# SELF-REPORTED WALKING DIFFICULTY: A SUB-GROUP FOR IDENTIFYING DIFFERENCES IN GAIT MECHANICS IN PATIENTS WITH KNEE OSTEOARTHRITIS

by

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A dissertation submitted to the Faculty of the University of Delaware in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Biomechanics and Movement Sciences

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## ABSTRACT

Walking limitations in patients with knee OA are at increased risk for developing poor outcomes[1]. Therefore, measuring walking ability in those with knee OA is important. Clinically, walking ability is measured via self-reported walking difficulty[2] and gait speed[3]. Measuring slow gait speed and its related interventions are well studied[3–7]. In contrast, self-reported walking difficulty is not as well studied. Clinicians can use clinical guidelines that addresses gait characteristics pertaining to slow gait speed for patients with slow gait speed and self-report walking difficulty and for patients with slow gait speed without walking difficulty. However, there are no known studies that examines those who walk at a fast and functional gait speeds but self-report walking difficulty. Although this sub-group exists, as Ferrer and colleagues found 17% of their subjects with fast gait speed self-reported walking difficulty[8], little is known to guide clinical practice. As a result, since knee OA is the leading cause of walking difficulty, the purpose of this dissertation is to examine gait characteristics based on the presence of knee OA and self-reported walking difficulty.

Methods: This cross-sectional study examines gait characteristics using self-reported walking difficulty and knee OA presence. Self-reported walking difficulty is defined based on responses ranging between *somewhat difficult* to *unable to walk* when answering the question *How does your knee affect your ability to walk* from the Knee Outcome Survey[2]. Gait characteristic differenences include comparisons among age and sex groups of subjects with knee OA and self-reported walking difficulty (Diff), knee OA and no walking difficulty (NoDiff), and no knee OA (Control) for knee kinetic and kinematics through motion capture and force plate, neuromuscular

strategies via muscle electromyography, and limb dynamics using inertial measurement units.

Results: Thirty-nine subjects, age and sex matched, participated in the study. Based on self-reported walking difficulty, the Diff group walked with smaller knee extension moment, $p \leq .05$, larger knee adduction moment, $p \leq .05$, larger lateral quadriceps-gastrocnemius co-contraction, $p \leq .05$, larger tibial limb dynamics, $p \leq .05$, and a relationships between limb dynamics and co-contraction that was different than the NoDiff group, $p \leq .05$. Based on knee OA presence, the NoDiff group walked with smaller knee extension excursion, $p \leq .05$, larger frontal plane knee excursion, $p \leq .05$, larger quadriceps activation, $p \leq .05$, and larger femoral limb dynamics than the control group, $p \leq .05$.

Discussion: This was the first study to examine self-perceived walking difficulty as a sub-group within knee OA. It was surprising to find that gait characteristics pertaining to knee extension (e.g., extension moment, quadriceps related activation) were different based on walking difficulty presence. This finding supported the importance of managing the quadriceps muscle in those with self-reported walking difficulty. The importance of effective quadriceps use may be further evidenced by the notable limb dynamic differences between the NoDiff and Diff group, which suggested that the Diff group used an ineffective neuromuscular strategy to stabilize the tibia. Further, for many known OA gait characteristics, no significant differences were found between the NoDiff and Control group, which may suggest that self-reported walking difficulty may account for some of known OA gait characteristics. Perhaps further examination of these gait characteristics may be beneficial for developing interventions that could combat walking difficulty.

Chapter 1

# INTRODUCTION

Knee osteoarthritis (OA) is a common problem, with prevalence exceeding 13.3 million known cases in the United States alone[1]. Knee OA is the leading cause of physical disability and functional limitations in adults that can negatively influence walking ability[2,3]. In fact, those with knee OA have a 9 times greater risk of gait or walking speed decline when compared to those without knee OA[4]. Slower gait speeds suggest larger risks for mortality in aging adults[5]. Knee OA most commonly affects older adults, with the incidence of knee OA sharply increasing at 55 years of age or older[6], and functional decline typically occurring within 3-5 years of knee OA diagnosis[7]. Therefore, knee OA can lead to detrimental outcomes in aging populations - especially when subjected to co-morbidities related to senesce (e.g., cancer, stroke diabetes, and cardiovascular issues)[8,9]. The limitations knee OA poses on walking can limit effective rehabilitation for diseases that need mobility for recovery, evidenced by the increased risk of mortality when knee OA is present with medical co-morbidities[10]. Given the medical complications that are common to aging, conservative management may be the most viable treatment option to optimize walking ability for this fragile population when faced with knee OA.

Despite the fact that knee OA is the single largest risk factor for developing walking difficulty[2]; few research studies examine the role of self-perceived walking difficulty within knee OA. Standard clinical practice for examining walking ability in those with knee OA is to measure gait speed[11]. However, performance testing gait

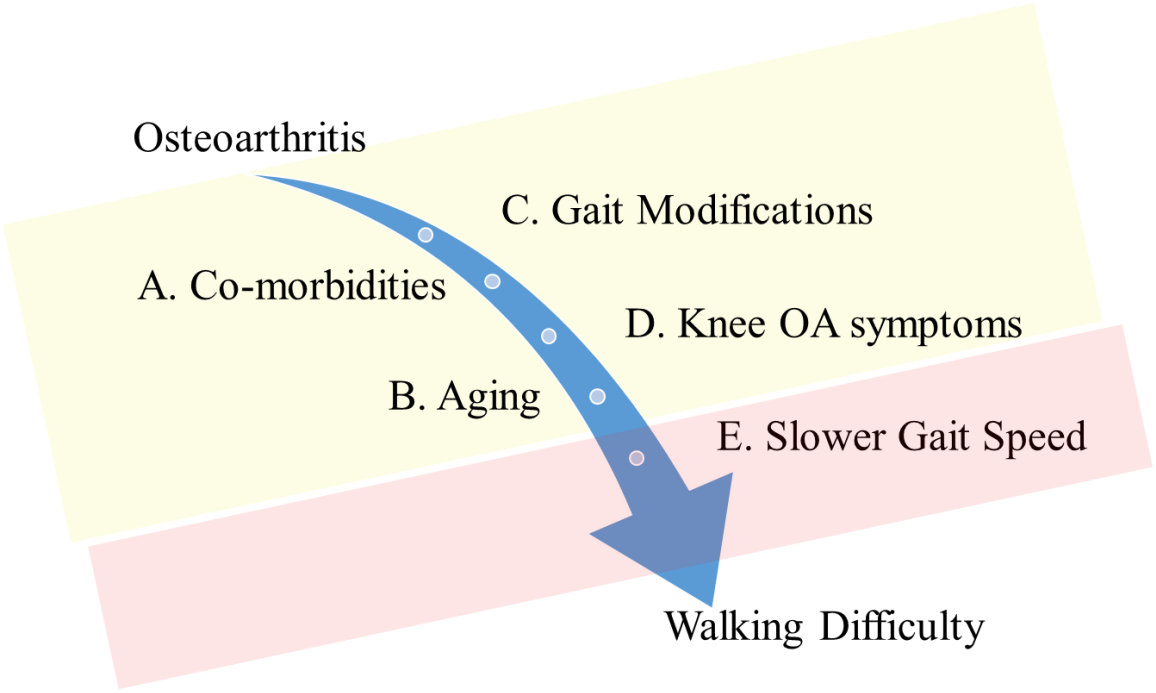
speed and self-reported measures of walking difficulty cannot be used interchangeably – especially given the fact that a walking difficulty question does not have strong agreements with performance testing[12]. In fact, Ferrer and colleagues found that gait speed had a specificity of 98%, a sensitivity of 58% suggesting frequent false negatives, and a moderate kappa of .55 when compared to self-reported walking difficulty[13]. The lack of agreement can suggest that gait speed and self-reported walking difficulty measure different constructs within the same phenomena, walking[13].

The lack of agreement also reveals an understudied sub-group: those with walking difficulty still able to walk at a functional gait speed. Ferrer and colleagues found that out of 853 older adults, 85 subjects self-reported walking difficulty and walked at a slower gait speed, while 75 subjects self-reported walking difficulty and walked at a faster gait speed[13]. Based on current standard practice and evidence based practice those walking at slower gait speeds would receive gait training in the clinic. The assumption is that clinicians query about walking ability and that patients with walking difficulty would be severe enough to verbalize such limitations to the clinician. However, even if walking difficulty was made aware to the clinician, little is known on the sub-group within knee OA that is able to walk at fast gait speeds but self-reports walking difficulty.

Self-perceived walking difficulty can be exacerbated by OA symptoms and lead to walking modifications. Farrokhi and colleagues found that knee OA symptoms, such as knee instability, has an odds ratio of 10.7 for self-reporting walking difficulty when comparing to those with knee OA but no knee instability[14]. Both knee OA symptoms and related gait modifications can be clinically evaluated in order to

address potential walking limitations. If walking modifications that pertain to walking difficulty are identified in knee OA patients capable of walking at functional speeds, interventions can focus on gait characteristics to possibly limit the risks for poor outcomes. Therefore, walking modifications using known OA related gait characteristics must first be established based on OA and walking difficulty sub-groups. As a result, the focus of this dissertation is to examine knee OA gait characteristics, as defined by knee kinematics and kinetics, neuromuscular strategies, and limb dynamics, based on symptomatic knee OA presence and self-reported walking difficulty in those who are functionally mobile.

Figure 1.1 Proposed pathway from knee osteoarthritis to walking difficulty. Factors including co-morbidities (A) and aging (B) are difficult to measure via biomechanics and can be difficult or unable to be modified but can lead to walking difficulty when combined with knee OA. Gait modifications (C) can be observed using biomechanics and both gait modifications and knee OA symptoms (D) can are clinically modifiable. Slower gait speeds (E) are an indicator of poor functional mobility and suggests greater risks for mortality. Therefore, identifying a sub-group population before gait speed decline occurs, based on gait modifications and OA related symptoms that pertain to walking difficulty, may be beneficial (■). Meanwhile, addressing walking difficulty after those are walking at slower gait speeds may be too late (■).




## 1.1 Walking Difficulty in Knee Osteoarthritis

The assessment of walking difficulty is much needed at this time, as there is a no general consensus on how to examine or treat self-reported walking difficulty. First the definition of self-reported walking difficulty is vague and adapted from various versions of patient reported outcome measure questionnaires[1,9,13,15,16]. Therefore, the measurement of walking difficulty lacks consistency, making interpretation of the

literature difficult and developing effective interventions for walking difficulty almost impossible. While self-reported measurements are important clinical measurements of functional mobility, there must be a consensus on the standard of measuring walking difficulty.

Walking difficulty questions are found in an array of questionnaires from general health outcomes to knee OA specific questionnaires[17,18]. Most recently, in knee OA studies, questions are extracted from OA specific questionnaires, including the Knee Outcome Survey (KOS) and Knee Outcome and Osteoarthritis Survey (KOOS)[14,19]. The KOS is validated and tested in the OA population, and asks strictly about walking difficulty, "How does your knee affect your ability to walk?" [17]. The KOOS poses questions about walking on a flat surface[20]. Other studies on walking difficulty use questions that quantify or qualify walking ability[9,13,21]. Ferrer and colleagues asked subjects about walking difficulty based on their ability to walk 4 meters[13]. Functionally, 4 meters is a small distance and may reflect household ambulation but definitely not a functional distance for community ambulation. Other questions for walking difficulty found in the literature include "walking ¼ of a mile or two to three blocks", "walking ½ a mile," or "How difficult is it for you to go outdoors and walk down the road on our own?[10], how difficult is walking by yourself, that is without help from another person or special equipment, do you have any difficulty in walking for a quarter of mile, that is about 2 or 3 blocks?"[22].

While many of these questions may be reasonable to ask about walking difficulty in those with knee OA, using a quantified measurement may add confusion

to interpretation. For example, reporting walking difficulty after a prolonged period of time may suggest endurance and cardiovascular limitations. Or difficulty with walking up a hill may require task specific training. Therefore, until further research establishes the specific constructs that are making walking difficult in those with knee OA adding quantifications or qualifications to the walking difficulty question may provide convoluted information. Perhaps to examine the role of walking difficulty in knee OA, it may be best to start with minimal quantification and qualifications to identify how self-perceived walking difficulty impacts those with knee OA. As a result, this study extracts the walking difficulty question from the Knee Outcome Survey due to the simplicity of the question in hopes of minimizing the potential effects that additional quantification or qualifications may add. Therefore, self-reported walking difficulty for this dissertation will be examined based on responses to the KOS question *How does your knee affect your ability to walk?* Self-reported walking difficulty will be defined by responses that range between *somewhat difficult* to *unable to walk difficult*[17]. The cut-off is adopted from studies that also uses the Knee Outcome Survey to sub-group subjects with symptomatic knee OA[23,24]. Further such cut-off ensures that walking is truly difficult, and that gait characterization found in this dissertation will best represent the sub-group.

## 1.2 Knee Kinematic and Kinetic

Gait characteristics are quantifiable using joint kinetics, or the measurement of joint movements without forces; and joint kinematics, the measurement of joint

movements with forces[25]. Knee kinetics and kinematics are important during gait because they can characterize knee movements and quantify loading strategies[26]. Altered movements and loading strategies during a repetitive task such as walking can cyclically load structures resulting in the breakdown of joint tissues[27]. Therefore, knee kinetic and kinematic differences between those with and without knee OA are more commonly measured during the stance phase, or weight bearing phase; and less during the swing phase, or the non-weight bearing progression of a limb[28,29]. In fact, the stance phase of gait requires a period of weight absorption, anterior translation of the body, and single limb stance that can require an osteoarthritic knee to withstand the entire body weight[30]. The stance phase is further divided into the weight acceptance and mid-stance gait intervals based on sagittal plane knee kinematics[31]. Early stance phase, or the weight acceptance interval, starts from heel strike and ends at peak knee flexion. The weight acceptance interval transfers body weight onto an outstretched limb and is characterized as the first period of double-limb support. Mid-stance interval picks up from where weight acceptance interval stops, at peak knee flexion angle, and ends at peak knee extension angle. The mid-stance interval is responsible for the anterior progression of the body over a single limb. Both the weight acceptance and mid-stance gait intervals are characterized by specific sagittal and frontal plane knee kinetics and kinematics that differ between those with and without knee OA[29,32,33].

The knee OA gait pattern is characterized by a knee stiffening strategy observed in both the weight acceptance and mid-stance intervals of the stance phase of gait[29]. During the weight acceptance interval, individuals with knee OA typically walk with larger sagittal plane knee angles at heel contact and smaller sagittal plane knee

angles at peak knee flexion and peak knee extension than those without knee OA[29,34]. As a result, the differences in sagittal plane knee angles, also known as sagittal plane knee excursion, through the weight acceptance and mid-stance intervals are much smaller in those with knee OA than those without knee OA[35]. Knee stiffening strategies become more apparent when comparing knee kinetics during gait between those with and without knee osteoarthritis, as many with knee OA attempt to adopt gait strategies that can result in immediate reduction of knee joint loads[36].

Knee kinetics is a critical measurement in examining knee OA gait patterns, as it has predictive indicators of OA progression[37]; and is identifiable and differs between those with and without knee OA during weight acceptance and mid-stance gait phase[29]. In a non-OA knee, knee kinetics starts with an immediate external knee extension moment at heel strike, followed by an external knee flexion moment peak around weight acceptance gait interval, and an external knee extension moment peak at the end of mid-stance gait interval. Studies have most commonly examined external knee flexion moment and external knee adduction moment for knee kinetic differences between those with and without knee OA. It appears that those with knee OA generally walk with smaller external knee flexion moment and greater knee adduction moment than their non-OA counterparts[38]. The larger knee adduction moment appears to have a larger consensus than the smaller knee flexion moment when comparing between those with and without knee OA[35]. Altered knee adduction and flexion moments in knee OA can provide indications of cartilage degradation in 5 years[37]. In fact, knee adduction moments can implicate femoral cartilage changes, while knee flexion moments can suggest tibial cartilage changes; however, these outcomes can be influenced by the amount of OA severity at baseline[37]. Although external knee

extension moments are less studied, several studies have shown a reduction in terminal knee extension coincides with smaller knee extension moment in those with knee OA[29,39].

The fear of altered joint loading shows the potential progression of knee OA severity. OA severity and the presence of medial versus lateral knee OA can influence knee kinetics and kinematics during gait. Astephen and colleagues found that those with severe knee OA (KL score of 3 and 4) walked with smaller sagittal plane knee motions and smaller knee extension moments, than the moderate knee OA groups (KL scores ranged from 1 to 4)[40]. Meanwhile the asymptomatic group walked with the largest sagittal plane knee angles, largest knee flexion and extension moments, and smallest knee adduction moments[40]. Therefore, these findings suggest that those with the more severe knee OA accentuated the OA gait characteristics, especially the ones that were most commonly different between those with and without knee OA. A systematic review examining knee kinematics and kinetics in knee OA suggests that there is not a consensus based on the sub-grouping of mild, moderate, and severe knee OA groups[35]. However, those with worsening medial knee OA severity were more likely to walk with varus knee alignment and accentuated OA gait characteristics[35].

Similarly, in the frontal plane, greater knee adduction moment and angles are observed in the OA groups when compared to the control groups. This is very apparent in those with higher grade medial knee OA versus lesser grade or when compared to lateral knee OA[41,42]. Higher knee adduction moment has been related to greater risks of development in knee OA and progression of knee OA severity, which is also related to poorer outcomes[43,44]. However, it is the amount of participation in walking and tolerance for walking that is related to better health outcomes[45]. So the

challenge lies in optimizing health outcomes related to walking but minimizing the risks of OA progression. The mechanisms of this relationship and potential interventions are outside the scope of this dissertation; however, the findings of this relationship may set the ground work for identifying future intervention and prognostic ideas.

Progression of radiographic OA severity is related to poorer functional outcomes; and altered biomechanical gait patterns are indicative of OA progression and can differ based on knee OA related symptoms. However, the specific effects of OA-related symptoms on biomechanical gait patterns are currently ambiguous. For example, although it should be apparent that knee OA invoked symptoms should change how a person walks - it is debatable if it serves as a protective mechanism to maintain stability for OA progression or function, or if it is detrimental to joint degradation. Reduction in pain induced by cortisone steroid injections has resulted in increased knee adduction moment in OA group[46]. Investigators suggest that greater knee adduction moment can progress knee OA[47]; therefore, some studies consider pain to be a protective mechanism if reduction of pain is related to increased knee adduction moment[46]. However, when compared between individuals, and not within an individual, those with greater pain generally walk with larger knee adduction moments[46]. Therefore, we know there is a relationship between pain and gait mechanics; however, how they vary and the roles they play within knee OA gait is uncertain.

Pain appears to be the most notable knee OA related symptom that motivates a patient to seek medical attention. Mechanical loading of the knee during repetitive activities such as walking are suggested to be implications of disease progression[48].

However, walking is a functional task that becomes a struggle with symptom provocation, and joint stress, which can result in altering gait mechanics to achieve functional tasks. Primarily, walking differences are observed between those with and without knee osteoarthritis during stance phase of gait[49]. Those within walking limitations in knee OA are more likely to shorten the stance time on the involved knee in order to limit or avoid pain during walking[50]. Therefore, this study focuses on gait mechanics during the stance phase of gait. Further, to ensure all subjects with knee OA are severe enough to seek medical attention and reflect the clinic population, we require an inclusion criteria KL score of greater than or equal to 2, as well as requiring all subjects with knee OA to have self-reported knee pain of 3 or greater.

Smaller knee flexion and extension moments and larger frontal plane knee moment are not only knee stiffening strategies adopted by those with knee OA, but are also correlated with poor knee extensor uses[29]. However, OA related gait mechanics correlating with muscles modifications during gait are clinically modifiable. Recent studies have also found that specific treatments and gait training can alter or even reduce knee moments[51]. Some of these strategies include walking with a lateral trunk lean, strengthening programs, and toe out gait patterns[44,48]. In fact, the altered gait mechanics including decreased knee flexion moment and extension moment are referred to as a quadriceps avoidance gait pattern[52]. If those with walking difficulty within the knee OA group utilize gait modifications specific to the known OA gait characteristics, perhaps addressing gait mechanics before gait speed decline occurs can limit the progression of walking difficulty in those with knee OA. As a result, known OA gait characteristics must be examined to determine if such gait mechanics are

specific to OA presence versus self-perceived walking difficulty within those with knee OA.

Therefore, the purpose of Aim 1 is to determine knee kinetic and kinematic differences during walking based on knee osteoarthritis and walking difficulty sub-groups. Knee kinematics are defined as knee ranges that occur without force measurements in the sagittal and frontal planes during walking. Knee kinetics are defined as measurements of knee forces that occur in the sagittal and frontal planes during walking.

Based on prior evidence of OA gait characteristics, we hypothesize the following:

Hypothesis 1.1a: When based on OA presence (regardless of walking ability) we hypothesize that gait patterns of the OA groups Diff and NoDiff will accentuate OA gait characteristics more than their age and sex matched control counterparts.

Hypothesis 1.1b: When based on walking difficulty within knee OA groups, we hypothesized that the Diff group will accentuate OA gait characteristics more than their age and sex matched counterparts in the NoDiff group.

In addition, we will further examine common knee OA symptoms and their role on gait mechanics in those with and without walking difficulty.

Hypothesis 1.2: We hypothesize that worsening knee OA related symptoms will accentuate OA related gait mechanics, and that this effect would be more apparent in the Diff group than the NoDiff group.

OA gait characteristics are defined by smaller sagittal plane knee kinematics and kinetics, and larger frontal plane knee kinematics and kinetics when compared to those without knee OA. Testing these hypotheses will determine gait mechanics that

are specific to knee OA presence, self-reported walking difficulty, and OA related knee symptoms. Such findings may lay the groundwork for future intervention-based studies to address these gait mechanics in hopes of reducing walking difficulty.

### 1.3 Neuromuscular Strategies

Given the altered knee kinetic and kinematics observed in those with knee OA when compared to those without knee OA, it is no surprise that neuromuscular strategies, or muscle use, can also be influenced by the presence of knee OA[29,34]. Normal gait mechanics require a cohesive and fluid activation pattern between the knee extensors, or quadriceps, and the knee flexors, hamstrings and gastrocnemius. Each muscle group has a unique contribution to gait. In the face of potential injury, or when the knee needs to be protected, knee muscles can also be recruited as a protective mechanism[53]. In such cases, when passive knee stabilizers are stretched, as observed in the case of those with knee OA walking with larger knee adduction moments, the nervous system elevates the amount of muscles that are recruited[53].

When muscle recruitment increases, the neuromuscular strategy becomes concurrent activation of antagonist muscles, or co-contraction. Knee co-contraction is believed to affect joint stability during high demand and balance tasks that can impact movement efficiency and load distribution[29]. For individuals with knee OA, co-contraction is typically higher than those without OA potentially due to poor joint congruency and reports of knee instability and prolonged pain during functional tasks. Daily activities such as walking, stairs, turning, and transitioning from a sit to stand position may place high demands on an arthritic knee that require knee stability via altered muscle activation[54]. Muscle activation patterns are consistently different

between patients reporting symptomatic knee OA and healthy adults, which led many researchers to conclude that neuromuscular strategies in the arthritic knee need to be addressed[29,55,56].

Based on previous research, OA related symptoms and various interventions can influence co-contraction. Specific interventions used to address co-contraction include: perturbation training [57], injection[58], and knee brace [51]. While OA related symptoms such as joint effusion[59], pain [58], and faster gait speeds can also affect co-contraction[60]. Based on this information, the assumption is that elevated muscle activation and co-contraction can have negative impacts to knee OA; however, in the same perspective, faster gait speeds require larger muscle activation. As a result, perhaps a sub-group within knee OA may require larger muscle activations to ease walking and maintain functional gait speed. Larger muscle activation levels and co-contraction are thought to be higher in knee OA in order to maintain joint stability. In contrast, compensatory muscle firing patterns can also alter joint forces and increase knee contact forces that can progress OA[26,61]. Larger muscle activations and co-contraction may increase muscle forces on the joint, alter gait mechanics, and make walking more difficult in a comparable sub-group within those with knee OA.

As a common OA related gait characteristic, larger muscle activations and co-contraction indices are observed during walking in those with knee OA when compared to those without knee OA[29,33,24], or those with worsening knee OA when compared to less severe knee OA. The neuromuscular strategy differences based on OA severity are also influenced by sub-grouping based on compartment and severity[60,62]. Over time, active and passive ranges of motion become limited and thus affect gait in those with more severe knee OA[63]. Therefore, the limited range of

motion can engage the passive stabilizers and tendons during walking through stretch reflex, which engages muscle activation and co-contraction. The elevated muscle activation and co-contraction indices may elevate joint forces and exacerbate knee OA severity[26,29]. However, function is not directly related to OA severity. Therefore, given the poor joint congruency that characterizes knee OA, the roles of muscle activation and co-contraction and how they may facilitate or inhibit function in knee OA are currently unknown.

The purpose of Aim 2 is to examine how neuromuscular strategies, both muscle activation and co-contraction indices, would vary based on walking difficulty, gait speed, and OA related knee symptoms. Based on prior evidence of OA gait characteristics, we hypothesize the following:

Hypothesis 2.1: Neuromuscular strategies, including muscle activation and co-contraction, will be lower for the control group and higher for the OA groups, and will be the highest for the walking difficulty OA group.

Hypothesis 2.2: Neuromuscular activation differences among the groups, based on the presence of OA and walking difficulty, would be influenced by gait speed conditions.

Hypothesis 2.3: A negative trend will be present in both OA groups, which suggests that a lower response, or worsening knee OA-related symptoms, will be related to larger muscle activation and co-contraction.

Examining these hypotheses will allow us to examine the mechanism of neuromuscular strategies in those with knee OA, and further determine whether a subgroup classification of OA, such as the proposed subgroup based on self-reported

walking difficulty, can accurately identify patients who may walk with elevated muscle activation and co-contraction.

## 1.4 Limb Dynamics

Limb dynamics, or the movement of the femur and tibia, during walking, in a non-pathological knee, are characterized by smooth and cyclic movements due to specific muscle activation and de-activation and good joint congruency. In knee OA, altered muscle activations and co-contraction, as discussed above in Section 1.2, and incongruent femoral and tibial alignments can create erratic limb movements during walking. Since conservative management is unable to reverse joint degradation, those with knee OA must adapt efficient and effective movement strategies in order to maintain function. Poor compensatory movements adopted by those with knee OA could result in poor control of erratic limb movements, which may exacerbate OA related symptoms and make walking difficulty.

Such erratic limb movements are small and not-observable with the naked eye, but quantifiable via limb dynamics using inertial measurement units (IMUs). One way of characterizing limb dynamics at the knee is by measuring linear acceleration and jerk, or time-derivative of linear acceleration, at adjacent limbs of the knee, the femur and tibia. Linear acceleration is defined as the change in speed over time. Larger femoral and tibial linear accelerations would suggest poor knee stability. Jerk is defined as the change in acceleration over time. Larger femoral and tibial jerk would suggest poor movement smoothness. Therefore, the presence of large linear acceleration and jerk could challenge stability and movement smoothness, which would make walking more difficult for those with knee OA. Although linear

acceleration is known to be larger in those with knee OA than those without knee OA, linear acceleration has yet to be examined based on walking difficulty, and jerk has never been examined based on OA or walking difficulty presence.

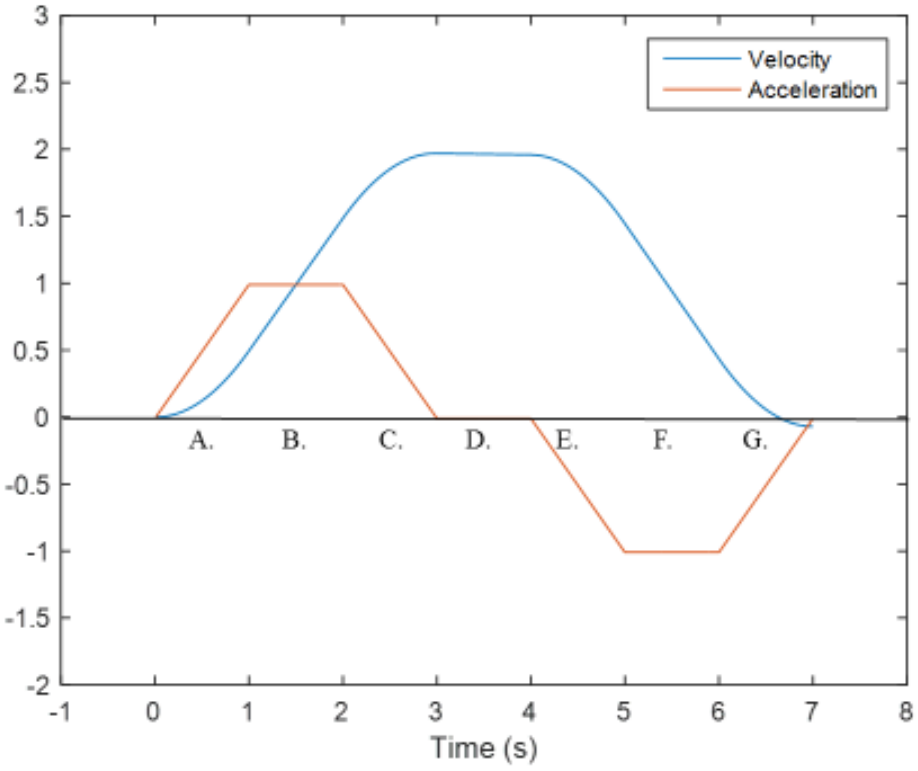
### 1.4.1 Linear Acceleration

Linear acceleration is defined as the change of velocity over time, or the time derivative of velocity. Positive and negative values for velocity suggests direction; however, for linear acceleration, positive or negative values can suggest either direction or the change in velocity. For example, a positive acceleration can suggest accelerating in the same positive direction as velocity or a declining acceleration, also known as deceleration, while moving in the same positive direction as the velocity (Figure 1.2). A zero acceleration can suggest that either velocity is also zero or peak velocity is reached. A negative acceleration, can suggest movement in the positive direction; however, a decrease in velocity. A larger decrease in velocity would yield a larger negative acceleration. Further, a negative acceleration could also suggest an acceleration in the opposite direction, or negative direction as set by velocity (Figure 1.2). Linear acceleration at the knee would be quantifiable based on the Cartesian coordinate system defining the anatomical planes, including positive and negative x-, y-, and z- representing anatomical planes of movement including: anterior-posterior, medial-lateral, and superior-inferior movements, respectively. However, large linear acceleration, regardless of direction or plane of movement, is related to self-reported instability in those status post total knee arthroplasty.

Similarly, when comparing linear acceleration between those with and without knee OA, those with knee OA walked with larger linear acceleration in all directions

and plane of movement. Therefore, this dissertation will compare peak linear acceleration magnitude among the groups.

Figure 1.2 Schematic diagram of velocity and acceleration over time. Linear acceleration is defined as the change in velocity over time. Therefore a larger change in velocity results in greater acceleration (A); when velocity increases at a constant rate, acceleration is positive but also constant (B); when the desired velocity is approaching, the velocity increases at a slower rate, acceleration is decreasing (C); when desired velocity is achieved and maintained, acceleration is zero (D); when velocity decreases at a changing rate, acceleration is negative or also known as deceleration (E); when velocity decreases at a constant rate, deceleration is constant (F); when velocity declines to approach zero, deceleration decreases to zero (G).

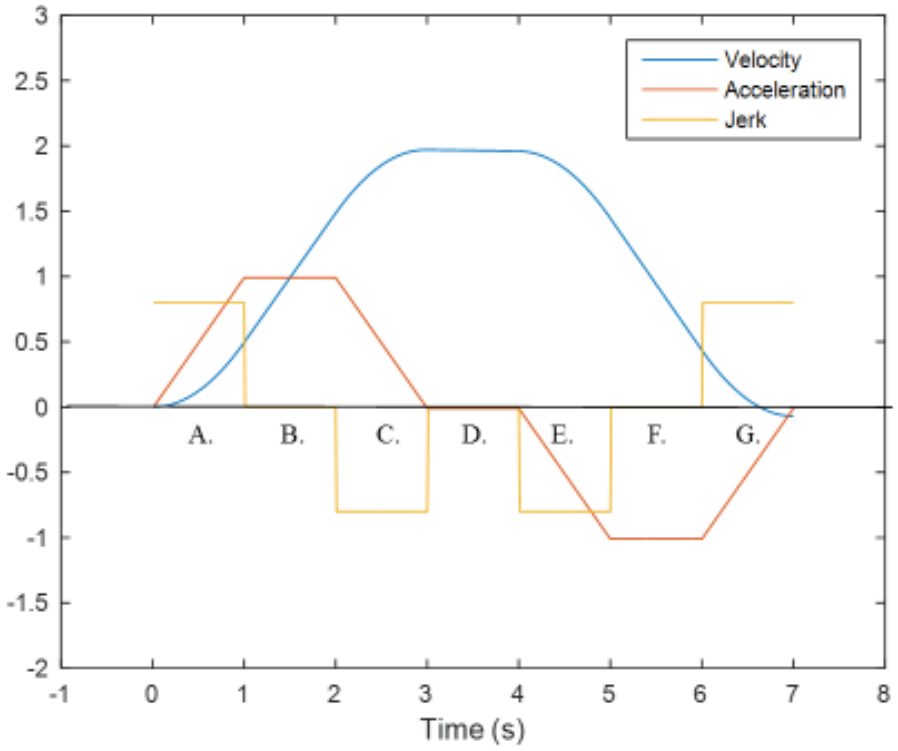



### 1.4.2 Jerk

The relationship between jerk and acceleration can parallel the relationship between acceleration and velocity. Jerk is defined as the change of acceleration over time. A positive jerk can suggest a larger change in acceleration, which could be either a positive increase in acceleration or a reduction of deceleration. Zero jerk can suggest peak acceleration, constant acceleration, zero acceleration, and peak deceleration. A

negative jerk can suggest a reduction in acceleration or an increase in deceleration (Figure 1.3). Jerk is related to movement quality; smaller jerk values are related to smoother movements in those with low back pain or Parkinson's disease. Jerk has yet to be examined in the knee OA population. Therefore, this dissertation will compare peak jerk magnitude among our groups based on OA presence and walking difficulty.

Figure 1.3 Schematic diagram of velocity, acceleration, and jerk over time. Jerk is defined as the change of acceleration over time. A quadratic increase of velocity, yields a linear increase of acceleration, and results in a positive jerk (A). A linear increase of velocity, yields a constant acceleration, and results in zero jerk (B). A quadratic increase of velocity but linear decrease of acceleration results in a negative jerk (C). Peak velocity results in zero acceleration and jerk (D). A quadratic decrease of velocity, linear decrease of acceleration, yields a negative jerk (E). A linear decrease of velocity, yields a (F). A quadratic decrease of velocity, linear increase of acceleration to zero, yields a positive jerk.




### 1.4.3 Relating Clinical Constructs to Limb Dynamics

As discussed, larger linear acceleration magnitudes suggest greater threats to stability, while larger jerk magnitudes suggest lesser movement smoothness.

Large linear acceleration magnitudes are related to self-reported instability, or the buckling and giving way of the knee, in patients with total knee arthroplasty or anterior cruciate ligamentous deficiency. Knee instability is a common problem in

knee OA with its prevalence as high as 78.1% [64] to 63% [23] for 1 or more episodes of knee buckling, and can lead to significant functional limitations[17,23]. Turcot and colleagues found larger linear acceleration in those with knee OA than those without knee OA; however, the OA group was small and heterogenic[65,66]. It is well known clinically, that patients with knee OA who reports knee instability, generally do no complain of stability as their only OA-related symptom. Farrokhi and colleagues found this clinical anecdote to be true, as those with knee OA who reports knee instability are also more likely to report knee pain that limits function than those with knee OA without knee instability[14]. The heterogeneity of the knee OA experience may include a combination of OA-related symptoms, which can make the mechanism of instability difficult to define, such as pain and stiffness.

Clinically, knee OA-related symptoms are known to co-exist and worsen over time. The clinical diagnoses criteria per Altman and colleagues requires knee pain to be present in addition to 3 or more clinical findings, which can include stiffness for less than 30 minutes and crepitus[67]. Similarly, there is growing evidence to better understand the mechanism of self-perceived instability and stiffness in knee OA, as both self-perceived knee instability[49] and stiffness[68] are not related to their mechanical measurements. Recently, Schmitt and colleagues found that self-perceived instability is not related to knee joint laxity in those with knee OA[49]. Self-perceived knee stiffness is not related to mechanical stiffness, as measured by the ratio between force and length change[68]. Therefore, the mechanism of stiffness and instability in knee OA are not quantifiable using mechanical measurements, which can make identifying effective interventions with good long outcomes difficult. Although the relationship between instability and stiffness appears to be contrasting concepts, growing research

in low back pain found that inducing spinal segmental stability through fusion is associated with the absence of instability sensations[69,70]. Therefore, comparing linear acceleration based on OA and walking difficulty presence may identify the mechanism of OA related symptoms, such as self-perceived instability, that could facilitate walking difficulty in knee OA.

