WALKING CHALLENGES IN MODERATE KNEE OSTEOARTHRITIS: A BIOMECHANICAL RESPONSE TO MEDIAL WALKWAY SURFACE PERTURBATIONS

by

Matthew Douglas Baker

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In memory of Mom,
for never missing an opportunity to tell me she was proud.

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Abstract

Knee osteoarthritis (OA) causes debilitations to mobility. It has been hypothesized that individuals walk with altered biomechanics to prevent symptoms of instability. Perturbations can be used to investigate how individuals respond to gait challenges. The purpose is to determine if gait is altered after medial perturbations in moderate OA and asymptomatic groups. Two groups of 12 participants walked barefoot on a dual-belt instrumented treadmill at self-selected speeds. Motions, ground reaction forces and moments were recorded. Participants experienced 12 unexpected medial, 1cm/3cm perturbations during stance on each leg. Motions and moments were calculated using Cardan/Euler rotations and inverse dynamics. Repeated measures ANOVA identified differences in gait metrics, using Bonferonni's correction for multiple comparisons. Immediately after perturbations both groups demonstrate quicker step times, wider step widths, more knee flexion at initial contact, less sagittal hip range and less dynamic flexion-extension moments. Results demonstrated both groups briefly alter walking patterns after medial perturbations.

List of Abbreviations Used

OA – Osteoarthritis

ROM – Range of Motion

FPA – Foot Progression Angle

MOA – Moderate Knee Osteoarthritis

ASYM – Asymptomatic

KOS – Knee Outcome Score

OARSI – Osteoarthritis Research Society International

TJA – Total Joint Arthroplasty

TKA – Total Knee Arthroplasty

ICF – International Classification of Functioning, Disability and Health

KL – Kellgren-Lawrence

KAM – Knee Adduction Moment

KFM – Knee Flexion Moment

ACR – American College of Rheumatology

BOS – Base of Support

NSHA – Nova Scotia Health Authority

NSHRF – Nova Scotia Health Research Foundation

REB – Research Ethics Board

KOOS – The Knee Injury and Osteoarthritis Outcome Score

WOMAC – The Western Ontario and McMaster Universities Arthritis Index

GRF – Ground Reaction Force

ASIS – Anterior Superior Iliac Spine

ANCOVA – Analysis of Co-Variance

ANOVA – Analysis of Variance

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Chapter 1 - Introduction

Osteoarthritis (OA) in Canada is expected to have significant bearings on the health of Canadians as well as tremendous economic costs in Canada today and over the next few decades (1,2). Estimates suggest that approximately 4.4 million Canadians are living with OA and this population is expected to increase to 10 million over the next 30 years (1). Despite incredible individual and socioeconomic burdens, heath care systems seem to inefficiently manage non-communicable chronic diseases such as OA (2,3). Current evidence-based guidelines encourage conservative, non-pharmacologic management strategies, yet these recommendations are not always present in clinical practice (2–4). Individuals with knee OA sustain greater financial burdens (5,6), access health care professionals more frequently (6) and require more assistance in terms of activities of daily living (7,8). To reduce this burden on Canada's health care system, researchers must focus on understanding the pathomechanics of OA and develop strategies to slow disease progression (9,10).

Lower extremity OA is a highly prevalent and debilitating disorder involving moveable joints and negatively impacts an individual's mobility (10–13). Historically, chondrocentric definitions described the joint disease but lacked information regarding the etiopathogenesis of OA (14–16). Recent literature describes osteoarthritis beginning with a cellular stress and molecular degeneration that is initiated by injury and activates an abnormal repair response (14–17). This evolves into an anatomic and/or physiologic disruptions in the joint that can culminate in illness (2,14,15). OA can be highly debilitating in the lower extremity, specifically when affecting the knee joint (17,18). Knee OA arises from failed repair or joint damage as a result of biomechanical, biochemical and/or genetic factors (14) and is the leading cause of morbidity in older adults (6,19,20). Most commonly, knee OA affects the medial tibiofemoral compartment to a greater extent than the lateral (21), thought to manifest through loading asymmetry during weight-bearing activities (22,23).

Physical activity and healthy living are a major focus of provincial and federal health departments as a management strategy to reduce the burden of chronic disease. Healthy older adults take, on average, between 6500-8000 steps in a day (24,25), where individuals with disability and/or chronic illness take approximately 5500 steps or less (25). Our ability to remain physically active lies within our capacity to walk, however many individuals with knee OA have a difficult time with this task due to a lack in confidence or fear that their knee will not support them (18,26,27). In many individuals with knee OA, decreased knee confidence is associated with knee instability (28). In individuals with knee OA, instability, assessed though self-reported measures, is defined as a sensation of buckling, shifting, or giving way of the knee (26,29,30). It can affect over 60% of people with knee OA (27,31) and is associated with significant functional limitations (26,29,30). Moreover, while joint proprioception is impaired in some individuals with knee OA (32,33), Knoop et al. (31) recently concluded that proprioception did not confound associations between self-reported instability and activity limitations. In fact, Fitzgerald et al. 2004 (27) concluded that self-reported instability affects physical functioning beyond that which can be explained by other impairments such as pain, muscle strength and reduced overall joint range of motion (ROM). These studies support the explanation that pain (12), reduced strength (31), and proprioceptive impairments contribute to limited physical functioning in knee OA populations, but also demonstrate that independently, perceived knee instability is contributing to deteriorated function, particularly during weight-bearing tasks such as walking.

