)
	CLBP		63.2 (1.2)
	Control	PMED	83.1 (1.0)
	CLBP		74.2 (8.5)
***†Pionnier et al. (2016)**	Control	ANT	80.5 (4.4)
	CAI		74.1 (11.1)
	Control	PLAT	83.2 (7.7)
	CAI		76.8 (10.4)
	Control	PMED	97.5 (7.1)
	CAI		92.7 (7.1)
***Fullam et al. (2014)**	Healthy	ANT	67.1 (5.0)
	-		-
	Healthy	PLAT	99.7 (8.7)
	-		-
	Healthy	PMED	106.1 (7.9)
	-		-

*Used optoelectronic system

†Extracted their data values from their figure with a web-based digitizer (WebPlotDigitizer v.3.11, Austin, Texas, USA)
ANT = Anterior; PLAT = Posterolateral; PMED = Posteromedial; CLBP = Chronic low back pain group; CAI = Chronic ankle instability group

5.4 Active Hip Abduction Test

The fourth question in this study sought to determine whether PDs would be scored worse on maintaining lumbopelvic alignment and exhibit larger arc length magnitudes when exposed to additional external weight during the active hip abduction test.

The results of analyzing the participants' peak rated ordinal scores revealed that they experienced greater difficulty in maintaining lumbopelvic alignment during AHA with the addition of a 10-lb ankle weight (i.e., AHA+). However, this study did not show any moderating effects with pain status on performance. This may be a result of not sufficiently challenging each participant equally, given the standardized ankle weight magnitude. Previous studies have selected additional external loads arbitrarily with no explicit rationale besides its' relationship to athletic or occupational endeavors usually requiring additional external load challenges (Glass, 2015). One group used a standardized weighted vest that mimicked weight used in tactical carriage in the military (Glass, 2015). The 10-lb ankle weight was chosen to simplify logistics throughout the collection process and is a readily accessible equipment item that can be used in clinical practice.

On the question of arc length, this study revealed PDs exhibited similar angular displacement arc length (ADAL) values during the active hip abduction test (AHA) compared to non-PDs. However, PDs performed worse during the high demand variation (AHA+) than the unloaded AHA, whereas this result was not visible in non-PDs. The AHA+ supports neuromuscular control differences between pain status groups, with potential facilitation for larger differences to be observed and enable improved capacity to stratify pain status groups. Although no directly comparable studies are present for this finding, its' inference is in accords

with earlier studies that showed PDs perform poorly compared to non-PDs during the AHA. In addition, Sorensen et al. (2016) found asymmetric lumbopelvic movement timing between PDs and non-PDs, a parallel characteristic found in a different hip-related movement within LBP patients (Sorensen et al., 2016). Given that movement is a by-product of interacting elements between individual, task, and environment, the consequential irregular movement has been largely attributed to the individual's inadequate trunk stabilization to maintain lumbopelvic alignment. These results reiterate and support previous studies that analysis of movement smoothness – continuous and non-intermittent performance of a given action – during the AHA or AHA+ are an important quality to distinguish PDs from non-PDs. One explanation for why the pain status groups differed in the AHA+ and not the AHA may be related to the interplay between coordination and strength required to perform the test. For instance, Nelson-Wong et al. 2013 showed a proportion of an unstratified group of healthy individuals who exhibited a normal proximal-to-distal muscle sequencing during the AHA actually performed poorly on the test, suggesting coordination alone does not predict performance. In addition, baseline hip abduction strength measures did not differ between pain status groups in this study and previous studies ((Marshall et al., 2011) (Viggiani & Callaghan, 2018). It may be that adequate lumbopelvic stabilization is available up to a certain threshold, to which stabilization is sacrificed for force production (Gabriel et al. 2007), and that this capacity is reduced in PDs. However, this irregularity may also arise from the novel aspect of performing the AHA with minimal familiarity provided during the testing protocol (i.e., single trial with no voluntary practice) (Balasubramanian et al., 2015).

Surprisingly, angular velocity arc length (AVAL) values did not provide the same results. This inconsistency may be due to the inability to compare the arc length values derived from the peak scores from participants due to experimental collection constraints. The quantifiable arc lengths for participants in category 3 were limited to two values. The sample sizes for this study raises some caution for interpretation, given the inability to capture the variety of ways a person may fall into that category. In addition, a posteriori analysis on how arc length values differed between scores revealed that ADAL values are significantly different from each category ($p < 0.05$). However, AVAL values between categories 0 - 1, and 2 are significantly different from each other. Category 3 was similar to all of them. A mathematical attribution to this unexpected finding may be the angular velocity normalizing process to make the effects of trial length and speed negligible. For instance, a subject in Category 3 exhibited patterns of the following from the AHA criterion: slight wobble at initiation or throughout, noticeable effort/'ratcheting', tipping of pelvis, trunk, or shoulder rotation, increased hip flexion/rotation of moving limb, and rapid or uncontrolled movement (Figure 39). Due to the former, the ability to capture the kinematic attributes related to Category 3 using the AVAL may be insensitive (e.g., rapid or uncontrolled movement). Nonetheless, it has been recommended that a valid measure of movement smoothness be “dimensionless” (i.e., independent of time and amplitude) (Balasubramanian et al., 2015).

Lastly, the focused quantitative analysis of arc length measures within the frontal plane may be less revealing than capturing and reporting other performance measures from sagittal or transverse planes, given the performance criterions relate to aberrant patterns that deviate from the frontal plane.

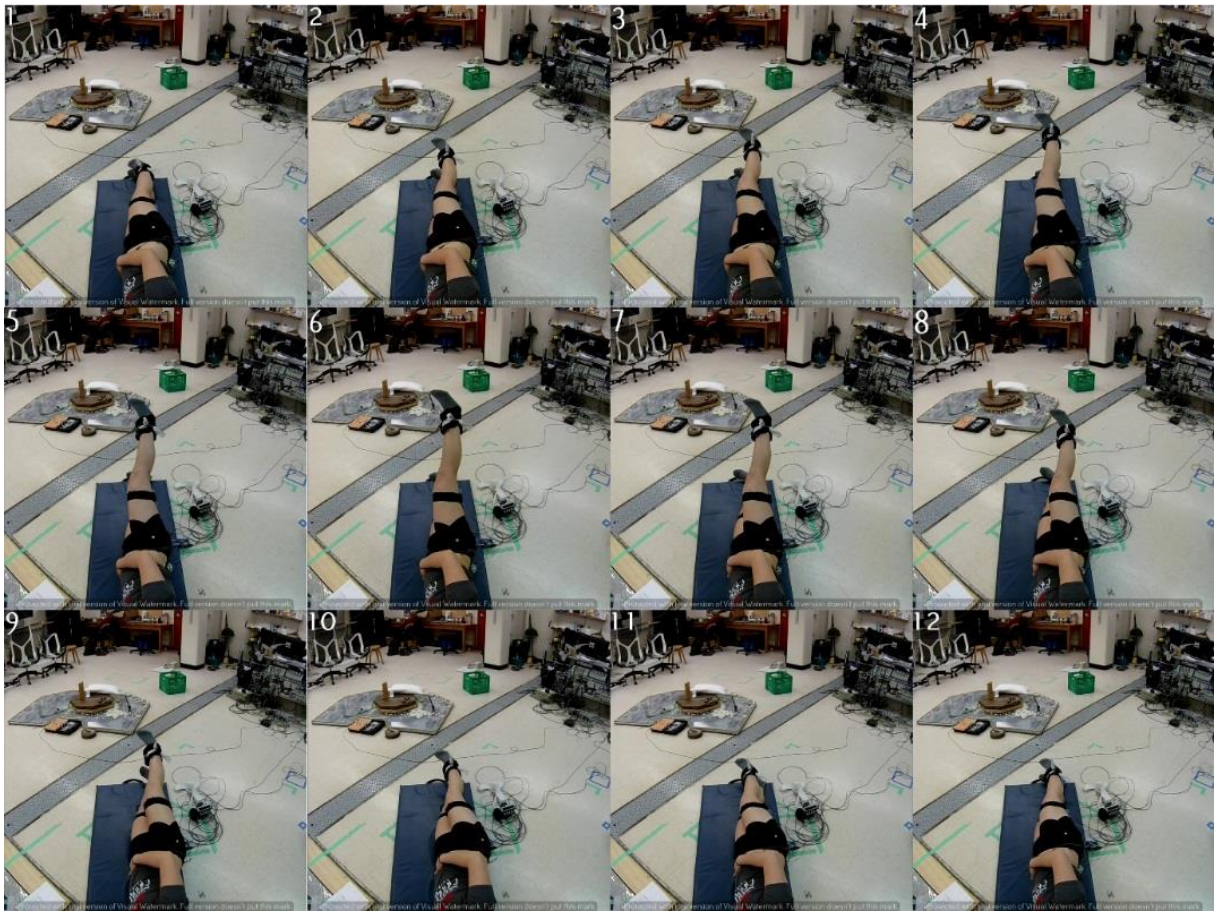


Figure 39 – A visual depiction of performance of a subject scored 3 in the AHA test with slight wobble at initiation or throughout, noticeable effort/'ratcheting', tipping of pelvis, trunk, or shoulder rotation, increased hip flexion/rotation of moving limb, and rapid or uncontrolled movement

Lastly, caution must be applied, as the findings are related to a non-clinically specialized research scientist rating the AHA performances of participants. Nonetheless, attempt to control for lack of experience was done by reviewing similar training material provided in a previous study and practice providing ratings with previous videos used (Davis et al., 2011). An intra-rater reliability of the current study revealed an $ICC_{(3,1)} = 0.72$. This value indicated ‘high correlation’

and close to the average intra-rater reliability of 0.74 from a group of practicing physical therapists, with values ranging from 0.53 to 0.93 (Davis et al., 2011). In addition, the differences in arc lengths for each category provides support for competent rating of AHA performances (Section 6.4.4.3).