Jerk, a measurement of movement smoothness, also, has not been examined in the knee OA population. Characterizing jerk may be best described as the smoothness of a ride in a hospital bed. Small or no change in acceleration generally results in a smooth ride. However, a large change in acceleration while being pushed in a hospital bed can lead to motion sickness due to the lack of smoothness of the ride. At the knee, large changes in acceleration can result in inefficient movement, which can increase the risk for developing instability and make walking more difficult.

Consequentially, those with knee OA tend to walk at slower speeds in order to ease their walking ability or limit the exacerbation of OA related symptoms. Slower gait speeds allow individuals to better control knee movements, which allows the exchange of precision for activity demand. When gait speed increases greater demands are required to perform the task and larger values of jerk are observed. This relationship between increasing task demand and increasing jerk are found when comparing jerk between walking, running, and jumping in young adults with no knee pathologies. In knee OA and older adults, functional demands may be increased when these individuals must face knee OA, walking difficulty, and fast and functional gait speeds.

Therefore, the purpose of Aim 3 is to examine how limb dynamics vary based on OA presence, walking difficulty presence within knee OA, and gait speed. Given that limb dynamics vary with functional demand, we hypothesize the following:

Hypothesis 3.1: Limb dynamics would be the greatest for the walking difficulty (Diff) group, followed by the no walking difficulty (NoDiff) group, and the least in the control group when walking at a controlled gait speed of 1.0 meter per second.

Hypothesis 3.2: Further, we hypothesize that the limb dynamic differences based OA presence and walking difficulty presence would be accentuated in the presence of self-selected fast gait speeds.

### 1.4.4 Mechanism of Jerk

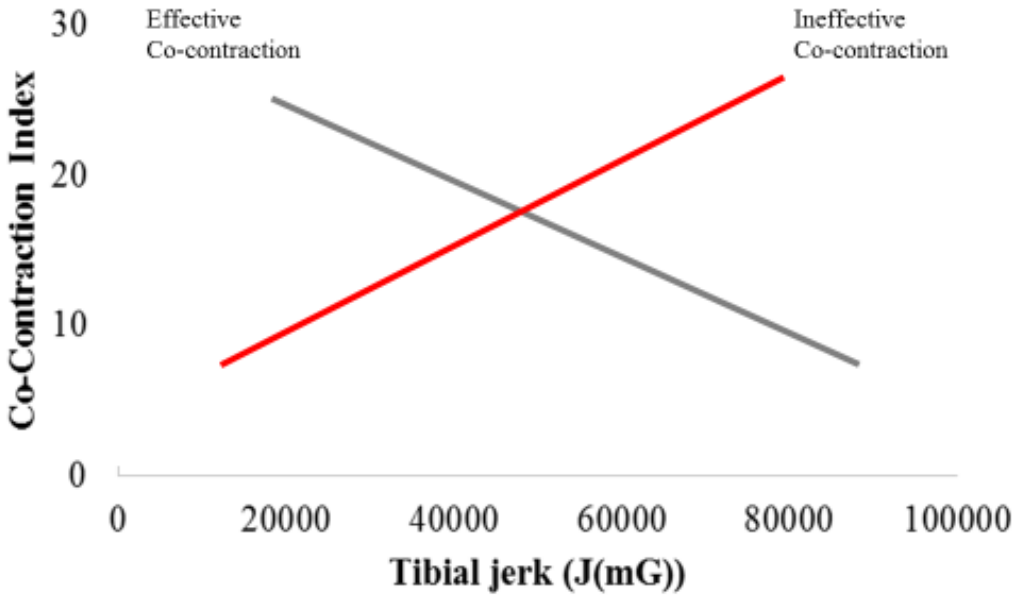
According to neuromuscular control research studies, jerk is primarily facilitated by muscle forces acting on the limbs. Sudden changes in muscle forces can create excessive limb movements and increase jerk. Anatomical constraints to limit limb movements at the knee comes from passive structures (skeletal alignment and ligaments), and control systems (central and peripheral nervous systems) that facilitate muscle and tendon control on the joint. In knee OA, passive structures are damaged or altered, and the control systems must compensate for such changes in order to meet functional demands. A control system that can minimize jerk but maximize movement smoothness while maintaining functional mobility would suggest optimal performance based on the dynamic optimization principle[71].

According to the dynamic optimization principle, the human system performs tasks that maximizes smoothness and precision that may be necessary to maintain functional walking ability in those with knee OA. Movement optimization occurs on a

feed forward-feedback loop between the control systems, the passive structures, and muscle and tendon control. High jerk in a situation where the same task can be accomplished with lower jerk could indicate less optimal movement strategies. Optimization would occur in those with knee OA who uses just enough muscle activation to minimize jerk.

The goal of measuring jerk is to examine movement efficiency and optimal movement patterns facilitated by neuromuscular control. Increases in co-contraction of multi-segmental muscles in the arm can improve movement smoothness by reducing the movement variability and improving accuracy[72,73]. If those with knee OA, optimize their neuromuscular strategy given the unstable environment produced by joint degradation, larger co-contraction indices in those with knee OA may be necessary to control erratic limb movements. Therefore, a negative relationship between jerk and co-contraction, or larger co-contraction observed with smaller jerk, would limit erratic limb movements and be an effective neuromuscular strategy. However, a positive relationship between jerk and co-contraction indices, or larger co-contraction observed with larger jerk, would be considered an ineffective co-contraction strategy. Flash and Hogan propose that jerk is produced by sudden changes in forces generated by muscle activation, an altered neuromuscular system, such as those observed in knee OA, may facilitate elevated muscle activation that can challenge movement smoothness[71]. In such cases co-contraction indices may exceed necessary muscle activation to maintain limb stability and facilitate an unstable environment

Figure 1.4 Schematic diagram of effective and ineffective co-contraction. ─Effective co-contraction would be defined as a negative relationship between co-contraction and tibial jerk, or larger co-contraction indices would result in smaller tibial jerk. ─Ineffective co-contraction would be defined as a positive relationship, where larger co-contraction indices are related to larger tibial jerk.




Many neuromuscular research proposes the relationship between the neuromuscular system and movement smoothness, as a potential explanation for observed movement variability or larger jerk observed in pathological populations. However, no known studies have actually investigated the relationship between neuromuscular strategies and limb dynamics. Therefore, in Aim 3 we will also examine the relationship between muscle co-contraction and limb dynamics in those with knee OA.

Hypothesis 3.3: We hypothesize that walking difficulty would moderate the relationship between co-contraction indices and limb dynamics when walking at a controlled gait speed of 1.0 meter per second.

## 1.5 Conclusion

The pathway from knee OA to walking difficulty is not immediate but can progress over time; however, confounding factors related to knee OA may expedite functional disability. Perhaps OA-related gait mechanics specific to knee OA in those with OA related symptoms can be addressed before walking speed is attenuated to levels of functional dysfunction. Known OA specific gait characteristics, as compared to those without knee OA, include smaller sagittal plane knee kinetics and kinematics and larger frontal plane knee kinetics and kinematics, which suggest knee excursion movement strategies and abnormal force distributions; altered muscle activation and elevated muscle co-contraction, which can alter and elevate contact forces that would progress knee OA; and larger limb dynamics, which can identify knee instability and ineffective movement patterns. Examining these known OA gait characteristics based on self-reported walking difficulty and knee OA presence is important as it (1) relates a self-perceived question to biomechanical measurements; (2) examines specific gait mechanics that are related to self-reported walking difficulty, which could lay the ground work for developing interventions that would ease walking; and (3) identifies a sub-group within knee OA that may require further clinical and research attention.

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Chapter 2

# INFLUENCES OF KNEE OSTEOARTHRITIS AND WALKING DIFFICULTY ON KNEE KINEMATICS AND KINETICS

## 2.1 Introduction

Knee osteoarthritis (OA) is a common problem, with a prevalence of 13.3 million known cases in the United States alone[1]. OA prevalence increases with age, as the incidence of knee OA sharply increases after 50 years old[2]. As knee OA progresses, function declines[3–5]. Functional decline typically occurs within 3 to 5 years of knee OA diagnosis[6]. Therefore, those combating functional decline pertaining to knee OA are also dealing with age related changes[7–9].

Knee OA can affect health due to its adverse impacts on walking[7,8]. When knee OA is combined with co-morbidities that pertain to aging (e.g., stroke, cardiovascular, etc.), the incidence for mortality increases[8]. Consequentially, knee OA can negatively impact walking in an already fragile population[8]. Walking ability is measurable using self-reported walking difficulty and gait speed[10,11]. Self-reported walking difficulty is measured by the question *How does your knee affect your ability to walk?*, adopted from the Knee Outcome Survey, and defined by responses ranging from *somewhat difficult* to *unable to walk*[12]. Self-reported walking difficulty is linked to overall health and functional decline in aging adults[10,13,14]. Knee OA is one of the leading cause of walking difficulty[7]. Gait speed is a measurement of physical performance[15]. Individuals diagnosed with knee OA are 9 times more likely to exhibit gait speed decline than those without knee OA[4]. Slower walking speeds are an indicator of mobility limitations and risks for mortality[15,16]. In older adults, for every 0.5 meter per second, m/s, decline in gait speed, the risk of developing walking difficulty increases by 2.04[17]. As a result, there is a relationship between gait speed

and walking difficulty. However, when compared to each other gait speed and walking difficulty did not show strong agreement[11]. Therefore, self-reported walking difficulty and gait speed appear to measure different constructs of the same phenomena[11].

Examination and interventions for gait speed are well studied and established[15,18–20], while examination and interventions for walking difficulty is less understood. Since, gait speed and self-reported walking difficulty measure different constructs of walking[11], current established evidence and interventions that address gait speed cannot be used to address self-report walking difficulty. Ferrer and colleagues found that approximately 17% of those with faster gait speeds reported walking difficulty[11]. Yet, little is known about the sub-group who self-report walking difficult but are able to walk at fast and functional gait speeds.

Many studies have compared knee mechanics between those with and without knee OA[21–24], within knee OA based on OA severity[24,25], and within knee OA based on single symptom sub-groups (e.g., stable versus unstable)[26–28]. However, no studies have examined knee mechanics based on a walking difficulty sub-groups. Using walking difficulty as a sub-group within knee OA, may provide a heterogenic classification that is more inclusive of the knee OA experience. Individual knee OA symptoms have been used as sub-groups to examine gait mechanics, including pain[25], stiffness[26] , and instability[27]. Knee OA symptoms examined alone may not best represent knee OA, as the clinical diagnosis of knee OA requires the presence of pain and 3 or more signs or symptoms[28]. Farrokhi and colleagues found that patients with knee OA reporting knee instability not only walked with different knee mechanics but were also more likely to report other and more severe knee OA-related symptoms than those with knee OA without instability[29]. Farrokhi and colleagues also found that

those with knee OA and knee instability are 10.7 times more likely to have walking difficulty than those with knee OA and no knee instability[29]. Therefore, knee OA symptoms are related to walking difficulty, and examining sub-reported walking difficulty as a sub-group, instead of inddividual syptoms, may be more inclusive of the various knee OA symptoms.

Based on the previously used homogenous sub-group that include either specific symptom or severity, it appeared that knee mechanics during gait that are significantly different between those with and without knee OA, or referred to as knee OA gait characteristics, can be exacerbated with any worsening OA condition (e.g., radiographic OA severity, pain, stiffness, etc.)[30–34]. Known OA gait characteristics are measurable using knee kinematics and kinetics[30,31,35]. Knee kinematics is the measurement of knee motion during walking, and can be quantified in the sagittal and frontal plane[30,31,35,36]. Knee kinematics of those with knee OA generally walk with smaller sagittal plane and larger frontal plane knee angles than those without knee OA[22,37,38] Knee kinetics is the measurement of knee movement pertaining to force. Knee kinetics of those with knee OA generally walk with smaller sagittal plane knee moments and larger frontal plane knee moments when compared to those without knee OA[22,37,38]. Small sagittal plane knee kinematics and kinetics are suggestive of knee stiffening gait strategies, which can increase joint loads and alter forces to areas in the knee that are less capable of withstanding repetitive weight bearing loads[22]. Worsening knee OA severity and worsening knee OA related symptoms, such as pain and instability, can accentuate knee OA gait characteristics[39]. Many of the known OA gait characteristics are clinically modifiable[38,40,33,41–43].; therefore, examining gait

mechanics in terms of a walking difficulty sub-group within knee OA would identify gait mechanics that could benefit from interventions.

Therefore, the primary purpose of this study is to determine knee kinematic and kinetic differences during gait based on knee OA and walking difficulty sub-groups.

We hypothesized the following:

Hypothesis 1.1A: When examining knee kinematic and kinetic based on OA presence, gait patterns of the OA groups with (Diff) and without walking difficulty (NoDiff) will most represent OA gait characteristics than their age and sex matched control counterpart.

Hypothesis 1.1B: When examining knee kinematic and kinetic based on walking difficulty with the OA groups, we hypothesize that the Diff group will accentuate OA gait characteristics more than their NoDiff age and sex matched counterpart.

In addition, due to the large role knee OA symptoms can play on gait mechanics and walking ability, we will further examine how knee OA symptoms vary among those with and without walking difficulty.

Hypothesis 1.2: Worsening knee OA related symptoms would accentuate OA-related gait mechanics, and that this effect would more apparent in the Diff group than the NoDiff group.

## 2.2 Methods

Subjects were recruited from the community via newspaper ads and physician and physical therapy offices. Inclusion criteria for all subjects were English-speaking adults with and without knee OA, who were community dwelling, and between the

ages 50 to 80 years of age. Inclusion criteria for participation in the OA groups included a knee OA Kellgren-Lawrence Severity Score (KL) of grade II or greater in the medial compartment, and an instance of worst knee pain of "2" or more on a scale of 0 to 10, with "0" being no pain and "10" being worst pain imaginable[24]. Exclusion criteria for all groups included: (1) surgery, injury, or signs or symptoms of injury to the trunk, lower back, hip, leg, or foot/ankle within the past 3 months; (2) symptomatic arthritis in the lower back, hip, leg, foot, or ankle; (3) history of knee replacement or skeletal re-alignment surgery in either leg; (4) treatments (e.g., PT, injections, etc) for the trunk, lower back, hip, or foot/ankle in either leg in the past 6 weeks; (7) history of debilitating respiratory, cardiovascular, systematic, or neurological diseases; and (9) inability to walk without an assistive device (e.g., walker, wheelchair, cane). Exclusion criteria for participation in the control group included the presence of knee pain, one or more positive finding on the Altman's Criteria for knee OA (i.e., AM stiffness < 30 minutes, crepitus, bony tenderness, bony enlargement, palpable warmth)[32], or any prior history of diagnoses of knee OA. In cases where subjects presented with bilateral knee OA, the more functionally severe knee, as reported by the patient, was used as the test knee.

Subjects with knee OA were stratified into two groups based on the walking question from the Knee Outcome Survey (KOS), *How does your knee affect your ability to walk*?, to measure walking difficulty, which was scored on a 6-point scale (5 = *Not Difficult, 4 = Minimally Difficult, 3 = Somewhat Difficult, 2 = Fairly Difficult, 1 = Very Difficult, and 0 = Unable to do)*[12]. Responses of (5) *not difficult* or (4) *minimally difficult* were grouped into the "not difficult" group (NoDiff). Responses that ranged from (3) somewhat difficult to (0) unable to do were grouped into the

"difficult" group (Diff). Scoring stratification was selected to mirror prior research studies that sub-grouped patients based on single questions extracted from self-reported knee outcome surveys[22,32].

Participants in the Diff, NoDiff, and control groups were sex-matched and age-matched within 2.5 years. All participants provided written informed consent approved by the Health Sciences Institutional Review Board of the University of Delaware. The protocol for this study was approved by the Institutional Review Board of the University of Delaware.

### 2.2.1 Self-reported knee symptoms and function

The subjects answered questions, which were derived from their respective KOS scores, about knee-related symptoms including pain, stiffness, swelling, weakness, limping, catching, grinding, and stability. Responses for each symptom were ranged on a 6-point scale, with 0 as the greatest impact on function and 5 not havig the symptom ("I do not have the symptom" = 5; "I have the symptom, but it does not affect my activity" = 4; "the symptom affects my activity slightly" = 3; "the symptom affects my activity moderately" = 2; "the symptom affects my activity severely" = 1; "the symptom prevents me from all daily activities" = 0)[12].

### 2.2.2 Radiograph assessment

Knee OA severity was assessed using a standing, posterior-anterior radiograph with 20 degrees of knee flexion. An experienced radiologist, who was blinded to the subject's knee complaints and walking difficulty classification, scored radiographs based on the 4-point Kellgren-Lawrence scale: 1 = Doubtful narrowing of joint space and possible osteophytic lipping; 2 = Definite osteophytes, definite narrowing of joint

space; 3 = Moderate multiple osteophytes, definite narrowing of joint space, some sclerosis, and possible deformity of bone contour; 4 = Large osteophytes, marked narrowing of joint space, severe sclerosis, and definite deformity of bone contour[33]. Only individuals in the OA groups, NoDiff and Diff, with a Kellgren-Lawrence scale of 2 or greater were included in the analyses of this study.

### 2.2.3 Gait testing

Subjects walked first at a self-selected gait speed and then at a controlled gait speed of 1.0 meter per second (m/s) and self-selected gait speed over a 10-meter walkway, which included two in-ground force plates. Subjects wore retro-reflective markers during gait testing. The self-selective gait speed trials were to ensure that each subject could reach a gait speed of at least 1.0 meter per second. Also, the trials at self-selected speed allowed subjects to familiarize themselves with walking with gait analysis equipment. The examiner used an external timer to measure self-selected gait speed during the first trials and to ensure that gait speed did not deviate more than .05 m/s from the controlled rate of 1.0 m/s. At the end of each controlled gait speed trial, the examiner provided verbal cues to increase or decrease gait speed. Subjects walked a minimum of 5 accepted trials at each gait speed condition. Trials were only accepted if they included a minimum of two strides without altering gait patterns and with each foot clearly hitting one of the force plates. A 1 minute break, or more time if needed, was provided in between each trial to limit the effects of fatigue and exacerbation of knee symptoms. During each trial, subjects were asked to rate their knee pain on a 10-point scale.

### 2.2.4 Motion analysis

All subjects stood on the force plates for 5 seconds for calibration, which also provided data on height, weight, and knee alignment. For walking trials, subjects walked over two in-ground force plates (AMTI Force Plate, Watertown, MA) with retro-reflective markers secured to the head, shoulders, trunk, pelvis, hips, thigh, knee, leg, foot, and ankle on both legs for calibration and to identify the respective joint center. Rigid thermoplastic shells, with four retro-reflective markers firmly affixed, were attached to the pelvis, lateral femur, lateral tibia, and dorsal surface of the foot. Markers were secured either directly to the skin through self-adhesion or using ace-wrap depending on location. Eight 3-dimensional motion analysis cameras (Qualisys, Inc., Göteborg, Sweden) were used to track markers. The combination of the cameras' and force plates' data allowed for the calculation of joint angles and joint moment to define gait intervals and calculated gait speed. Data were collected at 1000 Hz for force plates, and 100 Hz for cameras collected data at 100 Hz.

### 2.2.5 Data management and processing

We collected data via the Qualisys system and exported raw motion capture data to Visual 3D$^{TM}$ (C-Motion, Rockville, MD), for processing. Force platform data and motion capture markers were low-pass filtered with a second-order Butterworth filter at 40 Hz and 4 Hz, respectively. During calibration, the location of the head marker in the z-direction, or superior-inferior direction, was used to calculate the subject's height in meters, and the sum of the two force plates was converted to kilograms to calculate the subject's weight.

Frontal and sagittal plane knee angles were calculated via Visual 3D$^{TM}$ using Euler angles. Knee angles relative to the hip and foot, taken from standing calibration,

were used to calculate knee alignment. The force plate data and knee angles were used to determine gait intervals. Final gait speed was calculated for two continuous strides on each limb, with one stride hitting the force plate, using temporal distance properties within Visual 3D$^{TM}$. The average of three trials for each gait speed condition was used for analysis. Gait intervals were divided, using motion capture and force plate, into weight acceptance and mid-stance, and normalized to 100 data points to account for time differences. Weight acceptance began at initial contact on the first force plate and lasted through peak knee flexion angle. Mid-stance began at peak knee flexion angle and lasted through peak knee extension angle. Knee angle excursion was defined as the maximum joint angle minus the minimum joint angle for knee flexion excursion during weight acceptance and knee extension excursion during mid-stance. Positive values suggested knee flexion, while negative values suggested knee extension. Frontal plane knee excursion was defined as the largest joint angle minus the smallest joint angle, where positive values suggested valgus knee angles and negative values suggested varus knee angles. External joint moments were normalized to height times weight, and positive joint moments represented knee flexion and varus moments and negative values represented extension and valgus moments for the sagittal and frontal planes, respectively.

### 2.2.6 Statistics

Statistical analysis was performed using SPSS (version 13, Chicago, IL). Homoscedasticy was tested using the Levene's test for homoscedasticity and normal distribution was tested using the Kolmogorov-Smirnov test. Variables that were significant for either test, with a p-value $\leq .05$, were examined using non-parametric testing. Between-group differences were tested using one-way ANOVA with repeated

measures for parametric testing and the Wilcoxon signed rank test for non-parametric testing. Further analyses were performed to examine the effects of BMI and knee alignment on each dependent variable using descriptive statistics and quartiles. Group comparisons were determined *a priori*, with the primary focus to examine group comparisons between the Diff and NoDiff groups for differences based on walking difficulty and NoDiff and Control groups for differences based on OA presence. Therefore, the p-value was not adjusted for repeated comparison with significance set at $p \leq .05$. Power analysis was performed *a priori* to determine adequate sample size for matched comparisons. In order to achieve a power of 80% at a significant level of 0.05, a total sample size of 27, or 9 in each group, would be needed.

To examine how OA-related symptoms negatively impacted function in the Diff and NoDiff groups, we calculated the percentage of subjects within each group that gave responses of 3 or less. We then sub-tracted the percent between the two groups, which represented the percent difference between the Diff and NoDiff groups who had the knee OA symptom that most negative affected their function. We chose the three top knee OA symptoms with the largest percent difference between the Diff and NoDiff groups, to examine their effect on gait mechanics. Specific gait mechanics were averaged within each OA group based on OA-related symptom responses (e.g., knee flexion excursion angles were averaged for all subjects within the Diff group who reported their knee pain as a 1, or as affecting their activity severely). Again, after gait testing, gait mechanics averages within each symptom and each group were visually examined for trends.

## 2.3 Results

Thirty-nine subjects participated in the study. Subjects were age-matched (average age for all subjects = 66.0) and sex (N= 5 males per group, total males = 15). BMI was not significantly different between the groups; however, when visually examining actual BMI values, the Diff walking group overall had the largest BMI, followed by the NoDiff, with the smallest BMI in the control group (Table 1). However, in all of our groups, there were no observable trends in sagittal and frontal plane gait mechanics when broken down into BMI quartiles. Specific characteristics of the subjects are presented in Table 1.

### 2.3.1 Gait mechanics

Knee kinematics were smaller in the sagittal plane and larger in the frontal plane for the Diff group than the NoDiff group and for the OA groups than the Control group. Average knee flexion excursion was the smallest for the Diff group (average, 95% CI [lower, higher]; 8.0°, 95% CI [6.1, 9.8]), followed by the NoDiff group (8.5°, 95% CI [7.0, 9.9]), and the largest for the Control group (9.4°, 95% CI [8.3, 10.6]). Knee flexion excursion differences based on OA presence, between NoDiff versus Control $t(12) = -.98$, $p = .17$, $d = .23$ and between Diff versus Control $t(12) = 1.18$, $p = .13$, $d = .25$, were not significant and had small effect sizes (Figure 2.1). Similar, flexion excursion differences based on walking difficulty presence within knee OA, Diff versus NoDiff $t(12) = -.69$, $p = .06$, $d = .28$, were not significant and had a small effect size (Figure 2.1).

Average knee extension excursion was the smallest for the Diff group (6.8°, 95% CI [5.2, 8.5]), followed by the NoDiff group (7.7°, 95% CI [5.7, 9.7]), and the largest in the Control group (10.3°, 95% CI [7.8, 12.7]) (Figure 2.1). Extension

excursion differences based on OA presence, between the Diff and Control group, t (12) = 2.31, p = .02, d = .73 and between the NoDiff and Control group, t (12) = -1.78, p = .05, d= -1.5, were significantly different and had medium to large effect sizes (Figure 2.1). However, between the Diff and NoDiff groups, t (12) = .82, p =.22, d = .25, knee extension excursion was not significantly different and had a small effect size (Figure 2.1).

Average frontal plane knee excursion was the largest for the Diff group (3.9, 95% CI [3.1, 4.5]), followed by the NoDiff group (3.5, 95% CI [2.5. 4.6]), and the smallest in the Control group (2.5 95% CI [1.8, 3.1]) (Figure 2.2). Frontal plane knee excursion differences based on OA presence, between the Diff and Control group, t (12) = 2.4, p = .02, d = .55, and between the NoDiff and Control group, t (12) = 1.76, p =.05, d =.47, were significantly different and had small to medium effect sizes (Figure 2.2). However, when based on walking difficulty, frontal plane knee excursion was not significantly different between the Diff and NoDiff group, t (12) = .54, p =.30, d =.15, and had an effect size that was less than small (Figure 2.2).

Differences among the groups were also observed for knee kinetics. Average external knee extension moment was the smallest for the Diff group (.10 Nm/Kg*m, 95% CI [.03, .16], followed by the NoDiff group (.16 Nm/Kg*m, 95% CI [.11, .22]), and the largest for the Control group (.21, [.15, .27]) (Figure 2.1). Knee extension moment between the NoDiff and Control groups, t (12) = 1.4, p = .09, d = .38, was not significantly different and had a small effect size (Figure 2.1). Knee extension moment between the Diff and the Control groups, t (12) = 2.7, p = .01, d = .68, were significantly different and had a medium effect size (Figure 2.1). Meanwhile, based on walking difficulty presence, knee extension moment, between the Diff and the NoDiff

groups, t (12) = 1.9, p = .04, d = .59, was significantly different and had a medium effect size (Figure 2.1).

Average external knee flexion moment was the largest for the Diff group (.22 [.16, .28]), and similar between the NoDiff (.17 Nm/Kg*m, 95% CI [.11, .22]) and the Control (.18 Nm/Kg*m, 95% CI [.13, .22]) groups (Figure 2.1). However, based on OA presence, both comparisons between the NoDiff and Control groups, t (12) = .5, p = .32, d = .15, and between the Diff and Control groups, t (12) = 1.0, p = .17, d = .22, were not significantly different and had small to less than small effect size sizes (Figure 2.1).

Average first peak knee adduction moment was the largest for the Diff group (.20 Nm/Kg*m, 95% CI [.25, .34]) and similar between the NoDiff (.21 Nm/Kg*m, 95% CI [.15, .27]) and the Diff (.21, [.18, .24]) groups. The first peak knee adduction moment was not significantly different between the NoDiff and Control groups, z = -.22, p = .41, r = -.04, and had a less than small effect size (Figure 2.3). The first peak adduction moment was significantly different between the Diff and Control groups, z = 2.5, p = .01, r = .49, and had a medium effect size (Figure 2.3). Between the OA groups, the first peak adduction moment was significantly different between the Diff and NoDiff groups, z= 2.1, p = .02, r = .42, and had a medium effect size (Figure 2.3).

Average second peak knee adduction moment was the largest for the Diff group (.24 Nm/Kg*m, 95% CI [.18, .30]), smallest for the NoDiff group (.18 Nm/Kg*m, 95% CI [.13, .22]), and the Control (.21 Nm/Kg*m, 95% CI [.17, .24]) group fell between the Diff and NoDiff groups (Figure 2.3). The second peak adduction moment was not significant based on OA presence, as no significant differences were found for either the Diff and Control groups, t (12) = 1.3, p = .11, d =

.37, or between the Diff and Control group t (12) = .90, p = .19, d = .29, and both comparisons had small effect sizes (Figure 2.3). Meanwhile, between the Diff and NoDiff groups, t (12) = 1.9, p = .04, d = .61, the second peak knee adduction moment was significantly different and had a medium effect size (Figure 2.3).

### 2.3.2 OA Symptoms

The distribution of subjects' responses on how knee symptoms impact function, per the KOS, are shown in Table 2. No subjects, in either of the OA groups, reported a "0," or inability to function, for any of the symptoms. All subjects in the Diff group reported that pain and stiffness negatively affected function, defined as a response of "3" or lower. Ten, or 76.9%, of the subjects in the Diff group reported that limping affected function negatively. Meanwhile, in the NoDiff group, 69.2% reported pain, 55.4% reported stiffness, and 46.2% reported limping affected function negatively (Figure 2.4). Therefore, for all OA-related symptoms, more subjects in the Diff group than the NoDiff group indicated that the symptoms affected function negatively, with the exception of swelling. For swelling both groups had 46.2% of their sample reporting negative effects; therefore, a difference of 0% (Figure 2.4). In contrast, the largest percent differences between the Diff and NoDiff groups for all symptoms were pain, stiffness, and limping (Figure 2.4). Based on this finding, responses to pain, stiffness, and limping were used to examine their influence on gait mechanics among subjects with knee OA but between those with and without walking difficulty.

Through visual inspection, there was an apparent trend observed between self-reported pain and knee mechanics in the OA groups. For the Diff group, worsening knee pain trended with larger external knee flexion moment and smaller extension

moment (Table 2.3). For the NoDiff group, worsening knee pain trended with smaller knee flexion excursion, larger knee flexion moment, and larger knee adduction moment (Table 2.3).

Apparent trends were observed between self-reported knee stiffness and knee mechanics in the OA groups. For the Diff group, worsening knee stiffness trended with larger knee extension and larger knee flexion excursion (Table 2.4). For the NoDiff group, worsening knee stiffness trended with smaller knee flexion excursion and knee flexion moment (Table 2.4).

With respect to limping complaints, trends were only observed in the NoDiff group. Worsening self-reports of limping trended with smaller knee flexion and extension excursions in the NoDiff groups (Table 2.5).

## 2.4 Discussion

Knee kinematics and kinetics vary based on the presence of knee OA and walking difficulty. Our findings suggest that knee kinematics, knee extension and frontal plane knee excursion, appear to be similar between the OA groups, Diff and NoDiff, but significantly different between the OA and control groups. While, knee kinetics, external knee extension and knee adduction moment, appear to be similar between the NoDiff and control and significantly different between the OA groups. Therefore, knee kinematics appear to vary more based on OA presence, and knee kinetics appear to vary more based on walking difficulty presence. It is especially interesting that little to no differences for knee kinetic are found between the NoDiff and Control group, as inclusion criteria required all OA subjects to have knee OA severe enough to seek medical attention (e.g., KL score $\geq 2$ and pain $\geq 3$). In support of our hypothesis the trends of knee kinematics relating to knee OA gait characteristics

were most accentuated by subjects the Diff group, followed by those in the NoDiff group, and least accentuated in the control group. Also consistent with our initial hypothesis, self-reported knee pain and stiffness exhibited some trends with sagittal plane knee kinetics and kinematics, and such trends varied based on walking difficulty within the knee OA groups. These findings suggest that factors relating to knee kinetic differences may be contributing to walking difficulty in those with knee OA, while knee kinematics differences may be an unavoidable knee OA gait characteristic.

Our hypothesis that those the Diff group would demonstrate the largest frontal plane knee and kinematics, followed by the NoDiff group, and would be the smallest in the control group was supported by examining the trends in our data. However, our hypothesis for comparisons between the NoDiff and control groups were not statistically supported. Differences between the NoDiff and Control groups were not statistically signficant. This finding was suprising, as generally frontal plane knee kinetics and kinematics is related to OA severity and all of our subjects had medial compartment knee OA. However, our subjects with knee OA can also have lateral compartment knee OA that was less serve than the medial compartment, which could affect walking and standing knee alignment.

Since, knee alignment can influence frontal plane knee mechanics [47], we conducted a post-hoc analysis to the determine the potential effects of knee alignment on knee mechanics. The standard for measuring knee alignment is a posteroanterior long-leg radiograph[48], which was not performed in this study. Examining hip-knee-ankle alignment through motion capture has been found to produce excellent correlation with knee alignment via radiographs, r = .93 [49]. Using the motion capture standing calibration, we calculated hip-knee-ankle angle frontal plane alignment.

Average knee alignment was -.10 degrees for the walking difficulty group, .63 degrees for no walking difficulty group, and .11 degrees for the control group. Negative values represent varus angles, and positive values represent valgus angles. Frontal plane knee alignment was not statistically different among the three groups (Table 6). The NoDiff group had 1 outlier data point, and without this value the average of NoDiff decreased to .09 degrees, and group comparisons continued to be statistically non-significant. However, the visual examination of the overall averages suggest that the Diff group had the largest knee varus alignment, followed by the NoDiff group with the outlier value removed, and the smallest varus alignment was found in the control group. Although these values were small and potentially unable to determine based on the naked eye, they fell within those reported in the literature, $4.6^{\circ} \pm 6.5^{\circ}$ [49].

When we examined the influence of knee alignment on frontal plane knee mechanics trends, those with greater knee varus alignment appeared to walk with larger frontal plane knee excursion and adduction moment when compared to subjects with lesser knee varus alignment (Table 2.7). This trend was more apparent in the Diff group, but present in both OA groups and the Control group (Table 2.7). As a result lesser knee varus alignment in our NoDiff group when compared to Diff group may be linked to the significant differences found based on walking difficulty and lesser difference based on OA presence.

Interestingly, when examining knee alignment we also observed that those with more knee varus knee alignment, regardless of group walked with smaller knee flexion excursion (Table 2.7). In all groups, those with higher quartiles of knee alignment, or greater knee varus standing alignment, had lower knee flexion excursion than individuals in the lower quartile of knee alignment, or lesser knee varus

alignment (Table 2.7). Perhaps knee varus alignment may be creating a frontal plane knee stability deficit that is being compensated for by limiting knee flexion excursion in order to compensate for the lack of stability in the frontal plane. The lack of statistical difference for knee flexion mechanics may be due related to knee alignment

Our hypothesis that those with walking difficulty would demonstrate the smallest knee flexion excursion and moment, followed by the NoDiff group, and the largest would be observed in the control group was not supported by our findings. Given that smaller knee flexion moment was related to worsening knee OA severity, we expected our OA groups would walk with significantly less knee flexion moment than the Control group. However, not only did knee flexion moment not achieve significant differences; but when examining descriptive statistics knee flexion moments were similar between the NoDiff and control groups and the largest in the Diff group.

The lack of significant difference for knee flexion moment may be explained by study design and the construct of sub-groups. Evidence from previous studies on knee OA suggest that those with knee OA often adopt a knee stiffening gait strategy that combines lesser knee flexion excursion and moment with greater muscular co-contraction to maintain knee stability to meet the demands of the task[22,50]. However, knee flexion moment increases with age[50] and gait speed[33]. In our study, subjects were matched for age and walked at a controlled gait speed of 1.0 meter second. Recently, Zeni and Higginson also found non-signficant differences among subjects with no knee OA, moderate knee OA, and severe knee OA while walking on a treadmill at a controlled gait speed of 1.0 m/s[38]. Further, Zeni and Higginson reported that knee flexion moment averages were not significantly different but, via visual inspection,

larger knee flexion moments were observed in the OA group with more severe knee OA, diagnosed by radiographs, when compared to the group with moderate knee OA[38]. Combining the findings of our study to Zeni and Higginsons' study could suggest that knee flexion moment can vary with gait speed and examining the role of knee flexion moment may need to be done during a controlled gait speed. However, Zeni and Higginson classified subjects with OA using a different construct, radiographic OA severity, than our study, self-reported walking difficulty.

Most studies that examine sub-group classification with knee OA use OA severity[24,51]. Farrokhi and colleagues found that among those with knee OA, subjects reporting knee instability, or the buckling or giving way, when walking at self-selected gait speed, used larger knee flexion moment than the those in the stable group[28]. Farrokhi and colleagues also found in this same cohort that self-reported instability is related to knee pain and walking difficulty[28], which may justify the trends that we observed for knee flexion moment based on walking difficulty. It appears that knee flexion moment can show trends based on self-reported measures and may be influenced by gait speed.

The relationship between knee OA symptoms and knee flexion gait mechanics are further supported in our study when examining the trends knee flexion moment and excursion with worsening pain and stiffness. For pain, our subjects with greater knee pain walked with larger knee flexion moment in both OA groups. Surprisingly, for stiffness, we found contrasting effects of worsening knee self-perceived stiffness on knee flexion excursion. In the Diff group, those with worsening stiffness complaints walked with larger knee flexion excursion, and in the NoDiff, those with

worsening knee stiffness actually walked with smaller knee flexion excursion. Perhaps knee flexion moment may vary based on specific OA-related symptoms.

These findings may suggest knee flexion moment may be related to knee pain and stiffness. Knee pain alone may influence knee flexion moment, as such notable trends were observed based on pain despite the lack of statistcal differences between the Diff and NoDiff groups in our study. However, walking difficulty may moderate the relationship between self-percieved stiffness and knee moment, but more resesarch is needed to examine the effects of walking difficulty on self-percieved stiffness and OA gait mechanics.