To understand the relationships between impairments to joint structure/function and limitations in activity such as walking, a biomechanical gait analysis has served an important role. These analyses have been used to measure the mechanical demands during walking, and have provided researchers with information regarding OA pathomechanics (9,10,34,35). During dynamic activities, the knee joint aims to strike a balance between stability and mobility (36,37) and in individuals with knee OA, this balance is disrupted (9,38–40). For over a decade, literature has supported that individuals with knee OA generally walk with less ROM, primarily recorded in the sagittal plane (27,35,38,41–44) and this reduction in ROM is often coupled with a reduction in the difference between early peak knee flexion and late peak knee extension moment (34,35,38,39,45). In the frontal plane, literature generally supports that individuals with knee OA walk with an increased adduction moment (34,46–49), which has been described as increased loading across the medial compartment of the knee joint (34,49–51). Recently, a combination of decreased knee flexion ROM and lower flexion-extension moment range has been described as "stiff knee gait" (39,52,53). It is possible, that individuals with knee OA who perceive their joint to be unstable may adopt a "stiff knee strategy" to improve joint function and increase overall confidence in their ability to walk.

Physical structural changes, such as osteophyte formation (54,55) and joint capsule hardening (11), coupled with a reduction in sagittal plane laxity (56) may be altering dynamic knee mechanics; specifically causing resistance to tibiofemoral joint rotation during dynamic knee flexion as suggested by Zeni & Higginson (42). Concomitantly, with a reduction of sagittal plane knee joint dynamics being characteristic of knee OA (35,57), it is possible that individuals may be altering their gait patterns to safely and stably navigate their environment. Until recently, testing these hypotheses using common gait analysis techniques has been limited. Stability, in this case, is defined as the way a system behaves following a perturbation, and if the state of that system remains within specific boundaries of control (58–60). Our current methods of testing stability are limited in the sense that individuals walk in a self-selected, controlled manner. Challenges to joint stability could come from increasing walking speed, incline/decline walking or stair ascent/descent, however, these tasks are anticipated joint challenges and are not unexpected stressors. Research has demonstrated that individuals with knee OA, who may report knee instabilities, stiffen their gait in order to provide stability to the knee joint (61). Therefore, to move forward and understand stability in the context of knee OA walking mechanics researchers must challenge individuals, with unknown perturbations during walking, perhaps similar to the way individuals experience everyday activities.

To date, many studies on OA gait have been completed in stable controlled environments, providing the foundation for continued evolution of OA pathomechanics understanding. This evolution has recently taken the form of monitoring how individuals with OA respond to unexpected gait challenges through perturbation testing (62,63). Gait perturbations have been used in the past to investigate how individuals (i.e. healthy, older adults) respond in terms of spatiotemporal parameters, joint motions, joint moments and muscle activation patterns in healthy and pathological groups (64–67), but only recently have these paradigms been employed in knee OA populations (62,63). To date, only two studies could be found. Given frontal plane demands of OA gait, as a result of asymmetrical medial/lateral tibiofemoral OA distribution, these studies have focused on frontal plane perturbations in OA populations comparing self-reported stable knees and unstable knees (63), or to asymptomatic healthy groups (62) while monitoring sagittal plane movement mechanics. Both studies used a 5.4 cm lateral perturbation of the symptomatic limb during stance on an instrumented over-ground walkway and monitored sagittal plane knee mechanics directly after the perturbation. Researchers allowed participants to experienced perturbations before the collection began. While not discussed in these studies, this lateral perturbation is thought to destabilize the medial compartment, using an unnatural movement direction during stance, given the adduction (medial) moment that is typically created. The findings were equivocal. Schmitt & Rudolph (63) found no differences in knee flexion excursion during weight acceptance and mid-stance, while Kumar et al. (62) found a reduction in knee flexion excursion during the weight acceptance phase of gait, but this response was evident in both healthy controls and knee OA groups and was not statistically different between groups (i.e. both groups demonstrated similar responses). Both studies concluded that further work is required to comprehend implications of these findings for understanding OA joint function in uncontrolled environments but provide a basis for further testing hypotheses related to walking challenges in knee OA.