A note of caution is due here since participants performed the active hip abduction on a 1.5-inch foam mat. This may have inadvertently induced increased instability (Gosselin & Fagan, 2015). This is contrary to support surfaces involving a yoga mat (Davis et al., 2011) or a massage table (Nelson-Wong, Flynn, et al., 2009); whereas others did not detail the support surface (Sorensen et al., 2016). However, the participant's weight may have been large enough to compress the mat and reach the rigid surface beneath the mat (Gosselin & Fagan, 2015). In addition, given the surface area being larger than the individual, the mat may have exerted shear forces with respect to the participant as they deformed into the mat (Gosselin & Fagan, 2015), increasing contact surface area with the sides of the body and thereby improving performance in the active hip abduction.

5.5 Reverse Side Bridge

The fifth question in this study sought to determine whether PDs would exhibit lower time to fatigue (in seconds) and greater fatigability during the reverse side bridge. Contrary to expectations, this study did not show any significant differences between PDs and non-PDs with their time to fatigue in the reverse side bridge. This finding broadly supports the work of other studies in this area investigating time to fatigue during a side bridge and pain status (Table 28). For instance, Nelson-Wong (2009) found no differences between PDs and non-PDs among a group of healthy university students. In addition, Bussey et al. (2016) found no differences between PDs and non-PDs; although participants were elite female field hockey players. In contrast to earlier findings, Marshall et al. (2011) found significant differences between PDs and non-PDs, with the side-bridge endurance revealing predictive capabilities (i.e., PDs had lower endurance times). Marshall et al. (2011) adapted endurance times from healthy university students reported by McGill et al. (1999) and recommended standard endurance times for males (83 seconds) and females (64 seconds). Individuals falling below these thresholds were indicative of increased likelihood for being a PD based on Marshall et al (2011) results. In corroboration with the latter, Viggiani & Callaghan (2018) found less endurance performance time in PDs compared to non-PDs during a dynamic hip abductor fatigue protocol.

It seems possible that a source of uncertainty in the current findings are due to differential demands imposed on the trunk and hip musculature across participants throughout the reverse side bridge performance. For instance, depiction of entire trials for three participants (Section 6.4.3.1) revealed higher %MVC for the GMED in comparison to the LES and EO muscles for subject 16 (male non-PD), whereas subject 3 (male non-PD) and subject 36 (female PD) had

higher %MVC for the EO in comparison to the LES and GMED muscles. Additionally, a posteriori analyses revealed the mean and peak %MVCs from previous studies (Table 29;Table 30) investigating the side bridge muscle activation are much lower relative the current study results (Section 6.4.4.4). The current study found the EO muscle exceeded an individual's maximal voluntary contraction – a phenomenon unobserved in previous studies. This finding is largely attributed to the recruitment of additional motor units due to the falling out of fatigued motor units and/or increased firing rates to maintain the test position (De Luca, 1997; Kamen & Gabriel, 2010). Unfortunately, these %MVC comparisons to the current study results must be interpreted with caution because of the different side bridge position used, different duration of trials, different electrode type, and not being performed until fatigue. The median power frequency slopes showed that the EO muscle, aside from the targeted GMED muscle, were fatigued and may have been the limiting factor in maintaining the test position Table 31). In addition, the EO muscles presented with steeper slopes, suggesting greater fatigability in those muscles.

Table 28 – Overview of holding duration times (in seconds) for pain status groups from current study and previous studies

Population	Pain Status	Current Study	McGill, Childs, & Liebenson (1999)	Nelson-Wong (2009)	Marshall et al. (2011)	Bussey et al. (2016)
University Student Population	non-PD	89 (40)	-	92 (39)	113 (21)	*78 (29)
	PD	79 (41)	-	98 (42)	78 (29)	*76 (37)
	-	-	83 (35)	-	-	-

*based on elite female field hockey players

Table 29 – Overview of mean (SD) of peak percent maximal voluntary contractions for each muscle during submaximal side bridge exertions from previous studies compared to the current study's reverse side bridge to fatigue exertions

Muscle	Current Study	McGill, Juker, & Kropf (1996)	McGill (1998)	Ekstrom et al. (2007)	Youdas et al. (2014)
QL	-	†54 (28)	-	-	-
LES	53 (21)	†24 (15)	-	*40 – 42 (17 – 24)	*19 – 34 (14 – 17)
EO	102 (42)	†40 (20)	50 (NA)	69 (26)	37 (23)
GMED	55 (21)	-	-	74 (30)	74 (31)

QL = Quadratus Lumborum; LES = Lumbar Erector Spinae; EO = External Oblique; GMED = Gluteus Medius

† based on intramuscular electrodes

*based on longissimus thoracis and lumbar multifidus muscles

Table 30 – Overview of mean (SD) of mean percent maximal voluntary contractions for each muscle during submaximal side bridge exertion from a previous study compared to the current study's reverse side bridge to fatigue exertions

Muscle	Current Study	Escamilla et al. (2016)
LAT	-	12 (10)
LES	21 (9)	29 (16)
EO	43 (18)	62 (37)
GMED	23 (10)	-

LAT = Latissimus Dorsi; LES = Lumbar Erector Spinae; EO = External Oblique; GMED = Gluteus Medius

Table 31 – Overview of mean (SD) of slopes (Hz/s) from regression lines from a previous study's side bridge to fatigue compared to current study's reverse side bridge to fatigue

Pain Status	Muscle	Current Study	Marshall et al. (2011)
non-PD	LES	-0.06 (0.09)	-
PD		-0.09 (0.09)	-
non-PD	EO	-0.10 (0.08)	-
PD		-0.11 (0.07)	-
non-PD	GMED	-0.06 (0.10)	* -0.12 (0.19)
PD		-0.05 (0.13)	* -0.07 (0.11)

LES = Lumbar Erector Spinae; EO = External Oblique; GMED = Gluteus Medius

*used pre-standing values from the authors' results

These inconsistencies across study results may be due to the position of the reverse side bridge relative to the original side bridge (i.e., task dependency). As means of simplification, the traditional side bridge may be thought of analogous to the 3-point bend test. The feet and forearm are in contact with the ground while the center of gravity of the person is applied about their waist (i.e., the fulcrum). A moment generated by the GMED abducts the hip to stabilize the pelvis from below the fulcrum (represented by the GRF generated at the feet), whereas the muscles about the scapulothoracic and glenohumeral joints act to stabilize the joints[12] and simultaneously generate an abduction moment about the shoulder to stabilize the pelvis from above the fulcrum and keep it from contacting the ground (represented by the GRF generated at the forearm). The shift in body position brought on by resting on the shoulder in the reverse side bridge as opposed to the forearm requires a torque above the pelvis to abduct the torso from the ground. Given the absent forearm ground contact prevents the shoulder girdle muscles (e.g., latissimus dorsi) to generate a moment, this function is shifted to the lateral core musculature and as a result, likely create a larger demand on the EO muscles and LES[13].

Despite the initial familiarization process during data collection, a posteriori analysis on order of performance may suggest a possible learning effect from performing the reverse side bridge for the first time on the one side of the body relative to the second time on the other side ($p < 0.05$). Although the inter-session reliability for the traditional side bridge has been well-established to be high (i.e., 0.91 – 0.96) (McGill et al., 1999; Nelson-Wong, 2009), whether this

[12] This assertion may be supported by the recommendation of performing side plank for post-rehabilitation of shoulder injuries (Pabian et al., 2011).
[13] These inferences are postulated and adapted from the comparison between front plank and v-sit performance being affected by shoulder function capacity (Musalem et al., 2015).

is the case for the reverse side bridge is unknown. In addition, this study utilized the simple criterion for task termination of the hip contacting the ground may have afforded participants' holding durations to be different from other methods. For instance, Liebenson et al. (2014) recommended that after two consecutive verbal cues to request the participant to raise any observed lowering of their pelvis, the test is terminated and the holding duration is recorded (Liebenson et al., 2014). In addition, Pabian et al. (2011) meticulously defined task failure with respect to a reduction in a target force and their inability to correct for it after three consecutive verbal cues; although it was for a different trunk endurance test (Pabian et al., 2011). It is recommended that other precise methods be employed to substantiate reliability and validity of the test.

A source of uncertainty as to whether sufficient time was allotted for recovery between side testing (i.e., perform test on the right side, rest, then perform test on the left side) is concerning. Prior studies have permitted a minimum of 5 minutes of recovery (McGill et al., 1999) and Pereira & Gonçalves (2008) revealed sEMG indicators recovered within 30 seconds after a submaximal isometric fatiguing task. However, participants' recovery in their exertion perception or their ability to sustain submaximal contractions similar to their initial values required more than 15-40 minutes post task termination (Lind, 1959; Pereira & Gonçalves, 2008). Nonetheless, 5 minutes of recovery used in this study enabled timely collection times and applicability in clinical settings. Lastly, there may be potential for bilateral muscle co-contraction despite the intended unilateral challenge imposed (Youdas et al., 2014). Future investigations to validate the test as a unilateral assessment is warranted.