The hypothesis that those with walking difficulty would walk with smaller knee extension kinematics and larger frontal plane knee mechanics were supported by our hypothesis. As the quadriceps muscles eccentrically control knee flexion moment during weight acceptance it generates enough torque to produce an extension moment for mid-stance that allows the deactivation of the quadriceps[52]. This requires adequate strength in the quadriceps to control flexion knee mechanics, and it has been suggested that alteration of flexion gait mechanics may be related to quadriceps strength[53,54]. The lack of quadriceps strength is found in those with knee OA and worsening knee function, which can result in knee stiffening gait strategies[54,55]. Our findings suggest that small knee extension excursion appears to be a problem for knee OA regardless of walking difficulty, and knee extension moment appears to be a problem for walking difficulty as it was smaller for Diff group than the NoDiff group and similar between the NoDiff and control groups. So, if the Diff group has weaker quadriceps and is unable to provide adequate eccentric quadriceps load to generate enough torque for mid-stance, knee extension moment would be small and the quadriceps would need to

stay on longer to maintain knee stability and allow the anterior translation of body weight. The weak and prolonged activation of the quadriceps muscle may increase compressive forces at the knee, as the knee may further require co-contraction of antagonist muscles to maintain knee stability. Perhaps, addressing quadriceps strength and perhaps focusing gait training on reducing knee flexion moment and facilitating knee extension moment during early stance may be beneficial for reducing walking difficulty and maintaining knee stability.

Limitations of the present study include a small sample size and a cross-sectional, the findings garner limited information regarding the temporal nature of the relationship between walking difficulty and OA presence for knee kinematics and kinetics. Additional studies are needed to clarify whether knee kinematics are inevitable to knee OA progress and whether knee kinetics vary more based on self-reported walking difficulty presence.

The findings of this study should be considered in light of its limitations, especially given the controlled study design for age, sex, and gait speed. Despite the controlled nature, walking difficulty in those with knee OA appears to be most likely a multifactorial problem that may be influenced altered knee kinetics, as well as altered neuromuscular control strategies such as co-contraction, and quadriceps strength, factors that were not examined as part of this study. Further, our study specifically examined subjects with medial compartment knee OA, therefore the potential contributions of lateral compartment or patellofemoral joint involvement on walking difficulty remains unknown. Frontal and sagittal plane joint degradation and potential mechanisms of OA related symptoms may have an effect on walking difficulty but were not examined in this study. Future studies should consider the possible effects of

these factors and their potential effects of these interaction on knee mechanics during gait in order to gain a clearer concept of the relative contribution of such impairments to walking difficulty.

## 2.5 Conclusion

The findings of this study suggest that knee kinetic differences during gait appear to vary more based on self-reported walking difficulty, while knee kinetic differences appear to vary more based on OA presence. While knee flexion moment and excursion were not significantly different, trends appear to vary with OA related symptoms. In addition, it appears that those with knee OA and self-reported walking difficulty walked with small knee extension excursion and moments during stance phase of gait. Perhaps addressing knee extension excursion and moment clinically could attenuate walking difficulty in knee OA.

Table 2.1 Subject characteristics. Average (± SD) age, body mass index (BMI), and pain. Pain reported on a scale from 0, defined as no pain, to 10, defined as worst pain imaginable.

| | OA | | | |
|---|---|---|---|---|
| | Diff | Not Diff | Control | p-value |
| N | 13 | 13 | 13 | n/a |
| Age (years) | 66.1 ±6.3 | 65.8 ±5.8 | 66.1± 6.2 | n/a |
| Sex (N) | Females = 8; Males = 5 | | | n/a |
| BMI ($Kg/m^2$) | 31.4 ± 5.6 | 29.7 ± 5.6 | 27.6 ± 3.7 | p = .18 |
| OA Severity (N) | | | | p = .61 |
| 2 | 4 | 4 | N/A | |
| 3 | 5 | 6 | N/A | |
| 4 | 4 | 3 | N/A | |
| Pain (0 to 10) | 6.5 ±1.5 | 5.6 ±2.0 | N/A | p = .92 |

No significant differences were observed between our OA groups for OA severity or pain.

Table 2.2 Responses to OA symptoms. Distribution (N) of responses for knee symptoms of subjects with knee OA with (Diff) and without walking Difficulty (NoDiff) adopted from the Knee Outcome Survey (KOS)

| | | No Symptom | No Affect | Slightly | Moderately | Severely |
|---|---|---|---|---|---|---|
| Symptom | Group | 5 | 4 | 3 | 2 | 1 |
| Pain | Diff | 0 | 0 | 4 | 4 | 5 |
| | NoDiff | 1 | 3 | 2 | 7 | 0 |
| Stiffness | Diff | 0 | 0 | 3 | 6 | 4 |
| | NoDiff | 1 | 5 | 3 | 4 | 0 |
| Swelling | Diff | 3 | 4 | 1 | 2 | 3 |
| | NoDiff | 5 | 2 | 2 | 3 | 1 |
| Giving | Diff | 1 | 5 | 0 | 4 | 3 |
| Way | NoDiff | 3 | 4 | 3 | 2 | 1 |
| Weakness | Diff | 1 | 3 | 3 | 5 | 1 |
| | NoDiff | 3 | 3 | 5 | 1 | 1 |
| Limping | Diff | 0 | 3 | 5 | 4 | 1 |
| | NoDiff | 5 | 2 | 3 | 2 | 1 |

No subjects, in either OA groups, reported 0 or unable to function due to symptom for any of the symptoms; therefore, 0 was omitted from the table.

Table 2.3 Trends for knee kinematic and kinetic based on pain. Average knee kinetic and kinematic distributions based on self-reported knee pain from the Knee Outcome Survey.

| | 1 | 2 | 3 | 4 or 5 |
|---|---|---|---|---|
| Diff (N) | 5 | 4 | 4 | 0 |
| Not Diff (N) | 0 | 7 | 2 | 4 |
| Flexion Excursion (◦, average) | | | | |
| Diff | 8.8 | 6.8 | 8.1 | n/a |
| Not Diff¥ | n/a | 8 | 8.5 | 9.6 |
| Flexion Moment (Nm/Kg*m, average) | | | | |
| Diff¥ | 0.31 | 0.17 | 0.16 | n/a |
| Not Diff* | n/a | 0.19 | 0.14 | 0.14 |
| Extension Moment (Nm/Kg*m, average) | | | | |
| Diff¥ | -0.05 | -0.08 | -0.18 | n/a |
| Not Diff | n/a | -0.18 | -0.14 | -0.15 |
| First Peak Adduction Moment (Nm/Kg*m, average) | | | | |
| Diff | 0.30 | 0.31 | 0.27 | n/a |
| Not Diff¥ | n/a | 0.24 | 0.20 | 0.17 |

¥Marks the group when trends are observed

Table 2.4 Trend for knee kinematic and kinetic based on stiffness. Average gait mechanic distribution based on self-reported knee stiffness for the OA group with walking difficulty (Diff), and the OA group with no walking difficulty (NoDiff).

| | 1 | 2 | 3 | 4 or 5 |
|---|---|---|---|---|
| Diff | 4 | 6 | 3 | 0 |
| NoDiff | 0 | 4 | 3 | 6 |
| Extension Excursion (◦, average) | | | | |
| Diff[¥] | 9.2 | 6.12 | 4.98 | n/a |
| NoDiff | n/a | 8.4 | 9.11 | 6.56 |
| Flexion Excursion (◦, average) | | | | |
| Diff[¥] | 9.6 | 7.3 | 7.2 | n/a |
| NoDiff[¥] | n/a | 8.1 | 8.7 | 8.8 |
| Flexion Moment (Nm/Kg*m, average) | | | | |
| Diff | 0.23 | 0.26 | 0.12 | n/a |
| NoDiff[¥] | n/a | 0.25 | 0.15 | 0.11 |

[¥]Marks the group when trends are observed

Table 2.5 Trend for knee kinematic and kinetic based on limping. Average gait mechanic distribution based on self-reported limping for the OA group with walking difficulty (Diff), and the OA group with no walking difficulty (NoDiff)

| | 1 | 2 | 3 | 4 or 5 |
|---|---|---|---|---|
| Difficult | 1 | 4 | 5 | 3 |
| NoDiff | 1 | 2 | 3 | 7 |
| Flexion Excursion (◦, average) | | | | |
| Difficult | 11.4 | 8.3 | 7.1 | 7.6 |
| NoDiff[¥] | 2.3 | 6.2 | 8.6 | 9.2 |
| Extension Excursion (◦, average) | | | | |
| Difficult | 9.8 | 5.9 | 6.7 | 7.6 |
| NoDiff[¥] | 3.2 | 5.5 | 8.4 | 8.1 |

[¥]Marks the group when trends are observed

Table 2.6 Sagittal plane knee alignment. Average (± SD) frontal plane knee alignment, in degrees, during standing for the OA group with walking difficulty (Diff), the OA group without walking difficulty (NoDiff), and the Control group. Negative values represent knee alignment in the varus direction, and positive values suggest knee alignment in the valgus direction. 1 outlier noted in the NoDiff group, when removed average of NoDiff group decreased to .09°.

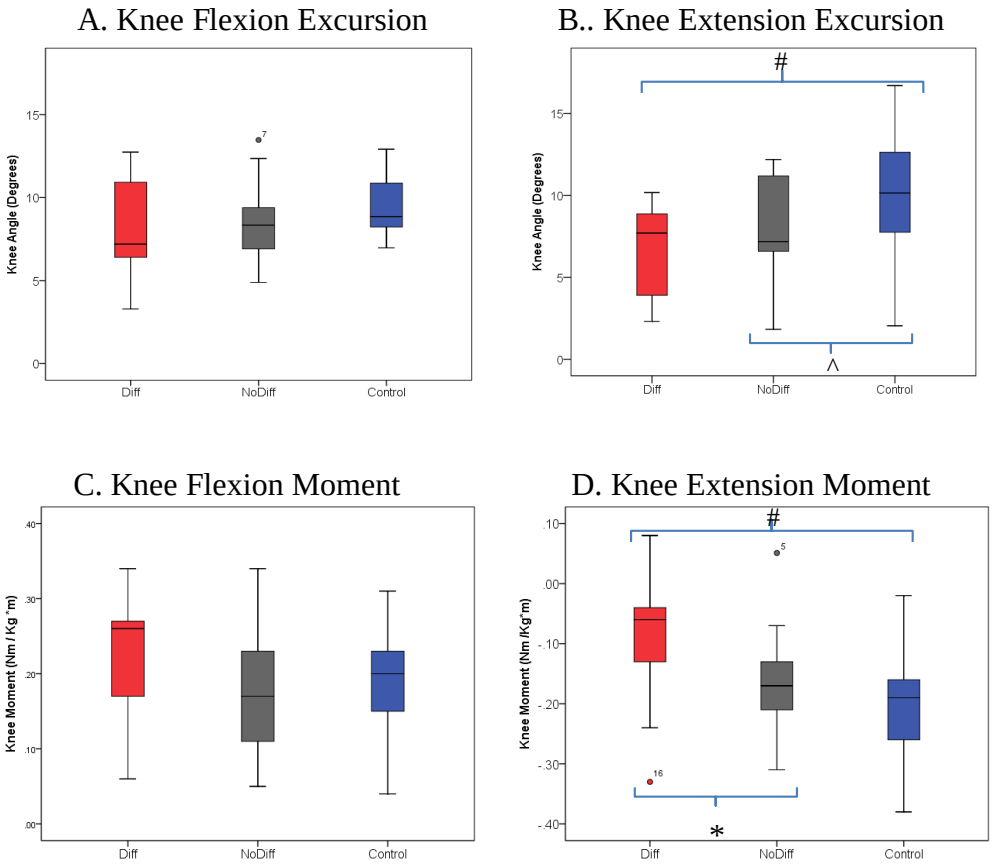
| | Diff | NoDiff | Control | P-value |
|---|---|---|---|---|
| Knee Alignment (◦) | -.10 ±.31 | .63 ± 1.9 | .11± .35 | p = .28 |

Table 2.7. Trend for knee kinematic and kinetic based on knee alignment. Average gait mechanics over knee alignment quartiles for the OA group with walking difficulty (Diff), the OA group with no walking difficulty (NoDfiff), and the control group. Negative values represent knee varus angles and positive values represent knee valgus angles.

| | Q1 | Q2 | Q3 | Q4 |
|---|---|---|---|---|
| | < -0.001 | -0.001- 0.0 | 0.1 - .2 | ≥.3 |
| Diff (N) | 4 | 4 | 3 | 2 |
| NoDiff (N) | 3 | 0 | 6 | 4 |
| Control (N) | 2 | 5 | 2 | 4 |
| Knee Flexion Excursion (◦, average) | | | | |
| Diffi¥ | 5.4 | 8.1 | 9.8 | 10.0 |
| NoDiff¥ | 7.7 | n/a | 8.8 | 8.8 |
| Control¥ | 8.4 | 8.9 | 10.5 | 10.1 |
| Frontal Plane Excursion (◦, average) | | | | |
| Difficult¥ | 4.5 | 4.2 | 3.6 | 2.6 |
| NoDiff | 4.6 | n/a | 3.0 | 3.5 |
| Control | 3.1 | 2.0 | 2.8 | 2.7 |
| 1st peak adduction moment (Nm/Kg*m, average) | | | | |
| Diff¥ | -0.36 | -0.3 | -0.23 | -0.24 |
| NoDiff¥ | -0.23 | n/a | -0.22 | -0.18 |
| Control¥ | -0.23 | -0.19 | -0.21 | -0.21 |

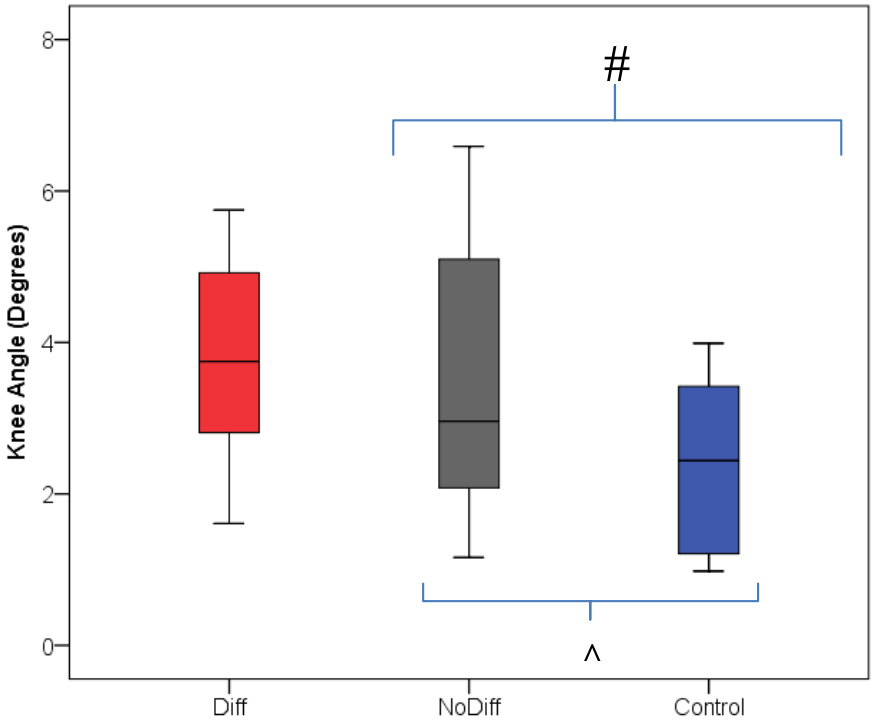
¥Marks the group when trends are observed

Figure 2.1 Sagittal plane knee kinematic and kinetic. First row shows knee kinematics and second row shows knee kinetics for the – Difficult (Diff); – Not Difficult (NoDiff); and – Control groups. Greater positive values for the first row represent increasing knee excursion, or larger positive values suggest larger knee flexion or extension excursion. In the 2nd row, positive values represent flexion moment ©, while negative values represent extension moment (D). Top whisker represent the highest quartile, or those who walk with the largest knee excursion, largest knee flexion moment, or smallest knee extension moment. Box represents the 2nd and 3rd quartile separated by a line, or the median. Bottom whisker represent the lowest quartile that uses the smallest degree of knee excursion per group (A and B), smallest knee flexion moment (C), and largest knee extension moment (D).




(#) Significant between the Diff and Control groups
(^) Significant between the NoDiff and Control groups
(*) Significant between Diff and NoDiff

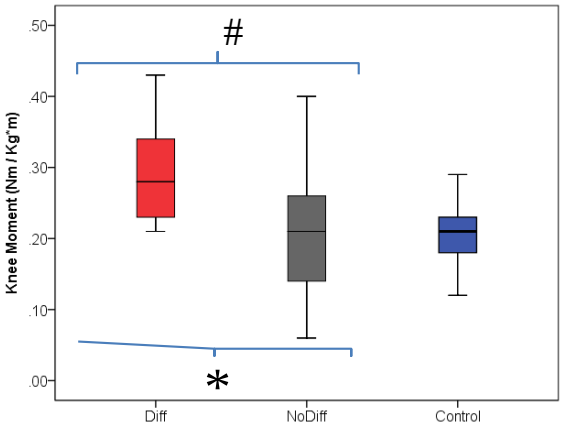
Figure 2.2. Frontal Plane Knee Excursion. Frontal plane knee excursion from heel strike to toe off (A). Positive values represent varus angles, and negative values represent valgus values. Frontal plane knee excursion was calculated as the difference between peak varus and peak valgus (B). Top whisker represents the highest quartile that uses the most frontal plane knee excursion. The box represents the 2nd and 3rd quartile separated by a line or the median. Bottom whisker represents the lowest quartile that uses the smallest degree of knee excursion per group. – *Difficult (Diff);* – *Not Difficult (No Diff); and* – *Control;*



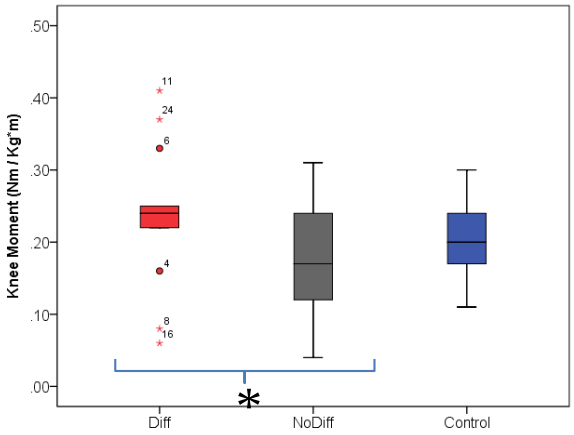

(#)Significant between Diff and Control
(^) Significant between NoDiff and Control
(*)Significant between Diff and NoDiff

Figure 2.3 Frontal plane knee moment. First (A) and second (B) peak knee adduction moment for – Difficult (Diff); – Not Difficult (No Diff); and – Control groups. Top whisker represents the highest quartile within each group that uses the largest knee adduction moment. Box represents the 2nd and 3rd quartile, with line representing the median. Bottom whisker represents the lowest quartile per group.

A. Knee Adduction Moment – 1st Peak

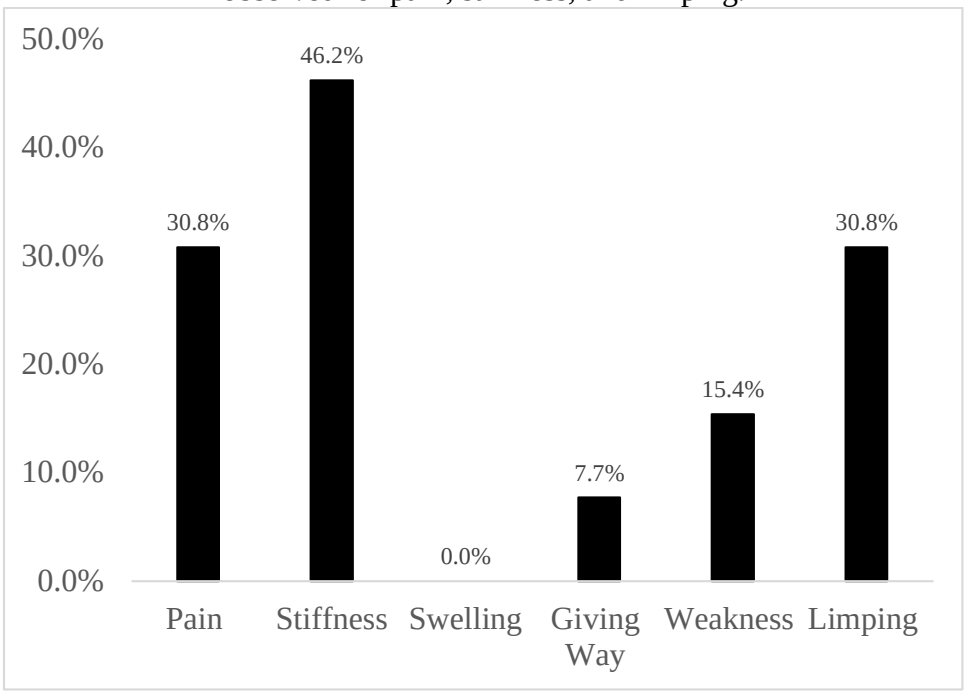



B. Knee Adduction Moment – 2nd Peak




(*) Significant between Diff and NoDiff, $p \leq .05$.
(#) Significant difference between Diff and Control, $p \leq .05$.

Figure 2.4 Percentile differences between those with and without walking difficulty reporting that OA-related symptoms negatively impact function. The value above each bar represents the percentage difference between the groups that reports the symptom negatively affects ability to function. Negatively affects ability to function was defined as responses of 3 or less on the knee outcome survey (KOS). In all cases, the walking difficulty group had a larger percent; so values were calculated as a percent of individuals reporting "3" or worst for each symptom in the walking difficulty minus the no walking difficulty group. Value interpretation suggests that a greater percent of the walking difficulty group had symptoms that negatively impact function than the no walking difficulty group. The largest differences between the two groups were observed for pain, stiffness, and limping.



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Chapter 3

# NEUROMUSCULAR STRATEGIES BASED ON KNEE OSTEOARTHRITIS, WAKING DIFFICULTY, AND GAIT SPEED

## 3.1 Introduction

The prevalence of knee osteoarthritis (OA) exceeds more than 3 million known cases in the United States[1]. Knee OA is the leading cause of functional disability, which usually occurs within 3-5 years of knee OA diagnosis[1]. Since knee OA primarily effects aging adults, as the incidence of knee OA sharply increases after 50 years of age[2], those with knee OA are combating functional decline from both the natural course of aging and the progression of knee OA[3].

The severity of knee OA symptoms are thought to have significant impact on functional mobility and overall health status. For example, high pain levels pertaining knee OA can limit the ability to walk[4]. Walking ability limitations associated with knee OA can have negative impacts on health, as common comorbidities related to aging can result in poor outcomes when walking becomes difficult[5]. Patients with already potentially life threatening diseases, such as cardiovascular episodes, dementia and stroke, have a higher incidence for mortality when these co-morbidities are combined with knee OA[5]. Therefore, not examining and addressing walking limitations that pertain to knee OA in this fragile population can lead to detrimental outcomes.

Walking ability in the clinic is examined by self-reported walking difficulty and gait speed. Self-reported walking difficulty is measured based on the question *How does your knee affect your ability to walk* from the Knee Outcome Survey[6]. Responses that range between *somewhat difficult* to *unable to walk difficult*[6] are considered to have walking limitations linked to their knee OA. The cut-off is adopted

from studies that also uses the Knee Outcome Survey to sub-group subjects with symptomatic knee OA[7,8]. Self-reported walking difficulty is linked to functional mobility limitations and overall health[5,9]. Knee OA is one of the leading cause of self-reported walking difficulty in adults[9]. Gait speed is a physical performance measurement that is also related to mobility limitations and mortality[10,11]. Those with knee OA, when compared to those without knee OA, are 9 times more likely to demonstrate a decline in gait speed[12]. Although walking difficulty and gait speed are linked, as for every .05 meter per second decline in gait speed there is a 2.04 increase in risk for developing walking difficulty, when compared to each other walking difficulty and gait speed do not show strong agreements[13]. In fact, slow gait speeds can exist without walking difficulty and walking difficulty can exist with fast and functional gait speeds[13,12]. When comparing between self-reported walking difficulty and gait speed, Ferrer and colleagues found that 17% of their subjects walking with faster gait speeds reported walking difficulty[13]. Since these individuals are able to walk at faster gait speeds, evidence and clinical practice that addresses gait speed cannot be applied to the sub-group who are able to walk at fast and functional gait speed but self-reports walking difficulty.

Regardless of walking difficulty, the examination and interventions for addressing gait speed are well examined and standard clinical practice are established; however, in contrast, walking difficulty is less understood. Evidence suggests that strength, or more specifically the ability to produce power, and neuromuscular, or muscle use, inefficiency are important factors for the onset and progression of mobility deficits[14,15]. Rapid activation of the quadriceps and plantarflexors are associated with faster gait speeds and the de-activation of their antagonist muscles are

associated with reduced metabolic cost[16]. Clinically, knee extension and plantar flexion strength are commonly examined and addressed when patients present with slow gait speeds, which are also influenced age[17,18]. Older adults are more likely to exhibit quadriceps and plantarflexion strength deficits and metabolically expensive muscle activation strategies[16,17]. In fact, at any gait speed, older adults are more likely to engage in co-contraction between the agonist and antagonist at the thigh, which are linked to higher energy costs, than younger adults[16].

Those with knee OA use a similar neuromuscular strategy, which include higher and more prolonged muscle activation that also result in larger co-contraction when compared to those without knee OA[19,20]. The consequences of such muscle activation characteristics and co-contraction can include potential generations of muscle tendon forces that are transferrable to the knee joint[21,22]. Therefore, large activation or co-contraction can create contact forces within the knee joint that may progress joint degradation[22].

Metabolically and joint costing muscle strategies could facilitate walking difficulty by requiring more energy and exacerbating OA related symptoms. Worsening knee OA radiographic severity and worsening OA symptoms are related to altered muscle activation and larger co-contraction[23,24]. However, the actual mechanism of altered muscle activation and elevated co-contraction are unclear. The presence of altered muscle activation and co-contraction appears to multifactorial and dependent on age, OA severity, and OA symptoms, which can similarly make walking difficult. Examining neuromuscular strategies based on walking difficulty in those with knee OA would help determine specific muscles that may need to be targeted for examination and intervention when addressing walking difficulty in the clinic.

Therefore, the purpose of this study is to compare neuromuscular s*tr*ategies, both muscle activation and co-contraction, during walking with subjects grouped by self-reported walking difficulty and OA presence, in adults aged 50 years and older, who are aged and sex matched during various gait speed conditions. We examined neuromuscular strategies at a controlled gait speed of 1.0 meter per second (m/s), a self-selected gait speed, and a fast gait speed. The controlled gait speed trials allow us to compare group differences without the potential effects of walking speed. The self-selected and fast gait speed trials allow us to compare group differences without the potential effects of walking at a gait speed that would elicit gait patterns different from the subject's innate gait patterns. Further, the self-selected and fast gait speed trials allow us to examine neuromuscular differences based on task demand.

We hypothesized the following:

Hypothesis 2.1: When walking at a controlled gait speed of 1.0 m/s, neuromuscular patterns, including muscle activation and co-contraction, will be the highest in the Diff group, followed by the NoDiff group, and the lowest in the Control group.

Hypothesis 2.2: Muscle activation and co-contraction differences among the groups will be the largest in the fastest gait speed trials, follow by the self-selected gait speed trials, and the smallest differences will be observed during the controlled gait speed trials.

Hypothesis 2.3*:* Subjects with worsening knee-OA-related symptoms will exhibit the largest muscle activation and co-contraction within the OA groups, and this relationship will be the more apparent in the Diff than the NoDiff group.

## 3.2 Methods

Adults aged 50 to 80 years old, who were community-dwelling, English-speaking, and with and without knee OA were recruited from the community and physicians' and physical therapy offices. Exclusion criteria included (1) History of surgery pertaining to the low back, hip, or foot/ankle in either leg; (2) Injury or signs or symptoms of injury to the trunk, low back, hip, leg or foot/ankle within the past 3 months; (3) Symptomatic arthritis in the low back, hip, leg, foot or ankle in either leg that affected movement or function; (4) History of knee replacement or skeletal re-alignment surgery in either leg; (5) PT for the trunk, low back, hip, or foot/ankle in either leg in the past 6 weeks; (6) Injections in low back, hip, knee, leg foot/ankle in the past 6 weeks; (7) History of respiratory, cardiovascular, systematic, or neurological diseases; (8) Current or potential pregnancy; and (9) inability to walk without an assistive device (e.g. walker, wheelchair, cane). Exclusion criteria for participation in the OA group included a knee OA Kellgren-Lawrence Severity Score (KL) of less than 2; and reporting average worst, best and current knee pain as 2 or less on a scale of 0 to 10, with 0 being no pain, and 10 being worst pain imaginable. Exclusion criteria for participation in the control group included the presence of knee pain or one or more positive finding on the Altman's Criteria for knee OA (i.e. AM stiffness < 30 minutes, crepitus, bony tenderness, bony enlargement, palpable warmth)[25].

Participants with knee OA were divided into groups based on the walking question from the Knee Outcome Survey (KOS), *How does your knee affect your ability to walk?,* in order to measure walking difficulty[26]. Responses were scored on a 6-point scale (5 = Not Difficult, 4 = Minimally Difficult, 3 = Somewhat Difficult, 2 = Fairly Difficult, 1 = Very Difficult, and 0 = Unable to do)[26]. Subjects who responded

*not difficult* (4) or *minimally difficult* (5) were grouped into the no walking difficulty group (NoDiff). Subjects who gave a response that ranged from *somewhat difficult* (3) to *unable to do* (0) were grouped into the difficult walking group (Diff). This scoring stratification was selected to mirror previous research studies that sub-grouped patients based on single questions extracted from self-reported knee outcome surveys[27,28]. Walking difficulty sub-group classification for knee was taken from the Knee Outcome Survey due to its previously tested reliability in the knee OA population[29]. Further, the question in the Knee Outcome Survey asked specifically about walking difficulty without added quantification or qualification (e.g., distance, surface, etc.) [26]. The three groups, Diff, NoDiff, and Control, were then matched based on sex and age, which were within 2.5 years among all 3 groups. The examiner was blinded to the sub-grouping of the subjects, during data collection and processing.

### 3.2.1 Radiograph assessment

Knee OA severity was assessed using a standing, posterior-anterior radiograph with 20 degrees of knee flexion. An experienced radiologist, blinded to each subject's classification within the OA group, scored OA severity based on the 4-point Kellgren-Lawrence (K-L) scale. The K-L scale is defined as 1: Doubtful narrowing of joint space and possible osteophytic lipping; 2: Definite osteophytes, definite narrowing of joint space; 3: Moderate multiple osteophytes, definite narrowing of joint space, some sclerosis, and possible deformity of bone contour; 4: Large osteophytes, marked narrowing of joint space, severe sclerosis, and definite deformity of bone contour) [30].

### 3.2.2 Body measurement

Subjects first stood still on two in-ground force plates (see below) for 5 seconds to obtain standing calibration. The standing calibration data was used to calculate body mass index (BMI) using equation 1. [31] Weight was measured via the force plates and converted to kilograms (Kg) and height was measured using a motion-capture camera system and retro-reflective marker on top of the subject's head and converted to meters (m). See below for further discussion of motion analyses.

$$(1) \quad \text{BMI} = \frac{\text{Weight (Kg)}}{\text{Height (m)x Height (m)}}$$

### 3.2.3 Walking and task demand

Subjects walked over two force plates at three speeds: a controlled gait speed of 1.0 m/s, a self-selected gait speed for the low-demand task, and a self-selected fast gait speed, or fast gait speed, for the high-demand task. During the controlled gait speed trials, an external timer was used by the examiner to ensure that gait speed did not deviate more than .05 m/s from 1.0 m/s. At the end of each controlled speed trial, the examiner provided verbal cues to increase or decrease gait speed as necessary. During the trials at a low self-selected gait speed, subjects were instructed to *please walk at a normal speed like you would when walking on the street or at the store*. During the trials at a fast self-selected gait speed, subjects were instructed to *please walk as fast, but as safely, as you can.* Further encouragement was provided to ensure that running was not allowed, and subjects were encouraged to walk at the safest pace close to falling during the fast gait speed trials. Subjects walked a minimum of 5 accepted trials at each gait speed condition. Accepted trials included a minimum of

two strides without altering gait patterns and with each foot clearly hitting one of the force plates.

During pilot testing, we found that the order of testing had an effect on subsequent gait speeds. For example, when testing started with fast gait speed, subjects would usually start their self-selected gait speed trials faster, and then reduce their speed in later trials. However, when testing started with controlled gait speed, the next testing condition, whether self-selected or fast speeds, would usually start out slower and then increase in speed. Therefore, to minimize the test order effects and prevent excessive trials, the subjects walked first at self-selected speeds, then fast speeds, and last at the controlled gait speed. After each trial, a one-minute rest break, or more as necessary, were provided to limit potential effects of fatigue.

### 3.2.4 Motion analysis

All subjects walked over two in-ground force plates (AMTI Force Plate, Watertown, MA) while wearing retro-reflective markers and electromyography (EMG) equipment. The force plates collected data at 1000 Hz. Eight 3-dimensional motion analysis cameras (Qualisys, Inc., Göteborg, Sweden) tracked the position of the reflective markers at 100 Hz. Reflective markers were secured to the head, shoulders, trunk, pelvis, and hips, as well as the thigh, knee, leg, foot, and ankle on both legs for calibration and to identify respective joint centers. Rigid thermoplastic shells with four markers firmly affixed were attached to the pelvis, lateral femur, lateral tibia, and the dorsal surface of the foot.

Electromyography (EMG) was recorded at 1000 Hz using a 16-channel EMG system (Motion Lab Systems, Baton Rouge, LA) interfaced with the force plates and motion analysis camera for simultaneous recording. Disposable self-adhered surface

electrodes were used to measure electrical activity of the medial (MQ) and lateral (LQ) quadriceps, medial (MH) and lateral (LH) hamstrings, and medial (MG) and lateral (LG) gastrocnemius muscles according to the Surface Electromyography for the Non-Invasive Assessment of Muscles (SENIAM) guidelines for electrode placement. Muscle EMG signals from maximal voluntary contractions (MVC) were used to normalize EMG signals from the gait trials. Knee flexor and extensor MVCs were measured via isometric contraction using the Biodex System III dynamometer at 60 degrees of knee flexion and 80 degrees of hip flexion, which have demonstrated excellent reliability.[32] This position also minimizes the potential effects of anterior knee pain in patients with knee OA. To ensure ankle MVCs during walking did not exceed EMG values obtained with the Biodex, plantarflexion MVCs were measured during standing bilateral heel raises with manual resistance through the shoulders. This testing procedure is an adapted version of the standardized manual muscle testing position for plantarflexion per Kendall et al.[33] The adaption was chosen because many patients with knee OA were unable to maintain a single leg balance safely.

### 3.2.5 Data management and processing

All data collection was completed through the Qualisys system, and all data was processed using Visual 3D™ (C-Motion, Rockville, MD). Force platform data and motion capture markers were low-pass filtered with a second-order Butterworth filter at 40 Hz and 4 Hz, respectively. Frontal and sagittal plane knee angles were calculated via Visual 3D using Euler angles to determine gait intervals. Final gait speed was calculated for two continuous strides on each limb, with one stride hitting the force plate, using temporal distance properties within Visual 3D. For each subject, the average of three trials per each gait speed condition was used for analyses. Due to

human variability that occurs with over-ground walking, gait speed deviations of plus or minus .05 m/s were considered acceptable in the controlled speed trials. Self-selected and fast gait speed trials were selected based on the quality of data and fastest gait speeds for both conditions.

Stance phase of gait was divided into weight acceptance and mid-stance gait interval, which was completed via motion capture and force plate data. Weight acceptance started at initial contact on the first force plate and continued up to the first peak knee flexion angle. Mid-stance started at the peak knee flexion angle and continued up to first peak knee extension angle. To account for influence of time and number of point differences we normalized each gait interval to 100 data points.

All electromyography (EMG) signals were high- and low-passed filtered using a 4$^{th}$ order Butterworth filter at 20 Hz and 350 Hz, respectively, to remove offsets and noise artifacts. Filtered signals were then rectified and low-pass filtered with a fourth-order Butterworth filter at 10 Hz to eliminate high-frequency filters of the muscles. Processed gait EMG signals were normalized to similarly processed MVC EMG to calculate percentage maximum of muscle activation. Synchronous EMG signals from each gait interval were used to calculate co-contraction indices based on *equation 2.* The co-contraction equation accounts for the simultaneous muscle activations of opposing muscle groups: medial quadriceps-medial hamstrings (MQMH), lateral quadriceps-lateral hamstrings (LGLH), medial quadriceps-medial gastrocnemius (MQMG), and lateral quadriceps-lateral gastrocnemius (LQLG) [34]:

$$(2)\ Co-contraction\ Index = \left(\sum_{i=IC}^{TASK}\left(\frac{EMG_S}{EMG_L}(EMG_S + EMG_L)\right)\Big/100\right)$$

The co-contraction index was calculated by using signals of opposing muscles after they were normalized to their respected MVCs and 100 time points. Each co-contraction index was calculated by dividing the smaller EMG signal ($EMG_s$) by the larger EMG signal ($EMG_{L)}$, and multiplied by the sum of the small and large EMG signals. The equation to calculate co-contraction indices was formulated to prevent small EMG signals that may be close to noise from being considered as high co-contraction and avoided the potential error of dividing over zero[34]. After the EMG signals were divided and summed and combined into 1 signal, it was then integrated over the entire phase of the movement.