At this moment, there is a narrow and unclear understanding of how individuals with moderate knee OA (MOA) respond to unexpected frontal plane walking challenges that may emulate challenges the knee joint experiences day-to-day. With every step, individuals with medial compartment knee OA are responding to adduction moments that alter medial compartment load and may even induce lateral compartment lift off (51). This response involves mechanical and neuromuscular factors. It is acknowledged that in order to maintain joint function, muscular contributions are required, as conceptualized by Panjabi and Solomonow (36,37). Moving forward, challenging these individuals by providing a perturbation in the direction of tibial adduction that theoretically may increase medial compartment load and further induce lateral compartment lift-off is appropriate and novel. The focus of this thesis will be on mechanical responses to perturbations in the direction of tibial adduction (medially directed), namely spatiotemporal characteristics, knee and hip joint motions and knee joint moments. Currently, literature in this area of study is limited both in application of perturbations and in understanding how individuals respond. For instance, what are the mechanical responses to an unexpected medial perturbation; perturbations that may stress the natural mechanisms to maintain joint function during walking? Challenges to the knee during routine activities of daily living can impact physical function. These challenges are often unexpected and we are currently unaware of how individuals with knee OA respond. Given the relationship between symptoms of buckling, giving-way and functional limitations, how individuals respond to these perturbations may provide important information on knee function that cannot be gleaned from stable walking conditions, and capacity for physical activity in real-world situations. This information can be used to impact clinical decision making by improving our understanding of how the knee functions, particularly regarding stability, and impacts our ability to remain mobile.

1.1 Overall Objective

Knee OA has a major impact on mobility and activity levels with pathomechanical alterations occurring to joint function that affect knee biomechanics during walking. Instability reported by individuals with knee OA significantly contributes to limitations in walking and poor confidence in this fundamental task. Are altered knee biomechanics a response to a person's perception of instability (giving-way, buckling), as previously speculated? Given the importance of these symptoms to physical function in individuals with knee OA, understanding the potential interaction with walking mechanics is important for the continued evolution of management strategies that target pathomechanical processes of this disease. If people with knee OA do not walk because they are afraid their knee is going to give way, a vicious cycle of inactivity may begin that has less than ideal consequences for chronic disease and poor quality of life.

The main purpose of this study is to determine how individuals with moderate medial compartment knee OA respond to medial unexpected walkway surface translations during gait compared to an ASYM control group and whether a relationship exists between these responses and self-reported instability.

1.2 Specific Objectives

The specific study objectives are:

1. To determine if unexpected 1 and 3cm medial walking surface translations to the symptomatic limb during stance will result in immediate alterations to spatiotemporal gait characteristics (stride time, step width, foot progression

angle (FPA), etc.) in individuals with moderate knee OA (MOA) compared to an asymptomatic (ASYM) control group.

a. To determine if self-reported measures of stability, specifically question 6 of the Knee Outcome Score (KOS) which outlines sensations of buckling, shifting or giving-way are related to spatiotemporal outcomes during dynamic perturbation testing.

2. To determine if unexpected 1 and 3cm medial walking surface translations to the symptomatic limb during stance will result in immediate alterations in:
    - Sagittal and frontal knee motions during gait in individuals with MOA compared to an ASYM control group.
    - Sagittal and frontal hip motions during gait in individuals with MOA compared to an ASYM control group.
    - Sagittal and frontal knee moments during gait in individuals with MOA compared to an ASYM control group.

    a. To determine if self-reported measures of stability, specifically question 6 of the KOS which outlines sensations of buckling, shifting or giving-way are related to kinematic or kinetic outcomes during dynamic perturbation testing.

1.3 Hypothesis

The null hypotheses of the aforementioned objectives are as follows:

1. For Objective 1, it is hypothesized that medial 3cm walkway translations will alter spatiotemporal characteristics of both MOA and ASYM groups. Immediately after the perturbation, it is hypothesized that there will be an

decrease in stride time, stance time, swing time and step time. An decrease in step length will be accompanied by an increase in step width and an increase in FPA in both groups. Medial 1cm walkway translations will not alter spatiotemporal characteristics in either group.

a. A significant positive relationship will exist between self-reported measures of stability from the KOS and spatiotemporal characteristics measured during dynamic gait.

2. For Objective 2, it is hypothesized that:

    - No changes will occur in frontal plane knee motions in both MOA and ASYM groups immediately after a 1cm and 3cm medial walkway translations. No changes will occur in the sagittal plane knee motions after a 1cm medial walkway translation. Immediately after a medial 3cm walkway translation significant difference will be found, with both groups striking in more flexion at initial contact, however, both groups will experience similar range from initial contact to peak flexion and from peak flexion to peak extension.

    - No changes will occur in frontal plane hip motions in both MOA and ASYM groups immediately after 1cm and 3cm walkway translation. No changes will occur in sagittal plane knee motions after a 1cm medial walkway translation. Immediately after medial 3cm walkway translation a significant difference will be found in total hip ROM during stance in both groups.

- No changes will occur in frontal plane knee moments in both MOA and ASYM groups immediately after 1cm and 3cm walkway translations. No changes will occur in the sagittal plane knee moments after a 1cm medial walkway translation. Immediately after medial 3cm walkway translation, the dynamic range of the sagittal plane moment (peak flexion to peak extension moment) will be reduced in both groups.

a. A significant positive relationship will exist between self-reported measures of stability from the KOS and kinematic and kinetic outcomes measured during dynamic gait.