5.6 Questionnaires

A secondary question in this study sought to determine whether PDs would exhibit similar characteristics in ankle function and beliefs/attitudes towards pain relative to non-PDs with the various questionnaires used in this study. Ankle function was investigated due to previous reports linking interventions involving alterations to foot/ankle position with reductions in self-reported LBP. For instance, sloped surfaces have shown to reduce self-reports of LBP in PDs and largely attributed to the consequential hip and trunk kinematic alterations brought on by the change in foot/ankle position (Gallagher et al., 2013; Nelson-Wong & Callaghan, 2010d). Contrary to expectations, this study did not find a significant difference between self-reported ankle function and pain status groups. Although there may be some evidence to suggest lower limb injuries to impact hip function (Friel et al., 2006; Steinberg et al., 2017), and theoretically, postural control during prolonged standing (Shumway-Cook & Woollacott, 2012), these self-reported ankle function measures did not show this to be the case.

Surprisingly, this study revealed significant differences between PDs and non-PDs for pain catastrophizing and fear of pain questionnaires. A posteriori analysis with two-way ANOVA revealed no significant sex effects for either the FOP or PCS scores. However, a posteriori analysis on the different subscales (i.e., severe, minor, and medical pain) in the FOP questionnaire revealed another surprising finding. The minor and medical pain subscale scores revealed no differences between pain status groups. However, the severe pain subscale scores were significantly different between PDs and non-PDs, with PDs scoring higher on the subscale (Section 6.4.4.5).

This finding is contrary to previous studies which have suggested that individual psychosocial factors (i.e. beliefs and attitudes regarding disability, injury, and pain) did not reveal differences between PDs or non-PDs (Gallagher & Callaghan, 2015a; Nelson-Wong, 2009). This result may be explained by the fact that Nelson-Wong (2009, p. 48-49) administered modified questionnaires which included the following: Cognitive Risk Profile for Pain (CRPP) (Cook & Degood, 2006), the Survey of Pain Attitudes-b (SOPA-b) (Tait & Chibnall, 1997), and the Fear Avoidance Beliefs Questionnaire (FABQ) (Waddell et al., 1993). These questionnaires differed from the ones used in this current study.

When comparing the average FOP total scores from the current study's PDs and non-PDs to previous studies examining university student populations, PDs from this current study exhibited higher fear of pain (Table 32). However, examining the average subscale total scores from the current study's PDs and non-PDs (Table 33) reveal similar values in minor and medical subscales to a different university student population (n = 660) (McNeil & Rainwater, 1998). However, the severe subscale in PDs resembled those of chronic pain patients (i.e., patients suffering from neck pain, head pain, and chest pains) c. Despite the health screening questionnaires, this result may suggest that PDs in this study may have had ailments in other regions outside of the emphasized lumbopelvic region and hip injuries that were not explicitly reported by participants and used for exclusion from participation.

Table 32 – Overview of total non-adjusted mean (standard deviation) fear of pain questionnaire scores (ranging from 30-150) for each group and corresponding study

Population	Pain Status	Current Study	Sorensen et al. (2016)	McNeil & Rainwater (1998)
University Student Population	non-PD	71.7 (22.8)	69.3 (20.6)	
	PD	85.8 (18.2)	*66.6 (21.5) to *76.5 (18.2)	
	-	-		79.0 (19.0)
Medical Patients				78.1 (25.1)
Chronic Pain Patients				79.7 (16.2)

*based on PDs categorized with a different VAS threshold

Table 33 – Overview of total subscale non-adjusted mean (standard deviation) fear of pain questionnaire scores for each pain status group

Population	Pain Status	Subscale	Current Study	McNeil & Rainwater (1998)
University Student Population	non-PD	Medical	23.0 (9.3)	-
		Minor	16.3 (6.4)	-
		Severe	32.4 (9.0)	
	PD	Medical	26.6 (7.8)	
		Minor	19.4 (4.7)	
		Severe	39.8 (6.6)	
	-	Medical		27.0 (8.5)
		Minor		18.4 (6.0)
		Severe		33.5 (8.7)
Medical Patients	-	Medical		24.7 (9.3)
		Minor		19.6 (8.3)
		Severe		33.8 (11.0)
Chronic Pain Patients	-	Medical		23.4 (6.3)
		Minor		19.2 (6.1)
		Severe		37.1 (7.4)

The questionnaires used in this study were also implemented by Sorensen et al. (2016), who examined the relationship between the intensity of the LBP developed during prolonged standing and measured scores of attitudes towards fear of pain (i.e. Fear of Pain Questionnaire-III or FPQ-III) (McNeil & Rainwater, 1998) and catastrophic thoughts towards pain (i.e. Pain Catastrophizing Scale or PCS) (Sullivan et al., 1995) in PDs and non-PDs. The researchers found no group differences in scores on FPQ-III or PCS when categorizing non-PDs and subgroups of PDs (PDs separated based on the maximum and average VAS scores of < 20 mm or ≥ 20 mm). However, large relationships between the FPQ-III and PCS were found in average VAS ($r = 0.87$ - 0.97; $p = 0.03$; 0.06) and to a lesser extent in max VAS scores ($r = 0.53$ - 0.60; $p = 0.30$; 0.36) $\geq$ 20 mm in self-reported pain in PDs (Sorensen, George, et al., 2016). These relationships suggest that PDs with ≥ 20 mm of pain reports may have psychological beliefs that, when reaching a specific level of self-reported pain, may differ in subsequent pain reports. Based on the researcher's preliminary data (i.e., only 5 subjects made up the PD ≥ 20 mm group), psychological factors on attitudes and thoughts towards pain do not differ at baseline between PDs and non-PDs. Rather, it was suggested that psychological factors modulate pain at a "clinically relevant threshold" and explains the severity of pain or pain perception rather than affecting the likelihood of LBP development during standing (Sorensen, George, et al., 2016). However, Hwang et al. (2018) found no differences in PCS scores between PDs and non-PDs.

In contrast to the former, this study results suggests some measure of pre-disposing differences in psychological measures and pain status during prolonged standing. However, these results need to be interpreted with caution, given the absence of stricter exclusion criteria (Hwang et al., 2018) and the current study's inclusion of participants who may have experienced

lower limb injuries. In addition, the severe pain scale was previously seen to be significantly different between chronic pain patients relative to healthy controls (McNeil & Rainwater, 1998). The aforementioned further supports the assertion for cautioned interpretation.

5.7 Hip Abductor Strength

A secondary question in this study sought to determine whether PDs would exhibit similar hip abduction strength compared to non-PDs. Not surprisingly, this study did not show any significant differences between PDs and non-PDs. This finding was also reported by Marshall et al. (2011). This result may be explained by the fact that a risk factor for developing LBP during standing does not correspond directly to hip abductor strength but more so to its capacity, with strength implying what can be performed in a single exertion, whereas capacity reflects what can be done for an extended duration (Ayoub, 1989). Given the low level demand of constrained standing, the aforementioned is supported by previous indicators suggesting an aberrant activation pattern during prolonged standing preceding pain development (Gallagher, 2015; Nelson-Wong, 2008) and efficacy of an exercise intervention focused on the lumbopelvic region (Nelson-Wong & Callaghan, 2010a).

5.8 Limitations

Several general limitations are present within the methods employed. These findings cannot be extrapolated to all patients, given the focus on a healthy asymptomatic university population. In addition, emphasis on exclusion criteria based on previous studies was focused on the lumbopelvic region. However, participants with history of lower limb injuries or manual materials handling experience were not explicitly excluded, which may have confounded the results involving the lower limb performance (e.g., during the mSEBT) or trunk kinematics (e.g., during lifting).

The completion of the two sessions were not constrained to a specific period between sessions. This period between sessions ranged from several days to several weeks; only one male non-PD returned after a few months. As a result, participants' physical condition measures may have changed within the period preceding the second session. However, the researcher took measures to inquire about whether any changes occurred in physical health in between the first and second session that may have altered their eligibility for participation.

Baseline differences observed between pain status groups in fear of pain and pain catastrophizing questionnaires may indicate these stratified groups from this study are different from previously stratified groups and potentially confounded the results. Nonetheless, a posteriori analyses of subscales for fear of pain questionnaire revealed that PDs did not differ in their minor or medical pain subscales and that these values were similar to a previously larger sample size (n = 660) of university students (McNeil & Rainwater, 1998). Given that standing-induced LBP is transient in nature and dissipates upon standing cessation, it may be considered a minor type of pain. This suggests pain status groups were comparable. In addition, the severe

subscale values in PDs resembled those of previously reported chronic pain patients (i.e., patients suffering from neck pain, head pain, and chest pains) (McNeil & Rainwater, 1998). Despite the health screening questionnaires, this result may suggest that PDs in this study may have had previous ailments in other regions outside of the emphasized lumbopelvic region and hip injuries used in this study. Nonetheless, the symmetric-trunk flexion tasks used in this study has been used to clearly distinguish healthy controls from low back pain patients. This study results did not reveal differences between pain status groups, providing additional evidence for pain status groups being back healthy participants prior to and during study participation.

Lastly, the data reduction measures employed in this study consequently disregards the temporal characteristics of participant's kinematics throughout their various task performances. There may be a possibility that despite similar motion patterns, differences with respect to joint loading may be evident across participants (Wrigley et al. 2005).