This co-contraction equation has been previously studied during various gait speeds, and was found to have excellent to good reliability (ICC =0.76-0.89) in those with and without knee OA.[35] A larger co-contraction index suggests a higher concurrent use of the two opposing muscles. In other studies, co-contraction indices for knee OA have ranged from close to 0 up to 100, and appeared to be affected by muscle groups, gait intervals, and gait conditions[23,36]. Therefore, in this study, co-contraction indices were compared under specific parameters, which included specific opposing muscle groups (e.g. medial knee extensior and medial knee flexor), within each gait interval (i.e. weight acceptance and mid-stance), and during the same gait conditions (i.e. controlled gait speed, selfselected gait speeds, and fast gait speeds).

To examine how muscle activation and co-contraction indices differed between a low demand task, or self-selected gait speed, and high demand task, or fast gait speed, within each group, we subtracted the normalized EMG signal and co-contraction indices between the two gait speed conditions.

In order to examine the effects knee symptoms on adopted neuromusuclar strategies, we first examined how responses from the Knee Outcome Survey varied between the Diff and NoDiff group. Responses ranged include 5, NoSymptom, 4, NoAffect, 3-Sliightly affect, 2-moderately, 1-severely affects, 0 – symptom prevents function[26]. Based on the percentage of subjects with and without walking difficulty we calculated the percent difference between the OA groups that responded with a 3 or less, as it would best represent the symptom(s) that may be leading to walking difficulty in knee OA. As a result those with no walking difficulty would have less reports of the selected knee symptom impacting their function. After we selected the knee symptoms that may be influeing walking difficulty, we averaged muscle activation or co-contaction index of those with the same response in the Diff group and those of the same response in the NoDiff group for each symptom.

Muscle activation and co-contraction indices from controlled gait speeds were averaged togeter who for those who gave the same responses, with the exception of a response of a 4 and 5. Subjects with a 5 or 4 were grouped together, as these included subjects with knee OA who either did not complain of the specific knee symptom or reported that the knee symptom had no impact on knee function. We then visually examined for positive or negative trends within each OA group. Since worsening knee symptoms were marked by smaller numbers, and no less symptoms were marked by larger numbers, positive trends were marked by smaller muscle activation or co-contraction idncies and worsening knee symptoms and larger averages and no or less worsening symptoms. While, negative trends were marked by lrager muscle activation or co-contraction indicies observed by worsening OA related symptoms

We only examined the impact of knee complaints on muscle activation co-contraction using the controlled gait speed trials, as gait speed differences can potentially influence muscle activation and co-contraction indicies[37].

### 3.2.6 Statistics

Statistical analyses were performed using SPSS (version 13, Chicago, IL). We tested for homoscedasticy, using the Levene's test, and normal distribution, using the Shapiro-Wilks test, in our dependent variable, or muscle activation and co-contraction indices. A p-value of .05 for the Levene's test suggested that the variable was heteroscedastic, and for the Shapiro-Wilks test suggested that the variable was not normally distributed. Either violations required group differences for the variable to be examined using a non-parametric test.

Muscle activation and co-contraction differences among the three groups were tested using paired comparisons due to the matched design. Differences between the OA and control groups and within the OA groups were planned comparisons, determined a priori; therefore, the P-value was not adjusted for multiple comparisons. Subjects were age-matched to 2.5 years and sex-matched among all three groups; therefore, these variables were not controlled statistically. Also, for all hypotheses, BMI and OA severity required further examination of their potential influence on the dependent variable. Higher BMI, faster gait speed, and greater OA severity have all been shown to elevate muscle activation and co-contraction indicies. In order to minimize the number of statistical test, and therefore minimize potential errors, we used descriptive statistics to examine the potential influences that BMI, gait speeds, and OA severity had on the dependent variable. Quartiles for BMI and gait speeds were first calculated for all subjects. Within each group, muscle activation and co-

contraction indices were averaged together of the subjects that fell into the same quartiles. This was completed based on BMI and gait speed quartiles. The average of muscle activation or co-contraction indicies for each quartile of each group (i.e. Diff, NoDiff and Control) were visially examined. The dependent variables, or the average of muscle activation or co-contraction indicies, that subsequently increased or decreased based on BMI or gait speed quartiles were considered to have a trend. Larger muscule activation or co-contraction indicies that were related to larger BMI or faster gait speeds were considered positive trends. Smaller muscle activaiton or co-contraction indicies that were related to larger BMI or faster gait speeds were considered negative trends. If 1 quartile fell outside the positive or negative trends of the other 3 quartiles but within .5 of their adjacent quartiles, we still considered the co-variate to have some influence on the dependent variable. However, if 2 or more quartiles had averages that fell outside a positive or negative trend, we considered that there were minimal to no trends betewen the co-variate and the dependent variable.

For knee OA severity, we averaged the depenendent variables based on K-L scores for the Diff and NoDiff groups. Within each group, subjects with the same KL scores had their muscle activation or co-contraction index averaged together and examined for positive or negative trends as already discussed. Another words, as KL scores increase with OA severity within the OA groups, the dependent variable also increases or decreases for a positive or negative trend, respectively.

To examine the effects of self-reported knee complaints on neuromuscular strategies, we selected knee symptoms based on responses from the Knee Outcome Survey. Knee symptom responses were rated on a 6-point scale, with a 5, I do not have the symptom, 4 I have the symptom, but it does not affect my activity, 3, the

symptoms affects activity slightly, 2, the symtpom affects my activity moderately, 1, symptom affects my activity severely, and 0 the symptom prevens me from all daily activities. For each symptom, we examined the difference in the percent of subjects in the NoDiff and the percent of subjects in the Diff group that reported a 3 or lower. We used a 3 as the cut-off, since responses of a 4 or a 5 would suggest that either the symptom does not afffect acitivity or that they do not have the symptom. Since a larger percent difference between the NoDiff and the Diff group would suggest that symptom is most likely to be affect walking ability in knee OA, symptoms with the largest difference between the NoDiff and Diff groups were used to examined its impact on muscle activation and co-contraction indicies.

Within each selected knee symptom, we averaged muscle activation or co-contraction indicies of the subjects with the same responses for the NoDiff group and for the Diff group, except for responses of a 4, *I have the symptom but it does not affect my activity*, or a 5 – *I do not have the symptom*. Subjects with resposnes of a 4 or a 5 were grouped together due to the lack of presence or impact of the knee symptom.

We then visually examined the relationship between worsening knee symptoms and the average muscle activation or co-contraction indicies of the subjects who shared the same response. A positive trend was noted when knee symptom responses had a higher score, better knee symptom and less impact on function, and larger muscle activation or co-contraction indicies than those with a lower knee symptom score. A negative trend was noted when knee symptoms had a higher score that was associated smaller muscle activation or co-contraction indicies than those with a lower knee symptom score. We examined the impact of knee complaints on

muscle activation and co-contraction indicies measured during the controlled gait speed trials, as gait speed differences can potentially influence muscle activation and co-contraction indicies[37].

## 3.3 Results

Twenty subjects in the control group and 33 subjects in the OA group participated in the study. However, only 39 subjects (13 per group), matched for sex (5 males) and age (average = 66 years), were used for analysis in this study. Specific subject characteristics are described in Table 1, with no significant differences of BMI, Kellgren-Lawrence scores, or gait speeds among the groups. Although not significantly different, on average the Diff group had the largest BMI and walked with the slowest gait speed when compared to the NoDiff and Control groups. While, BMI was slightly larger in the NoDiff group but gait speeds were similar when compared to the control group.

Distribution of knee OA symptoms in the Diff and NoDiff groups are exhibited in Table 2. Giving way, weakness, and swelling were similarly distributed throughout both OA groups; however, pain, stiffness, and limping seem to have worsening effects on activity in the Diff group than they did in the NoDiff group.

### 3.3.1 Neuromuscular strategies during controlled gait speed

Variables that were not normally distributed or were heteroscedastic and required non-parametric testing, included the MQ, LG, MG, LQLG from weight acceptance gait interval and all EMG and co-contraction indices from mid-stance.

#### 3.3.1.1 Neuromuscular strategies during weight acceptance of controlled gait speed

Mean and median group trends for muscle activation and co-contraction indices were the largest in the Diff group, followed by the NoDiff, and Control groups during weight acceptance gait interval of controlled gait speed. NoDiff was larger than the Control group for all muscle activation and co-contraction, except for MH, LG, LQLH, MQMG, which were similar for the two groups during weight acceptance gait interval of controlled gait speed.

Statistically, the NoDiff group walked with significantly larger MQ than the Control group, t (12) = 3.2, p = .01, effect size d = 1.6, during weight acceptance of controlled gait speed (Figure 3.1). All other muscle activations and all co-contraction indices were not significantly different (p = .12 to .92) between the NoDiff and Control groups during weight acceptance interval of controlled gait speed and had a small to less than small effect size, (d = .08 to .49; r = .02 to .06) (Figures 3.1 and 3.2).

The Diff group walked with significantly larger MQ t (12) =-2.86, p = .01, d = .9; and LQ, z = -2.5, p = .01, r = .5, activations than the Control group, during weight acceptance interval of controlled gait speed and had a large effect size. While, MG activation was not significantly different between the Diff than the Control groups, but had a medium effect size, z = 1.9, p = .06, r = .36 (Figure 3.1). Further, MH t (12) = 1.2, p = .25, d = .33, LH t (12) = .80, p = .44, d = .20; and LG, z = 1.4, p = .17, r = .26, activations were also not significantly different between the Diff and Control group and had a small effect size (Figure 3.1). In the case of co-contraction, MQMH, t (12) = 2.8, p = .02, effect size d = .8; and MQMG, z = -1.9, p = .05, effect size r = .4, indices were significantly larger in the Diff than the Control groups during weight acceptance interval of controlled gait speed (Figure 3.2). While, LQLH, t (12) = 2.0, p = .07, d =

.66, and LQLG, z = 1.8, p = .07, r = .35, co-contraction indices were not significantly different between the Diff and the Control group, but had medium effect sizes (Figure 3.2).

Within the OA groups, muscle activations were not significantly different between the Diff and the NoDiff groups p = .07, r = .35, but LQ, z= -1.6, p =.12, r = -.31; MH t(12) = 1.6 , p = .13, d = .55, and LG z= 1.8; p = .07, r = .3 activations had medium effect sizes; MQ t(12) = .73 , p = .48, d = .28, and MG z = .66, p = .51, r = .13 activations had small effect sizes; and LH activation t(12) = .34, p = .74, d = .08 had an effect size less than small. In the case of co-contraction, the Diff group walked with significantly larger LQLG index z= 2.1, p = .04, r = .40 than the NoDiff group during weight acceptance of controlled gait speed (Figure 3.1). While no other co-contraction indices were significantly different between Diff and NoDiff during weight acceptance of controlled gait speed, but MQMH, t (12) = 1.2, p = .24, d = .44, and MQMG, z = .87, p = .38, r = .17, indices had a small effect size and LQLH, t (12) = 1.2, p = .25, d = .10, index had an effect size less than small (Figure 3.2).

#### 3.3.1.2 Neuromuscular strategies during mid-stance of controlled gait speed.

Mean and median group trends for MH and LH activations during mid-stance of controlled gait speed were the largest in the Diff group, followed by the NoDiff group, and the smallest in the Control group (Figure 3.1). Although the mean of LQ activation and all co-contraction indices during mid-stance of controlled gait speed followed the group trends aforementioned, the median of LQ activation and co-contraction indices were the largest in the Diff group while similar between the NoDiff and Control groups (Figures 3.1 and 3.2). While, the mean and median values for MQ and MG activations were the largest in the Control group followed by the Diff

group, and the smallest in the NoDiff group during mid-stance of controlled gait speed (Figure 3.1). Mean and median group trends varied for LG activation during mid-stance of controlled gait speed (Figure 3.1). Mean LG activation was the largest for the Diff group, followed by the control, and the smallest in the NoDiff group (Figure 3.1). Whereas, median LG activation was the largest for the NoDiff group, followed by the Control group, and the smallest in the Diff group (Figure 3.1).

Statistically, MQ was significantly different between the NoDiff group and Control group during mid-stance of controlled gait speed, $z = 2.3$, $p = .02$, $r = .45$. No other muscle activations were significantly different between NoDiff and Control group, $p = .15$ to $.86$, and had small to less than small effect sizes, $r = .03$ to $.28$. In the case of co-contraction, the MQMG ($z= 1.8$, $p = .08$, $r = .35$) had a medium effect size, but was not significantly different between the NoDiff and Control groups during mid-stance of controlled gait speed (Figure 3.1). All other co-contraction indices were not significantly different, $p = .51$ to $.86$, between the NoDiff and Control groups during mid-stance interval of controlled gait speed and had a small to less than small effect size, $r = .03$ to $.13$ (Figure 3.2).

MQ, $z = 2.9$, $p < .01$, $r = .57$, and LQ, $z = 2.9$, $p = < .01$, $r = .57$, activations were significantly different between the Diff and the Control groups during mid-stance interval of controlled gait speed, and had large effect sizes (Figure 3.1). No other muscle activations were significantly different, $p = .25$ to $.65$, between the Diff and Control groups, and had small to less than small effect sizes, $r = .08$ to $.23$. In the case of co-contraction, MQMH, $z = 2.5$, $p = .01$, $r = .43$, MQMG, $z = 2.5$, $p = .01$, $r = .49$, and LQLG, $z = 3.2$, $p < .01$, $r = .62$, were significantly different between the Diff and Control group, and had effect sizes that ranged from large to medium (Figure 3.2).

While, the LQLH co-contraction index, z = 1.9, p = .06, r = .36, was not significantly different between the Diff and Control groups during mid-stance of controlled gait speed but had a medium effect size (Figure 3.1).

Between the two OA groups, LQ activation, z = 1.6, p = .10, r = .32, had a medium effect size but was not significantly different between the Diff and NoDiff groups during mid-stance interval of controlled gait speed (Figure 3.1). All other muscle activations were also not significantly different, p = .13 to .75, between the Diff and NoDiff groups during mid-stance interval of controlled gait speed and had a small to less than small effect size, r = .29 to .06. In the case of co-contraction, LQLG index, z = 1.9, p - .06, r = .36, had a medium effect size but was not significantly different between the Diff and NoDiff groups during mid-stance interval of controlled gait speed (Figure 3.1). All other muscle co-contraction indices were not statistically different, p = .22 to .31, between the two OA groups and had small to less than small effect sizes, r = .20 to .24 (Figure 3.2).

### 3.3.2 Effects of gait speed on neuromuscular strategies

#### 3.3.2.1 Self-selected gait speed

For self-selected gait speed trials, MQ activation was significantly different between the NoDiff and the Control groups during the weight acceptance interval, t (12) = 3.4, p = .01, and had a large effect size, d = 1.04 (Figure 3.3). No other muscle activations were significantly different between the NoDiff and Control groups (p = .08 to .86), but LH activation had a medium effect size, t (12) = 1.90, p = .08, d = .55, and all other muscle activations had small to less than small effect sizes (d = .14, r = .03 to .13) (Figure 3.3). With respect to co-contraction, during weight acceptance

interval of self-selected gait speed, MQMH index was significantly different between the NoDiff and Control group, $z = 2.0$, $p = .05$, $r = .38$ (Figure 3.4). All other co-contraction indices during weight acceptance of self-selected gait speed were not significantly different between the NoDiff and Control groups, $p = .27$ to $.70$, and had small to less than small effect sizes, $d = .38$ and $r = .08$ to $.16$ (Figure 3.4).

MQ, $t(12) = 2.2$, $p = .05$, $d = .73$, LQ, $z = .22$, $p = .03$, $r = .43$, and LH, $t(12) = 2.2$, $p = .05$, $d = .62$, activations were significantly different between the Diff and the Control groups during weight acceptance interval of self-selected gait speed trials, and had medium to large effect sizes (Figure 3.3). While, a medium effect size was found for LG, $z = 1.9$, $p = .06$, $r = .37$, and small effect sizes were found for MH, $t(12) = .87$, $p = .40$, $d = .29$, and MG, $z = .52$, $p = .60$, $r = .10$, but these muscle activations were not significantly different between the Diff and the Control groups during weight acceptance interval of self-selected gait speed trials (Figure 3.3). With respect to co-contraction indices, during weight acceptance interval of self-selected gait speed trials, MQMG, $t(12) = 2.1$, $p = .05$, $d = .76$, and LQLG, $z = 2.3$, $p = .02$, $r = .45$, indices were significantly different between the Diff and Control groups and had medium effect sizes (Figure 3.4). While, MQMH, $z = 1.5$, $p = .13$, $r = .29$, and LQLH, $z = 1.4$, $p = .17$, $r = .27$, indices were not significantly different between the Diff and Control groups during weight acceptance of self-selected gait speeds and had small effect sizes (Figure 3.4).

LG activation, $z = 1.9$, $p = .05$, $r = .38$, was significantly different between the Diff and NoDiff group with a medium effect size during weight acceptance interval of self-selected gait speed trials (Figure 3.3). MQ activation, $t(12) = 1.9$, $p = .10$, $d = .77$, had a large effect size, but was not significantly different between the Diff and NoDiff

group during weight acceptance interval of self-selected gait speed trials. All other muscle activation differences between the Diff and NoDiff groups were not statistically significant, $p = .55$ to $.98$, and had small to less than small effect sizes, $d = 0.0$ to $.14$ and $r = .02$ to $.12$ (Figure 3.3). With respect to co-contraction, LQLG activation, $z = 2.1$, $p = .04$, $r = .40$, was significantly different between the Diff and the NoDiff groups during weight acceptance interval of self-selected gait speed trials with a medium effect size (Figure 3.4). All other co-contraction indices during weight acceptance interval of self-selected gait speed trials were not significantly different between the Diff and NoDiff groups, $p = .42$ to $.85$, and had small to less than small effect sizes, $d = .07$, $r = .13$ to $.16$ (Figure 3.4).

During mid-stance interval of self-selected gait speed trials, MQ, $z = 3.1$, $p < .01$, $r = .61$, and MG, $z = 3.0$, $p = .04$, $r = .40$, activations were significantly different between the NoDiff and the Control groups, and had large to medium effect sizes. All other muscle activations were not significantly different, $p = .31$ to $.97$, between the NoDiff and Control group during mid-stance of self-selected gait speed and ranged from small to less than small effect sizes, $d = .36$ and $r = 0.0$ to $.14$ (Figure 3.3). With respect to co-contraction, the MQMG index, $z = 2.8$, $p < .01$, $r = .56$, was significantly different between the NoDiff and Control groups, and had a large effect size during mid-stance of self-selected gait speed (Figure 3.4). The MQMH index, $z = 1.6$, $p = .12$, $r = .31$, had a medium effect size, but was not significantly different between the NoDiff and the Control groups during mid-stance interval of self-selected gait speed trials (Figure 3.4). All other co-contraction indices were not significantly different, $p = .51$ to $.65$, between the NoDiff and Control groups during mid-stance of self-selected

gait speed trials and had small to less than small effect sizes, d = .02 and r = .09 to .13 (Figure 3.4).

For comparisons between the Diff group and the Control group during mid-stance of self-selected gait speed trials, MQ, $z = 3.1$, $p < .01$, $r = .61$, and LQ, $z = 3.0$, $p < .01$, $r = .60$, activations were significantly different and had large effect sizes. MG, $z = 1.6$, $p = .12$, $r = .31$, had a medium effect size, but was not significantly different between the Diff and the Control groups during mid-stance of selected gait speed trials (Figure 3.3).

All other muscle activations were not significantly different, $p = .12$ to .96, between the Diff and Control groups, and ranged from small to less than small effect sizes, $r = .04$ to .31. With respect to co-contraction, all indices were significantly different between the Diff and Control groups during mid-stance of self-selected gait speed trials; however, large effect sizes were observed for MQMG, $z = 2.9$, $p < .01$, $r = .57$, and LQLG, $z = 3.1$, $p < .01$, $r = .61$, indices, and medium effect sizes were observed for MQMH, $z = 2.4$, $p = .02$, $r = .47$, and LQLH, $z = 2.3$, $p = .02$, $r = .45$, indices (Figure 3.4).

For comparisons within the OA groups during mid-stance of self-selected gait speed trials, LQ activation, $z = 1.6$, $p = .10$, $r = .32$, had a medium effect size, but no significant differences between the Diff and the NoDiff groups (Figure 3.3). All other muscle activations were also not significantly different, $p = .22$ to .97, between the Diff and NoDiff group during mid-stance of self-selected gait speed trials, but had small to less than small effect sizes, d = .20 and r = 0 to .24 (Figure 3.3). With respect to co-contraction, the LQLG index, $z = 1.9$, $p = .06$, $r = .36$, had a medium effect size but was not significantly different between the Diff and NoDiff groups during mid-

stance of self-selected gait speed trials (Figure 3.4). All other co-contraction indices were not significantly different, p = .25 to .46, between the Diff and NoDiff group during mid-stance of self-selected gait speed trials and had small effect sizes, r = .14 to .23 (Figure 3.4).

#### 3.3.2.2 Self-selected fast gait speed

For fast gait speed trials, MQ activation, t (12) = 1.89, p = .08, r = .63, had a medium effect size, but was not significantly different between the NoDiff and Control groups during weight acceptance interval (Figure 3.5). All other muscle activations had small to less than small effect sizes, d = .09 to .38 and r = .01 to .03, and were not significantly different between the NoDiff and Control groups during weight acceptance interval of fast gait speed trials, p = .23 to .97 (Figure 3.5). With respect to co-contraction, the MQMH index, z = 1.6, p = .12, r = .31, had a medium effect size, but was not significantly different between the NoDiff and Control groups during weight acceptance interval of fast gait speed trials (Figure 3.6). All other co-contraction indices had small to less than small effect sizes, d = .12 to .34 and r = .14, and were not significantly different, p = .30 to .75, between the NoDiff and Control groups during weight acceptance interval of fast gat speed trials (Figure 3.6).

Between the Diff and Control groups, MQ activation, t (12) = 2.5, p = .03. d = .83, was significantly different during weight acceptance interval of fast gait speed trials, and had a large effect size. LH, t (12) = 2.1, p = .06, d = .66, and LG, t (12) = 2.1, p = .06, d = .63, activations had medium effect sizes, but were not significantly different between the Diff and Control groups during weight acceptance interval of fast gait speed trials (Figure 3.5). All other muscle activation differences between the Diff and Control groups during weight acceptance interval of fast gait speed trials

were not statistically significant, p = .27 to .60 and had small to less than small effect sizes, d = .33 and r = .11 to .17 (Figure 3.5). With respect to co-contraction indices, MQMH, z = 2.1, p = .04, r = .40, MQMG, z = 2.1, p = .03, r = .42, and LQLG t (12) = 2.2, p = .05, d = .07, indices were significantly different between the Diff and Control groups and had medium effect sizes during weight acceptance interval of fast gait speed trials (Figure 3.6). While, the LQLH index, t(12) = 1.50, p = .16, d = .61, had a medium effect size, but was not significantly different between the Diff and Control groups during weight acceptance interval of fast gait speed trials (Figure 3.6).

Between the OA groups, MH activation t(12) = 1.2, p = .11, d = .58, had a medium effect size, but was not significantly different between the Diff and NoDiff group during weight acceptance interval of fast gait speed trials (Figure 3.5). All other muscle activations were not significantly different, p = .11 to .97, between the Diff and NoDiff group during weight acceptance interval of fast gait speed trials and had effect sizes that ranged from small to less than small (d = .10 to .25 and r = .01 to .11) (Figure 3.5). With respect to co-contraction indices, no differences were significant between the Diff and NoDiff group during weight acceptance of fast gait speed trials and all effect sizes were small or less than small (Figure 3.6).

During mid-stance gait interval of fast gait speed trials, MQ z = 1.9, p = .05, r = .38, activation was significantly different between the NoDiff and the Control groups and had a medium effect size. MG activation, t (12) = 2.1, p = .06, d = .70, had a medium effect size but was not significant different between the NoDiff and the Control groups during mid-stance of fast gait speeds (Figure 3.5). All other muscle activations were not significantly different between the NoDiff and the Control groups (p = .25 to .92) and had effect sizes that were small or less than small (d = .03 and r =

.05 to .23) (Figure 3.5). With respect to co-contraction, no differences were significant between the NoDiff and the Control groups during mid-stance of fast gait speed trials and all effect sizes were small or less than small (r = .29 to .01) (Figure 3.6).

Between the Diff and the Control groups, MQ, $z = 3.0$, $p < .01$, $r = .58$, and LQ, $z = 2.5$, $p = .01$, $r = .49$, activations were significantly different during mid-stance interval of fast gait speed trials and had large and medium effect sizes. MG activation, $t(12) = 1.6$, $p = .14$, $d = .51$, had a medium effect size but was not statistically different between the Diff and the Control groups during mid-stance interval of fast gait speed trials (Figure 3.5). All other muscle activations were not significantly different, p = .48 to .92, between the Diff and Control groups during mid-stance interval of fast gait speed trials, and had small to less than small effect sizes, d = .21 and r = .02 to .05 (Figure 3.5). With respect to co-contraction, MQMG $z = 2.0$, $p = .05$, $r = .39$, and LQLG, $z = 2.6$, $p = .01$, $r = .50$, indices were significantly different between the Diff and Control groups and had medium and large effect sizes during the mid-stance interval of fast gait speed trials (Figure 3.6). While, MQMH, $z = 1.6$, $p = .12$, $r = .31$, and LQLH, $z = 1.6$, $p = .10$, $r = .32$, indices had medium effect sizes but were not significantly different between the Diff and Control groups during the mid-stance interval of fast gait speed trials (Figure 3.6).

Between the OA groups, all muscle activations or co-contraction indices were not statistically different, p = .25 to .94, between the Diff and NoDiff groups during mid-stance of fast gait speed, and effect sizes ranged from small to less than small, d = .02 to .19 and r = .05 to .23 (Figure 3.6).

### 3.3.3 Effects of knee OA symptoms on neuromuscular strategies

A greater percentage of subjects in the Diff group than in the No Diff group reported that pain, stiffness, and limping negatively affected their activity (Figure 3.7). Other knee symptoms, including swelling, giving way, and weakness from the Knee Outcome Survey, had less differences and were more evenly distributed than pain, stiffness, and limping between the Diff and NoDiff groups (Figure 3.7). Trends between neuromuscular strategies and knee symptoms were visually examined by averaging muscle activation and co-contraction indices of those who provided the same response for pain, stiffness, and limping within each OA group, Diff and NoDiff.

Distribution of self-reported effects of knee pain on function are reported in Table 2. During the weight acceptance interval in the Diff group, pain had negative trends with MG and LG activations; however, in the NoDiff group, pain trends were negative for MQ activation and positive for the LH activation (Table 3A). With respect to co-contraction, trends were negative between pain and LQLH, MQMG, and LQLG indices for the Diff group; but in the NoDiff group, no trends were observed between pain and co-contraction indices during weight acceptance interval (Table 3A). During the mid-stance interval, in the Diff group, negative trends were observed between pain and MQ, LQ, MH, and LG activations; while in the NoDiff group, a negative trend was observed for pain and the LQ activation (Table 3B). With respect to co-contraction during mid-stance interval, negative trends were observed between pain and MQMH, LQLH, and LQLG indices for both the Diff and the NoDiff groups (Table 3B).

For stiffness, during weight acceptance interval, the Diff group appear to have a positive trend between stiffness and MQ, LQ, MH, and LG activations; and the NoDiff group appear to have a negative trend between stiffness and the MQ activation

(Table 4A). With respect to co-contraction during weight acceptance interval, the Diff group had positive trends between stiffness and MQMH and LQLG indices; while the NoDiff group had a negative trend between stiffness and the LQLG index (Table 4A). During mid-stance, the Diff group had a negative trend between stiffness and LG activation; yet in the NoDiff group, stiffness had positive trends with MQ and LQ activations, but negative trends were observed between stiffness and MH, LH, and LG activations (Table 4B). With respect to co-contraction during mid-stance interval, a negative trend was observed between stiffness and the MQMG index for the Diff group; but no trends were observed between stiffness and co-contraction indices for the NoDiff group (Table 4B).

For limping, during weight acceptance interval, the Diff group appear to have a negative trend between limping and the MQ activation; while, the NoDiff group had a positive trend between limping and the MG activation (Table 5A). With respect to co-contraction during weight acceptance interval, a negative trend was observed between limping and the MQMH index for the Diff group; while, a positive trend was observed between limping and the MQMG index for the NoDiff group (Table 5A). During mid-stance, the Diff group had a negative trend between limping and LG activation; while, the NoDiff group had positive trends between limping and LH and MG activations (Table 5B). With respect to co-contraction during mid-stance, the Diff group had negative trends between limping and MQMH and MQMG indices; while no trends were observed between limping and co-contraction in the NoDiff group (Table 5B).

### 3.4 Discussion

This study determined if neuromuscular strategies during walking varied based on self-reported walking difficulty and OA presence. Consistent with previous studies,

we found that those in the OA groups walked with altered muscle activation and higher co-contraction when compared to those in a control group[23,38,39,8,24]. However, in this current study, in addition to knee OA presence, we examined differences in neuromuscular strategies based on a self-reported walking difficulty sub-group among those with knee OA, as well as different walking speed conditions. We were able to identify that neuromuscular strategies appear to be influenced by various factors that are commonly measured in the clinic including, OA presence, self-reported measurements, and gait speed.

During the controlled gait speed condition, although visual trends can identify larger muscle activation and co-contraction indices in the Diff group, followed by the NoDiff group, and the smallest in the control group, statistical differences were primarily found between the OA and control groups. In fact, the difference between the Diff and control groups were significantly different for the quadriceps (i.e. MQ and LQ), MQMH, LQLH, MQMG, and LQLG. While only MQ significantly different between the NoDiff and control groups, and only LQLG was significantly different between the Diff and NoDiff groups. It appears that OA presence or self-reported measurements alone cannot explain muscle activation and co-contraction strategies.

Interestingly, the quadriceps muscle consistently followed the trend of our hypothesis and exhibited the largest significant differences based on OA presence. Quadriceps activations, especially the medial quadriceps, were larger in our Diff and NoDiff groups than the control group during both weight acceptance and mid-stance gait intervals of controlled gait speed. However, no differences are found between the two OA groups. Our findings are consistent with Zeni and colleagues who found larger quadriceps activity in those with knee OA when compared to a control group,

and minimal to no differences within the OA groups when subjects were sub-grouped by radiographic OA severity[24]. The larger medial quadriceps activation found in the OA groups than the control group during walking, suggest that both OA groups are recruiting a larger percent of their maximum activation to perform a similar task. This larger medial quadriceps activation are observed in OA groups that are able to walk at a fast and functional gait speed. Therefore, the lack of difference within the OA groups based on self-reported measure in on our study and radiographic disease severity based on Zeni and colleagues finding[24] and the significant differences between the OA and control groups in both studies could suggest that elevated quadriceps activation may be a knee OA specific gait characteristic that is unavoidable in the presence of knee OA.

Larger medial muscle activation, as such by medial quadriceps, can facilitate co-contraction, and joint loading, which can worsen knee OA. Manal and colleagues found through EMG driven modeling that elevated muscle activation levels can increase joint contact forces at the knee[22]. Since all of our subjects had medial knee OA only or medial knee OA that is worse than lateral knee OA, the elevated medial quadriceps muscles can heighten contact forces that can further progress knee OA. However, our findings are consistent with prior literature that suggest altered quadriceps use, such as quadriceps muscle weakness, in those with knee OA[23,38,40]. Our findings are consistent with previous literature that suggests the importance of quadriceps training to maintain or improve function in knee OA[40,41]. Quadriceps training could facilitate better recruitment of the quadriceps to maintain gait speed regardless of OA severity or walking difficulty[17]. The pattern observed in MQ was not as strongly seen in LQ. Medial compartment knee OA may account for the lack of

significant difference between the NoDiff and control group for LQ. All of our subjects with knee OA either had medial knee OA only or medial knee OA that was worse than the OA in their lateral compartment. Along with quadriceps, we found larger co-contraction indices between the OA and control groups for medial quadriceps and medial knee flexors, or MQMH and MQMG. Larger co-contraction indices are linked to higher compressive loads and potentially distributing forces to areas less capable of withstanding weight bearing loads, which can also worsen knee OA[21,42].

Although we expect muscle activation differences to be present and affected by gait speed, we did not expect group differences to be attenuated by fast gait speed trials. The control and NoDiff groups walked with similar gait speeds for both the self-selected and fast trials. However, MQ, LH, MQMH, and MQMG that were significantly larger in the NoDiff than the control group during self-selected trials were no longer larger during fast trials. In fact, no muscle activation or co-contraction strategies were significantly different between the NoDiff and control group during the fast trials, despite the OA presence in the NoDiff group. The lack of difference may suggest that when walking at the fastest gait speed possible, individuals in the NoDiff group with knee OA may be recruiting similar neuromuscular strategies as those without knee OA.

Unlike the lack of gait speed differences between the NoDiff and control groups, the Diff group walked with self-selected and fast gait speeds that were slower than the NoDiff group. However, the group differences based on walking difficulty within the OA groups continued to be attenuated in the fast gait speed trials. For self-selected gait speed, LG and LQLG were significantly larger in the Diff than NoDiff

groups; however, these differences were attenuated during the fast gait speed trials. Previous authors have suggested that decreasing gait speed in knee OA may be an a strategy to limit joint loading at the knee[43]. Reduced walking speed is suggested to protect those with knee OA by potentially limiting compressive forces, external reaction forces, and muscle activation patterns associated with specific knee movements[43]. While muscle activation and co-contraction indices increased within subjects, the lack of group differences at the fast gait speed conditions, where the Diff walked slower than both the NoDiff and control groups, suggest that walking at slower gait speed does not effectively reduce muscle activity to normal levels. In fact, if muscle activation and co-contraction indices do not vary based on walking difficulty and only vary based on OA presence during self-selected gait speed, perhaps gait training during fast gait speeds may be beneficial in optimizing muscle activation and co-contraction strategies.

The hypothesis that higher muscle activation and co-contraction indices trended with worsening knee OA symptoms were supported by our findings for knee pain and limping but not for self-reported knee stiffness. Worsening knee pain appeared to trend with larger quadriceps and gastrocnemius activation in both the NoDiff and Diff groups. Greater co-contraction indices also trended with worsening knee pain in both OA groups. These findings for both muscle activation and co-contraction indices were consistent with previous literature that pain presence can result in muscular adaptations[44]. Therefore, larger muscle activation and co-contraction indices may suggest pain related adaptations in knee OA. Interestingly, the trends between worsening knee stiffness and neuromuscular strategies varied based on walking difficulty presence in knee OA. For example, we observed inverted muscle

activation trends between OA subjects with and without walking difficulty. Among the subjects with worsening knee stiffness complaints, those in the Diff group used lower MQ and LQLG, while those the NoDiff group used higher MQ and LQLG during weight acceptance. During mid-stance, regardless of walking difficulty, subjects in both groups with knee stiffness used lower LG. Therefore, the inverted trends observed during mid-stance may suggest that those with knee OA related walking difficulty who has knee stiffness limitations, may be using an ineffective neuromuscular strategy. However, given the small sample size of this study, especially when examining OA-related symptoms within a sub-group, further research is needed to determine the effects of knee stiffness on walking difficulty in knee OA. The effects of self-reported limping on muscle activation and co-contraction in the OA groups were less pronounced as compared to self-reported pain and stiffness. However, limping was related to higher MQMH in the Diff group and lower MQMH in the NoDiff group during weight acceptance. These observable trends, especially with pain and stiffness, suggest that knee-related complaints may influence muscle activation and contraction, especially examined within those with knee OA with and without self-reported walking difficulty.

However, the small sample size and cross-sectional study design makes it difficult to further to subgroup subjects with knee OA beyond walking difficulty, and the findings provide limited information concerning the temporal relationship between walking difficulty and OA presence for neuromuscular strategies. The relationship between OA related symptoms, walking difficulty, and neuromuscular strategies need to be further examined in a larger sample size that allow multiple sub-groups to be established.

The results of this study needs to be considered despite its limitations, especially given the controlled study design for age, sex, and gait speed. Despite the controlled nature, walking ability in knee OA appears to be most likely a multifactorial problem that may be influenced by quadriceps strength and lateral compartment knee OA, factors that were not examined as part of this study. Further, our study examined subjects with knee OA in the medial compartment, therefore the potential contributions of lateral compartment OA on neuromuscular strategy differences based on walking difficulty remains unknown. Potential lateral compartment knee OA may influence their respective neuromuscular strategies but were not examined. Future studies should consider the possible effects of these factors and their potential effects of these interaction on neuromuscular strategies during gait in order to gain a clearer concept of the relative contribution of such impairments to walking difficulty.

## 3.5 Conclusion

The findings of this study suggest that neuromuscular strategies during gait appear to vary more based on knee OA presence; however, group differences were attenuated at faster gait speeds. The attempt to walk at faster gait speeds appear to recruit similar muscle patterns despite the presence of OA presence, as the NoDiff and control groups had similar fast gait speeds. Meanwhile, the Diffs much slower fast gait speed, yielded similar neuromuscular strategies. Therefore, it appears neuromuscular strategies may be impacted by effort, which may suggest that training those with walking difficulty and knee OA at fast gait speeds may optimize muscle recruitment and neuromuscular strategy.