Chapter 2 - Review of Relevant Literature

2.1 The Burden of Osteoarthritis

2.1.1 Economics

Osteoarthritis ranks among the top ten causes of disability worldwide, and significantly alters physical function and independence (5,6,68). As individuals age, they experience more severe symptoms and higher levels of disability (6), highlighting the progressive nature of the disease (9). The Arthritis Alliance of Canada reported 1 in 4 Canadians and approximately 30% of the labour force will be living with OA in 30 years (1). Cost of illness studies have focused on personal, out-of-pocket costs to patients and direct economic costs to the Canadian health care system (6).

Living with OA impacts an individual's participation in certain social roles, such as employment, parenting, leisure activities and community involvement (68). Social role participation is understood as an involvement in a role, perception of role importance, self-appraisal of role performances and satisfaction with ability to perform a role (68). OA is linked with role loss, role conflict, depression, and individuals affected with OA report higher fatigue levels, more pain and lower health scores (68,69). Today, more than 220,000 workers are living with moderate-to-severe disability due to OA (1), with half reporting arthritis related absenteeism and over a third reporting reduced work hours (70,71).

Gupta et al. (6) reported the likelihood of incurring OA-related costs was relatively constant up to age 75, after which it increased significantly. Economic burden decreased with improved health, but rose sharply with OA disease severity (6). On average, 60% of individuals report OA-related costs, with average annual out-of-pocket expenses totalling $12,000 (6,72). For those reporting OA-related expenditures, 80% of this economic burden was a result of indirect costs.

From a national perspective, OA has a significant impact on the public health care system and the economy. The annual economic burden of OA is over $6 billion with two-thirds of this involving older (aged 35-64) working Canadians (1). This results in almost 30% of the employed labour force experiencing difficulties working as a result of OA (1,73). The Arthritis Alliance of Canada estimates that OA currently accumulates approximately $10 billion in direct health care cost and $17 billion in indirect health care cost (1). In the next 30 years, these cumulative expenses are expected to rise to $550 billion direct and $909 billion in indirect costs.

It is not clear how Canadians and Canada's health care system are going to cope. The economic burden of OA is increasingly troublesome on individuals, the overall health care system and the economy. In order to understand how to minimize its economic effects, a better understanding of the disease and the impact it has on mobility is needed.

2.1.2 Understanding Osteoarthritis

Osteoarthritis Research Society International (OARSI) established a working group, which aimed to generate a standardized definition of OA that accurately defines the disease state. Kraus et al. (15), have defined OA as "a disorder involving movable joints characterized by cell stress and extracellular matrix degradation initiated by micro- and macro-injury that activates maladaptive repair responses including pro-inflammatory pathways of innate immunity. The disease manifests first as a molecular derangement (abnormal joint tissue metabolism) followed by anatomic, and/or physiologic derangements (characterized by cartilage degradation, bone remodelling, osteophyte formation, joint inflammation and loss of normal joint function, that can culminate in illness (15)." This definition encompasses the molecular, anatomic and physiologic indicators of OA, without implying certain biases towards OA phenotypes.

It is important to understand that, although disease and illness are sometimes used synonymously, they are inherently different. While disease refers to abnormal structure and function of body systems described with reference to biological, chemical or other evidence; illness refers to the human response to the disease (15,74). Simply put, an illness is something the person has, while disease is something affecting the biological system (15,74). The illness associated with OA is difficult to define, as patients can experience a variety of physical and emotional symptoms. Pain (75), instability (26,31) and physical limitations (30) are commonly reported in patients diagnosed with knee OA, alongside these physical symptoms are emotional symptoms such as depression and anxiety (18). Disease classification is often based on both structural damage (disease) and reports of joint pain, stiffness and disability (illness), however, only weak correlations have linked symptoms and pathology (14). Given this multidimensional nature, it is no wonder OA is a condition that is often poorly managed in clinical practice, despite its high impact of disability (4).

There is no cure for OA and as a result current treatment modalities focus on reducing pain (4). This strategy of managing symptoms has done very little to reduce the demands on total joint replacement surgery where end stage OA is the number one indicating diagnosis. OA accounts for 95% of hip and knee total joint arthroplasty (TJA) procedures (76), with TJA remaining the most frequently performed procedure by orthopaedic surgeons in developing countries (4). Total knee arthroplasty (TKA) incidence has increased dramatically worldwide, with more younger individuals requesting surgery (77). Furthermore, cost-utility analysis ranks joint replacements among the most expensive surgical interventions (76) questioning the sustainability of TKA as a management approach.

OA is a disease of mechanics (9). Thus, mechanics should be the focus of studies attempting to uncover the pathomechanical processes underlying OA development and progression. Understanding mechanics sheds light on how OA affects physical function and a person’s ability to move and remain active.