Chapter 6 – Conclusions

The aim of the present research was to examine the movement behavior and muscle recruitment patterns in healthy individuals that either develop transient low back pain (LBP) during standing (i.e., pain-developers or PDs) or not (i.e., non-pain developers or non-PDs), during a protocol of tasks with increased functional demand and variety. The results of this investigation show that the low and/or high-demand challenges of the symmetric trunk flexion-extension (STF) exertions, symmetric floor-to-knuckle lift (SLIFT), modified star excursion balance test (mSEBT) and the reverse side bridge (RSB) may have demonstrated changes in various kinematic and muscle activation patterns across participants. However, it did not always coincide with an individual's pain status. It is therefore unlikely that such connections exist between these tasks and higher demand challenges to elicit previously unseen or larger differences and to reinforce pre-existing movement and muscle recruitment differences between pain status groups. One of the more significant findings to emerge from this study is the potential interaction an external weight has on pain status with their performance during the active hip abduction, with greater difficulty observed in PDs relative to non-PDs. In addition, quantitative validation of the active hip abduction (AHA) test and its' criterion scores further support its' validity and usefulness as performance indicators for risk of standing LBP development. Taken together, these findings provide minimal support for PDs to be a high-risk group and for standing induced LBP to be a by-product of pre-existing neuromuscular control differences.

6.1 Contributions

The findings reported here shed new light on the following:

1) Various kinematic and muscle sequencing measures during submaximal and maximal exertions in symmetric trunk flexion-extension and symmetric lifting does not differ between pain developers and non-pain developers.

2) Kinematic and dynamic postural control measured during the modified star excursion balance test do not differ between pain developers and non-pain developers

3) The potential utility of weighted active hip abduction test that may enable screening and stratification of individuals that are at risk for standing LBP development and quantitative support/validation of its' use.

4) Muscular endurance and fatigability during the reverse side bridge does not differ between pain developers and non-pain developers; though differential responses of hip and trunk musculature were observed across participants.

5) Expanded knowledge upon previous findings in the literature and further support or rejection of existing conclusions about this topic.

6.2 Future Directions

This research has created many questions in need of further investigation:

1) In-depth analyses of kinematic variables throughout partitioned stages of trunk-flexion extension and symmetric lifting.
2) Future studies may consider investigating balance control using force plate parameters during the star excursion balance test or assessing through other means (e.g., support surface translations).
3) Further research could explore the feasibility of inertial measurements units on patients for immediate quantitative measures of the active hip abduction within a clinical setting.
4) More information on different horizontal positions of the reverse side bridge to determine efficacy in evaluating lateral core and hip musculature.
5) Further work may benefit to establish whether thorough evaluation of foot and ankle (e.g., chronic ankle instability) function and its' relationship with pain status groups.
6) Investigate the constructs of physical literacy and its' relationship with balance control within pain status groups

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6.4 Appendices

6.4.1 Appendix A – Questionnaires

6.4.1.1 Modified Minnesota Physical Activity Questionnaire

#	Activity	Metabolic Activity	Weeks	Frequency	Duration	AMI
010	Walking for pleasure	3.5				
020	Walking to Work/School	4.0				
030	Use stairs when elevator is available	8.0				
040	Cross-country Hiking	6.0				
050	Back Packing	7.0				
060	Mountain Climbing	8.0				
115	Bicycling to Work and/or for Pleasure	8.0				
125	Dancing-Ballroom, Square and/or Disco	4.5				
135	Dancing- Aerobic, Ballet	6.5				
140	Horseback Riding	4.0				
150	Home Exercise	3.5				
160	Health Club Exercise	7.0				
180	Jog/Walk Combination	6.0				
200	Running	8.0				
210	Weight Lifting	3.0				
220	Water Skiing	6.0				
235	Sailing in Competition	5.0				
250	Canoeing or Rowing for Pleasure	3.5				
260	Canoeing or Rowing for Competition	12.0				
270	Canoeing on a Camping Trip	4.0				
280	Swimming (at least 50 ft) at a Pool	6.0				
295	Swimming at the Beach	6.0				
310	Scuba Diving	7.0				
320	Snorkeling	5.0				
340	Snow Skiing, Downhill	6.0				
350	Snow Skiing, Cross Country	8.0				
360	Ice (or Roller) Skating	7.0				
370	Sledding or Tobogganing	7.0				
390	Bowling	3.0				
400	Volleyball	4.0				
410	Table Tennis	4.0				
420	Tennis, Singles	8.0				

430	Tennis, Doubles	5.0				
440	Softball	5.0				
450	Badminton	7.0				
460	Paddle Ball	6.0				
470	Racket Ball	7.0				
480	Basketball: Non-Game	6.0				
490	Basketball: Game	8.0				
500	Basketball: Officiating	7.0				
510	Touch Football	8.0				
520	Handball	12.0				
530	Squash	12.0				
540	Soccer	7.0				
070	Riding a Power Cart	3.5				
080	Walking, Pulling Clubs on Cart	4.3				
090	Walking and Carrying Clubs	4.5				
550	Mowing Lawn With Riding Mower	2.5				
560	Mowing Lawn Walking Behind Power Mower	5.5				
570	Mowing Lawn Pushing Hand Mower	6.0				
580	Weeding and Cultivating Garden	4.5				
590	Spading, Digging, Filling in Garden	5.0				
600	Raking Lawn	4.0				
610	Snow Shoveling by Hand	6.0				
620	Carpentry in Workshop	3.0				
630	Painting, Wallpapering Inside House	4.5				
640	Carpentry Outside	6.0				
650	Painting Outside of House	5.0				
660	Fishing from River Bank	4.0				
670	Fishing in Stream with Wading Boots	6.0				
680	Hunting Pheasants or Grouse	6.0				
690	Hunting Rabbits, Prairie Chickens, Squirrels, Raccoon	5.0				
710	Hunting Large Game: Deer, Elk, Bear	6.0				
	Ice Hockey	8.0				
					Total	

6.4.1.2 Fear of Pain Questionnaire III

Fear of Pain Questionnaire—III

Name: _____ Date: _____

INSTRUCTIONS: The items listed below describe painful experiences. Please look at each item and think about how FEARFUL you are of experiencing the PAIN associated with each item. If you have never experienced the PAIN of a particular item, please answer on the basis of how FEARFUL you expect you would be if you had such an experience. Circle one rating per item to rate your FEAR OF PAIN in relation to each event.

AMOUNT OF FEAR					
Not at All	A little	A Fair Amount	Very Much	Extreme	
1	2	3	4	5	1. Being in an automobile accident
1	2	3	4	5	2. Biting your tongue while eating
1	2	3	4	5	3. Breaking your arm
1	2	3	4	5	4. Cutting your tongue licking an envelope
1	2	3	4	5	5. Having a heavy object hit you in the head
1	2	3	4	5	6. Breaking your leg
1	2	3	4	5	7. Hitting a sensitive bone in your elbow-your "funny bone"
1	2	3	4	5	8. Having a blood sample drawn with a hypodermic needle
1	2	3	4	5	9. Having someone slam a heavy car door on your hand
1	2	3	4	5	10. Falling down a flight of concrete stairs
1	2	3	4	5	11. Receiving an injection in your arm
1	2	3	4	5	12. Burning your fingers with a match
1	2	3	4	5	13. Breaking your neck
1	2	3	4	5	14. Receiving an injection in your hip/buttocks
1	2	3	4	5	15. Having a deep splinter in the sole of your foot probed and removed with tweezers
1	2	3	4	5	16. Having an eye doctor remove a foreign particle stuck in your eye
1	2	3	4	5	17. Receiving an injection in your mouth
1	2	3	4	5	18. Being burned on your face by a lit cigarette
1	2	3	4	5	19. Getting a paper-cut on your finger
1	2	3	4	5	20. Receiving stitches in your lip
1	2	3	4	5	21. Having a foot doctor remove a wart from your foot with a sharp instrument
1	2	3	4	5	22. Cutting yourself while shaving with a sharp razor
1	2	3	4	5	23. Gulping a hot drink before it has cooled
1	2	3	4	5	24. Getting strong soap in both your eyes while bathing or showering
1	2	3	4	5	25. Having a terminal illness that causes you daily pain
1	2	3	4	5	26. Having a tooth pulled
1	2	3	4	5	27. Vomiting repeatedly because of food poisoning
1	2	3	4	5	28. Having sand or dust blow into your eyes
1	2	3	4	5	29. Having one of your teeth drilled
1	2	3	4	5	30. Having a muscle cramp

Note. The FPQ-III is copyrighted by the authors. Permission is given for users to reproduce this instrument for clinical and research purposes.

6.4.1.3 Cumberland Ankle Instability Tool Questionnaire

Please tick the ONE statement in EACH question that BEST describes your ankles.

	LEFT	RIGHT
1. I have pain in my ankle		
Never	☐	☐
During sport	☐	☐
Running on uneven surfaces	☐	☐
Running on level surfaces	☐	☐
Walking on uneven surfaces	☐	☐
Walking on level surfaces	☐	☐
2. My ankle feels UNSTABLE		
Never	☐	☐
Sometimes during sport (not every time)	☐	☐
Frequently during sport (every time)	☐	☐
Sometimes during daily activity	☐	☐
Frequently during daily activity	☐	☐
3. When I make SHARP turns, my ankle feels UNSTABLE		
Never	☐	☐
Sometimes when running	☐	☐
Often when running	☐	☐
When walking	☐	☐
4. When going down the stairs, my ankle feels UNSTABLE		
Never	☐	☐
If I go fast	☐	☐
Occasionally	☐	☐
Always	☐	☐
5. My ankle feels UNSTABLE when standing on ONE leg		
Never	☐	☐
On the ball of my foot	☐	☐
With my foot flat	☐	☐
6. My ankle feels UNSTABLE when		
Never	☐	☐
I hop from side to side	☐	☐
I hop on the spot	☐	☐
When I jump	☐	☐
7. My ankle feels UNSTABLE when		
Never	☐	☐
I run on uneven surfaces	☐	☐
I jog on uneven surfaces	☐	☐
I walk on uneven surfaces	☐	☐
I walk on a flat surface	☐	☐
8. TYPICALLY, when I start to roll over (or "twist") on my ankle, I can stop it		
Immediately	☐	☐
Often	☐	☐
Sometimes	☐	☐
Never	☐	☐
I have never rolled over on my ankle	☐	☐
9. After a TYPICAL incident of my ankle rolling over, my ankle returns to "normal"		
Almost immediately	☐	☐
Less than one day	☐	☐
1–2 days	☐	☐
More than 2 days	☐	☐
I have never rolled over on my ankle	☐	☐

6.4.2 Appendix B – Task Instructions

Symmetric Trunk Flexion-Extension[14]

1. Cross your arms in front of your chest
2. Stand with your feet shoulder width apart, and keep them in the same location for all conditions

    a. This is your starting position.