Table 3.1 Subject Characteristics. Average (± SD) age, body mass index (BMI), pain, and self-selected and self-selected fast gait speeds. Pain reported on a scale from 0, defined as no pain, to 10, defined as worst pain imaginable.

| | OA | | | |
|---|---|---|---|---|
| | Difficult | Not Difficult | Control | p-value |
| N | 13 | 13 | 13 | n/a |
| Age (years) | 66.1 ±6.3 | 65.8 ±5.8 | 66.1± 6.2 | n/a |
| Sex (N) | Females = 8; Males = 5 | | | n/a |
| BMI ($Kg/m^2$) | 31.4 ± 5.6 | 29.7 ± 5.6 | 27.6 ± 3.7 | p = .13 to .26 |
| OA Severity (N) | | | | p = .61 |
| 2 | 4 | 4 | N/A | |
| 3 | 5 | 6 | N/A | |
| 4 | 4 | 3 | N/A | |
| Pain (0 to 10) | 6.5 ±1.5 | 5.6 ±2.0 | N/A | p = .92 |
| Self-selected gait speed (m/s) | 1.23 ± .19 | 1.34 ± .16 | 1.31 ± .10 | p = .09 to 23 |
| Fast gait speed (m/s) | 1.57 ± .28$^{*\#}$ | 1.76 ± .23$^{*}$ | 1.75 ±.12$^{\#}$ | p = .04$^{*}$<br>p = .02$^{\#}$<br>p = .44 |

$^{*}$ Significant between the Difficult and Not Difficult groups, $p \leq .05$.
$^{\#}$Significant between the Difficult and Control groups, $p \leq .05$.

Table 3.2 Responses to OA symptoms. Distribution of responses for knee symptoms of subjects with knee OA with and without walking difficulty (N) adopted from the Knee Outcome Survey (KOS)

| Symptom | Group | No Symptom 5 | No Affect 4 | Slightly 3 | Moderately 2 | Severely 1 |
|---|---|---|---|---|---|---|
| Pain | Diff | 0 | 0 | 4 | 4 | 5 |
| | NoDiff | 1 | 3 | 2 | 7 | 0 |
| Stiffness | Diff | 0 | 0 | 3 | 6 | 4 |
| | NoDiff | 1 | 5 | 3 | 4 | 0 |
| Swelling | Diff | 3 | 4 | 1 | 2 | 3 |
| | NoDiff | 5 | 2 | 2 | 3 | 1 |
| Giving Way | Diff | 1 | 5 | 0 | 4 | 3 |
| | NoDiff | 3 | 4 | 3 | 2 | 1 |
| Weakness | Diff | 1 | 3 | 3 | 5 | 1 |
| | NoDiff | 3 | 3 | 5 | 1 | 1 |
| Limping | Diff | 0 | 3 | 5 | 4 | 1 |
| | NoDiff | 5 | 2 | 3 | 2 | 1 |

No subjects in either OA groups reported 0 or unable to function due to symptom for any of the symptoms; therefore, 0 was omitted from the table.

Table 3.3 Trend for muscle activation and co-contraction based on pain**.** Percent of MVC, grouped by self-reported knee pain severity. Based on self-reported knee pain, average percent of maximal voluntary contraction (% of MVC) and co-contraction indices for medial quadriceps = MQ; lateral quadriceps = LQ; medial hamstrings = MH; lateral hamstrings = LH; medial gastrocnemius = MG; and lateral gastrocnemius = LG used during weight acceptance (Column A) and mid-stance (Column B) gait intervals during normalized gait speed of 1.0 meter per second within those diagnosed with knee osteoarthritis and self-reporting walking difficulty (Diff) and no walking difficulty groups (NoDiff).

| | | A. Weight Acceptance | | | | | B. Mid Stance | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 or 5 | | 1 | 2 | 3 | 4 or 5 |
| MQ | Diff | 18.8 | 12.5 | 13.8 | n/a | Diff ¥ | 15.5 | 6.9 | 6.4 | n/a |
| | NoDiff ¥ | n/a | 15.3 | 13.0 | 12.7 | NoDiff ^ | n/a | 8.6 | 4.1 | 4.3 |
| LQ | Diff | 19.0 | 19.4 | 15.9 | n/a | Diff ¥ | 15.1 | 10.7 | 5.9 | n/a |
| | NoDiff | n/a | 14.3 | 11.9 | 14.9 | NoDiff ¥ | n/a | 8.9 | 4.5 | 4.1 |
| MH | Diff | 19.4 | 16.6 | 22.3 | n/a | Diff ¥ | 7.9 | 7.6 | 7.4 | n/a |
| | NoDiff | n/a | 12.4 | 24.6 | 15.0 | NoDiff | n/a | 5.3 | 4.6 | 11.8 |
| LH | Diff | 18.0 | 13.0 | 22.3 | n/a | Diff | 12.2 | 5.6 | 12.4 | n/a |
| | NoDiff ¥ | n/a | 13.7 | 18.3 | 19.7 | NoDiff | n/a | 6.2 | 3.1 | 11.0 |
| MG | Diff ^ | 8.1 | 6.5 | 6.7 | n/a | Diff | 16.8 | 11.6 | 22.3 | n/a |
| | NoDiff | n/a | 9.7 | 1.3 | 4.7 | NoDiff | n/a | 9.7 | 1.3 | 4.7 |
| LG | Diff ¥ | 10.6 | 10.5 | 6.3 | n/a | Diff ¥ | 18.6 | 15.3 | 11.2 | n/a |
| | NoDiff | n/a | 7.7 | 2.6 | 4.5 | NoDiff | n/a | 5.3 | 4.6 | 11.8 |
| MQMH | Diff | 22.4 | 15.9 | 18.2 | n/a | Diff ¥ | 10.4 | 7.0 | 5.0 | n/a |
| | NoDiff | n/a | 16.3 | 19.9 | 14.7 | NoDiff ^ | n/a | 6.4 | 3.4 | 3.4 |
| LQLH | Diff ¥ | 23.0 | 20.6 | 19.1 | n/a | Diff ¥ | 12.9 | 7.8 | 5.1 | n/a |
| | NoDiff | n/a | 15.1 | 12.3 | 17.7 | NoDiff ^ | n/a | 7.1 | 3.1 | 3.6 |
| MQMG | Diff ^ | 11.3 | 8.1 | 8.2 | n/a | Diff | 12.1 | 7.6 | 8.9 | n/a |
| | NoDiff | n/a | 9.0 | 1.5 | 6.1 | NoDiff | n/a | 8.9 | 3.5 | 5.6 |
| LQLG | Diff ¥ | 14.3 | 13.0 | 8.6 | n/a | Diff ¥ | 16.9 | 9.3 | 7.8 | n/a |
| | NoDiff | n/a | 10.0 | 3.5 | 5.6 | NoDiff ¥ | n/a | 5.6 | 5.5 | 5.1 |

¥Marks the group when trends are observed

^Marks the group with no trend, but values are equal or close (± 0.5)

Table 3.4 Trend for muscle activation and co-contraction based on stiffness. Based on self-reported knee stiffness, average percent of maximal voluntary contraction (% of MVC) and co-activation indices for medial quadriceps = MQ; lateral quadriceps = LQ; medial hamstrings = MH; lateral hamstrings = LH; medial gastrocnemius = MG; and lateral gastrocnemius = LG used during weight acceptance (A) and mid-stance (B) gait intervals during normalized gait speed of 1.0 meter per second within those diagnosed with knee osteoarthritis and self-reporting walking difficulty (Diff) and no walking difficulty groups (NoDiff).

| | | A. Weight Acceptance | | | | | B. Mid Stance | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 or 5 | | 1 | 2 | 3 | 4 or 5 |
| MQ | Diff ¥ | 14.2 | 19.9 | 20.1 | n/a | Diff | 9.9 | 10.4 | 6.4 | n/a |
| | NoDiff ¥ | n/a | 16.1 | 15.2 | 12.3 | NoDiff ¥ | n/a | 8.4 | 8.2 | 4.5 |
| LQ | Diff ¥ | 13.5 | 16.1 | 16.5 | n/a | Diff | 10.4 | 13.2 | 7.0 | n/a |
| | NoDiff | n/a | 14.6 | 18.0 | 12.0 | NoDiff ¥ | n/a | 9.9 | 8.4 | 3.9 |
| MH | Diff ¥ | 17.5 | 18.8 | 23.2 | n/a | Diff | 3.5 | 10.2 | 8.2 | n/a |
| | NoDiff | n/a | 8.1 | 23.4 | 15.5 | NoDiff ^ | n/a | 2.4 | 9.4 | 9.3 |
| LH | Diff | 12.7 | 23.3 | 13.6 | n/a | Diff | 5.2 | 17.5 | 2.5 | n/a |
| | NoDiff | n/a | 10.2 | 19.8 | 18.5 | NoDiff ^ | n/a | 3.8 | 8.8 | 8.7 |
| LG | Diff ¥ | 6.5 | 9.6 | 12.1 | n/a | Diff ¥ | 11.9 | 15.1 | 20.3 | n/a |
| | NoDiff | n/a | 6.4 | 6.7 | 5.3 | NoDiff ¥ | n/a | 8.8 | 11.0 | 14.1 |
| MQMH | Diff ¥ | 16.4 | 20.0 | 21.1 | n/a | Diff | 4.1 | 10.7 | 6.4 | n/a |
| | NoDiff | n/a | 12.0 | 25.6 | 14.4 | NoDiff | n/a | 3.1 | 9.7 | 3.9 |
| MQMG | Diff | 6.5 | 11.3 | 9.2 | n/a | Diff ¥ | 8.83 | 8.7 | 5.1 | n/a |
| | NoDiff | n/a | 6.1 | 12.6 | 4.7 | NoDiff | n/a | 7.6 | 12.2 | 7.8 |
| LQLG | Diff ¥ | 8.8 | 13.0 | 15.0 | n/a | Diff | 11.4 | 13.1 | 9.4 | n/a |
| | NoDiff ¥ | n/a | 9.0 | 7.9 | 6.6 | NoDiff | n/a | 7.3 | 10.1 | 5.1 |

¥Marks the group when trends are observed

^Marks the group with no trend, but values are equal or close (± 0.5)

No trends were observed for MG and LQLH based on gait intervals nor groups.

Table 3.5 Trend for muscle activation and co-contraction based on limping**.** Based on self-reported limping, average percent of maximal voluntary contraction and co-contraction indices for medial quadriceps = MQ; lateral quadriceps = LQ; medial hamstrings = MH; lateral hamstrings = LH; medial gastrocnemius = MG; and lateral gastrocnemius = LG used during weight acceptance and mid-stance gait intervals during normalized gait speed of 1.0 meter per second within those diagnosed with knee osteoarthritis and self-reporting walking difficulty (Diff) and no walking difficulty groups (NoDiff).

| | | A. Weight Acceptance | | | | | B. Mid Stance | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 or 5 | | 1 | 2 | 3 | 4 or 5 |
| MQ | Diff ¥ | 27.8 | 17.1 | 13.8 | 11.3 | Diff | 14.1 | 8.7 | 11.0 | 5.6 |
| | NoDiff | 13.0 | 12.5 | 14.8 | 14.1 | NoDiff | 4.6 | 6.0 | 9.3 | 5.9 |
| LH | Diff | 22.4 | 17.0 | 21.0 | 12.0 | Diff | 8.3 | 10.6 | 14.8 | 2.9 |
| | NoDiff | 14.7 | 10.6 | 10.0 | 20.7 | NoDiff ¥ | 2.5 | 2.8 | 4.6 | 10.2 |
| MG | Diff | 13.8 | 6.0 | 9.4 | 2.8 | Diff | 22.8 | 17.3 | 14.2 | 18.8 |
| | NoDiff ¥ | 1.2 | 1.7 | 6.4 | 9.4 | NoDiff ¥ | 3.3 | 6.1 | 16.0 | 18.2 |
| LG | Diff | 13.3 | 8.5 | 11.9 | 4.4 | Diff ^ | 35.2 | 15.1 | 15.1 | 9.2 |
| | NoDiff | 2.6 | 6.9 | 7.6 | 5.4 | NoDiff | 7.1 | 12.7 | 10.0 | 12.9 |
| MQMH | Diff ¥ | 38.5 | 20.5 | 17.6 | 13.3 | Diff ^ | 9.6 | 8.5 | 8.6 | 4.4 |
| | NoDiff | 23.1 | 12.5 | 11.8 | 18.2 | NoDiff | 2.8 | 4.3 | 3.2 | 6.2 |
| MQMG | Diff | 20.5 | 8.6 | 11.3 | 3.8 | Diff ¥ | 15.9 | 11.0 | 9.4 | 6.5 |
| | NoDiff ¥ | 1.4 | 1.9 | 7.5 | 8.9 | NoDiff | 3.9 | 4.3 | 10.5 | 6.8 |

¥Marks the group when trends are observed

^Marks the group with no trend, but values are equal or close (± 0.5)

No trends were observed for LQ, MH, LQLH, LQLG based on gait intervals nor groups.

Table 3.6 Subject distribution based on gait speed. Distribution for gait speed is based on individuals (N) in the walking difficulty group (Diff), no walking difficulty group (NoDiff), and control group for self-selected and fast gait speed quartiles measured in meter per second, m/s.

| Self-Selected Gait Speed | | | | |
|---|---|---|---|---|
| | *Low* | | | *High* |
| | 1 | 2 | 3 | 4 |
| | *< 1.18 m/s* | *1.18 -1.32 m/s* | *1.32-1.41 m/s* | *> 1.41 m/s* |
| Diff | 5 | 3 | 3 | 2 |
| NoDiff | 4 | 2 | 2 | 5 |
| Control | 2 | 3 | 6 | 2 |
| Fast Gait Speed | | | | |
| | *Low* | | | *High* |
| | 1 | 2 | 3 | 4 |
| | *< 1.55 m/s* | *1.55-1.72 m/s* | *1.72-1.92 m/s* | *> 1.92 m/s* |
| Diff | 6 | 3 | 2 | 2 |
| NoDiff | 3 | 2 | 3 | 5 |
| Control | 0 | 6 | 4 | 3 |

Table 3.7 Trend for muscle activation and co-contraction based on self-selected gait speed for those with knee OA with walking difficulty (Diff), without walking difficulty (NoDiff), and the control group. Muscles included medial (MQ) and lateral (LQ) quadriceps; medial (MH) and lateral (LH) hamstrings; medial (MG) and lateral (LG) gastrocnemius during weight acceptance and mid-stance gait intervals at a self-selected gait speed. Gait speed quartiles included ≤ 1.55 meter per second (m/s) in the lowest quartile; 1.18-1.32 m/s in the 2nd quartile; 1.32-1.41 m/s in the 3rd quartile; and gait speed ≥ 1.41 m/s in the 4th quartile.

| | | Weight Acceptance | | | | | Mid Stance | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | *Low* | | | *High* | | *Low* | | | *High* |
| | | 1 | 2 | 3 | 4 | | 1 | 2 | 3 | 4 |
| MQ | Diff | 15.1 | 17.0 | 21.1 | 18.6 | Diff | 9.6 | 7.5 | 12.2 | 13.2 |
| | NoDiff | 23.5 | 14.2 | 21.2 | 21.0 | NoDiff | 10.7 | 6.2 | 4.2 | 7.8 |
| | Control | 11.8 | 9.7 | 14.7 | 13.6 | Control | 3.8 | 3.1 | 4.5 | 3.3 |
| LQ | Diff | 21.9 | 17.9 | 16.7 | 29.2 | Diff | 14.4 | 6.9 | 10.5 | 19.9 |
| | NoDiff | 20.7 | 15.1 | 17.7 | 22.0 | NoDiff | 9.3 | 7.1 | 5.5 | 6.5 |
| | Control | 14.0 | 14.3 | 17.5 | 15.3 | Control | 4.5 | 4.2 | 6.5 | 3.9 |
| MH | Diff | 23.4 | 16.7 | 27.5 | 17.2 | Diff | 11.3 | 7.7 | 3.3 | 6.5 |
| | NoDiff | 24 | 19.5 | 21.4 | 17.4 | NoDiff | 10.2 | 3.9 | 11.2 | 7.8 |
| | Control | 14.4 | 14.9 | 24.2 | 14.9 | Control | 5.7 | 8.0 | 8.8 | 4.7 |
| LH | Diff | 18.4 | 28.4 | 22.1 | 27.4 | Diff | 7.3 | 16.3 | 4.8 | 10.5 |
| | NoDiff | 35.9 | 21.7 | 17.8 | 19.6 | NoDiff | 16.3 | 4.2 | 4.5 | 7.7 |
| | Control | 11.0 | 18.1 | 20.0 | 13.1 | Control | 6.2 | 7.9 | 8.5 | 3.4 |
| MG | Diff ¥ | 12.8 | 11.6 | 5.6 | 4.0 | Diff | 20.8 | 25.8 | 11.4 | 12.5 |
| | NoDiff | 15.3 | 6.7 | 7.0 | 11.6 | NoDiff | 18.6 | 11.1 | 17.2 | 21.5 |
| | Control | 5.8 | 12.5 | 9.5 | 1.6 | Control | 21.6 | 32.6 | 25.7 | 20.2 |
| LG | Diff | 17.8 | 7.6 | 10.3 | 8.3 | Diff | 24.3 | 14.5 | 13.0 | 14.8 |
| | NoDiff | 11.1 | 8.0 | 4.9 | 7.9 | NoDiff | 14.5 | 15.3 | 13.9 | 15.6 |
| | Control | 8.2 | 6.3 | 9.9 | 2.1 | Control | 17.7 | 13.1 | 19.0 | 16.2 |
| MQMH | Diff | 19.0 | 16.5 | 22.5 | 21.3 | Diff | 6.7 | 7.4 | 3.8 | 7.8 |
| | NoDiff | 29.3 | 20.5 | 21.4 | 22.1 | NoDiff | 7.2 | 4.5 | 4.0 | 8.0 |
| | Control | 14.7 | 10.2 | 20.5 | 12.6 | Control | 4.5 | 3.5 | 5.0 | 1.7 |
| LQLH | Diff | 21.6 | 23.8 | 19.5 | 37.7 | Diff | 11.2 | 8.3 | 5.8 | 13.4 |
| | NoDiff | 25.6 | 18.7 | 12.6 | 23.8 | NoDiff | 9.1 | 4.5 | 2.2 | 6.7 |
| | Control | 13.0 | 18.3 | 19.9 | 15.3 | Control | 5.2 | 7.8 | 6.7 | 3.5 |
| MQMG | Diff ¥ | 16.3 | 15.7 | 7.3 | 5.6 | Diff | 11.0 | 10.8 | 7.8 | 14.1 |
| | NoDiff | 18.5 | 6.1 | 8.6 | 12.1 | NoDiff | 11.8 | 5.8 | 4.6 | 10.0 |
| | Control | 7.7 | 10.0 | 10.5 | 2.0 | Control | 5.0 | 3.8 | 5.3 | 3.4 |
| LQLG | Diff | 24.1 | 11.1 | 13.6 | 12.1 | Diff | 19.4 | 10.2 | 11.1 | 13.4 |
| | NoDiff | 15.8 | 10.9 | 5.2 | 8.7 | NoDiff | 9.5 | 9.4 | 3.4 | 7.4 |
| | Control | 12.8 | 6.5 | 12.3 | 2.6 | Control | 5.5 | 6.2 | 7.3 | 3.8 |

¥Marks the group when trends are observed

^Marks the group with no trend, but values are equal or close (± 0.5)

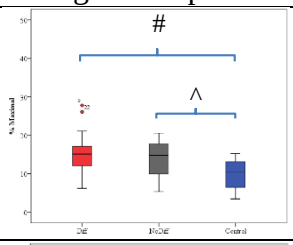
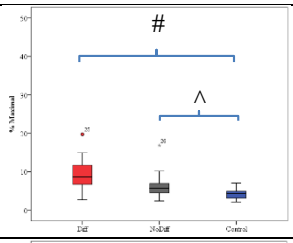
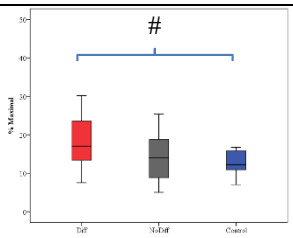
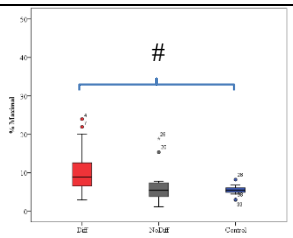
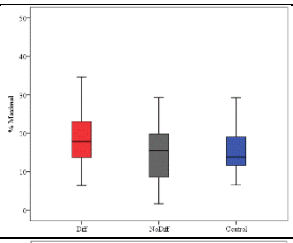
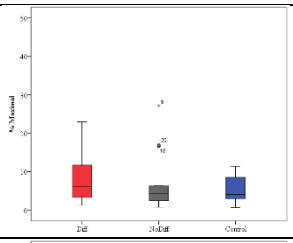
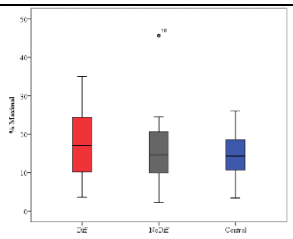
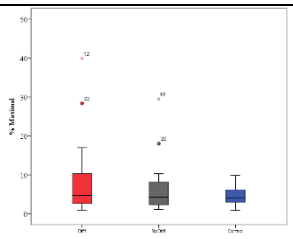
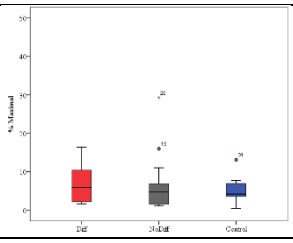
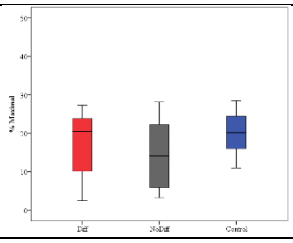
Table 3.8 Trend for muscle activation and co-contraction based on fast gait speed for those with knee OA with walking difficulty (Diff), without walking difficulty (NoDiff), and the control group. Muscles included medial (MQ) and lateral (LQ) quadriceps; medial (MH) and lateral (LH) hamstrings; medial (MG) and lateral (LG) gastrocnemius during weight acceptance and mid-stance gait intervals at a fast gait speed. Gait speed quartiles included ≤ 1.55 meter per second (m/s) in the lowest quartile; 1.55-1.72 m/s in 2nd quartile; 1.72-1.92 m/s in 3rd quartile; and ≥ 1.92 m/s in the highest or 4th quartile.

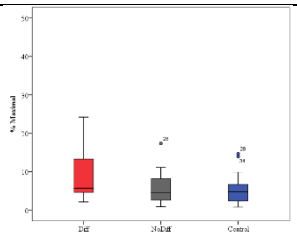
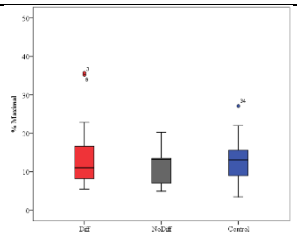
| | | Weight Acceptance | | | | | Mid Stance | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Quartiles | *Low* 1 | 2 | 3 | *High* 4 | | *Low* 1 | 2 | 3 | *High* 4 |
| MQ | Diff | 24.1 | 33.0 | 21.9 | 40.4 | Diff ^ | 14.5 | 16.8 | 16.5 | 34.9 |
| | NoDiff | 29.0 | 22.2 | 24.3 | 35.1 | NoDiff | 17.2 | 12.6 | 13.4 | 17.5 |
| | Control^ | n/a | 20.4 | 20.4 | 23.8 | Control[¥] | n/a | 8.7 | 8.9 | 14.5 |
| LQ | Diff | 28.4 | 26.8 | 27.0 | 40.7 | Diff | 13.9 | 12.7 | 28.4 | 26.9 |
| | NoDiff | 19.1 | 34.7 | 28.7 | 30.9 | NoDiff | 12.9 | 16.4 | 12.1 | 16.5 |
| | Control | n/a | 24.6 | 32.4 | 25.8 | Control[¥] | n/a | 7.9 | 9.2 | 14.0 |
| MH | Diff | 33.4 | 33.6 | 37.0 | 27.2 | Diff | 12.5 | 6.7 | 49.7 | 9.4 |
| | NoDiff | 24.7 | 31.9 | 25.0 | 27.1 | NoDiff | 6.6 | 27.3 | 5.2 | 14.3 |
| | Control | n/a | 22.4 | 35.2 | 27.6 | Control | n/a | 6.7 | 17.8 | 8.3 |
| LH | Diff | 32.7 | 34.5 | 33.1 | 44.5 | Diff | 15.6 | 10.4 | 24.1 | 18.1 |
| | NoDiff | 31.4 | 78.7 | 22.5 | 32.4 | NoDiff | 9.9 | 35.6 | 5.8 | 18.5 |
| | Control | n/a | 25.9 | 28.9 | 23.3 | Control | n/a | 10.4 | 13.5 | 20.4 |
| MG | Diff | 15.6 | 12.3 | 10.1 | 12.6 | Diff | 32.2 | 24.1 | 18.3 | 27.8 |
| | NoDiff | 19.2 | 18.5 | 6.6 | 16.7 | NoDiff | 27.8 | 35.1 | 16.1 | 34.1 |
| | Control[¥] | n/a | 13.1 | 13.0 | 12.9 | Control | n/a | 33.0 | 29.9 | 45.9 |
| LG | Diff | 20.1 | 8.4 | 18.0 | 16.9 | Diff | 27.3 | 20.2 | 35.1 | 37.1 |
| | NoDiff | 14.7 | 21.9 | 10.8 | 13.1 | NoDiff | 23.8 | 35.3 | 26.4 | 24.7 |
| | Control[¥] | n/a | 10.9 | 10.3 | 8.9 | Control[¥] | n/a | 22.0 | 23.2 | 35.6 |
| MQMH | Diff | 31.8 | 31.6 | 22.2 | 37.0 | Diff | 13.3 | 6.8 | 11.7 | 13.0 |
| | NoDiff | 35.9 | 37.3 | 26.1 | 33.0 | NoDiff | 9.1 | 19.7 | 7.4 | 13.6 |
| | Control | n/a | 23.3 | 28.1 | 21.9 | Control[¥] | n/a | 7.0 | 8.5 | 9.3 |
| LQLH | Diff | 32.7 | 31.7 | 31.0 | 63.3 | Diff | 13.0 | 9.7 | 34.3 | 24.3 |
| | NoDiff | 23.7 | 52.9 | 29.3 | 37.2 | NoDiff | 10.3 | 25.6 | 6.9 | 12.9 |
| | Control | n/a | 29.3 | 34.7 | 28.5 | Control | n/a | 8.9 | 8.2 | 17.1 |
| MQMG | Diff | 23.1 | 14.5 | 14.5 | 18.9 | Diff | 18.2 | 15.1 | 14.5 | 42.9 |
| | NoDiff | 24.9 | 22.9 | 9.6 | 19.6 | NoDiff | 20.4 | 18.6 | 11.3 | 22.0 |
| | Control | n/a | 14.2 | 11.7 | 13.5 | Control | n/a | 11.7 | 10.1 | 20.1 |
| LQLG | Diff | 26.6 | 11.2 | 29.0 | 22.8 | Diff | 19.8 | 14.4 | 39 | 40.2 |
| | NoDiff | 22.0 | 32.7 | 14.0 | 13.0 | NoDiff | 16.6 | 25.1 | 15.3 | 14.9 |
| | Control^ | n/a | 13.0 | 13.4 | 13.1 | Control[¥] | n/a | 8.5 | 10.3 | 17.7 |

[¥]Marks the group when trends are observed

^Marks the group with no trend, but values are equal or close (± 0.5)

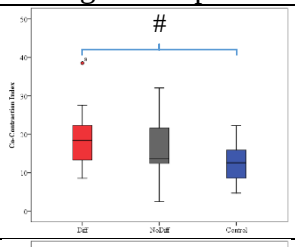
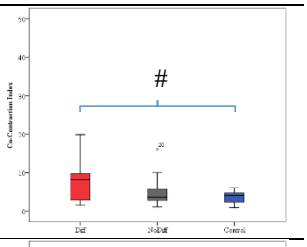
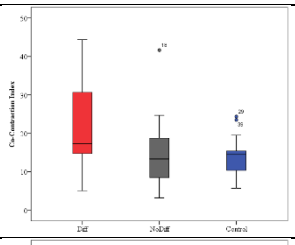
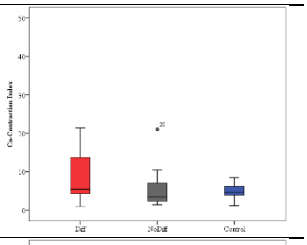
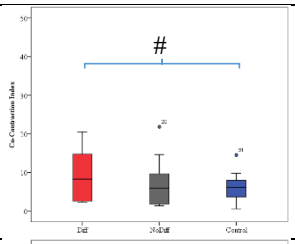
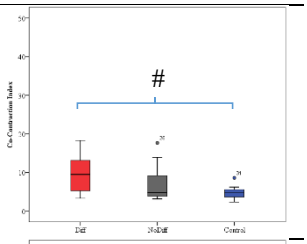
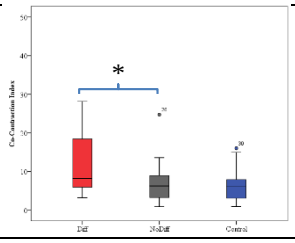
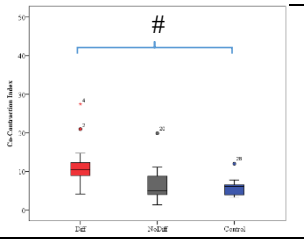
Figure 3.1 Muscle activation for controlled gait speed. Quartiles for percent of maximal muscle activation, as measured via electromyography, for the (■) walking difficulty group (Diff), the (■) no walking difficulty group (NoDiff), and the (■) control group during the weight acceptance and mid-stance gait intervals of controlled gait speed trials. Top whiskers represent the highest quartile, or those within each group who walked with the largest percentages of maximal muscle activation. Box represents 2nd and 3rd quartiles, with the line representing the median. Bottom whiskers represent the lowest quartile. Dots with numbers represent potential outliers.

| | Weight Acceptance | Mid-Stance |
|---|---|---|
| Medial Quadriceps |  |  |
| Lateral Quadriceps |  |  |
| Medial Hamstring |  |  |
| Lateral Hamstring |  |  |
| Medial Gastrocnemius |  |  |

| | | |
|---|---|---|
| Lateral Gastrocnemius |  |  |

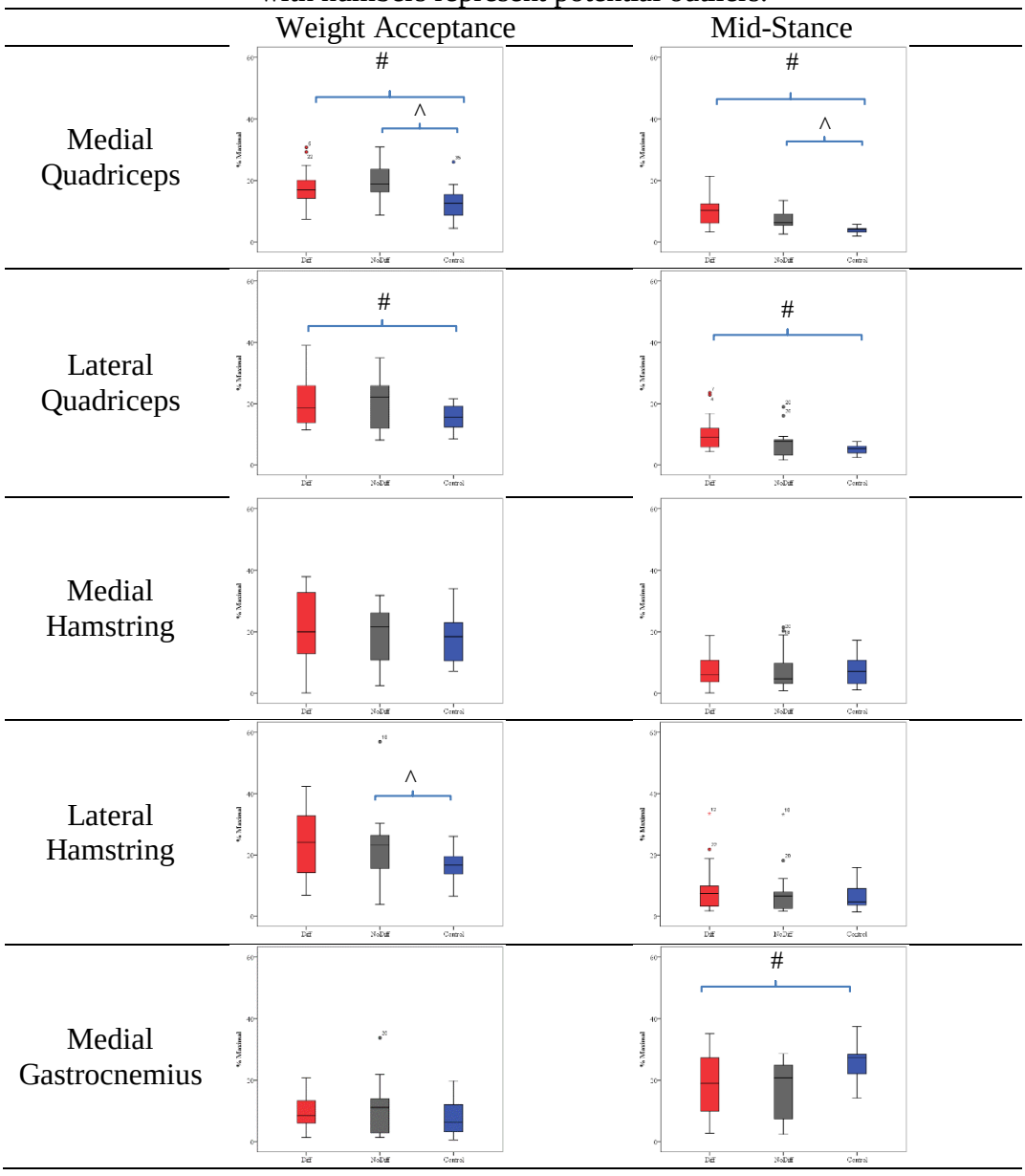
^ Signficant differences between the NoDiff and Control groups, $p \leq .05$.
[#] Signficant differences between the Diff and Control groups, $p \leq .05$.

Figure 3.2 Co-contraction index for controlled gait speed. Quartiles for co-contraction, as derived from electromyography inserted into the co-contraction equation, for the (■) Walking Difficulty group (Diff), the (■) No Walking Difficulty Group (NoDiff), and the (■) Control group during weight acceptance and mid-stance gait intervals when walking a controlled gait speed of 1.0 meter per second. Top whiskers represent the highest quartile, or those within each group who walked with the largest co-contraction indices. Box represents 2nd and 3rd quartiles, with the line representing the median. Bottom whiskers represent the lowest quartile, or those within each group who walked with the smallest co-contraction indices. Dots with numbers represent potential outliers.

| | Weight Acceptance | Mid-Stance |
|---|---|---|
| Medial Quadriceps -Hamstrings |  |  |
| Lateral Quadriceps-Hamstrings |  |  |
| Medial Quadriceps-Gastrocnemius |  |  |
| Lateral Quadriceps-Gastrocnemius |  |  |

* Signficant differences between the Diff and NoDiff groups, $p \leq .05$.
# Signficant differences between the Diff and Control groups, $p \leq .05$.

Figure 3.3 Muscle activation for self-selected gait speed. Quartiles for percent of maximal muscle activation, as measured via electromyography, for the (■) Walking Difficulty group (Diff), (■) No Walking Difficulty Group (NoDiff), and (■) Control group during weight acceptance and mid-stance gait intervals when walking at a self-selected gait speed. Top whiskers represent the highest quartile, or those within each group who walked with the largest percentages of maximal muscle activation. Box represents 2nd and 3rd quartiles, with the line representing the median. Bottom whiskers represent the lowest quartile. Dots with numbers represent potential outliers.