2.1.3 Physical Activity

The International Classification of Functioning, Disability and Health (ICF), illustrated in Figure 2-1, provides a standard framework for the description of health and health-related states (78). Components of the ICF cover functioning and disability, emphasize body functions, structures, activities and participation and contextual influences, focusing on environmental and personal factors (78). In regards to knee OA, the ICF model, provides a theoretical framework to understand how impairments at the joint lead to activity limitations, and vice versa (79). The ICF Comprehensive Core Set for OA includes walking as a relevant category specific to OA, within the component of limitations and restrictions to activity and participation (79). Limitations in activity and participation are very important measures to patients with OA, in which nine ICF measures focus on an individual's mobility. The ICF core sets for OA, including measures of activity and participation, have been shown to be valid and reliable measures within a knee OA population (80).

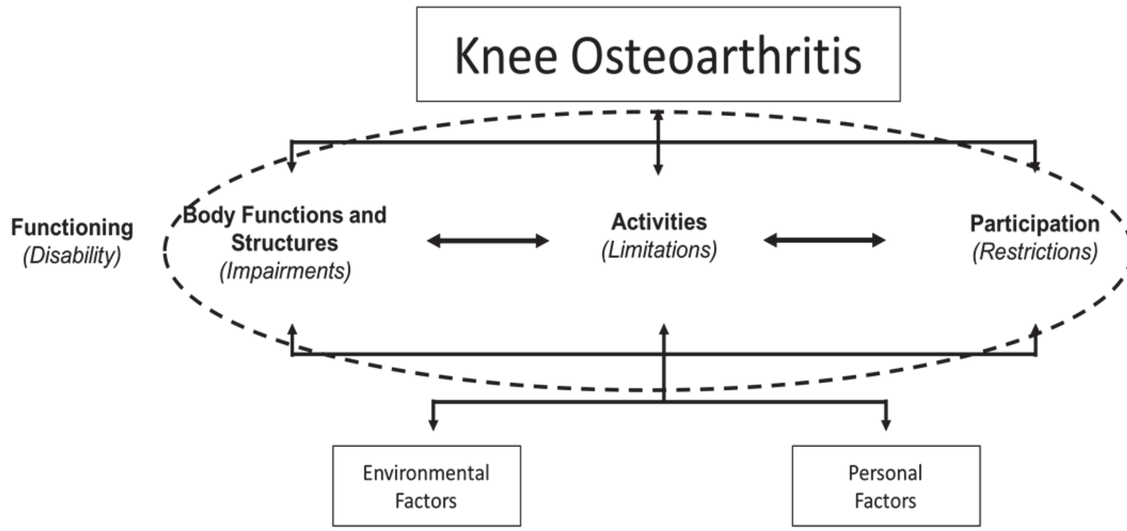

Figure 2-1: International Classification of Functioning, Disability and Health framework adopted from the World Health Organization (77) and modified to reflect the disease of knee OA.

Maintaining mobility and activity levels has the potential to both prevent the onset of and ease the pain associated with OA. The ICF and Canada's Physical Activity Guide to Healthy Living encourages individuals to make a commitment to avoiding sedentary lifestyles and to maintaining mobility. Reduced levels of activity and participation are associated with OA progression, disease severity, declining function and reduced quality of life (13). However, even though increased levels of activity and mobility are beneficial for the health of Canadians, over 60% of individuals with OA report sedentary activities during leisure time (73).

Individuals who participate in moderate-to-vigorous activity advance their functional capacity, without causing damage to joints (13,81). Reduced activity and mobility can exacerbate OA by reducing joint movement and function, increasing fatigue and depression, lowering pain tolerance, and increasing the risk of developing co-morbidities (13,81,82). This level of inactivity can also lead to muscle atrophy, joint instability and further limit function. With the ICF placing high importance on mobility, it is essential to understand the relationship between walking and joint impairments. One way researchers capture this relationship is through the analysis of gait mechanics.

2.2 Gait Mechanics

The knee joint is comprised of different tissues (articular cartilage, ligaments, bone and synovium) which function to assist with movement. Active, passive and neurological subsystems act in unison to provide joint stability and mobility (36,37). OA is a multi-factorial disease and is traditionally assessed in the clinic by radiography (83). Articular cartilage and bone are the tissues that are primarily compromised in knee OA (11,83,84). Deformities of the subchondral bone, sclerosis, cyst formation, osteophytosis, increased bone volume density, and decreased bone mineral density are typical of OA (54,85) and these deformities predict cartilage loss and degradation (54). When anatomic and physiological changes occur at the knee joint, this results in alterations to the way people walk. Anatomic and physiologic changes caused by OA are more frequently observed in the medial compartment of the knee compared to the lateral (21), with higher loading being transferred through the medial compartment (22,23). One question that arises is how these altered mechanics interact with joint impairments and our ability to move.

Gait analysis is a useful tool in assessing functional changes in walking patterns that may be associated with knee OA. The study of gait or human locomotion, is attempting to identify coordinated kinematic and kinetic patterns required to control human movement. Technological advances regarding observational tools and force capturing systems have increased the capacity to quantify the spatiotemporal parameters and three-dimensional biomechanics of human gait. Three-dimensional biomechanics specific to knee OA commonly includes sagittal, frontal and transverse plane motions and moments of the knee joint. From this biomechanical viewpoint, alterations in spatiotemporal parameters and three-dimensional kinematics and kinetics demonstrate defining characteristics that are evident in the walking patterns of individuals with knee OA. These metrics have been measured by evaluating discrete metrics associated with gait (38,46,86) as well as the principal patterns that occur over the gait cycle (87).