3. While maintaining straight knees, bend your trunk forward and back to your starting position:

    a. [at a self-selected speed]
    b. [as fast as you comfortably can]

4. Do you have any questions?

Number of Practice Trials

1. Self-selected

Number of Testing Trials

1. Only 3

Rest Time

1. Self-selected or researcher imposed

Signs of Failure

1. Unable to maintain straight knees
2. Arms not crossed

[14] Adapted from Marras et al. (1990)

Symmetric Floor-To-Knuckle Lift and Lower[15]

1. You will lift the ___ kg (low load = [M] empty / [F] empty or high load = [M] 18 kg / [F] 12 kg) crate from the floor to knuckle height

    a. [at a self-selected speed]
    b. [as fast as you comfortably can]

    and then lower it back down.

2. The crate is to be lifted with the handles on the sides of the crate.
3. Keep your feet shoulder width apart and do not move your feet while lifting.
4. Lift with your "natural lifting technique". This means you can choose your preferred strategy to lift the box.
5. _____ will instruct you on when to lift the crate off the ground and when to place it back down.
6. Do you have any questions?

Number of Practice Trials

1. Self-selected

Number of Testing Trials

1. Only 3 for each condition

Rest Time

1. Self-selected or researcher imposed

Signs of Failure

1. Lifts heel off the ground

[15] Adapted from Chen (2012)

Modified Star Excursion Balance Test[16]

1. Please position your standing foot (RIGHT/LEFT) appropriately with the line.
2. Stand with your hands across your chest and feet together.
3. This is your starting position.
4. Use your other foot (RIGHT/LEFT) to reach as far as possible in the (ANT, PLAT, PMED) direction and make a light tap on the tape and, without pushing off the ground, return your foot back to the starting position.
5. You may make any movements you wish to reach as far as possible, as long as you keep your stance foot planted and your hands on your shoulders.
6. Do you have any questions?

Number of Practice Trials[17]

1. 4-6 in each direction

Number of Testing Trials

1. 3 in each direction (ANT, PLAT, PMED)

Rest Time

1. Self-selected or researcher imposed

Signs of Failure[18]

1. Not keeping hands across chest
2. Lifts the heel or shifts any part of the stance foot
3. Making 'heavy' contact on the ground with the reaching limb
4. Attempting to regain balance by using the reaching limb to contact the ground or unable to exhibit controlled return from maximum reach
5. Does not make contact with the tape

[16] Adapted from Gribble et al. (2013)
[17] Adapted from Hertel et al. (2000) and Kinzey & Armstrong (1998)
[18] Adapted from Gribble et al. (2012)

Active Hip Abduction Test[19]

Participants will be placed into a side-lying position with both lower extremities straight and aligned with the torso. The pelvis will be positioned so that it is in the frontal plane and perpendicular to their support surface.

1. Place your bottom hand underneath head and top hand on your stomach
2. This is your starting position
3. While keeping your knee straight and legs in line with your body, please raise your top thigh and leg towards the ceiling up to the height I showed you
4. Then return to your starting position
5. Try not to let your hip/pelvis tip forwards or backwards
6. Do you have any questions?

Number of Practice Trials

1. None; participants were taken through the motion passively by the researcher

Number of Testing Trials

1. Only 1 on each side

Rest Time

1. Self-selected or researcher imposed

Signs of Failure

1. Refer to **Error! Reference source not found.** on different evaluation categories

[19] Adapted from Nelson-Wong et al. (2009, 2013)

Reverse Side Bridge[20]

Participants will be placed into a side-lying position with both lower extremities straight and aligned with the torso. Based on their preference, a combination of a foam mat and pillow(s) will be used to rest their head and shoulder. For standardizing purposes, their feet (level of the malleolus) will be placed on top of a height-adjustable board that has been set to half of the participant's shoulder width.

1. When I say "go", you will support yourself on your shoulder and feet while lifting your hips off the floor to create a straight line over the length of your body
2. You will maintain this position for as long as you can
3. Do you have any questions?

Number of Practice Trials

1. None; just familiarization with position

Number of Testing Trials

1. Only 1 on each side to failure

Rest Time

1. Minimum of 5 minutes

Signs of Failure[21]

1. When the participant's hip makes contact with the floor

[20] Adapted from McGill (2009) and Tvrdy (2012)
[21] Adapted from McGill et al. (1999)

6.4.3 Appendix C – A Priori Analyses: Additional Figures

6.4.3.1 Reverse Side Bridge Muscle Activation Responses

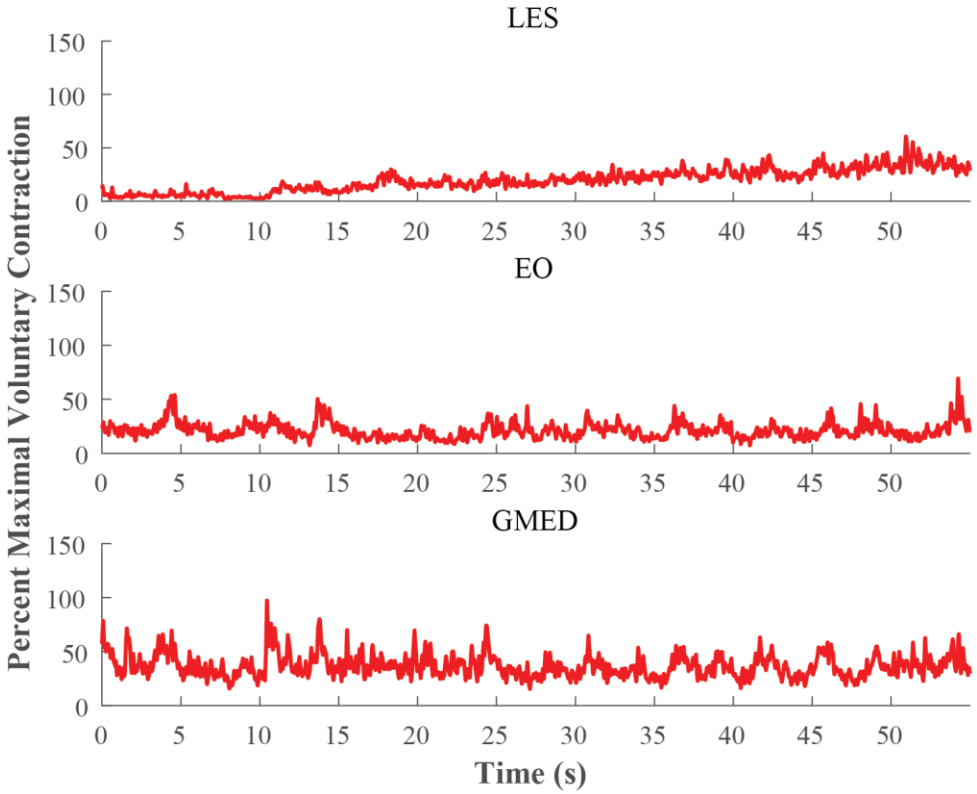

Figure 40 – Depiction of percent maximal voluntary contraction throughout a male non-PD (subject 16) reverse side bridge on the right side. All muscles presented are from the right side only.

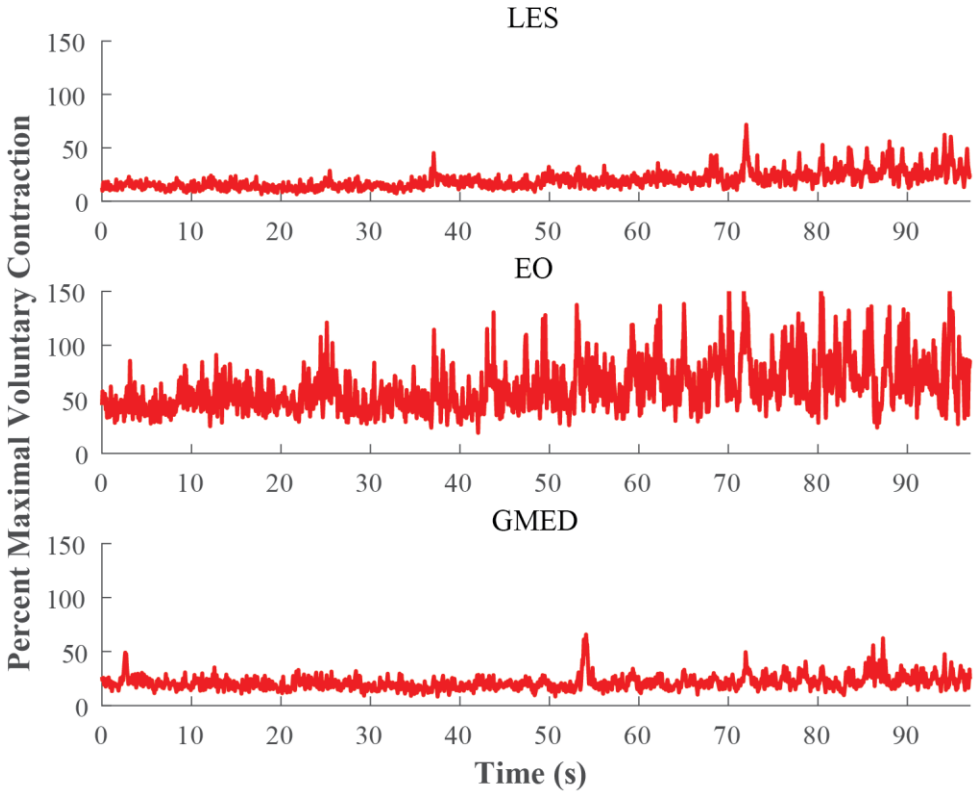

Figure 41 – Depiction of percent maximal voluntary contraction throughout a male non-PD (subject 2) reverse side bridge on the left side. All muscles presented are from the left side only.