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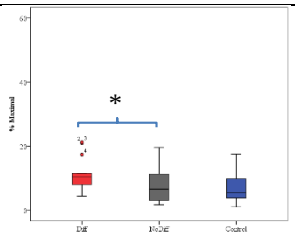
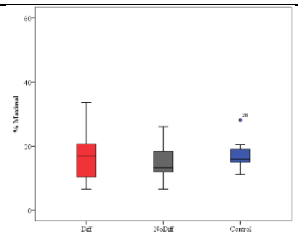
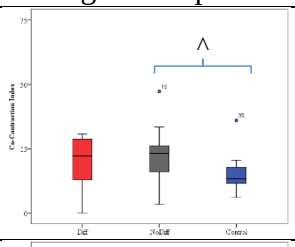
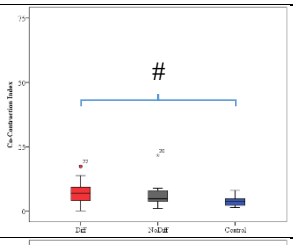
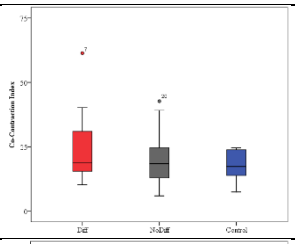
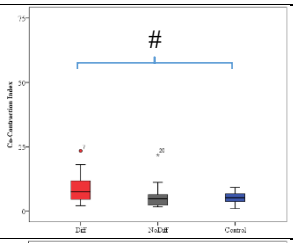
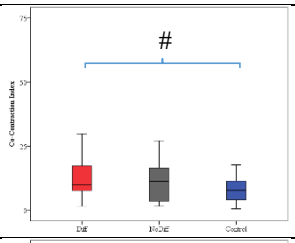
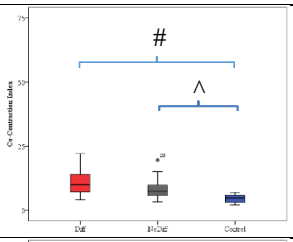
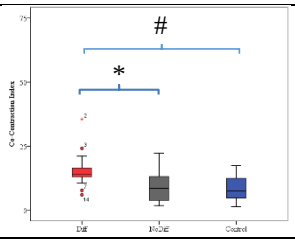
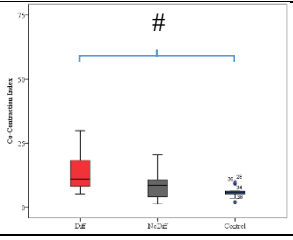
|---|---|---|
| Lateral Gastrocnemius |  |  |

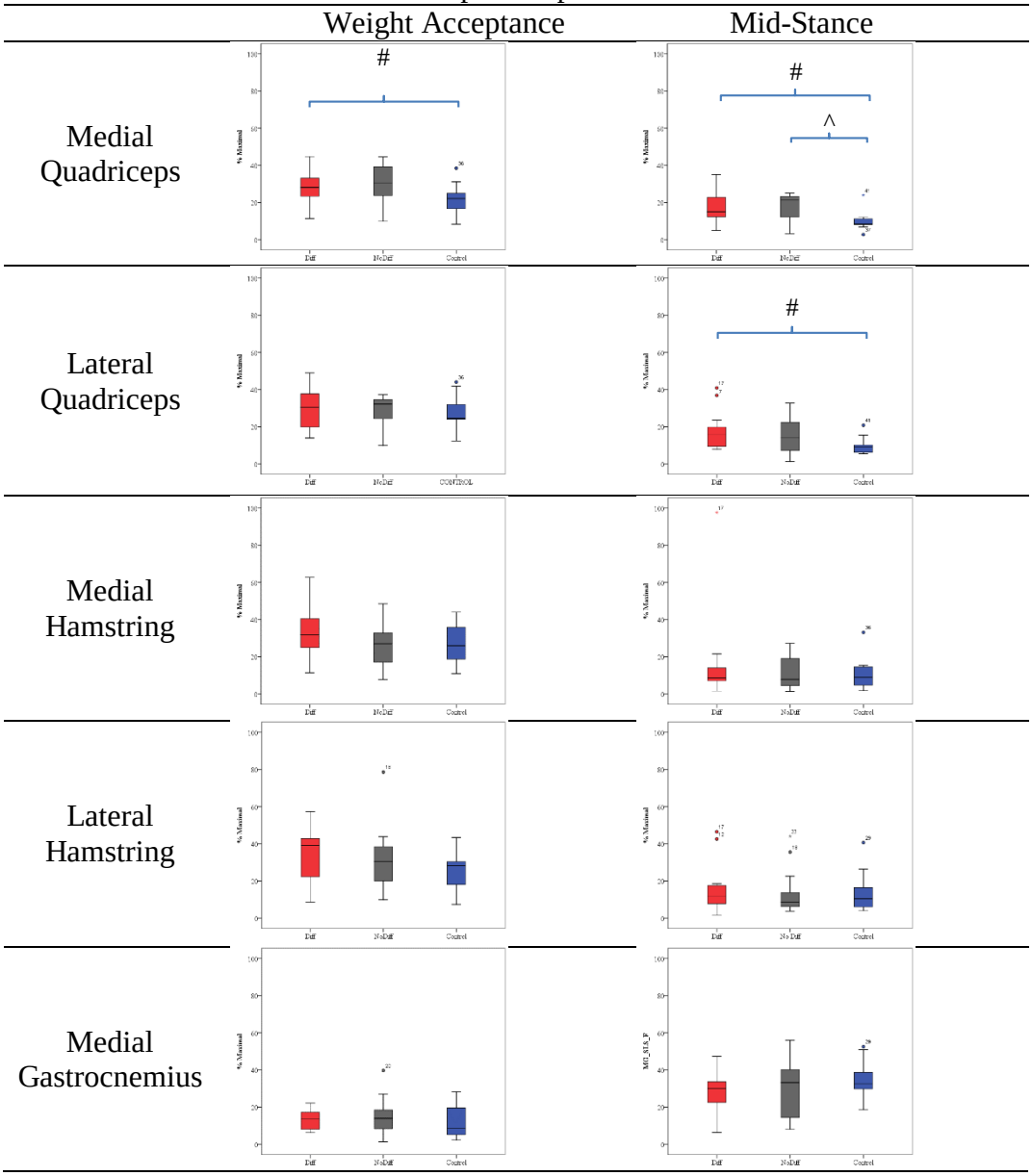
* Signficant differences between the Diff and NoDiff groups, p ≤ .05.
^ Signficant differences between the NoDiff and Control groups, p ≤ .05.
# Signficant differences between the Diff and Control groups, p ≤ .05.

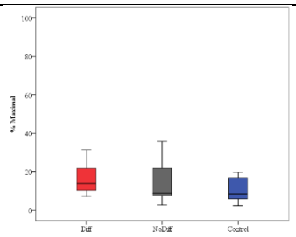
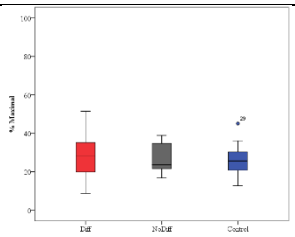
Figure 3.4 Co-contraction for self-selected gait speed. Quartiles for co-contraction, as derived from electromyography inserted into the co-contraction equation, for the (■) walking difficulty group (Diff), the (■) no walking difficulty group (NoDiff), and the (■) control group during weight acceptance and mid-stance gait intervals when walking at a self-selected gait speed. Top whiskers represent the highest quartile, or those within each group who walked with the largest co-contraction indices. Box represents 2nd and 3rd quartiles, with the line representing the median. Bottom whiskers represent the lowest quartile. Dots with numbers represent potential outliers.

| | Weight Acceptance | Mid-Stance |
|---|---|---|
| Medial Quadriceps -Hamstrings |   |   |
| Lateral Quadriceps-Hamstrings |  |   |
| Medial Quadriceps-Gastrocnemius |   |   |
| Lateral Quadriceps-Gastrocnemius |   |   |

*Signficant between the Diff and NoDiff groups, $p \leq .05$.
^ Signficant between the NoDiff and Control groups, $p \leq .05$.
# Signficant between the Diff and Control groups, $p \leq .05$.

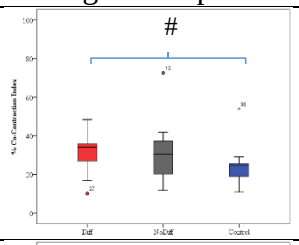
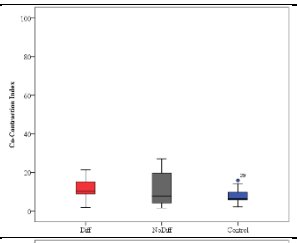
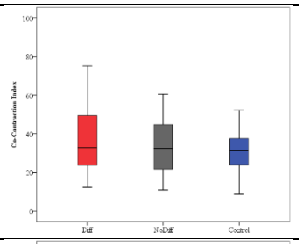
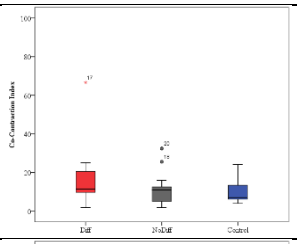
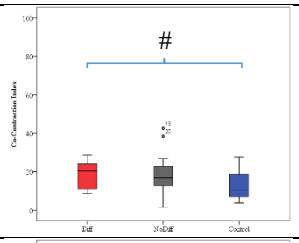
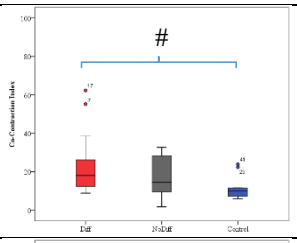
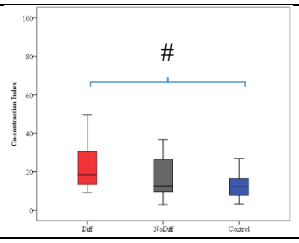
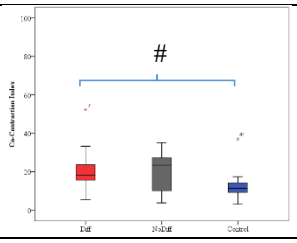
Figure 3.5 Muscle activation for fast gait speed. Quartiles for percent of maximal muscle activation, as measured via electromyography, for the (■) Walking Difficulty group (Diff), the (■) No Walking Difficulty Group (NoDiff), and the (■) Control group during weight acceptance and mid-stance gait intervals when walking at fast gait speed. Top whiskers represent the highest quartile, or those within each group who walked with the largest percentages of maximal muscle activation. Box represents 2nd and 3rd quartiles, with the line representing the median. Bottom whiskers represent the lowest quartile. Dots with numbers represent potential outliers.



| | | |
|---|---|---|
| Lateral Gastrocnemius |  |  |

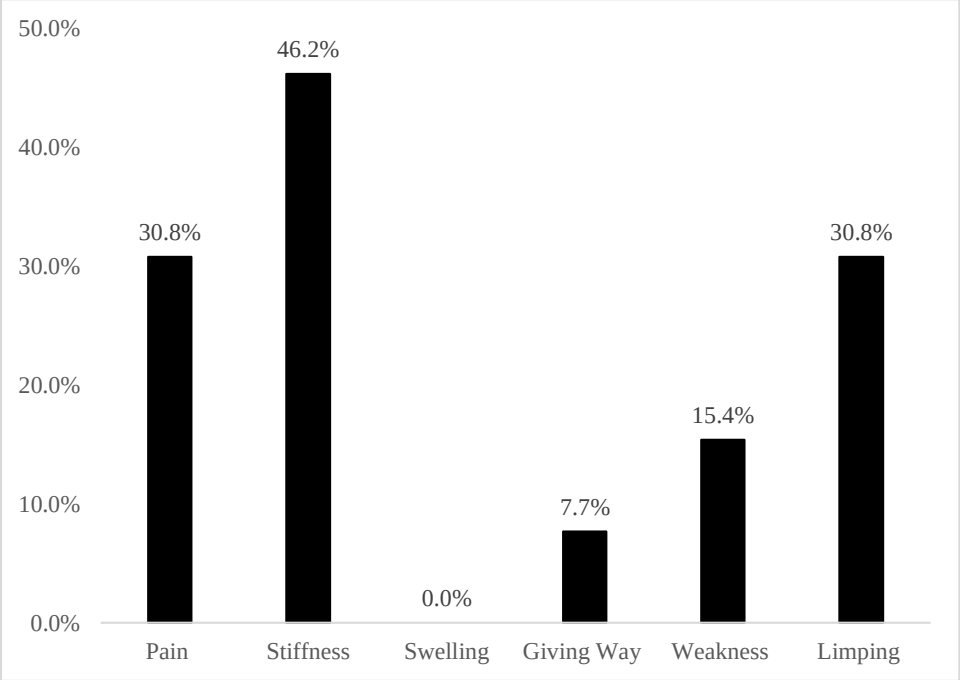
^ Signficant differences between the NoDiff and Control groups, $p \leq .05$.
# Signficant differences between the Diff and Control groups, $p \leq .05$.

Figure 3.6 Co-contraction for fast gait speed. Quartiles for co-contraction, as derived from electromyography inserted into the co-contraction equation, for the (■) Walking Difficulty group (Diff), the (■) No Walking Difficulty Group (NoDiff), and the (■) Control group during weight acceptance and mid-stance gait intervals when walking at a fast gait speed. Top whiskers represent the highest quartile, or those within each group who walked with the largest co-contraction indices. Box represents 2nd and 3rd quartiles, with the line representing the median. Bottom whiskers represent the lowest quartile. Dots with numbers represent potential outliers.

| | Weight Acceptance | Mid-Stance |
|---|---|---|
| Medial Quadriceps -Hamstrings |  |  |
| Lateral Quadriceps-Hamstrings |  |  |
| Medial Quadriceps-Gastrocnemius |  |  |
| Lateral Quadriceps-Gastrocnemius |  |  |

[#] Signficant differences between the Diff and Control groups, $p \leq .05$.

Figure 3.7 Percentile differences between those with and without walking difficulty reporting that OA symptoms negatively impact function. The value above each bar represents the percentage difference between the groups that reports the symptom negatively affects ability to function. Negatively affects ability to function was defined as responses of 3 or less on the knee outcome survey (KOS). In all cases, the walking difficulty group had a larger percent; so values were calculated as a percent of individuals reporting "3" or worst for each symptom in the walking difficulty minus the no walking difficulty group. Value interpretation suggests that a greater percent of the walking difficulty group had symptoms that negatively impact function than the no walking difficulty group. The largest differences between the two groups were observed for pain, stiffness, and limping.



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Chapter 4

# EXAMINING LIMB DYNAMICS AS A MECHANISM FOR CO-CONTRACTION AND WALKING DIFFICULTY IN KNEE OSTEOARTHRITIS

## 4.1 Introduction

Knee osteoarthritis (OA) is a leading cause of functional decline, which typically occurs within 3 to 5 years of diagnosis[1]. The prevalence of knee OA dramatically increases after the 5$^{th}$ decade of life[2]. Therefore, leaving older adults having to combat functional decline relating to both the natural course of aging and knee OA. Diseases found in aging adults, such as stroke, cardiovascular episodes, and dementia, have a greater risk for mortality when these co-morbidities are combined with knee OA[3,4]. Such poor outcomes can be partially explained by the negative impacts knee OA symptoms have on walking ability.

The severity of knee OA related symptoms can effect functional tasks. For example, severe pain related to knee OA can limit walking[5]. As a result, walking ability, if not carefully examined can lead to poor outcomes. Clinically, walking ability is tested by self-reported walking difficulty and gait speed[6,7]. Self-reported walking difficulty can be measured using the question *How does your knee affect your ability to walk* from the Knee Outcome Survey[8]. Subjects with responses that range between *somewhat difficult* to *unable to walk difficult* are considered to have walking limitations that are negatively affected by their knee OA. The classification scheme is adopted from studies that also uses the Knee Outcome Survey to sub-group subjects with symptomatic knee OA[9,10]. There is no true consensus on how self-perceived walking difficulty is measured. However, various versions of walking difficulty questions have noted that knee OA is one of the leading cause of walking difficulty[11].

Self-reported walking difficulty is related to mobility disability and overall health status in aging adults[7,12,13]. Gait speed, a measurement with more consensus when compared to walking difficulty, is measured by the time it takes to walk a specific distance. Individuals with knee OA have a 9 times greater risk for developing gait speed decline than those without knee OA[13]. Slower gait speed is related to a decline in functional mobility and increased risk for mortality[3,7]. Gait speed and walking difficulty are linked, as for every 0.5 meter per second gait speed decline the risk for developing walking difficulty increases by 2.04[13]. Nevertheless, the agreements between self-reported walking difficulty and gait speed are not strong[6]. Although some with self-reported walking difficulty walk at slow gait speeds, some with walking difficulty walk with fast and functional gait speeds. In fact, Ferrer and colleagues found that around 17% of those demonstrating faster gait speeds also reported walking difficulty[6]. In such cases, the management of this sub-group population who are able to walk at fast and functional gait speed but self-report walking difficulty are unclear.

In order to better understand walking ability in knee OA, we must examine how the knee OA experience is different based on walking difficulty differences among those with knee OA. Farrokhi and colleagues recently suggest within those with knee OA, individuals that self-reported knee instability, defined as the buckling or giving way of the knee, have an increased odds of walking difficulty by 10.7 when compared to those with knee OA but no instability[14]. Perhaps poor joint congruency between the femur and tibia created by the natural progression of knee OA are generating erratic limb movements. Previous studies were not successful in finding a relationship between joint laxity and self-reported instability in those with knee OA[15].

The lack of difference for mechanical laxity between those with and without may be better understood if limb movements are examined during walking.

Erratic limb movements may be less observable to the naked eye and only present during functional tasks, which would require limb dynamic measurements. Limb dynamic measurements can include linear acceleration, or the time-derivative of speed, and jerk, or the time-derivative of acceleration. Linear acceleration is a measurement of stability. In studies on total knee arthroplasty[16] and ACL[17,18], self-perceived knee instability is related to larger femoral and tibial linear acceleration values. In knee OA studies, linear acceleration, is reliably measured through inertial measurement units (IMUs)[19], is responsive to clinical interventions[20], and is larger in those with knee OA than those without knee OA[21]. However, no known studies have examined linear acceleration within a sub-group of knee OA. Linear acceleration's time derivative, jerk is better known in studies on motor control and is related to movement smoothness[22]. In patients with Parkinson's disease those with greater hand tremors have larger jerk values[23]. Therefore, large linear acceleration and jerk values could suggest a knee with an unstable environment and ineffective motor patterns resulting in movements that are not smooth, respectively.

The role linear acceleration and jerk may play in knee OA based on walking difficulty presence is currently unknown. Understanding the relationship between limb dynamics and walking difficulty may allow us to better understand the neuromuscular strategies that those with knee OA may adopt during gait.

Therefore, the purpose of this study is to examine how limb dynamics vary based on OA presence and walking difficulty presence within knee OA. Also, this

study considers how limb dynamics may be influenced by neuromuscular strategies, or muscle use, in those with knee OA.

We hypothesized the following:

Hypothesis 4.1: Limb dynamics, as measured by linear acceleration and jerk, will be greatest for the walking difficulty (Diff) group, follow by the no walking difficulty (NoDiff) group, and the least in the control group when walking at a controlled gait speed of 1.0 meter per second.

Hypothesis 4.2: Limb dynamic group differences will be the largest in the fast gait speed trials, follow by the self-selected gait speed trials, and the smallest differences will be observed during the controlled gait speed trials.

Hypothesis 4.3: Within the knee OA groups, when walking at a controlled gait speed, self-reported walking difficulty will moderate the relationship between co-contraction and limb dynamics.

## 4.2 Methods

Adults ages 50-80 years who (at the time of the study) were community dwelling, English speaking, with and without knee osteoarthritis were recruited from the community, and physician and physical therapy offices. Exclusion criteria included (1) History of surgery pertaining to the low back, hip, or foot/ankle in either leg; (2) Injury or signs or symptoms of injury to the trunk, low back hip, leg or foot/ankle within the past 3 months; (3) Symptomatic arthritis in the low back hip, leg, foot or ankle in either leg that effects movement or function; (4) History of knee replacements or skeletal re-alignment surgery in either leg; (5) PT for the trunk, low back, hip, or foot/ankle in either leg in the past 6 weeks; (6) Injections in low back, hip, knee, leg foot/ankle in the past 6 weeks; (7) History of respiratory, cardiovascular,

systemic, or neurological diseases; (8) Current or potential pregnancy**;** and (9) Unable to walk without an assistive device (e.g. walker, wheelchair, cane). Exclusion criteria for participation in the OA group included a Kellgren-Lawrence OA (KL) score of < 2; and (11) Reporting average knee pain of best, worst, and current of 2 or less on a scale of 0, being no pain, and 10 being worst pain imaginable. Exclusion criteria for participation in the control group included the presence of knee pain or one or more positive finding on the Altman's Criteria for knee OA (i.e., AM stiffness < 30 minutes, crepitus, bony tenderness, bony enlargement, palpable warmth)[26].

### 4.2.1 Knee Outcome Survey

To define walking difficulty sub-groups within our knee OA group we used the Knee Outcome Survey (KOS), which asks about various functional tasks including walking, and is commonly used in a clinical setting. We extracted the response to the question *How does your knee affect your ability to walk*. The question was selected from the Knee Outcome Survey, due to its previous tested validity and reliability in the knee OA population[8]. We adopted stratifying techniques that paralleled previous research studies that defined knee OA sub-groups based on responses to a single question taken from a self-reported knee outcome surveys [27,14]. Responses were scored on a 6-point scale (*5 = Not Difficult, 4 = Minimally Difficult, 3 = Somewhat Difficult, 2 = Fairly Difficult, 1 = Very Difficult, and 0 = Unable to do)* [8]. Subjects that responded with *not difficult* (4) or *minimally difficult* (5) were placed into the no walking difficulty group (NoDiff). Subjects that responded with *somewhat difficult (3) to unable to do (0)* were placed into the walking difficulty group (Diff). Further, the question in the Knee Outcome Survey asked specifically about walking difficulty without added quantification or qualification.

The three groups, the Diff group, the NoDiff group, and the control group, were sex and age matched within 2.5 years among all groups. The Examiner was blinded to the sub-grouping of the OA group, walking difficulty or normal difficulty, during data collection and processing.

### 4.2.2 Radiograph assessment

Knee OA severity was assessed using a standing, posterior-anterior radiograph with 20 degrees of knee flexion. An experienced radiologist, blinded to the walking difficulty classification within the OA group, scored OA severity based on the 4-point Kellgren-Lawrence (K-L) scale. The K-L scale was scored as 1: Doubtful narrowing of joint space and possible osteophytic lipping; started;2: osteophytes, definite narrowing of joint space 3: moderate multiple osteophytes, definite narrowing of joints space, some sclerosis and possible deformity of bone contour; 4: Large osteophytes marked narrowing of joint space, severe sclerosis and definite deformity of bone contour)[28].

### 4.2.3 Body measurement

We calculated body measurement including height, weight, and BMI from the standing calibration. Weight was measured via force plates and converted to kilograms (Kg), and height was measured using a marker on top of the subject's head and converted to meters (m). See below for further discussion on motion analyses[29].

$$(1) \quad \text{BMI} = \frac{\text{Weight (Kg)}}{\text{Height (m)x Height (m)}}$$

### 4.2.4 Walking

Subjects walked at a controlled gait speed of 1.0 meters per second, self-selected gait speed, and self-selected fast gait speed, or fast gait speed, for 10 meters. An external timer was used by the examiner to ensure gait speed did not deviate more than .05 meters per second from the 1.0 meters per second. The examiner instructed subjects at the end of each trial to walk *a little faster, to walk a little slower, or to maintain same gait speed*. Subjects walked a minimum of 5 accepted trials at each gait speed condition. Accepted trials included a minimum of two strides without altering gait patterns and with each foot clearly hitting each force plate through visual observation and real-time visual examination of each recorded trial. After each trial, a one-minute rest break, or more as necessary, was provided to limit potential effects of fatigue. The results of initial pilot testing found that starting with controlled gait speed of 1.0 meter per second resulted in slower self-selected and fast gait speed; however, starting with fast gait speed resulted in faster self-selected gait speed. Therefore, to minimize the effects of test order we started with self-selected gait speed, fast gait speed, and controlled gait speed.

### 4.2.5 Limb dynamics

Subjects walked with 5 inertial measurement units (IMUs) strapped to the posterior pelvis, bilateral femurs, and bilateral tibias to measure real-time linear acceleration and joint angles during walking. Each IMU (37.6 mm x 52mm x18.1 mm) weighed 34 g and included an onboard gyroscope and accelerometer that corrects for gravity and measures angular velocity and accelerometer, respectively. Femoral IMUs were strapped to the anterior femur just superior to the patella and bisected the patella. Tibial IMUs were strapped to the anterior tibia just inferior to the tibial tuberosity. The

pelvis IMU was strapped to the posterior surface of the sacrum bisecting bilateral PSIS and at the sacral ridge of S2. Selected IMU locations, on each body part, were to maximize the reduction of movement and soft tissue artifact by maximizing bone contact that was closest to the joint line[30] . Further, this testing procedure demonstrates excellent reliability[31] .Software calibration, for anatomical neutral and body size, compared the pelvic IMU to the more distal IMUs while in standing. Noraxon Software (Noraxon, 3D Motion) collected data at 100 Hz.

### 4.2.6 Motion analysis

In addition to IMUs, all subjects walked over two in-ground force plates (AMTI Force Plate) with reflective markers and electromyography (EMG). Force plates collected data at 1000 Hz. Eight, 3-dimensional, motion analysis cameras (Qualisys, Inc.) tracked the position of the reflective markers at 100 Hz. Reflective markers were secured to the head, shoulders, trunk, pelvis, hips, thigh, knee, leg, foot and ankle on both legs for calibration and to identify particular joint centers. Rigid thermoplastic shells, with four markers firmly affixed, were attached to the pelvis, lateral femur, lateral tibia, and dorsal surface of the foot.

EMG was recorded at 1000 Hz using a 16-channel (Motion Lab Systems, Baton Rouge, LA) interfaced with the force plates and motion analysis camera for simultaneous recording and gait interval identification. Disposable, self-adhered surface electrodes were used to measure electrical activity of the medial (MQ) and lateral (LQ) quadriceps, medial (MH) and lateral (LH) hamstrings, and medial (MG) and lateral (LG) gastrocnemius muscles according to the Surface ElectroMyoGraphy for the Non-Invasive Assessment of Muscles' (SENIAM) guidelines for electrode placement. Muscle EMG signals from maximal voluntary contraction (MVC)

normalized EMG signals from gait trials. Knee flexor and extensor MVCs were measured via isometric contraction using the Biodex System III dynamometer at 60 degrees of knee flexion and 80 degrees of hip flexion, which demonstrates excellent reliability.[32] This position minimizes the potential effects of anterior knee pain in patients with knee OA. To ensure ankle MVCs during walking did not exceed EMG values on the Biodex, plantar flexion MVCs were measured via standing bilateral heel raises with manual resistance through the shoulders. This testing procedure is an adapted version of the standardized manual muscle testing position for plantar flexion per Kendall et al.,[33] as many individuals with knee OA were unable to maintain single leg balance safely.

Recordings for motion capture, EMG, and IMU were synced using an external trigger. Due to electromechanical delay from the wireless IMU, data between IMU and motion capture were visually inspected. Pilot data identified synchronized start; however, trials appeared to include a non-consistent frame shift in the IMU data. Therefore, peak knee flexion findings and heel strike were marked on each trial for comparisons of gait intervals and stride.

### 4.2.7 Data management and processing

Qualisys collected raw motion capture and EMG data. Noraxon collected raw dynamic limb dynamics data. Data from both software packages were exported to Visual 3D™ (C-Motion, Rockville, MD) for processing. Force platform data and motion capture markers were low-pass filtered with a second-order Butterworth filter at 40 Hz and 4 Hz, respectively. Frontal and sagittal plane knee angles were calculated via Visual 3D using Euler angles to measure knee angles. The sagittal plane knee angles were used to determine gait intervals. Final gait speed was calculated for two

continuous strides on each limb, with one stride hitting the force plate, using temporal distance properties within Visual 3D. Due to human variability that occurs with over-ground walking, gait speed deviations of ±.05 meters per second were considered acceptable. Gait intervals were divided, using motion capture and force plate, into weight acceptance (initial contact of the first force plate through peak knee flexion angle) and mid-stance (started at peak knee flexion angle to peak knee extension angle), and normalized to 100 data points to account for time and number of point differences.

All electromyography (EMG) signals were high-pass and low-pass filtered using a 4$^{th}$ order Butterworth filter at 20 Hz and 350 Hz, respectively to remove offsets and noise artifacts. Filtered signals were then rectified and low passed filtered with a 4$^{th}$ order Butterworth filter at 10 Hz to eliminate high-frequency filters of the muscles. Processed gait EMG signals were normalized to similarly processed MVC EMG to determine percentage maximum of muscle activation. Synchronous EMG signals from each gait interval were used to calculate co-contraction indices. Co-contraction indices were calculated using *equation 2* for the subsequent simultaneous muscle activations of opposing muscle groups: medial quadriceps-medial hamstrings (MQMH), lateral quadriceps-lateral hamstrings (LGLH), medial quadriceps-medial gastrocnemius (MQMG), and lateral quadriceps-lateral gastrocnemius (LQLG). A co-contraction index was calculated based on equation 2:[34]

$$(2)\ Co-Contraction\ Index = \left(\sum_{i=IC}^{TASK}\left(\frac{EMG_S}{EMG_L}(EMG_S + EMG_L)\right)\Big/100\right)$$

Co-contraction indices divided $EMG_S$, defined as the smaller of the two EMG signals, by $EMG_L$, the larger of the two EMG signals, and integrated over the entire

cycle phase of movement and used in the analysis.[34] The co-contraction equation prevents small EMG signals that may be close to noise to be considered as high co-contraction and potential error of dividing over zero.[34] Co-contraction indices for knee OA has ranged from close to 0 up to 100, pending muscle groups, task and gait intervals.[24,35] Co-contraction indices were calculated for each gait interval for all gait speeds. A larger co-contraction index would suggest a higher concurrent use of the two muscles. A research study found excellent to good reliability (ICC =0.76-0.89) for the combination of muscles aforementioned, in both individuals with and without knee OA.[36]

Raw linear acceleration and joint angle data from the femoral and tibial IMUs were used to calculate limb dynamics, or linear acceleration and jerk, for each gait interval. Raw linear acceleration data was low passed Butter-worth filter at 30Hz and normalized to 100 points. Raw acceleration data were normalized to 100-time points to account for time and duration differences. Jerk was calculated based on the magnitude of the first derivative of processed linear acceleration in the anterior-posterior direction, x-, medial-lateral direction y-, and superior-inferior direction z-. Inserting the x, y, and direction data into the Pythagoras' theorem, equation 3, we calculated the magnitude (m) of femoral and tibial acceleration and jerk at each time point. Magnitudes ($m_{\text{segment, limb dynamics}}$) were calculated for femoral acceleration ($m_{f,a}$), tibial acceleration ($m_{t,a}$), femoral jerk ($m_{f,j}$), and tibial jerk ($m_{t,j}$).

$$m = \sqrt{x^2 + y^2 + z^2}$$

The peak magnitude for each limb dynamic was averaged for each group. Between-group comparisons were made, and significant levels allowed further analyses of the specific vector that was significantly different amount the groups.

Squaring the magnitude accounts for maximal peaks in the positive and negative directions. Therefore, the magnitude of femoral and tibial jerk and acceleration was compared between the groups, against knee symptoms, and against co-contraction. Using peak values of limb dynamics demonstrated excellent reliability [31] and validity[16]. Since previous literature suggest each linear acceleration value has moderate to excellent reliability, it can be assumed that relating values would share similar reliability[19,37]. As a result, since linear acceleration magnitude is the sum of linear acceleration, and jerk is the derivative of linear acceleration, then these measurements would also share moderate to strong reliability.

Raw limb dynamics data collected via the IMUS were processed and exported from Noraxon Software. Recordings for motion capture and IMU were synced using an external trigger. Due to electromechanical delay from the wireless IMU, data between IMU and motion capture were visually inspected. Pilot data identified synchronized start; however, visual inspections identified non-consistent frame shifts in the IMU data with each trial. Therefore, peak knee flexion findings and heel strike were marked as events on each trial for both motion analyses and IMU data. Time in between events for each trial, for both motion analyses and IMU, were calculated and compared to sync stride and gait intervals. Weight acceptance EMG data included 100ms before heel strike to account for the electromechanical delay. The average of three trials, for each gait speed condition, determined limb dynamic, muscle activation, and co-contraction values. Statistical analyses were performed using SPSS (version 13, Chicago, IL). All data of interest was first examined for homogeneity of variance using the Levene's test and graphed and Shapiro-Wilk test for normal distribution. Variables that did not meet requirements for normal distributions,

including the shape of the curve and a priori set p-value for Levene's test ( $p < .05$), were examined using non-parametric testing.

Limb dynamic differences among the three groups were tested using paired t-test for parametric testing and Wilxcon Sign Rank Test for non-parametric testing due to the matched design. Planned comparisons to examine differences based on OA presence involved comparisons between the two OA groups and Control groups, including Diff versus Control and NoDiff versus Control. Comparisons to examine differences based on walking difficulty involved comparisons within the OA groups, including comparisons between the Diff and NoDiff groups. Comparisons were determined a priori; therefore, the P-value was not adjusted for multiple comparisons.

The relationships between co-contraction and limb dynamics were examined using stepwise regression analyses. Four separate stepwise regression analyses examined co-contraction as the outcome variable, with the main effect of limb dynamics, the main effect for group, and an interaction effect for limb dynamics*group. Self-perceived walking difficulty served as the moderator variable to examine sub-grouping influences on the relationship of co-contraction and limb dynamics. Post-hoc regression diagnostic examined data points of variables that were normally distributed and homoscedastic. Standardized residual values > 1.96 were considered potential outliers and further examined with Cook's distance, with those > 1.0 suggesting a possible influence on the regression equation. In such cases, regression analyses were presented with and without outliers. Multicollinearity among the variables were tested using variance influence factor (VIF), with high collinearity defined as the largest VIF value > 1, average VIF > 1, tolerance < 0.1, and tolerance below 0.2. Levene's test and Shapiro-Wilks tested for normal distributions and

homoscedasticy. A p-value ≤ .05 would suggest that variables violated assumptions for parametric testing; therefore, respective non-parametric tests were used. Potential outliers were visually examined using the box and whisker plots Values that fell outside the whiskers were considered outliers and further examined for possible influences on the regression equation.

Subjects were age and sex matched; therefore, these variables were not further examined to determine their influences on the variables of interest. Comparisons between the Diff and NoDiff groups were interpreted as differences due to walking difficulty presence. Comparisons between the Diff and Control and NoDiff and Control were interpreted as differences due to OA presence. Comparisons during controlled gait speed conditions allowed for comparisons without gait speed variation. Controlled gait speed was set at 1.0 meter per second based on its clinical importance for functional mobility, and to ensure all of our subjects had self-selected gait speeds equal to or faster than the controlled gait speed. Potential covariates included BMI, knee OA-related symptoms, OA severity, and gait speed during self-selected and fast speed condition.

Limb dynamics were averaged based on BMI to determine BMI and gait speed influences on limb dynamics for all 3 groups. Limb dynamics were also averaged and examined for trends based on respective OA severity within the Diff and NoDiff groups. Power analyses were conducted a priori for matched comparisons, with an effect size of .45, alpha of .05, and power of .80, we needed a total sample size of 32 or 11 in each group. Given the experimental nature of examining the interaction of walking difficulty on limb dynamics and co-contraction indices, we followed the suggested rule of 1 variable for every 10 subjects for regression analysis. Since the

regression model included two independent variables, 20 subjects, or 10 per group, would suffice.

## 4.3 Results

A total of 57 subjects participated in the study; however, only 13 subjects per group were matched based on age (average = 65.3, range 53.2 to 76.2 years) and sex (8 females per group). As a result, a total of 39 subjects were used for analyses. OA severity, pain severity, body mass index (BMI) were not statistically different between the OA groups. See Table 1 for specific group characteristics. However, the average self-selected gait speed self-selected, or fast gait speed, for the Diff group was more than 0.1 meter per second slower than the NoDiff and Control groups; therefore, the Diff group's self-selected gait speed exceeded significantly clinical differences[38]. Similarly, BMI values above 29.9 were categorized as overweight, and at risk for type II diabetes, osteoarthritis, and physical disability, which described the NoDiff and Control groups. Whereas, an average BMI greater than > 30.0, as in the Diff group, in addition to diabetes, osteoarthritis, and physical disability these individuals are considered in and at risk for mortality and cardiovascular disease. OA severity distribution was similar between the two OA groups. Average pain differences were also similar between the two OA groups, and differences were less than 2 points, the clinically significant difference.

### 4.3.1 Limb dynamics during weight acceptance

Tibial acceleration for all three group and tibial jerk for the Diff group during weight acceptance interval of controlled gait speed were not normally distributed or

heteroscedastic, $p < .05$. All other limb dynamics during weight acceptance interval of controlled gait speed met the requirements for parametric testing.

With gait speed controlled, during weight acceptance interval, all limb dynamics were not significantly different and had small to less than small effect sizes between the groups based on OA presence (NoDiff versus control, $p = .51$ to $.89$, $d = .05$ to $.20$, $r = .11$ to $.13$; Diff versus Control, $p = .22$ to $.84$, $d = .06$ to $.44$, $r = .24$) and based on walking difficulty within the OA groups (Diff versus NoDiff, $p = .39$ to $.77$, $d = .05$ to $.44$ and $r = .09$) (Figures 4.1 and 4.2).

However, group trends were observed for tibial limb dynamics during weight acceptance of controlled gait speed. The average tibial acceleration and jerk measured during weight acceptance interval was the largest in the Diff group, followed by the NoDiff group, and the smallest in the Control group during controlled gait speeds.

### 4.3.2 Linear acceleration during mid-stance

Linear acceleration was normally distributed during mid-stance of controlled gait speed for all groups. All linear acceleration was homoscedastic during mid-stance among the groups when walking at a controlled gait speed, except for tibial acceleration, $F(2, 36) = 3.63$, $p = .04$ (Figure 4.1).