Spatiotemporal parameters are a basic measurement of gait analyses, which can be easily captured and used in a clinical setting. These measurements are able to provide information regarding the functional capabilities of an individual's gait, and some metrics can be measured with only the use of a stopwatch. Using a pressure-sensitive walkway, clinicians can gain information on an individual's walking velocity, FPA, step width, step length, time in stance, etc. that provides more evidence to the individual's capabilities. Spatiotemporal parameters have also been utilized in the literature to understand the functional capabilities of a person with knee OA (88,89). Researchers have shown that individuals with MOA walk slower (35,47,51,86,90–92), and with an increased time spent in the stance phase of the gait cycle (34,86,91,92) compared to ASYM individuals. Conflicting results have been found for step length with some studies demonstrating similar lengths compared to healthy controls (34) and others reporting smaller step lengths in an OA population (86,91,92). Researchers have also demonstrated larger step widths (92) in OA populations compared to healthy controls, but similar FPAs (93,94). Elbaz et al. (88) demonstrated that certain spatiotemporal characteristics are good indicators for the functional severity of OA. Demonstrating in a cohort of 2911 individuals with Kellgren-Lawrence (KL) grades I-IV, that step length and stride length both decreased, while step time and percentage of stance time both increased with increasing severity (88). Elbaz study is an example of using an individual's functional capability to better understand knee OA severity status using tools available to clinicians. Yet, to fully understand the underlying joint related biomechanics, kinematics and kinetics are used to express the underlying mechanics of joints.

In knee OA literature, features within sagittal plane kinematics are commonly identified and change along with increasing disease severity (35) . In comparison to healthy, ASYM groups, individuals with knee OA tend to strike the ground at initial contact in a more flexed position (41,49,95), demonstrate reduced peak knee flexion angles during the loading response (38,41,86,96), and demonstrate a reduced knee flexion excursion during the stance phase of the gait cycle (41,95,96). Some studies have also reported a reduction in the swing phase knee angle in individuals with OA compared to a ASYM group (35). Figure 2-2 illustrates how the development of OA affects the sagittal plane knee flexion motion, specifically demonstrating reductions in the knee flexion angle during loading for both moderate and severe OA compared to an asymptomatic group, and during swing for the severe OA group.

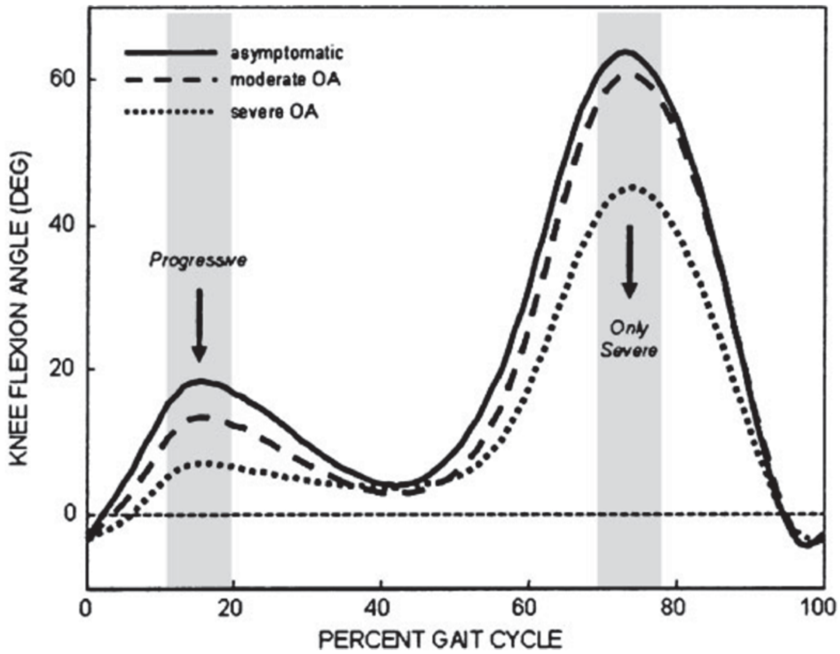

Figure 2-2: Sagittal plane knee angle over a gait cycle for an asymptomatic group, a groups of individuals with moderate OA and a group of individuals with severe OA (35). Obtained from Astephen et al., 2008, Journal of Orthopaedic Research. See Appendix A for permissions.

Changes in frontal plane knee kinematics are also commonly reported in OA literature. Specifically, studies focus on the maximum knee varus angle during stance. Individuals with knee OA demonstrate higher knee varus angles compared to ASYM cohorts (86,97). This increased knee frontal plane angle is expected in OA due to medial joint space narrowing and an opening of the lateral compartment (86). However, limitations can arise when estimating bone movement from skin mounted markers for three-dimensional motions (86), with error estimated between 2-3 degrees during the stance phase (98). As a result, these methodological concerns must be taken into consideration when frontal and transverse plane motions are interpreted.