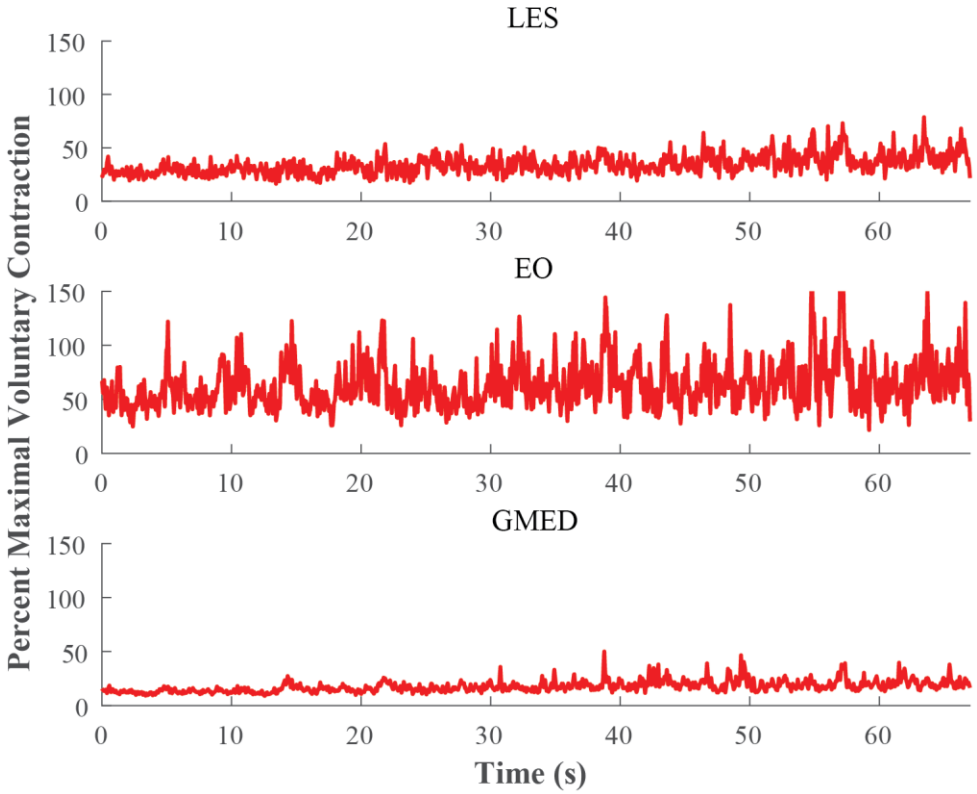

Figure 42 – Depiction of percent maximal voluntary contraction throughout a female PD (subject 36) reverse side bridge on the right side. All muscles presented are from the right side only.

6.4.4 Appendix D – A Posteriori Analyses: Additional Results

6.4.4.1 Symmetric Trunk Flexion Task Order Effects

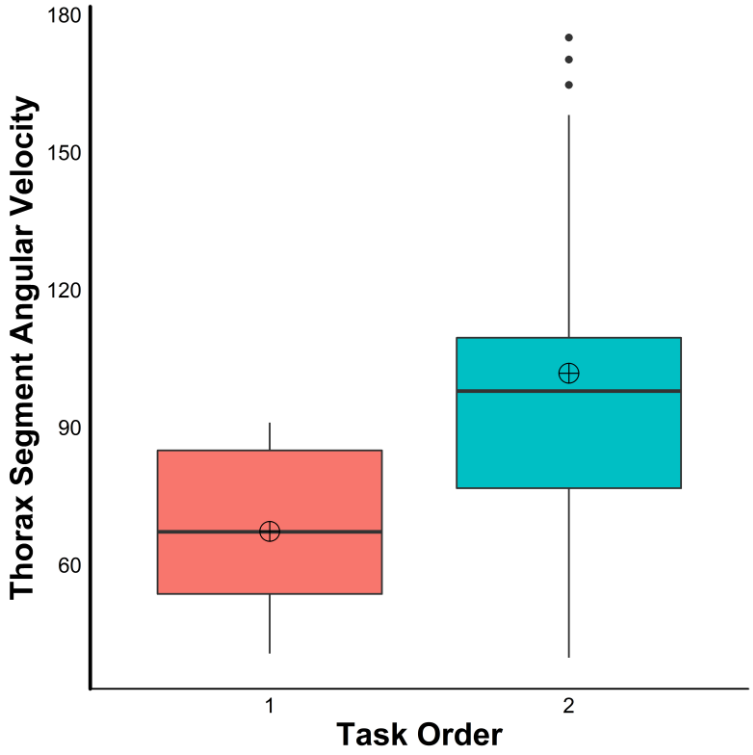

Figure 43 – Boxplot of thorax segment angular velocity during extension from trunk-flexion, organized by participants who performed the STF first (1) or performed it second (2). ⊕ = unadjusted means. Dots represent outliers.

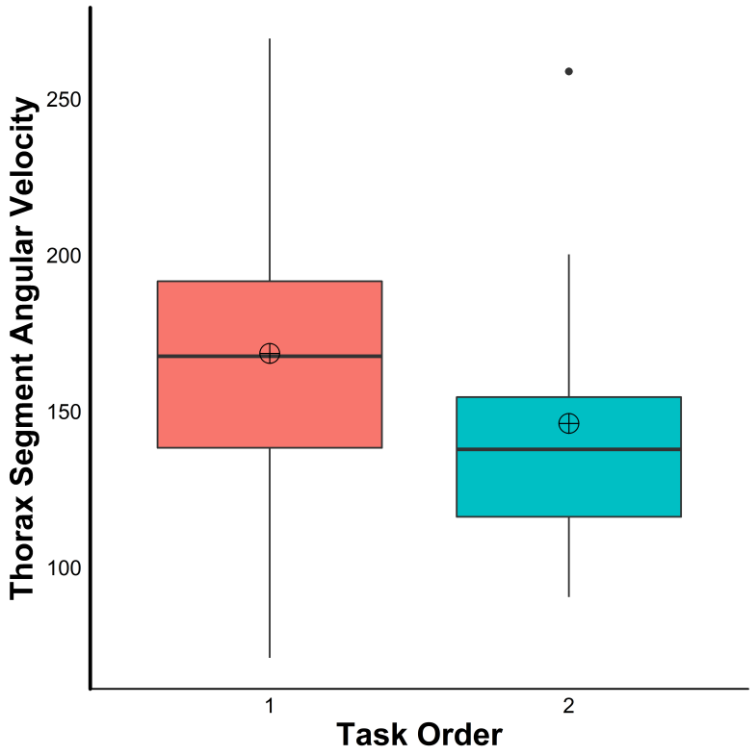

Figure 44 – Boxplot of thorax segment angular velocity during extension from trunk-flexion, organized by participants who performed the STF+ first (1) or performed it second (2). ⊕ = unadjusted means. Dots represent outliers.

6.4.4.2 Modified Star Excursion Balance Test Joint Angles

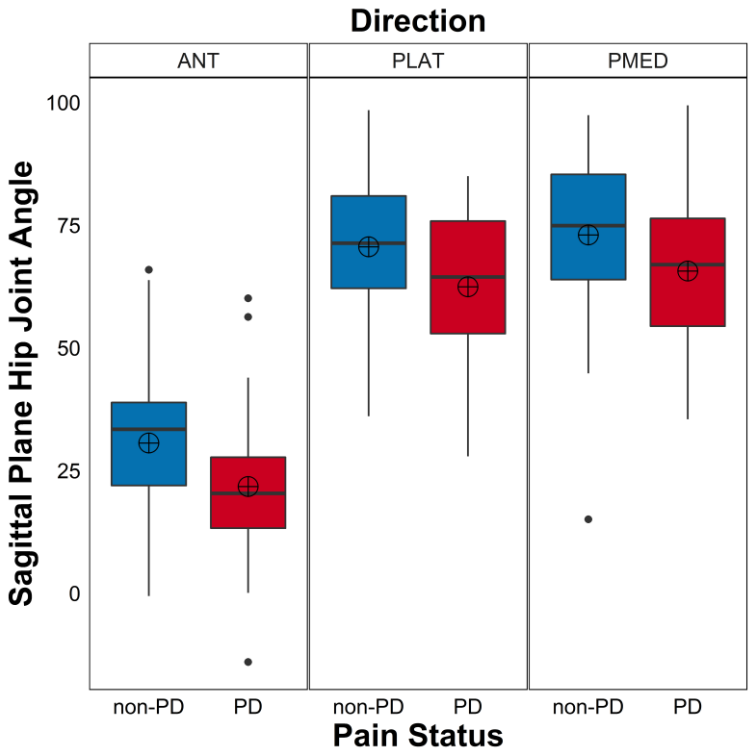

Figure 45 – Boxplot of sagittal plane hip joint angle at the moment of maximum reach for pain status groups facetted by direction of reach. Larger positive values indicate larger hip flexion. ⊕ = unadjusted means. Dots represent outliers.