Based on OA presence, femoral acceleration was significantly larger in the OA groups than the Control group (Diff versus Control $t(12) = -2.56$, $p = .01$, $d = 1.08$; NoDiff versus Control $t(12) = 2.18$, $p = .02$, $d = .64$) during mid-stance of controlled gait speed (Figure 4.1). Similarly, tibial acceleration was significantly larger in the OA groups (Diff versus Control $z = -2.6$, $p = .01$, $r = -.51$ and NoDiff vs. Control $z = -1.7$, $p = .05$, $r = -.33$) than the control groups during the mid-stance interval of controlled gait speed (Figure 4.1).

Based on walking difficulty within the OA groups, femoral acceleration during the mid-stance interval of controlled gait speed was larger in the Diff group than the NoDiff group; however, group differences were not significant and the effect size was small, t (12) = 1.28, p = .11, d = .36 (Figure 4.1). Whereas, tibial acceleration magnitude during the mid-stance interval of controlled gait speed was significantly larger in the Diff group than the NoDiff group and had a medium effect, z = -1.85, p =.03, r = .36 (Figure 4.1).

### 4.3.3 Jerk during mid-stance

Femoral jerk magnitudes during mid-stance of controlled gait speed were not normally distributed for the Diff and the Control groups, p <.05. All other jerk magnitudes during mid-stance of controlled gait speed were normally distributed and homoscedastic.

Based on OA presence, femoral jerk magnitudes during mid-stance of controlled gait speed trials were significantly larger for the OA groups than the Control group (Diff vs. Control, z = -3.01, p < .01, r = -.60; NoDiff vs. Control, z = -2.62, p = .01, r = -.51) (Figure 4.2). Tibial jerk magnitudes between the NoDiff group and the Control group were not significantly different and had a small effect size t (12) = 1.10, p = .29, d = .40 (Figure 2). Whereas, tibial jerk magnitudes were significantly larger in the Diff than the Control and had a large effect size during mid-stance of controlled gait speed, t (12) = 3.55, p < .01, d = .97 (Figure 4.2)

Based on walking difficulty within the OA groups, the Diff group walked with larger femoral jerk than the NoDiff group; but, differences did not achieve significance and effect sizes were small, z = 1.15, p = .25, r = -26, during mid-stance of controlled gait speed (Figure 4.2). However, tibial jerk magintudes were

signficnalty larger for the Diff group than the NoDiff group, t (12) = -2.92, p = .01, d = .87 during mid-stance of controlled gait speed (Figure 4.2).

### 4.3.4 Self-selected gait speed

Tibial jerk was not normally distributed during mid-stance of self-selected gait speed for the control group d (13) = .84, p = .02. The variance for femoral acceleration during mid-stance were significantly heteroscedastic, F (2, 36) = 3.71, p = .03.

Similar to the control gait speed, no significant limb dynamic differences between the groups were observed during weight acceptance when walking at a self-selected speed and effect sizes ranged from less than small to small (p = .21 to .99, d = .00 to .40) (Figure 4.3).

However, during mid-stance significant differences were found for femoral and tibial acceleration based on OA presence. For femoral acceleration during mid-stance of self-selected gait speed trials, the Diff group and the NoDiff group were significantly larger than the control group and had medium effect sizes (Diff vs. control, z = -1.85, p = .03, r = .36; NoDiff vs. Control, z = -2.41, p = .01, r = .47) (Figure 4.3). For tibial acceleration during mid-stance of self-selected gait speed trials, the Diff group and the NoDiff group were significantly larger than the Control group and had large effect sizes (Diff vs. Control, t (12) = -4.48, p < .01, d = 1.6; NoDiff vs. Control, t (12) = -3.05, p = .01, d = 1.13) (Figure 4.3).

Femoral jerk was significantly larger in the OA groups than the Control group and had large effect sizes during the mid-stance interval of self-selected gait speed trials, Diff vs. Control t (12) -3.11, p = .01, d =.81; NoDiff vs. Control t (12) -3.48, p < .01, d = 1.18 (Figure 4.4). Tibial jerk was significantly larger in the OA groups than the Control group and had medium to large effect sizes during the mid-stance interval

of self-selected gait speed trials, Diff vs. Control z = 2.76, p = .01, r = .54; NoDiff vs. Control z = 1.78, p = .03, r = .35 (Figure 4.4).

Based on walking difficulty within the OA groups, the Diff group walked with larger, but not significantly different, femoral acceleration than the NoDiff group and had an effect size less than small during the mid-stance interval of self-selected gait speed trials z = -.45, p = .30, r = .09 (Figure 4.3). Whereas based on walking difficulty within the OA groups, tibial acceleration was significantly larger for the Diff group than the NoDiff group and had a medium effect size during the mid-stance interval of self-selected gait speed trials, t (12) = -1.8, p = .05, d = .60, (Figure 4.3).

For jerk during mid-stance of self-selected gait speed trials, femoral jerk was not significantly different and had a less than small effect size between the OA groups t (12) = .58, p = .57, d = -15; however, tibial jerk was significantly larger for the Diff group than the NoDiff group and had a medium effect size, z = 1.64, p = .05, r = .32 (Figure 4.4).

### 4.3.5 Self-selected fast gait speed

Femoral acceleration for the control group d (13) = .84, p = 02; tibial acceleration for NoDiff (d (13) = .81, p = .01; femoral jerk for control d (13) = .87, p = .05; and tibial jerk for NoDiff d (13) = .83 p =.02 during weight acceptance interval of fast gait speeds were not normally distributed. Heteroscedasticity was not significant for limb dynamics during weight acceptance of fast gait speeds. In regards to mid-stance interval of fast gait speeds, femoral jerk was not normally distributed for the control group, d (13) = .87, p = .05, and heteroscedastic among the groups, F (2, 36) = 3.73, p = .03.

No significant differences were found among the three groups for limb dynamics during either weight acceptance or mid-stance of fast gait speed trials (Figures 5 and 6).

### 4.3.6 Examining walking difficulty as a moderator variable between limb dynamics and co-contraction during controlled gait speed.

During controlled gait speed, greater group differences were observed with tibial jerk, whereas minimal to no group differences were observed for weight-acceptance. Therefore, to examine walking difficulty as a moderator variable, we examined for the main effect of group, main effect of tibial jerk during mid-stance, and the product term of group*tibial jerk in relationship to co-contraction of mid-stance. Significant effects were found for the lateral co-contraction indices, which included LQLH, the main effect of group, $R^2$ change = .08 F (1, 24) = 2.2, p = .15; the main effect of tibial jerk, $R^2$ change = .03, F (1, 23) = .74, p = .40; the interaction effect $R^2$ change = .20, F (1, 22) = 6.3, p = .02; and, LQLG, the main effect of group, $R^2$ change = .15, F (1, 24) = 4.3, p = .05; the main effect of tibial jerk, $R^2$ change = .007, F (1, 23) = .19, p = .67; the interaction effect $R^2$ change = .15, F (1, 22) = 4.8, p = .04 (Figure 4.7). Interaction effects were not significant for the medial co-contraction indices including MQMH, main effect of group $R^2$ change = .09 F (1, 24) = 2.2, p = .15; the main effect of tibial jerk, $R^2$ change = .01, F (1, 23) = .37, p = .55; the interaction effect $R^2$ change = .03, F (1, 22) = .85, p = .37; and MQMG main effect of group $R^2$ change = .08 F (1, 24) = 2.1, p = .16; the main effect of tibial jerk, $R^2$ change = .02, F (1, 23) = .40, p = .53; the interaction effect $R^2$ change = .05, F (1, 22) = 1.1, p = .30 (Figure 4.7).

Outliers were found for LQLH and LQLG. Regression analyses with the 2 outlier data points removed affected LQLH, main effect of group, $p = .36$; the main effect of tibial jerk, $p = .02$; the interaction effect, $p = .11$. For LQLG 1 data point was removed, with the main effect of group $p = .05$, effect of tibial jerk $p = .02$, and interaction effect $p = .004$. For medial co-contraction indices, removing the 1 outlier data points did not affect MQMH or MQMG main or interaction effects, $p > .05$.

## 4.4 Discussion

This study found that limb dynamics, including both linear acceleration jerk, varied based on OA presence, walking difficulty presence within those with knee OA, as well as effects based on gait speed. As suggested by our hypothesis, the overall trends for limb dynamics included the largest linear acceleration and jerk for the Diff group, followed by the NoDiff group, and the smallest was observed in the control group. Our findings of larger acceleration and jerk based on OA with walking difficulty were consistent with current literature, suggesting that those with knee related diagnoses (e.g., total knee replacements, ligamentous deficiency) and knee-related symptoms (e.g., pain, instability, etc.) walked with larger limb dynamics[16,21,39]. Interestingly, our findings may suggest that knee OA presence affected femoral limb dynamics and, within the knee OA groups, self-reported walking difficulty affected tibial limb dynamics; however, these differences were primarily observed during the mid-stance gait interval of slower gait speeds. Further a major finding of our study is that, walking difficulty moderated the relationship between limb dynamics, more specifically tibial jerk, and co-contraction in the OA groups. Therefore, the results of the study supported our hypotheses.

Our study used a novel technique of calculating limb dynamics, which provided a single value that represented the magnitude of linear acceleration or the magnitude of jerk. Limb dynamic magnitude, calculated from the Pythagorean Theorem, accounted for the instantaneous sum of vectors from the sagittal, frontal, and transverse planes, in both the positive and negative directions. Using a magnitude value collapsed 6 values into 1 for each segment. If examining both the femur and tibia single value vectors left at 6 for the femur and 6 for the tibia can be burdensome to a clinician and limit the clinical utility of this tool. However, in order to compare this novel technique to previous literature, we deconstructed our linear acceleration magnitude into respective peak values in the positive and negative direction for each anatomical plane (i.e., sagittal, and frontal) to compare our findings with prior research. Both our OA groups, regardless of walking ability had notable knee OA-related symptoms; therefore, we averaged the vectors of each plane for OA groups in order to make comparisons to the linear acceleration vectors reported in the literature. Our findings were slightly larger than those reported by Turcot and colleagues for maximal femoral acceleration (sagittal plane average ± SD: control =.38 ±.21g and symptomatic OA = 1.00 ±.27g; frontal plane: control =.18 ±.11g and symptomatic OA = .20 ±.17g) and maximal tibial acceleration (sagittal plane: control =.46±.19g and symptomatic OA = .55 ±.26g; frontal plane: control =.17 ±.06g and symptomatic OA = .48 ±.37g) for early stance phase[21]. Our average ± SD deconstructed linear accelerations in the sagittal plane in our symptomatic knee OA groups were 1.2 ± .41g for the femur and 1.9 ± .49g for the tibial, and, in the frontal plane, .48 ± .32g for the femur and .67 ± .53g for the tibia. In our control group, sagittal plane femoral acceleration was 1.2 ± .38g, sagittal plane tibial acceleration was 1.7 ± .45g, frontal

plane femoral acceleration was .53 ± .21g, and frontal plane tibial acceleration was .55 ±.17g. However, for our control group, tibial linear acceleration was similar or slightly less than those reported by Lafortune and colleagues (sagittal plane = 2.3 ± .37 g and frontal plane = 1.3 ± .46 g)[30]. Turcot and colleagues suggested that their linear acceleration values were smaller than those reported by Lafortune and colleagues due to the differences in age, device fixation and placement.[21] Similarly, our values may be slightly larger than Turcot and colleagues, due to the severity of disease found in our OA population (e.g., KL score including or not including I), faster walking speeds and sensor fixation. Our skin-mounted sensors from the control group outputted similar values as those presented by Lafortune and colleagues. Since our control group walked with similar linear acceleration as those reported by Lafortune and colleagues[30], and pathological knees generally walk with larger limb dynamics than non-pathological knees[16,21,20,18], the skin-mounted technique may explain why our OA group limb dynamics were bigger than those reported by Turcot and colleagues, and support the accuracy of our measurements to test our hypothesis.

For comparing limb dynamics based on OA presence and walking difficulty, our findings during weight acceptance did not support our hypothesis while our findings during mid-stance did support our hypothesis. If the data was examined by descriptive statistics, trends, and effect sizes both gait intervals would support our hypothesis. During weight acceptance gait interbal, the Diff group walked with larger femoral acceleration (effect size for parametric testing, d = .44), tibial acceleration (effect size for non-parametric testing, r = .24), and tibial jerk (r = .24), but smaller femoral jerk (d = .06) than the control group. Cohen proposed that effect sizes of .10 were small, .30 were medium, and .50 were large; therefore, suggesting that our

Control versus Diff group differences ranged from small to medium effect sizes[40]. Whereas, the control group walked with similar femoral acceleration (d = .05), greater femoral jerk (d = .20), and lesser tibial acceleration (r = .13) and tibial jerk (r = .13) than the NoDiff group. According to the effect size cut-offs recommended by Cohen et al., small effect sizes were found when comparing the Control versus NoDiff group[40]. Based on the small effect sizes noted between the OA and control groups, we believe that our findings during weight acceptance gait interval would suggest small to no limb dynamics differences based on OA presence. Based on walking difficulty within the OA groups, the Diff group on average walked with larger limb dynamics than the NoDiff group during weight acceptance. The lack of statistical significance between the Diff and NoDiff groups during weight acceptance may be explained by the distribution of OA-related symptoms. Limb dynamics in total knee replacement[16] and ligamentous insufficiency[18] suggested that limb dynamics quantified self-reported knee instability. Self-reported knee instability most likely occurred during weight acceptance interval of gait[41]. Since subjects with total knee replacement shared similar characteristics as those with knee OA, perhaps the even distribution of subjects with knee OA who reported instability in both the Diff and NoDiff groups may explain the lack of differences To ensure that the lack of significant differences observed during weight acceptance was valid and not related to potential covariates, we examined variables previously reported in the literature that may impact limb dynamics. BMI and sensor mounting technique (i.e., skin versus bone) can affect limb dynamic output via movement artifacts. Also, knee alignment[42,43] and movement speed[44] can affect limb dynamics. The study design kept gait speed and mounting technique consistent among all subject to minimize potential effects of movement variability and soft tissue

artifact. Therefore, we examined the possible effects of variables not controlled via study design, BMI and knee alignment, on limb dynamics. With surface mounted IMUs, larger BMI may induce soft tissue and movement artifacts that could inflate the limb dynamic values. Whereas, larger frontal plane limb dynamics were linked to greater knee varus alignment[18,45].

To determine the potential effects of BMI and knee alignment without losing power in our small sample size and to allow for non-parametric testing, we completed a post-hoc analysis that included averaged limb dynamics for each group (i.e., Diff, NoDiff, and control) who fell within the same BMI and knee alignment quartiles. BMI quartiles and distributions of our groups are shown in Table 3, and no apparent limb dynamic trends were observed for BMI. The reference standard to measure knee alignment required long-axis radiographs that were not performed in this study; therefore, we used standing calibrations to measure frontal plane knee alignment. Motion capture knee alignment shows an excellent relationship with standing full-leg radiographs[46]. Knee alignment quartiles in our sample size are shown in Table 4. Based on visual inspections, subjects with knee OA, for both Diff and NoDiff, who stood with greater knee varus alignment appear to walk with larger femoral acceleration during weight acceptance (Table 4). Also, visual inspections noted that those with knee varus alignment and walking difficulty appear to walk with larger limb dynamics than those with no walking difficulty and knee varus alignment. Visual trends were noted within the control group, greater knee varus alignment appeared to trend with larger tibial acceleration magnitude (Table 4). The trends between knee alignment and linear acceleration appear to be present regardless of knee OA presence or walking difficulty. Within the OA groups, the relationship may

be explained by the link between radiographic knee OA severity and knee alignment, as worsening medial knee OA is related to greater knee varus alignment. However, we did not examine lateral knee OA severity and the control group also exhibited an observable trend between knee alignment and limb dynamics. Regardless conclusions based on these findings would require future research to focus on knee alignment and limb dynamics in those with and without knee OA. However, the lack of strong relationships between limb dynamics and potential confounding variables when combined with the small variability for knee alignment in our sample size would suggest that limb dynamics during weight acceptance interval appear to be similar among our groups.

During mid-stance gait interval statistical group differences were observed based on OA presence and walking difficulty. In addition to statistical differences, average trends for mid-stance were consistent with our hypotheses, and previous research, which all suggest that those with pathological knees or worsening knee symptoms walked with larger limb dynamics limb[30,16,20]. The significant group differences during mid-stance suggested the importance of examining gait intervals separately, that our study achieved appropriate power, and that limb dynamics were different based on OA presence and walking difficulty.

Femoral limb dynamics were statistically different among the two OA groups versus the control group, while not all tibial limb dynamics shared the same group differences. Perhaps femoral limb dynamics may be linked to OA presence, as tibial jerk was not statistically different between the NoDiff and Control group. Joint degradation usually starts on the tibial plateau in those with knee OA; therefore, larger femoral dynamics may be accounting for the lack of ability to stabilize and smoothly

move the femur anteriorly during mid-stance. The unstable femoral movements and poor movement quality measured by linear acceleration and jerk in those with knee OA may be a characteristic of knee OA gait.

Based on subjects with knee OA and walking difficulty, tibial acceleration and jerk were statistically larger in the Diff group than the NoDiff group; but femoral acceleration and jerk differences did not achieve statistical significance. As a result, tibial limb dynamics may be more related to self-report walking difficulty within knee OA, and may be explained by already known factors of knee OA gait characteristics. Based on Aim 1, those with knee OA and walking difficulty are less likely to use necessary amounts of knee extension excursion and knee extension moment during mid-stance; therefore, knee stabilizing strategies known as the screw home mechanism are unable to engage. Screw home mechanism starts from weight acceptance through tibial external rotation around an internally rotating femur that is facilitated by intra-articular joint congruency and maintained through mid-stance[47]. In knee OA, smaller tibial rotations, larger knee adduction angles, and limited terminal knee extension ranges were observed in gait, which are also referred to as a knee stiffening gait strategiy[48]. Therefore knee OA gait mechanics are not conducive for achieving the structural stability facilitated by the screw home mechanism, which may account for the lack of knee stability and movement smoothness identified by linear acceleration and jerk, respectively. Our findings suggest that those with knee OA and walking difficulty may be less stable and use less optimal strategies during midstance of gait when compared to those with knee OA with no walking difficulty or the control group.

Our findings that limb dynamic group differences in the self-selected gait speed reflected similar findings as the controlled gait speed; however, group

differences were attenuated with the fast gait speed did not support our hypothesis. Considering that acceleration is speed and task dependent,[44] the lack of differences found during the fast gait speed may in part be related to the variability in gait speed. Fast gait speeds for the NoDiff and Control groups were similar; however, much faster than those in the Diff group. The lack of difference in the fast trials, despite the difference in gait speeds, may be explained by effort and demand. Faster gait speeds require mechanical stiffening and increased loading at the knee joint when compared to slower gait speeds[49]. With the joint loaded to the most tolerable position while walking, limb dynamic differences among the groups may be attenuated due to similar effort output. Movement optimization principles[50] may also explain the lack of significant group differences during fast gait speeds. Faster gait speeds may require movement patterns that maximize power output and inertia and minimizes precision[51]. The cost of walking at fast gait speed may be similar; however, the gait strategy in the Diff group did not result in gait speeds as fast as the NoDiff or Control groups. As a result, with precision reduced and walking speeds maximized, the NoDiff and Control groups were much better at optimizing limb dynamics for obtaining a better outcome, or in this case a faster gait speed.

Since functional mobility is more measured by speed and not by precision, our findings further support the benefits of walking and training at fast gait speed for patients with knee OA. Not only is gait speed a prognostic indicator of health and functional independence, but prior research also suggests that those walking with faster gait speeds with gait modifications are less likely to develop walking difficulty than those with slower walking speeds with gait modifications[13]. The negligible difference in gait modifications based on limb dynamics and the large amounts limb

dynamics found in our study may be necessary to accommodate the faster gait speeds and create a stabilizing force that is hard to replicate at slower speeds. However, due to the lack of significant difference and small sample size, further research must be done to discern the lack of differences between the OA and control groups during faster gait speed conditions presented in this study. More research that includes a controlled fast gait speed and reference standard to determine maximal effort during walking may be necessary to determine further effects of effort on limb dynamics.

The interaction effect identified a positive relationship between tibial jerk and co-contraction indices for the Diff group and a negative relationship for the NoDiff group supported our hypothesis. However, the interaction effect was only significant for the lateral co-contraction indices (i.e. LQLH and LQLG) and not significant for the medial co-contraction indices (i.e. MQMH and MQMG). Co-contraction can be affected by OA severity of the same compartment (i.e. medial versus lateral);[52] however, lateral compartment OA severity scores in our subjects were similarly distributed between the Diff (i.e. Grade 3 = 1; Grade 2 = 7; Grade 1 = 4; Grade 0 = 1) and NoDiff group (i.e. Grade 2 = 5; Grade 1 = 6; Grade 0 = 2). Therefore, we believe that the significant interaction effect was less impacted by lateral compartment knee OA severity and more by walking difficulty presence. In addition, the regression equations for the medial muscle co-contraction and limb dynamics, although statistically insignificant, suggested a small but positive relationship for the Diff ($MQMH = 7E^{-5}$, $R^2 = .02$; $MQMG = 8E^{-5}$, $R^2 = .03$) and negative relationship for the NoDiff ($MQMH = -5E^{-5}$, $R^2 = .07$; $MQMG = -6E^{-5}$, $R^2 = .10$). Outliers did not appear to affect the co-contraction indices for the medial muscle groups, as relationships continued to be non-significant. However, removing outliers did reduce the interaction

effect for LQLH and increase the interaction effect for LQLG. Regardless, the slope for LQLH continued to remain positive for the Diff group (.001) and negative for the NoDiff group ($-3.5E^{-5}$). Removing outliers would decrease the degrees of freedom and lower the power of our regression models; therefore, given the small sample size further research with a larger sample size is needed. However, the consistent differences in slope directions between our OA groups make it promising that walking difficulty can serve as a mediator variable for limb dynamics and co-contraction.

The interaction effect suggested that OA-related presence when combined with self-reported walking difficulty are linked to an altered neuromuscular system. When stabilizing knee structures fail, as in the case of the intra-articular surfaces of knee OA, the joint's muscular and ligamentous tissues work harder to maintain stability. In knee OA, individuals commonly adopt a knee stiffening gait pattern that alters the frontal and sagittal plane knee angles and moments and heightens muscle activation of agonist and antagonist muscles, or co-contraction[24]. Such gait adaptation can redistribute forces to areas less capable of withholding repetitive weight-bearing loads and rely greater on stiffening ligaments and tendons to maintain stability[53]. Muscle tendon forces generated from co-contraction can pull the joints that it crosses into various directions leading to erratic limb movements. The naked eye and the common motion capture analyses did not identify the micro-movements that may challenge stability via muscle contraction. This makes stiffness and instability difficult to quantify with mechanical laxity via x-rays or mechanical stiffness as measured by the slope of knee excursions versus joint moments in previous research[24,15].

Mechanically, instability and stiffness appear to be contradicting concepts; however, integrated passive and active systems may account for the relationship

between instability and stiffness in knee OA. In a similar contradiction, excessive movements measured in low back pain populations were correlated with perceived stiffness as an adaptation for dynamic instability[54]. In our study, the positive relationship between tibial jerk and co-contraction may suggest that those with walking difficulty and knee OA are engaging in knee stiffening gait patterns that overshoot femoral and tibial movements during mid-stance that are creating both instability and stiffness sensations. Original gait modifications may have developed to avoid exacerbation of OA-related symptoms; however, over time, gait modifications may become a learned behavior, facilitate neural plasticity, and be exacerbated by prolonged OA-related symptoms. In fact, pain and stiffness, common OA-related symptoms, can result in heightened muscle activation levels regardless when at rest or with movement. Perhaps the OA group with walking difficulty may have a poor feedback loop system, adopt a less effective and efficient motor pattern, and rely greater on an open loop system. In an open loop system, motor recruitment of the knee may implement an all or none neuromuscular feed forward system and rely less on the input of a feedback system during walking. The positive relationship between jerk and co-contraction in the Diff group may suggest that co-contraction occurs in this group regardless of its need. As a result, the muscle co-contraction could suggest an inefficient and ineffective neuromuscular system that may be over or under shooting due to its inability to regulate the peripheral limb. The feed forward system may be secondary to increased levels of pain for prolonged periods of times, damaged joint surfaces, and weakened knee extensors and flexors; which can result in a less optimal neuromuscular system that may best describe those with walking difficulty[22].

Subjects with knee OA but with no walking difficulty may be using a closed loop model during walking. A closed-loop model suggests a neuromuscular system that is regulated by a feedback-feedforward system[55]. The negative relationship found in the NoDiff group between tibial jerk and muscle co-contraction suggests an optimal use of co-contraction that facilitates tibial. As a result, those in the NoDiff group may demonstrate an optimal neuromuscular system that adapts to activity demands that are less observed in the Diff group.

Therefore, walking difficulty can be a sub-group that is not only clinically significant but also provide insight into the mechanism of movement patterns that are adopted by those with knee OA. However, the question still lies in the optimal gait patterns that characterize knee OA, especially regarding limb dynamics and co-contraction. Perhaps the neuromuscular system imposed by the group without walking difficult can result in the progression of knee OA and lead these individuals into the walking difficulty group, as seen in those with knee OA reporting walking modifications[13]. Given the constraints of a cross-sectional study design, potential long-term effects are difficult to discern. Therefore, further research in this area is needed. However, our findings are promising in that walking difficulty can play a role in sub-grouping knee OA. This study provides biomechanical details based on self-reported walking difficulty, an easy question already asked in the clinic by clinicians and via self-reported questionnaires. As a result, this study narrows the gap between biomechanical and self-reported constructs. However, further understanding of limb dynamics would help determine the specific mechanisms that may need to be clinically addressed when working with patients with knee OA faced with walking difficulty. The plasticity of the neuromuscular system and motor learning literature

suggest that repetitive training can be beneficial[20]. Perhaps future studies can focus on rehabilitation techniques that concentrate on re-training the neuromuscular system and restoring a closed-loop system.

## 4.5 Conclusion

The findings of this study suggest that femoral limb dynamics appear to vary more based on knee OA presence, and tibial limb dynamics appear to vary more based on self-reported walking difficulty. Regardless, group differences were attenuated at faster gait speeds. Perhaps future interventions that addresses reducing tibial limb dynamics through repetition and gait training and walking at faster gait speeds may be helpful in addressing self-perceived walking difficulty.

Table 4.1 Subject characteristics

| | OA | | | |
|---|---|---|---|---|
| | Difficult | Not Difficult | Control | p-value |
| N | 13 | 13 | 13 | n/a |
| Age (years) | 66.1 ±6.3 | 65.8 ±5.8 | 66.1± 6.2 | n/a |
| Sex (N) | Females = 8; Males = 5 | | | n/a |
| BMI ($Kg/m^2$) | 31.4 ± 5.6 | 29.7 ± 5.6 | 27.6 ± 3.7 | p = .18 |
| OA Severity (N) | | | | p = .61 |
| 2 | 4 | 4 | N/A | |
| 3 | 5 | 6 | N/A | |
| 4 | 4 | 3 | N/A | |
| Pain (0 to 10) | 6.5 ±1.5 | 5.6 ±2.0 | N/A | p = .92 |
| Self-selected gait speed (m/s) | 1.23 ± .19 | 1.34 ± .16 | 1.31 ± .10 | |
| Fast gait speed (m/s) | 1.57 ± .28 | 1.76 ± .23 | 1.75 ±.12 | |

Average (± SD) age, body mass index (BMI), self-selected and fast gait speed (meter per second, m/s) and pain. Pain reported on a scale from 0, defined as no pain, to 10, defined as worst pain imaginable.

Table 4.2 Responses to OA symptoms. Distribution (N) of responses for knee symptoms of subjects with knee OA with (Diff) and without walking Difficulty (NoDiff) adopted from the Knee Outcome Survey (KOS)

| | | No Symptom | No Affect | Slightly | Moderately | Severely |
|---|---|---|---|---|---|---|
| Symptom | Group | 5 | 4 | 3 | 2 | 1 |
| Pain | Diff | 0 | 0 | 4 | 4 | 5 |
| | NoDiff | 1 | 3 | 2 | 7 | 0 |
| Stiffness | Diff | 0 | 0 | 3 | 6 | 4 |
| | NoDiff | 1 | 5 | 3 | 4 | 0 |
| Swelling | Diff | 3 | 4 | 1 | 2 | 3 |
| | NoDiff | 5 | 2 | 2 | 3 | 1 |
| Giving Way | Diff | 1 | 5 | 0 | 4 | 3 |
| | NoDiff | 3 | 4 | 3 | 2 | 1 |
| Weakness | Diff | 1 | 3 | 3 | 5 | 1 |
| | NoDiff | 3 | 3 | 5 | 1 | 1 |
| Limping | Diff | 0 | 3 | 5 | 4 | 1 |
| | NoDiff | 5 | 2 | 3 | 2 | 1 |

No subjects, in either OA groups, reported 0 or unable to function due to symptom for any of the symptoms; therefore, 0 was omitted from the table.

Table 4.3 Trends for limb dynamics based on body mass index (BMI) quartiles for the walking difficulty (Diff), no walking difficulty groups (NoDiff) group, and the control group during weight acceptance and mid-stance gait intervals when walking at a controlled gait speed of 1.0 meter per second.

| | | *Lower* | | | *Higher* |
|---|---|---|---|---|---|
| | | *1st* | *2nd* | *3rd* | *4th* |
| BMI (Kg/m$^2$) | | < 25.3 | 25.3-30.2 | 30.3-34.0 | ≥34.1 |
| | Diff (N) | 1 | 3 | 2 | 6 |
| | NoDiff (N) | 3 | 3 | 3 | 4 |
| | Control (N) | 3 | 5 | 4 | 1 |
| Weight Acceptance | | | | | |
| Femoral Acceleration (mG) | Diff¥ | 1510.3 | 162.5.1 | 1081.2 | 1528.1 |
| | NoDiff | 1344.9 | 1367.8 | 1415.6 | 1365.8 |
| | Control | 1407.6 | 1323.9 | 1657.0 | 903.9 |
| Tibial Acceleration (mG) | Diff | 1976.0 | 1921.1 | 1491.2 | 2426.6 |
| | NoDiff | 1668.4 | 1849.4 | 2111.9 | 2017.8 |
| | Control | 1671.6 | 1946.7 | 1905.5 | 1212.8 |
| Femoral Jerk (da/dt) | Diff | 82347.6 | 82787.4 | 56524.6 | 80222.8 |
| | NoDiff | 83036.4 | 70068.2 | 75226.2 | 77586.6 |
| | Control | 78763.3 | 78905.4 | 106711.2 | 30793.4 |
| Tibial Jerk (da/dt) | Diff | 116262.0 | 101694.7 | 96017.6 | 147037.6 |
| | NoDiff | 94733.8 | 116952.3 | 114575.9 | 125231.2 |
| | Control | 105036.3 | 112797.3 | 117544.9 | 57301.8 |
| Mid-stance | | | | | |
| Femoral Acceleration (mG) | Diff | 842.2 | 628.2 | 785.7 | 1048.5 |
| | NoDiff | 597.9 | 704.4 | 792.1 | 766.9 |
| | Control | 526.9 | 623.8 | 412.0 | 504.9 |
| Tibial Acceleration (mG) | Diff | 1028.2 | 674.0 | 969.8 | 1008.5 |
| | NoDiff | 689.2 | 676.4 | 737.9 | 711.9 |
| | Control | 529.9 | 578.4 | 452.5 | 627.2 |
| Femoral Jerk (da/dt) | Diff | 28348.3 | 30492.9 | 28066.1 | 41524.1 |
| | NoDiff | 21145.8 | 22432.6 | 26843.3 | 31333.0 |
| | Control | 14701.5 | 18226.0 | 11039.6 | 7592.6 |
| Tibial Jerk (da/dt) | Diff | 41884.9 | 34250.8 | 32657.6 | 42798.1 |
| | NoDiff | 18841.5 | 16206.9 | 27563.5 | 26459.4 |
| | Control | 21046.2 | 20882.5 | 13774.2 | 20022.0 |

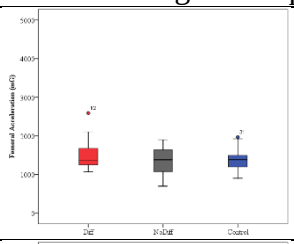
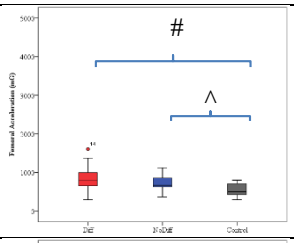
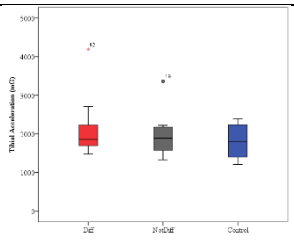
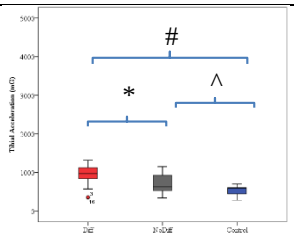
Table 4.4 Trends for limb dynamics based on knee alignment quartiles for the walking difficulty (Diff), no walking difficulty groups (NoDiff) group, and the control group during weight acceptance and mid-stance gait intervals when walking at a controlled gait speed of 1.0 meter per second. Values less than 0 degrees suggest knee varus alignment.

| | | *Lower* | | | *Higher* |
|---|---|---|---|---|---|
| | | *1st* | *2nd* | *3rd* | *4th* |
| Knee Alignment (°) | | < -0.001 | -0.001- 0.0 | 0.1 - .2 | ≥.3 |
| | Diff (N) | 4 | 4 | 3 | 2 |
| | NoDiff (N) | 3 | 0 | 6 | 4 |
| | Control (N) | 2 | 5 | 2 | 4 |
| Weight Acceptance | | | | | |
| Femoral Acceleration (mG) | Diff¥ | 1819.6 | 1452.2 | 1373.6 | 1281.2 |
| | NoDiff¥ | 1534.7 | n/a | 1363.6 | 1265.5 |
| | Control | 1214.9 | 1467.5 | 1197.5 | 1469.75 |
| Tibial Acceleration (mG) | Diff | 2680.7 | 1870.1 | 1900.5 | 1891.2 |
| | NoDiff | 2266.7 | n/a | 1684.3 | 2018.1 |
| | Control^ | 2030.3 | 1810.2 | 1751.8 | 1752.3 |
| Femoral Jerk (da/dt) | Diff | 94780.6 | 76330.7 | 66982.8 | 74156.5 |
| | NoDiff | 81372.7 | n/a | 85287.9 | 59873.4 |
| | Control | 81954.0 | 86641.1 | 50126.0 | 90820.9 |
| Tibial Jerk (da/dt) | Diff | 156949.0 | 107367.1 | 115054.3 | 107559.6 |
| | NoDiff | 126392.1 | n/a | 107058.7 | 114545.5 |
| | Control | 115518.6 | 112152.2 | 85955.3 | 109530.1 |
| Mid-stance | | | | | |
| Femoral Acceleration (mG) | Diff | 977.6 | 776.7 | 620.4 | 1197.9 |
| | NoDiff | 866.8 | n/a | 1363.6 | 1265.5 |
| | Control | 521.0 | 653.3 | 446.4 | 465.7 |
| Tibial Acceleration (mG) | Diff | 934.3 | 944.6 | 755.8 | 995.1 |
| | NoDiff | 936.1 | n/a | 599.6 | 688.0 |
| | Control¥ | 601.5 | 594.7 | 516.6 | 458.7 |
| Femoral Jerk (da/dt) | Diff | 32709.3 | 25855.3 | 27959.6 | 68870.9 |
| | NoDiff | 29863.1 | n/a | 21793.2 | 29062.1 |
| | Control | 12905.9 | 18527.2 | 9679.8 | 14091.1 |
| Tibial Jerk (da/dt) | Diff | 36114.2 | 43822.2 | 30383.8 | 49661.0 |
| | NoDiff | 34542.0 | n/a | 16376.2 | 22947.4 |
| | Control | 21218.7 | 20418.6 | 18685.8 | 16968.9 |

¥Marks the group when trends are observed

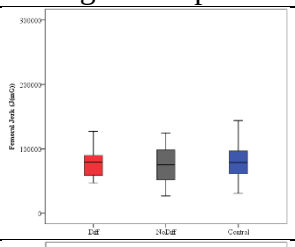
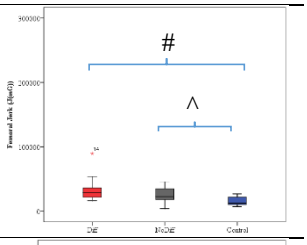
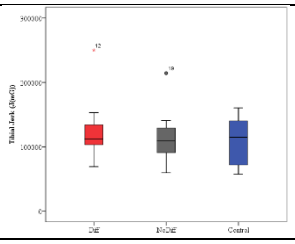
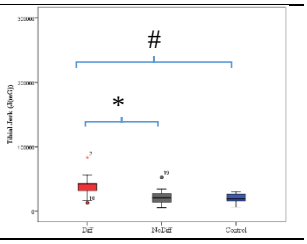
^Marks the group with no trend, but values are equal or close

Figure 4.1 Femoral and tibial acceleration for controlled gait speed. Quartiles for femoral and tibial acceleration magnitude for the (■) Walking Difficulty group (Diff), the (■) No Walking Difficulty Group (NoDiff), and the (■) Control group during (A.) weight acceptance and (B.) mid-stance gait intervals when walking at a controlled gait speed of 1.0 meter per second. Top whiskers represent the highest quartile of those within each group walking with the largest acceleration magnitude. Box represents 2nd and 3rd quartiles, with the line representing the median. Bottom whisker represent the lowest quartile. Dots with numbers represent potential outlier.

| | A. Weight Acceptance | B. Mid-Stance |
|---|---|---|
| Femoral Acceleration |  |  |
| Tibial Acceleration |  |  |

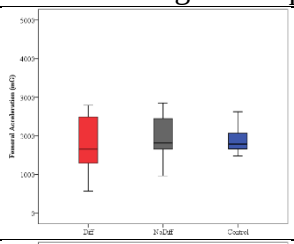
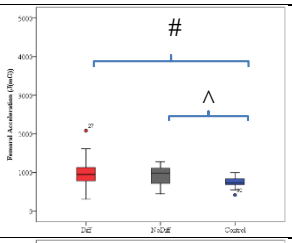
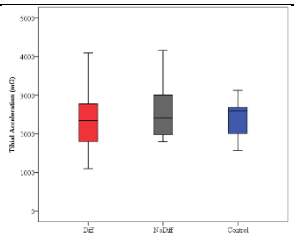
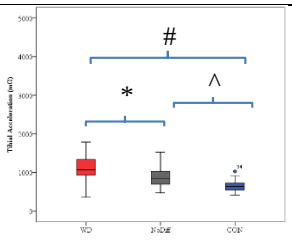
* Signficant differences between the Diff and NoDiff groups, $p \leq .05$.
^ Signficant differences between the NoDiff and Control groups, $p \leq .05$.
# Signficant differences between the Diff and Control groups, $p \leq .05$.