Joint kinematics provide an “outcome” of underlying pathomechanics. To begin understanding these pathomechanics, joint moments are often investigated; taking into consideration the forces involved in the movement. Changes in three-dimensional joint moments are present in knee OA literature and commonly reported. The knee adduction moment (KAM) describes the distribution of loading between the medial and lateral compartment (23) and has been associated with instrumented knee loads (23). The KAM has been linked to disease progression in knee OA and associated with a reduction in cartilage volume (10,50,99). Individuals with knee OA demonstrate a higher first peak KAM compared to ASYM, control groups (22,43,97). However, some research has demonstrate equivocal findings compared to a ASYM groups (47,95,100). This confounding finding may be a result of different criteria on the location (medial or lateral compartment) and grade (KL-score) of knee OA. Researchers have also investigated the importance of the mid-stance minimum, understood as necessary joint unloading. Individuals with knee OA, demonstrate a reduced mid-stance minimum compared to age-matched, ASYM groups (35). This finding, as well as an increased first peak KAM is illustrated in Figure 2-3.

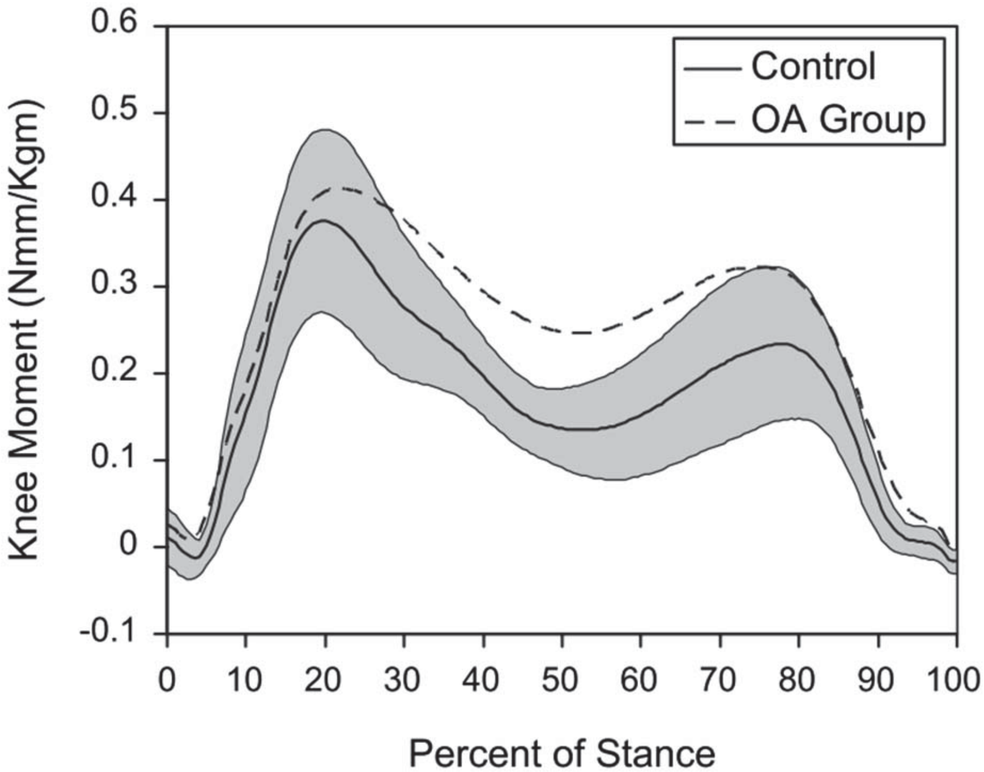

Figure 2-3: Knee adduction moment over a gait cycle comparing a group of asymptomatic individuals and a group of individuals with OA. It is important to note the elevation in both the 1st and 2nd peak, as well a reduction in the midstance minimum (43). *Obtained from Lewek et al., 2004, Osteoarthritis and Cartilage. See Appendix A for permissions.*

Knee OA literature has investigated the sagittal plane flexion-extension moment, specifically looking at the peak knee flexion moment (KFM) and the range of the flexion-extension moment. Individuals with knee OA walk with a reduced peak KFM during the stance phase of the gait cycle (22,49) however, some literature does not support this conclusion (47). A depression in flexion-extension dynamics, defined by a combination of a decreased peak flexion moment and a decreased peak late stance extension moment, is also commonly reported in individuals with knee OA (35,39,48,101,102). At this point, it is evident that individuals with knee OA walk with altered mechanics compared to healthy individuals.