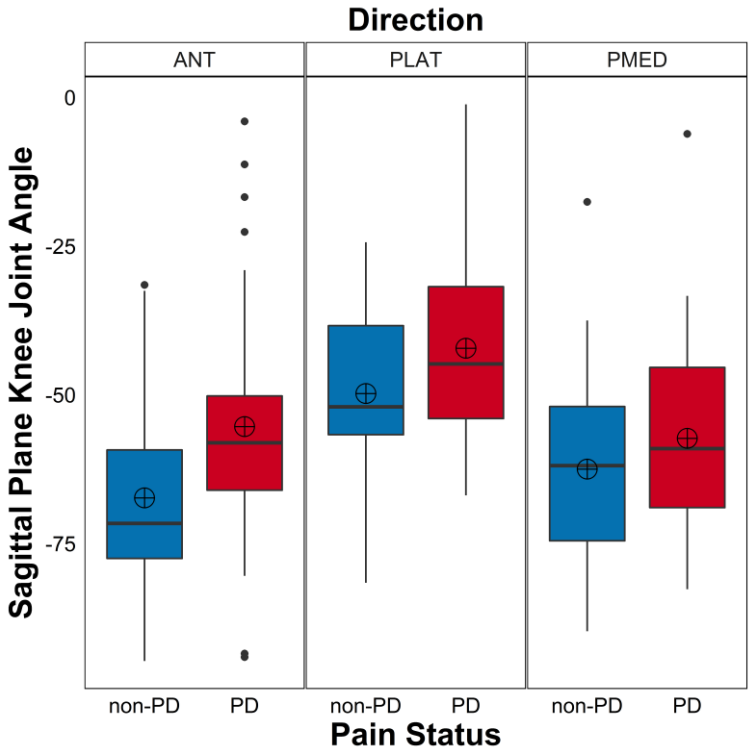

Figure 46 – Boxplot of sagittal plane knee joint angle at the moment of maximum reach for pain status groups facetted by direction of reach. Larger negative values indicate larger knee flexion. ⊕ = unadjusted means. Dots represent outliers.

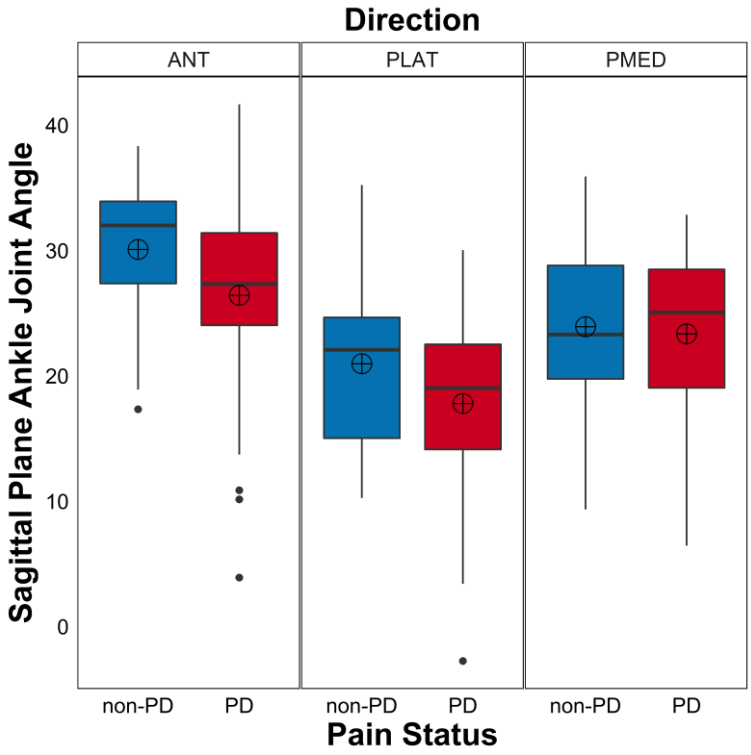

Figure 47 – Boxplot of sagittal plane ankle joint angle at the moment of maximum reach for pain status groups facetted by direction of reach. Larger positive values indicate larger dorsiflexion. ⊕ = unadjusted means. Dots represent outliers.

6.4.4.3 Active Hip Abduction Arc Length and Corresponding Score

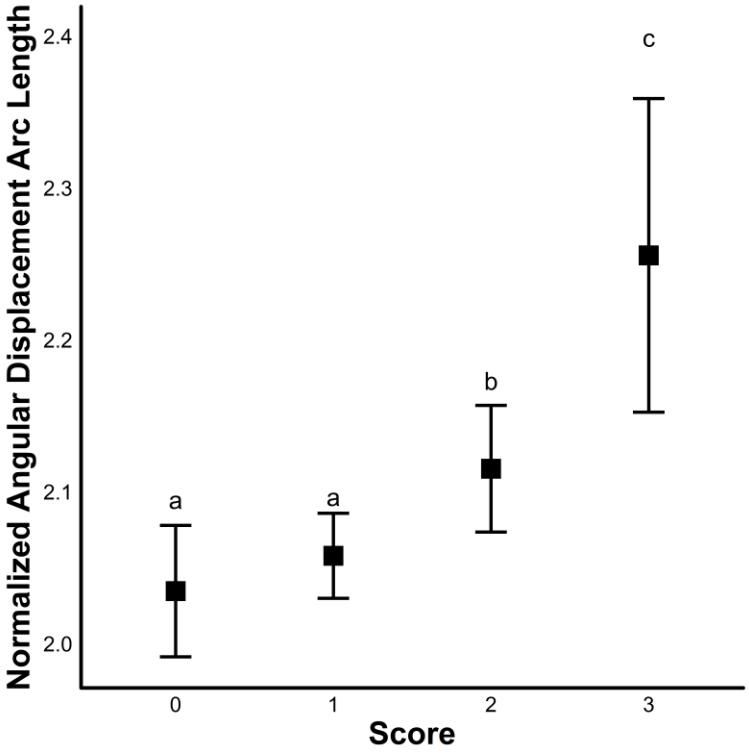

Figure 48 – Least square means plot of angular displacement arc length within each score/category. Means sharing a letter are not significantly different from each other (Tukey-adjusted pairwise comparisons). Error bars represent 95% confidence intervals. Combined participant count for scores 0 – 3 during both AHA and AHA+ are: 13, 46, 17, and 2, respectively.

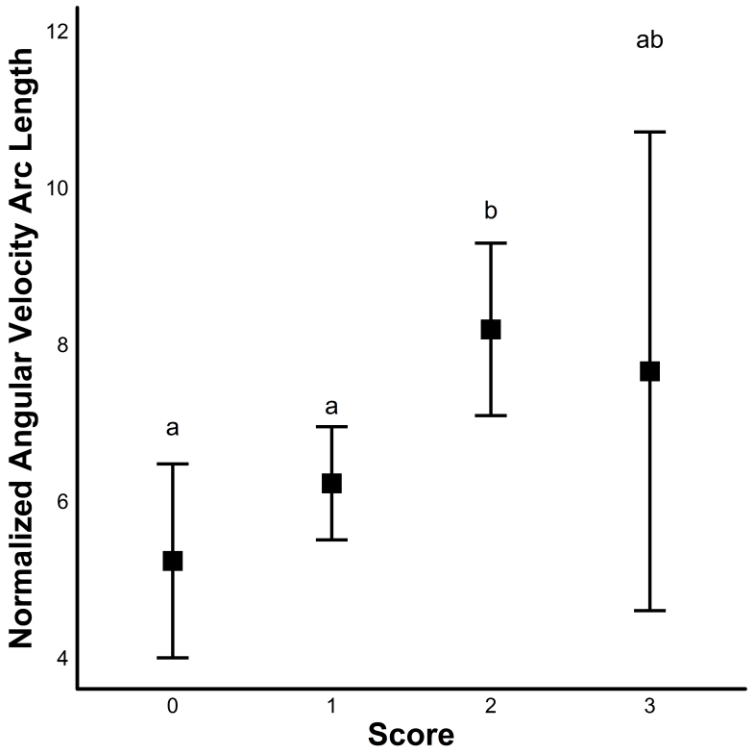

Figure 49 – Least square means interaction plot of angular velocity arc length within each score/category. Means sharing a letter are not significantly different from each other (Tukey-adjusted pairwise comparisons). Error bars represent 95% confidence intervals. Combined participant count for scores 0 – 3 during both AHA and AHA+ are: 13, 46, 17, and 2, respectively.