Figure 4.2 Femoral and tibial jerk for controlled gait speed. Quartiles for femoral and tibial jerk magnitude for the (■) Walking Difficulty group (Diff), the (■) No Walking Difficulty Group (NoDiff), and the (■) Control group during weight acceptance and mid-stance gait intervals when walking at a controlled gait speed of 1.0 meter per second. Top whiskers represent the highest quartile of those within each group walking with the jerk magnitude. Box represents 2nd and 3rd quartiles, with the line representing the median. Bottom whisker represent the lowest quartile. Dots with numbers represent potential outlier.

| | Weight Acceptance | Mid-Stance |
|---|---|---|
| Femoral Jerk |  |  |
| Tibial Jerk |  |  |

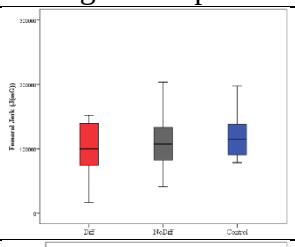
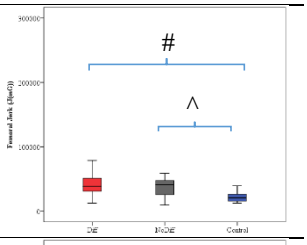
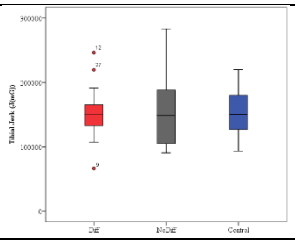
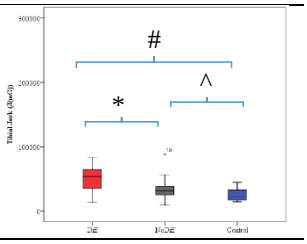
* Signficant differences between the Diff and NoDiff groups, $p \leq .05$.
^ Signficant differences between the NoDiff and Control groups, $p \leq .05$.
# Signficant differences between the Diff and Control groups, $p \leq .05$.

Figure 4.3 Femoral and tibial acceleration for self-selected gait speed. Quartiles for femoral and tibial acceleration magnitude for the (■) Walking Difficulty group (Diff), the (■) No Walking Difficulty Group (NoDiff), and the (■) Control group during (A.) weight acceptance and (B.) mid-stance gait intervals when walking at self-selected gait speed. Top whiskers represent the highest quartile of those within each group walking with the largest acceleration magnitude. Box represents 2nd and 3rd quartiles, with the line representing the median. Bottom whisker represent the lowest quartile. Dots with numbers represent potential outlier.

| | A. Weight Acceptance | B. Mid-Stance |
|---|---|---|
| Femoral Acceleration |  |  |
| Tibial Acceleration |  |  |

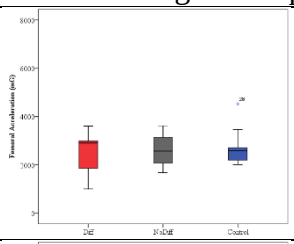
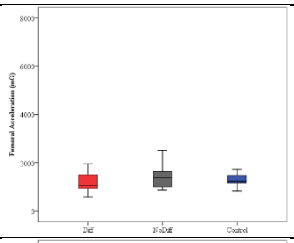
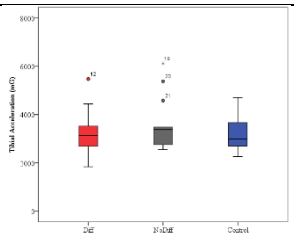
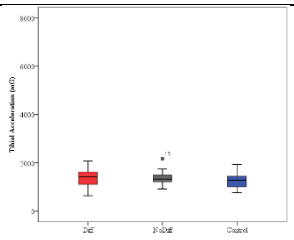
* Signficant differences between the Diff and NoDiff groups, $p \leq .05$.
^ Signficant differences between the NoDiff and Control groups, $p \leq .05$.
# Signficant differences between the Diff and Control groups, $p \leq .05$.

Figure 4.4 Femoral and tibial jerk for self-selected gait speed. Quartiles for femoral and tibial jerk magnitude for the (■) Walking Difficulty group (Diff), the (■) No Walking Difficulty Group (NoDiff), and the (■) Control group during weight acceptance and mid-stance gait intervals when walking at self-selected gait speed. Top whiskers represent the highest quartile of those within each group walking with the jerk magnitude. Box represents 2nd and 3rd quartiles, with the line representing the median. Bottom whisker represent the lowest quartile. Dots with numbers represent potential outlier.

| | Weight Acceptance | Mid-Stance |
|---|---|---|
| Femoral Jerk |  |  |
| Tibial Jerk |  |  |

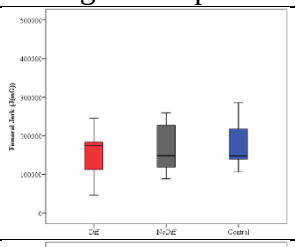
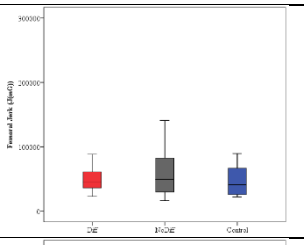
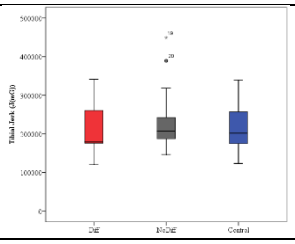
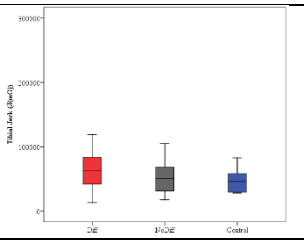
* Signficant differences between the Diff and NoDiff groups, $p \leq .05$.
^ Signficant differences between the NoDiff and Control groups, $p \leq .05$.
#Signficant differences between the Diff and Control groups, $p \leq .05$.

Figure 4.5 Femoral and tibial acceleration for fast gait speed. Quartiles for femoral and tibial acceleration magnitude for the (■) Walking Difficulty group (Diff), the (■) No Walking Difficulty Group (NoDiff), and the (■) Control group during (A.) weight acceptance and (B.) mid-stance gait intervals when walking at fast gait speeds. Top whiskers represent the highest quartile of those within each group walking with the largest acceleration magnitude. Box represents 2nd and 3rd quartiles, with the line representing the median. Bottom whisker represent the lowest quartile. Dots with numbers represent potential outlier.

| | A. Weight Acceptance | B. Mid-Stance |
|---|---|---|
| Femoral Acceleration |  |  |
| Tibial Acceleration |  |  |

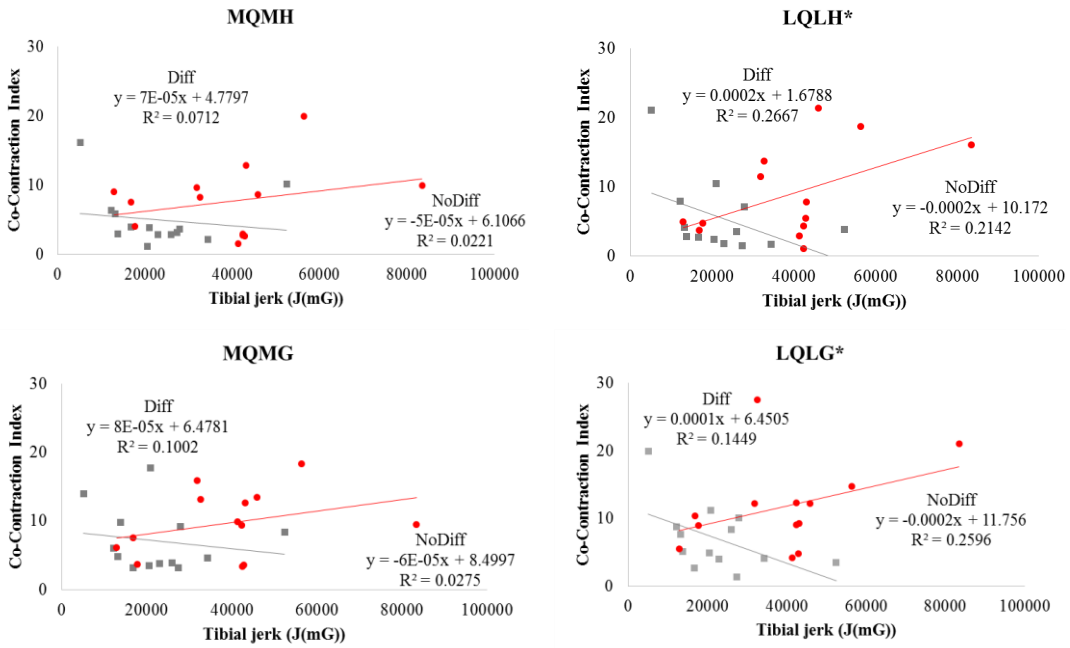
* Signficant differences between the Diff and NoDiff groups, $p \leq .05$.
^ Signficant differences between the NoDiff and Control groups, $p \leq .05$.
# Signficant differences between the Diff and Control groups, $p \leq .05$.

Figure 4.6 Femoral and tibial jerk for fast gait speed. Quartiles for femoral and tibial jerk magnitude for the (■) Walking Difficulty group (Diff), the (■) No Walking Difficulty Group (NoDiff), and the (■) Control group during weight acceptance and mid-stance gait intervals when walking at fast gait speeds. Top whiskers represent the highest quartile of those within each group walking with the jerk magnitude. Box represents 2nd and 3rd quartiles, with the line representing the median. Bottom whisker represent the lowest quartile. Dots with numbers represent specific subjects who served as a potential outlier.

| | Weight Acceptance | Mid-Stance |
|---|---|---|
| Femoral Jerk |  |  |
| Tibial Jerk |  |  |

* Signficant differences between the Diff and NoDiff groups, $p \leq .05$.
^ Signficant differences between the NoDiff and Control groups, $p \leq .05$.
# Signficant differences between the Diff and Control groups, $p \leq .05$.

Figure 4.7 Group interaction effects between co-contraction and tibial jerk for the (■) Walking Difficulty group (Diff), the (■) No Walking Difficulty Group (NoDiff), during mid-stance gait interval of controlled gait speed condition.




* Signficant interaction effects between the Diff and NoDiff groups, $p \leq .05$.

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Chapter 5

# CONCLUSION

The goals of this dissertation were to examine knee osteoarthritis (OA) gait modifications occurring in the presence of OA related walking difficulty, and in the absence of poor functional mobility. By paralleling studies that examined OA-related gait as a heterogenic whole, we sought to provide insight into the impact of gait modifications adopted by a walking difficulty sub-group within the knee OA population. Further, this dissertation examined if gait modifications based on OA presence and walking difficulty held true during gait speed conditions that were less controlled and better representative of the subject's innate gait speeds. To this end, this dissertation examined walking differences among those with knee OA with walking difficulty (Diff), with knee OA without walking difficulty (NoDiff), and with no knee OA.

## 5.1 Aim 1: Knee Kinematic and Kinetic Differences Based on Walking Difficulty and OA Sub-groups.

The objective of Aim 1 was to determine knee kinetic and kinematic differences based on OA and walking difficulty sub-groups. Knee kinetic and kinematics differences were well established between those with and without knee OA; therefore, notable differences based on walking difficulty would suggest it to be a viable sub-group within those with knee OA.

**Hypothesis 1.1a**. When based on OA presence and regardless of walking ability, we hypothesized that gait patterns of the OA groups Diff and NoDiff will accentuate OA gait characterization more so than the control counterpart.

The OA groups, Diff and NoDiff, walked with knee kinetics and kinematics that most represented OA-related characteristics; while the control group walked with knee mechanics that least represented OA gait patterns, which was consistent with our hypothesis. Significant differences between the OA and Control groups were primarily observed for knee kinematics and to a lesser extent for knee kinetics. Some knee kinetics were significantly different between the Diff and Control groups; however, no knee kinetics were significantly different between the NoDiff and Control groups. The lack of differences between the OA and Control groups for knee kinetic may indicate that knee OA presence would not inherently suggest knee kinetic modifications. In contrast, significant differences were found based on walking difficulty and OA presence for knee kinematics, including peak knee adduction and extension moments. Such gait strategies have been considered as knee stiffening strategies of knee OA that exchanged sagittal plane knee for frontal pane knee excursion.

**Hypothesis 1.1b**: When based on the presence of walking difficulty, we hypothesized the Diff group would walk with more accentuated OA gait characteristics than their age and sex matched counterparts in the NoDiff group.

Within the OA groups, there were no significant differences based on walking difficulty presence for knee kinematics, but there were significant differences for knee kinetics. Although significant differences were not achieved between the OA groups for knee kinematic, on average the Diff group's sagittal plane knee excursion were smaller and frontal plane knee excursion were larger when compared to the NoDiff group. Thus, there may be differences in knee kinematics based on walking difficulty; however, this would require further investigation.

The Diff group walked with significantly smaller peak knee extension moment, larger first peak knee adduction moment, and smaller second peak knee adduction moment than the NoDiff group. Our findings suggest that gait modifications in the presence of walking difficulty were less apparent when examining knee excursion and more apparent when examining force distributions. Therefore, knee kinetics pertaining to OA related gait do not necessarily develop in everyone with knee OA, but appear to have a larger impact on those with knee OA and walking difficulty. These findings suggest that future studies should further examine how knee moments impact walking ability in those with knee OA, and consider interventions that may increase knee extension moment and reduce knee adduction moments to combat walking difficulty.

**Hypothesis 1.2** Worsening knee OA related symptoms would accentuate OA related gait mechanics, this effect would be more apparent in the Diff group than the NoDiff group.

Pain, stiffness, and limping were OA related symptoms that more negatively affected the Diff group than the NoDiff group.

Although the observed trends were based on knee mechanics and pain in both groups, only knee flexion moment trends were observed in both OA groups. Worsening knee pain in both OA groups, regardless of walking difficulty, yielded larger knee flexion moments. Thus, given the lack of significant group differences, knee flexion moment may be more related to knee pain in those with knee OA.

Worsening self-reported knee stiffness in the Diff group was related to larger knee flexion excursion; while worsening stiffness in the NoDiff group related to

smaller knee flexion excursion. Thus, when faced with knee stiffness, strategies differ based on walking difficulty presence.

Trends based on limping and knee mechanics were difficult to discern, as trends were only observed in the NoDiff group.

Therefore, walking ability can be made difficult with OA related symptoms and the adopted gait strategies. These findings suggest that walking difficulty is multi-facted phonemena that would serve well as a sub-group within knee OA.

The objective of Aim 1 was to ensure that walking difficulty was a viable sub-group within knee OA based on known gait mechanics that are specific to knee OA.

## 5.2 Aim 2: Neuromuscular Strategies Based on Walking Difficulty and OA Presence.

The objective of Aim 2 was to examine how neuromuscular strategies for knee OA would vary based on walking difficulty, gait speed conditions, and OA related knee symptoms.

**Hypothesis 2.1**: Neuromuscular activation would vary based on OA presence and walking difficulty presence; therefore, we believed that the Diff group would use the largest muscle activation and co-contraction indices, followed by the NoDiff group, and the least would be observed in the control group when walking at the controlled gait speed of 1.0 m/s.

Overall, muscle activation and co-contraction indices were the largest in the Diff group, followed by the NoDiff group, and the smallest in the control group for both weight acceptance and mid-stance gait interval occurred during controlled gait speed trials, which supported our hypothesis. The largest muscle activation and co-contraction index differences were observed between the Diff and Control group,

followed by differences measured between the Diff and NoDiff group, and the smallest differences were observed between the NoDiff and Control group. These findings suggest that when external gait conditions (e.g. gait speed) are the same for all subjects, neuromuscular strategies differed based on walking difficulty within knee OA - not just the presence of knee OA alone.

**Hypothesis 2.2:** Neuromuscular activation differences among the groups, based on the presence of OA and walking difficulty, would be influenced by gait speed conditions. Therefore, we believed group differences for muscle activation and co-contraction indices would be the largest during the fast gait speed condition, followed by the self-selected gait speed condition, and the smallest group differences would occur when walking at the controlled gait speed condition.

Group differences based on muscle activation and co-contraction indices that were found during the slower gait speeds, or the controlled and self-selected gait speeds, were attenuated in the fast gait speed condition. Based on these findings, neuromuscular activation differences found at one gait speed condition cannot be interpreted for another gait speed condition in those with knee OA. Further, the largest group differences for muscle activation and co-contraction indices were clearly observed during the self-selected gait and least observed during the fast gait speeds. These findings may suggest that muscle activation may vary less with the actual gait speed itself but the amount of effort the individual may interpret for a task. In this case, when using similar amounts of muscle activation and co-contraction indices, the Diff group walked at a gait speed that was slow enough to exceeded minimally clinically important difference when compared to the fast gait speeds of the NoDiff

and Control groups. Although slower than their NoDiff and Control counterpart, the average fast gait speed would represent the Diff's interpretation of fast gait speed.

**Hypothesis 2.3*:*** A negative trend would be present in both OA groups, which suggests that a lower response, or worsening knee OA-related symptoms, would be related to larger muscle activation and co-contraction.

Muscle activation and co-contraction indicies trended with knee OA related symptoms in both the Diff and the NoDiff groups. These OA related symptoms included pain, stiffness, and limping; with a larger percentage of subjects in the Diff group reporting that these symptoms negatively affected their activity than the NoDiff group.

Worsening knee pain in both OA groups was related to larger muscle activation and co-contraction indices during weight acceptance and mid-stance of controlled gait speed, than those of less severe or no knee pain. This finding supported our hypothesis. However, the trend between muscle activation and co-contraction and stiffness and limping varied based on the OA group and gait interval. In a few cases, the trends between neuromuscular strategies and stiffness and limping were actually opposite between the OA groups. This was observed in the LQLG of weight acceptance gait interval, in which the Diff group walked with less co-contraction but with worsening stiffness, meanwhile the NoDiff group walked with more co-contraction and with worsening stiffness. Thus, conversing trends may suggest neuromuscular strategies were different based on walking difficulty within knee OA. As a result, those in the Diff group who are faced with stiffness and limping that negatively impacts their activity may be adopting poor neuromuscular strategies. In the NoDiff group, neuromuscular strategies may be effective for combating OA

related symptoms to maintain walking ability, even if muscle activation and co-contraction indices are larger than their control counterparts.

## 5.3 Aim 3: Limb Dynamic Differences Based on OA Presence and Walking Difficulty.

The objectives of Aim 3 are two-fold. First, to explore how limb dynamics vary based on OA presence and walking difficulty presence in those with knee OA. Second, to examine how limb dynamics are influenced by neuromuscular strategies in the knee OA groups, with and without walking difficulty.

**Hypothesis 3.1:** Limb dynamics would be the largest for the walking difficulty (Diff) group, followed by the no walking difficulty (NoDiff) group. The smallest would be found in the control group when walking at a controlled gait speed of 1.0 meter per second.

Although no between group differences reached significant levels during weight acceptance gait interval, the OA groups walked with significantly larger femoral and tibial acceleration and femoral jerk than the control group during mid-stance. Based on OA presence, tibial jerk was only significantly different between the Diff and Control group and not between the NoDiff and Control groups. These findings, when combined with the significant differences based on walking difficulty within the OA group including tibial acceleration and tibial jerk, can suggest that femoral limb dynamics may be more representative of OA presence; while tibial limb dynamics could represent walking difficulty presence. As a result, the findings of mid-stance supported our hypotheses, especially when examining group differences based on trends. Thus, future interventions to ease walking difficulty in knee OA may need to focus on strategies for optimizing tibial smoothness during mid-stance of gait.

**Hypothesis 3.2:** Limb dynamic differences among the groups would be exacerbated by faster gait speeds.

Similar to the control gait speed condition, group differences were observed during mid-stance; but not during weight acceptance. Group differences were observed during self-selected gait speeds, which were equal to or faster than the controlled gait speed. At mid-stance of self-selected gait speed, the OA groups walked with significantly larger femoral and tibial acceleration and, similarly, larger femoral and tibial jerk than the control group. Tibial acceleration and jerk were significantly larger in the Diff than the NoDiff group, and femoral limb dynamics did not achieve significant differences. Therefore, differences found at self-selected gait speed either were similar or accentuated differences observed during the control gait speed condition, indicating support for our hypothesis.

In contrast, at fast gait speeds, no group differences were noted between the groups, and therefore attenuated the findings of slower gait speed conditions. Faster gait speeds could trade precision for power, which may be present in all groups. Although limb dynamics were not significantly different among the groups, the Diff group's fast walking speed was much slower than the NoDiff or Control groups. As a result, the Diff group adopted a less optimal dynamic system than the NoDiff and Control groups by using a similar taxing system but lesser performance, or slower fast gait speed. The significant and non-significant findings indicate that limb dynamics are appropriate for measuring dynamic optimization of the lower limbs in the presence of OA and walking difficulty.

**Hypothesis 3.3:** For those with knee OA, the relationship between co-contraction and limb dynamics would be moderated by walking difficulty.

Walking difficulty signficantly moderated the relationship between lateral muscle co-contraction and tibial jerk in our OA groups. Although medial muscle co-contractions did not achieve significant levels, the slopes between medial co-contraction and tibial jerk were positive for the Diff and negative for the NoDiff. A positive slope suggests a larger muscle co-contracton was correlated with greater tibial jerk; therefore, indicating ineffective neuromuscular strategies. However, a negative slope suggest that larger muscle co-contraction was correlated with lesser tibial jerk; therefore, suggesting a more effective strategty to stabilize the knee. These findings, when combined with the larger tibial jerk and larger co-contraction observed in Aim 2 for LQLG, suggest that distal control may be an issue that needs to be targeted in those with walking difficulty.

## 5.4 Limitations

Despite successfully testing the hypotheses, this dissertation consists of some limitations. First, for all aims of this dissertation, the hypotheses were tested using a cross-sectional study design. A cross-sectional study was beneficial to test our hypotheses; however, we were unable to interpret long term outcomes or causational relationships between gait biomechanics and walking difficulty. Further, during the study design we did not consider knee alignment as a potential covariate; therefore, we did not measure knee alignment using the current reference standard of long axis radiographs. However, we were able to use standing alignment from motion capture analyses for measurements. Although motion capture analyses were not ideal for measuring knee alignment, the relationship between knee alignment and our biomechanical variables were not strong. Therefore, there was potentially little effect of knee alignment on our biomechanical findings.

We were also unable to match subjects based on body mass index; however, we observed minimal trends between BMI and our dependent variables. So potentially, the effects of BMI on our outcomes were minimal. However, given the small study size, more research may be needed based on BMI and gait mechanic differences based on walking difficulty in those with knee OA.

Last, many biomechanical measurements, especially for muscle activation, co-contraction indices, and limb dynamics were not normally distributed. Therefore, we had to run non-parametric testing for our sample which could reduce the power and potentially result in a type II error. Therefore, to combat the risk of type II error, we also examined effect sizes. Some variables described in this dissertation found medium to large effect sizes without significant differences. The other issue with biomechanical data is the potential risk of large variances and standard deviation - which were also observed in our data. The significant differences found in some of our variables based on walking difficulty showed some promise for future studies to repeat this study with a larger sample size.

## 5.5 Future Direction

The findings of this study show that walking difficulty is a promising sub-group for the management of knee OA. Therefore, we were able to lay the ground work for future studies. In addition to replicating the study with a larger sample sizes, this study also suggests the potential benefits of examining walking difficulty over time to determine the prognosis of those with walking difficulty or the change of walking difficulty.

This study also determined that among those with knee OA, those with walking difficulty actually walking differently than those without walking difficulty.

Given that knee kinetics, neuromuscular strategies, and limb dynamics were all significantly different, interventions can be tailored to specifically address these biomechanics in hopes to improve walking ability.

## 5.6 Conclusion

The overall findings of this dissertation suggest that walking difficulty can be used as a sub-group within knee OA to quantify gait biomechanics. Self-reported walking difficulty is an easily answered question currently asked in the clinic by clinicians through self-reported questionnaires. This dissertation suggests that self-perceived walking difficulty in those with knee OA may be associated with biomechanical gait modifications that may need to be addressed clinically. Further, the findings of this dissertation suggest that there is a sub-group population within knee OA able to walk at a self-selected gait speed of 1.0 m/s, but with difficulty. Therefore, not addressing walking difficulty in this sub-group population within knee OA may be detrimental and increase the risks for poor outcomes.

Consistently, through all three aims, those with walking difficulty walked with greater knee stiffening strategies and exacerbated knee OA gait characteristics more than those with knee OA without walking difficulty and those without knee OA. However, these differences were attenuated when walking at fast gait speeds. As a result, there may be some value in examining knee OA gait at fast gait speeds and providing interventions at fast gait speeds in order to optimize the use of OA gait characteristics. Perhaps the attenuation or accentuation of knee OA specific gait characteristics based on walking difficulty is a multi-faceted phenomenon that cannot be streamlined into one specific OA symptom or knee OA severity alone. Instead, the

heterogeneity of OA related symptoms, although overlapping, can alter gait patterns and, in some cases, may be necessary to walk at fast and functional gait speeds.

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# Appendix A

## IRB APPROVAL: KNEE MUSCLE CO-ACTIVATION IN PATIENTS WITH KNEE OSTEOARTHRITIS

UNIVERSITY OF DELAWARE
RESEARCH OFFICE
210 Hullihen Hall
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DATE: February 11, 2015

TO: Annalisa Na, PT, DPT, OCS
FROM: University of Delaware IRB

STUDY TITLE: [568952-3] Knee Muscle Co-Activation in Patients with Knee Osteoarthritis

SUBMISSION TYPE: Continuing Review/Progress Report

ACTION: APPROVED
APPROVAL DATE: February 11, 2015
EXPIRATION DATE: February 25, 2016
REVIEW TYPE: Expedited Review

REVIEW CATEGORY: Expedited review category # *(4)*

Thank you for your submission of Continuing Review/Progress Report materials for this research study. The University of Delaware IRB has APPROVED your submission. This approval is based on an appropriate risk/benefit ratio and a study design wherein the risks have been minimized. All research must be conducted in accordance with this approved submission.

This submission has received Expedited Review based on the applicable federal regulation.

Please remember that informed consent is a process beginning with a description of the study and insurance of participant understanding followed by a signed consent form. Informed consent must continue throughout the study via a dialogue between the researcher and research participant. Federal regulations require each participant receive a copy of the signed consent document.

Please note that any revision to previously approved materials must be approved by this office prior to initiation. Please use the appropriate revision forms for this procedure.

All SERIOUS and UNEXPECTED adverse events must be reported to this office. Please use the appropriate adverse event forms for this procedure. All sponsor reporting requirements should also be followed.

Please report all NON-COMPLIANCE issues or COMPLAINTS regarding this study to this office.

Please note that all research records must be retained for a minimum of three years.

Based on the risks, this project requires Continuing Review by this office on an annual basis. Please use the appropriate renewal forms for this procedure.

# Appendix B

# INFORMED CONSENT: KNEE MUSCLE CO-ACTIVATION IN PATIENTS WITH KNEE OSTEOARTHRITIS

*UD IRB Approval from 02/16/2016 to 02/25/2017*

## INFORMED CONSENT FORM

**Project Title:** The Mechanisms of Co-contraction in Individuals with and without Knee Osteoarthritis.

**Investigators:** Annalisa Na, PT, DPT, OCS
Thomas S. Buchanan, PhD

## PURPOSE/ DESCRIPTION OF THE RESEARCH

We are studying differences in people with and without osteoarthritis. In this study, we will look at how you move and how your muscles are activated by your brain. A total of 60 individuals will be asked to participate in this study. At your visit, you will be asked a series of questions in the eligibility screening process, followed by a questionnaire about your activity level, age, medical history, and ability to perform daily activities. We will also perform a series of measures that include knee motion, strength, and sensory testing. Sensory testing involves determining if you can feel small sensations applied to the skin surrounding your knee. Then we will ask you to perform a series of typical daily tasks while wearing self-adhesive electrodes on your legs and reflective markers on your trunk, hips, legs, and foot. The electrodes will allow us to determine which muscles you are using and the markers will allow us to analyze how you move your body during each task. Your information may be compared to other individuals, in order to determine how those with and without knee osteoarthritis move and use their muscles differently.

### Testing Procedures

Height, weight, and circumference measurements of your waist and hips are being used to determine your body mass index and body shape, which have been shown to affect knee pain and knee arthritis. You are asked to wear loose, comfortable clothing during your testing.

The physical examination will include a typical knee examination, such as knee range-of-motion, knee joint motion, knee sensations, leg strength, and functional tests. Specifically, knee sensation testing examines your sensitivity to vibration and to discriminate between two points We will also ask you to perform several common daily tasks that include walking at various speeds, walking and changing directions, stepping up and down from steps, and transitioning from sitting to standing. You will be given at least a one minute break between each task to rest and to ensure you are not fatigued from the task. The length of rest times and the number of rest breaks can be adjusted at your discretion. During these tasks and strength testing sessions, self-adhesive electrodes will be worn for electromyography (EMG). EMG allows us to see what muscles you use during each daily task and during strength testing. We will also ask you to wear reflective markers on your trunk, pelvis, and legs during these daily tasks, which will allow us to track your movement. Each task will be performed while you walk or stand on force plates that will measure the forces acting upon your body as you move.

If you are participating in the osteoarthritis group, we will also ask if you were previously diagnosed with knee osteoarthritis by your doctor and if he used x-rays to determine the severity of your arthritis, also known as a Kellgren-Lawrence Grading Scale (K-L Score). If you have not received a prior x-ray of your knee with an arthritis severity score, we may ask you to obtain an x-ray. X-rays are the single best test to determine if you have knee arthritis and to determine the

 **Participant's Initials: _____**

severity of your arthritis. If you have recently received knee x-rays and have a K-L Score, we will ask you to provide us with this information.

**Conditions of Subject Participation**

You may withdraw from the study at any time without consequence. Participation is strictly voluntary, therefore you may decide not to do any portion of the evaluation process and you may refuse to answer any questions. The physical therapist may terminate your participation if you experience excessive soreness or disclose any information that is part of the exclusion criteria at any point during the evaluation. If any additional risks are determined during the course of the study, you will be notified so that you may make an informed decision regarding your participation.

**Confidentiality**

All participants will be identified by number only. Only the investigators will have access to the data. Neither your name nor any identifying information will be used in publications or presentations resulting from this study. Data will be stored indefinitely for future additional research purposes. These data will be completely de-identified at the conclusion of the study to protect your identity.

**Risks and Benefits**

You may experience some stiffness, soreness, and/or discomfort with the positioning required for the tests and measures. We will make every attempt to minimize this with frequent rest breaks and position changes. This soreness is similar to the muscle soreness that you may feel if you lift weights or vigorously exercise and is often a sign that you have challenged your muscles beyond normal everyday activities. You may also experience potential loss of balance while performing these tasks. However, this is similar to stepping off an unexpected curb. Further, you may experience pain from sensory testing that is similar to being pricked unexpectedly by a sharp object. Finally, you may experience skin irritation from the electrodes or markers. In order to minimize these risks we will make sure the electrodes and markers are worn less than one hour.

If you are asked to obtain an x-ray, you may be exposed to radiation that may have minimal risks. The radiation exposure will be at the same level as a routine x-ray you get a doctor's office. We plan to minimize such potential risks by excluding those who may be pregnant, and requesting you only to obtain an x-ray if you have not received a K-L score.

The benefits of this study include health risk information (such as BMI) based on your height, weight, and body circumference measurements. You will also be educated on knee anatomy and may ask our experts questions specific to how you move during these tests of typical daily activities.

Furthermore, the information that we obtain with our testing may ultimately lead to the improvement of treatment of knee arthritis in your peers.

**Financial Considerations**

If you are participating in the non-osteoarthritis group you will be financially compensated $50. If you are participating in the knee osteoarthritis group, you will not receive financial compensation, but you will receive an examination of both knees and can discuss with the physical therapists any concerns you may have in regards to your knees.



**Participant's Initials: _____**

**Contacts**

If you have any questions concerning your rights as a research participant, you may contact the head of the Human Subjects Review Committee, University of Delaware at 302-831-2137. Further questions regarding the study may be addressed to: Annalisa Na, DPT, PT or Thomas S. Buchanan at the Delaware Rehabilitation Institute at (302) 831-2410.

**Subject's Assurances**

Your refusal to participate will not affect your ability to receive physical therapy services to which you are otherwise entitled at the University of Delaware Physical Therapy Clinic. Participation is strictly voluntary.

**Subject Statement**

By signing this informed consent, I signify that I choose to participate in this study. The investigators have explained the purpose of this study, defined what is expected of me as a subject, and have described the risks and benefits associated with my participation. The investigators have answered all of my questions about the procedures to my satisfaction.

De-identified data obtained from this study will be kept indefinitely for future additional research purposes.

If you are injured during research procedures, you will be offered first aid at no cost to you. If you need additional medical treatment, the cost of this treatment will be your responsibility or that of your third-party payer (for example, your health insurance). By signing this document you are not waiving any rights that you may have if injury was the result of negligence of the university or its investigators

Would you be willing to be contacted for future studies? ___ yes ___ no

I agree to participate in the research study described above.

_____ _____

Participant's Signature Date Witness Date

_____

Participant's Name



**Participant's Initials: _____**

# Appendix C

## KNEE OUTCOME SURVEY

ID:
Date:

**Knee Outcome Survey**
**Activities of Daily Living Scale**

**Instructions:**

The following questionnaire is designed to determine the symptoms and limitations that you experience because of your knee while you perform your usual daily activities. Please answer each question by **checking the one statement that best describes you over the last 1 to 2 days**. For a given question, more than one of the statements may describe you, but please mark only the statement which best describes you during your usual daily activities.

**Symptoms**

To what degree does each of the following symptoms affect your level of daily activity? (check one answer on each line)

| | I Do Not Have the Symptom | I Have the Symptom But It Does Not Affect My Activity | The Symptom Affects My Activity Slightly | The Symptom Affects My Activity Moderately | The Symptom Affects My Activity Severely | The Symptom Prevents Me From All Daily Activities |
|---|---|---|---|---|---|---|
| Pain | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Stiffness | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Swelling | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Giving Way, Buckling or Shifting of Knee | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Weakness | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Limping | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |

ID:
Date:

**Functional Limitations with Activities of Daily Living**

How does your knee affect your ability to… (check one answer on each line)

| | Activity Is Not Difficult | Activity is Minimally Difficult | Activity is Somewhat Difficult | Activity is Fairly Difficult | Activity is Very Difficult | I am Unable to Do the Activity |
|---|---|---|---|---|---|---|
| Walk? | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Go up stairs? | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Go down stairs? | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Stand? | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Kneel on the front of your knee? | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Squat? | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Sit with your knee bent? | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Rise from a chair? | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |

How would you rate the current function of your knee during your usual daily activities on a scale from 0 to 100 with 100 being your level of knee function prior to your injury and 0 being the inability to perform any of your usual daily activities?

_____

How would you rate the overall function of your knee during your usual daily activities? (please check the one response that best describes you)

- ☐ normal
- ☐ nearly normal
- ☐ abnormal
- ☐ severely abnormal

As a result of your knee injury, how would you rate your current level of daily activity? (please check the one response that best describes you)

- ☐ normal
- ☐ nearly normal
- ☐ abnormal
- ☐ severely abnormal