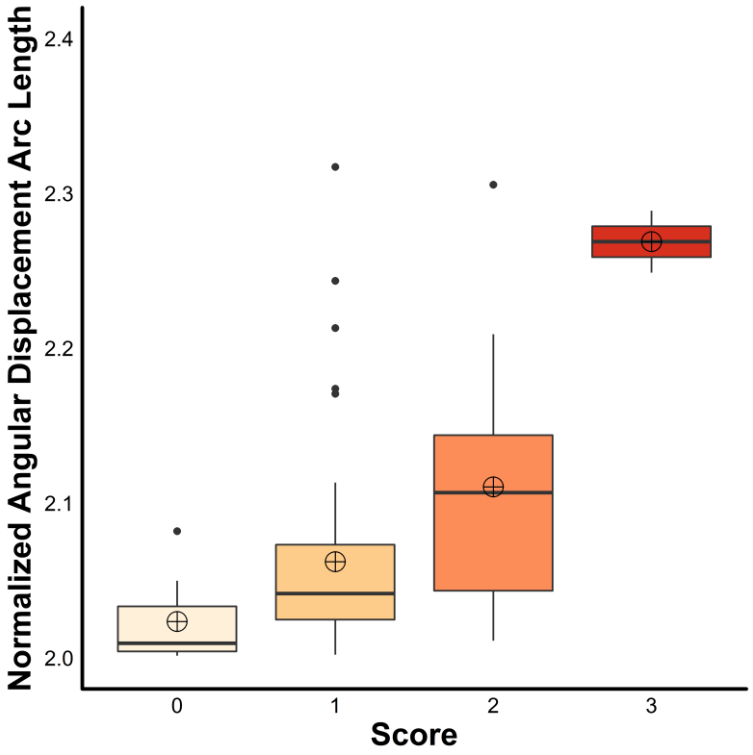

Figure 50 – Boxplot of normalized angular displacement arc length organized by rater-assessed active hip abduction score. ⊕ = unadjusted means. Combined participant count for scores 0 – 3 during both AHA and AHA+ are: 13, 46, 17, and 2, respectively. Dots represent outliers.

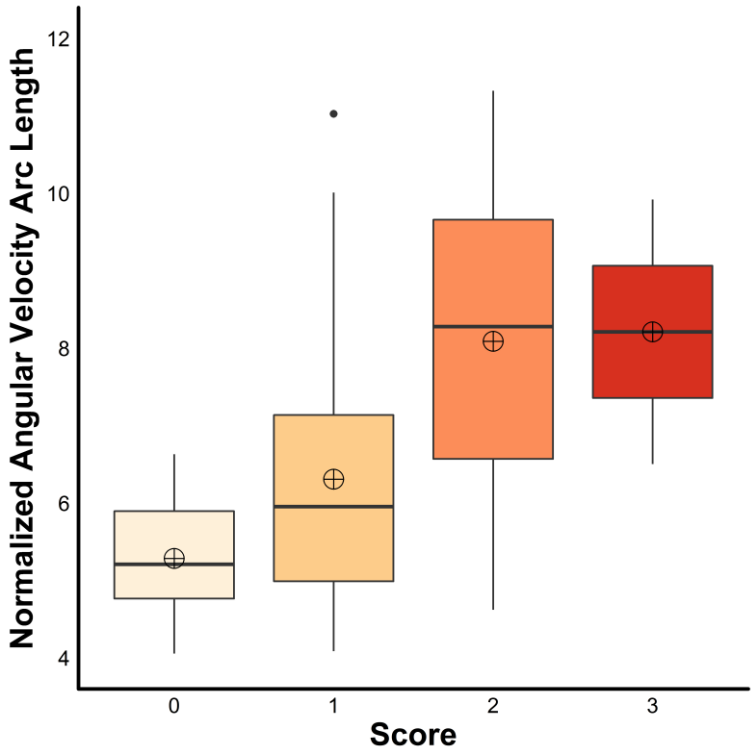

Figure 51 – Boxplot of normalized angular velocity arc length organized by rater-assessed active hip abduction score. ⊕ = unadjusted means. Combined participant count for scores 0 – 3 during both AHA and AHA+ are: 13, 46, 17, and 2, respectively. Dots represent outliers.

6.4.4.4 Reverse Side Bridge Trial Average and Peak Percent Maximal Voluntary Contractions

Table 34 – Non-adjusted mean of average percent maximal voluntary contraction during the RSB

Pain Status	Sex	Muscle	Mean	SD	SE
non-PD	F	LES	21.5	8.1	1.7
		EO	49.6	17.0	3.5
		GMED	27.4	10.3	2.1
	M	LES	18.1	8.5	1.9
		EO	29.9	10.5	2.4
		GMED	18.2	8.7	2.0
PD	F	LES	25.0	10.2	2.6
		EO	54.2	21.1	5.3
		GMED	22.9	11.2	2.8
	M	LES	20.0	6.8	1.7
		EO	37.7	11.1	2.7
		GMED	20.4	7.1	1.8

Table 35 – Non-adjusted mean of peak percent maximal voluntary contraction during the RSB

Pain Status	Sex	Muscle	Mean	SD	SE
non-PD	F	LES	53.0	23.8	5.0
		EO	111.5	42.7	8.7
		GMED	62.1	20.7	4.2
	M	LES	50.2	17.3	3.9
		EO	76.7	30.1	6.7
		GMED	51.4	24.6	5.5
PD	F	LES	57.9	23.4	5.8
		EO	125.6	48.9	12.2
		GMED	50.3	18.9	4.7
	M	LES	51.9	18.5	4.5
		EO	96.1	27.0	6.6
		GMED	55.0	16.2	4.0

6.4.4.5 Fear of Pain Questionnaire Subscale

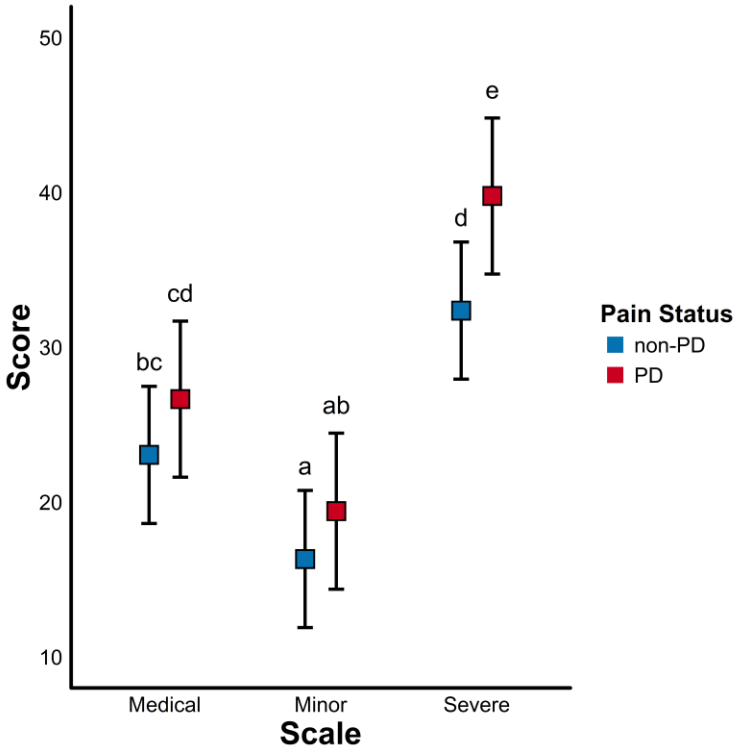

Figure 52 – Least square means plot of fear of pain questionnaire subscale score organized by pain status groups. Means sharing a letter are not significantly different from each other (Tukey-adjusted pairwise comparisons). Error bars represent 95% confidence intervals.

6.4.5 Appendix E – Previous Study EMG Frequency Cutoffs

Table 36 – Overview of studies and their frequency cutoffs (denoted 'fc') for processing of EMG data when using cross-correlation and/or co-contraction indices.

Study	Dependent Variable of Interest	EMG Processing Steps
(Nelson-Wong et al., 2008)	- Cross-correlation	- Systematic bias removed - Full-wave rectify - Digitally filtered with a low-pass, zero-lag, fourth order Butterworth filter (fc = 6 Hz)
(Nelson-Wong & Callaghan, 2010b)	- Cross-correlation - Co-contraction Index	- Systematic bias removed - Digitally filtered with a low-pass, zero-lag, fourth order Butterworth filter (fc = 400 Hz) - ECG removal by digital high-pass filter (fc = 35 Hz) - Digitally filtered with a band-stop filter (fc = 59 – 61 Hz) - Full-wave rectify - Digitally filtered with a low-pass, zero-lag, fourth order Butterworth filter (fc = 2.5 Hz)
(Nelson-Wong & Callaghan, 2010d)	- Co-contraction Index	- Systematic bias removed - Digitally filtered with a low-pass, zero-lag, fourth order Butterworth filter (fc = 400 Hz) - ECG removal by digital filter with a band-pass, zero-lag, fourth order Butterworth filter (35 – 400 Hz) - Full-wave rectify - Digitally filtered with a low-pass, zero-lag, fourth order Butterworth filter (fc = 2.5 Hz)
(Marshall et al., 2011)	- Cross-correlation	- Digitally filtered with a band-stop filter zero-lag, fourth order Butterworth filter (fc = 49 – 51 Hz) - Full-wave rectify

		- Digitally filtered with a low-pass, zero-lag, fourth order Butterworth filter (fc = 6 Hz)
(Nelson-Wong et al., 2012)	- Cross-correlation	- Digitally filtered with a band-pass filter (fc = 10 – 500 Hz) - Digitally filtered with a band-stop filter (fc = 59 – 61 Hz) - Full-wave rectify - Digitally filtered with a low-pass, zero-lag, fourth order Butterworth filter (fc = 2.5 Hz)
(Bussey et al., 2016)	- Cross-correlation	- Digitally filtered with a band-stop filter zero-lag, fourth order Butterworth filter (fc = 49.5 – 50.5 Hz) - Digitally filtered with a band-pass, zero-lag, fourth order Butterworth filter (fc =10 – 450 Hz) - Full-wave rectify - Digitally filtered with a low-pass, zero-lag, fourth order Butterworth filter (fc = 6 Hz)
(Viggiani & Callaghan, 2016)	- Co-contraction Index	- ECG removal by digital high-pass filter (fc = 35 Hz) - Digitally filtered with a band-stop filter (fc = 59 – 61 Hz) - Full-wave rectify - Digitally filtered with a low-pass, zero-lag, fourth order Butterworth filter (fc = 2.5 Hz)