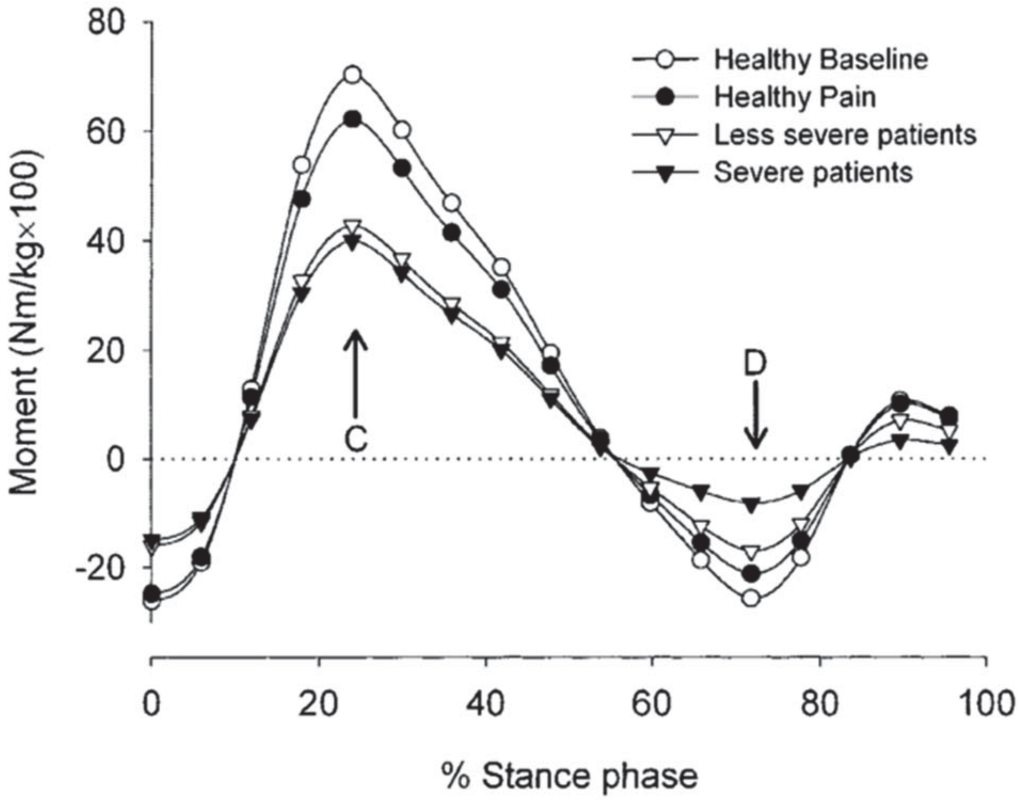

Figure 2-4: Sagittal plane knee moments over a gait cycle for an asymptomatic group, a groups of individuals with moderate OA and a group of individuals with severe OA (102). *Obtained from Henriksen et al., 2010, Arthritis Care & Research. See Appendix A for permissions.*

As evident in Figures 2-2, 2-3 and 2-4, as the disease becomes more severe, alterations in gait characteristics become more exacerbated. The knee flexion angle demonstrates reductions during the stance phase and the swing phase (41,86,95,96), with severe individuals experiencing larger reductions. Studies report that peak KAM and mid stance minimum, are altered in OA groups compared to ASYM controls (22,35,43). It is evident that biomechanical factors continue to change as the disease progresses and these factors may be linked to the progression of OA. Hatfield et al. (39) investigated if functional metrics can aid us in understanding which individuals will progress to a TKA. Using three-dimensional lower-extremity kinematics and kinetics, Hatfield et al. (39) sought to determine if differences between people with knee OA who progressed to a TKA versus people with knee OA who did not could be used as a predictive value for progression. The results of this study determined that certain gait metrics, including the overall magnitude of the KAM, demonstrated a 74% classification rate of progression to TKA (39). Other studies have supported this result and have linked the KAM with OA disease progression (50,103,104). Chehab et al. (99) also identified that the KFM is associated with OA progression, as it demonstrates that a lower peak KFM during loading response is correlated with a reduction in cartilage thickness. Together, research in the last two decades has provided an understanding that OA changes the way the joint functions. When it comes to knee mechanics, previous literature demonstrates reduced knee flexion, and a less dynamic flexion-extension moment, which indicates that the individuals could be protecting their symptomatic knee. Increased peak KAMs demonstrate that the medial compartment is under more stress and from consistent spatiotemporal findings, OA individuals are walking slower, with a wider and shorter step. The question remains what is causing the altered mechanics in a population with knee OA.

The underlying cause or causes for altered biomechanics is important for the development of gait analyses to assist understanding disease pathomechanics. Numerous studies have looked at changes with OA severity (35,40,103,105), pain (102,106,107) and radiographic evidence (55,107) however there has been a recent increase in interest pertaining to knee stability and whether this factor may also play a role (8,29,31,44). Feelings of instability can occur during any weight-bearing task, however studies have reported that most episodes of instability occur during gait (29,31,108). Recent literature has demonstrated that individuals who report instability display different mechanics than those who report stable knees (8,44). Schmitt & Rudolph (44) reported that knee instability is associated with a reduction in total knee flexion ROM during stance, however Farrokhi et al. (8) confounded this result, reporting an increase in flexion excursion in individuals who self-report instabilities. Farrokhi et al. (8) also reported an overall decrease in the total support moment, however, associated this metric to a similar reduction in walking speed in the unstable group. We often understand that a "stiff knee strategy" occurs with increased muscular contractions, less knee flexion excursion, and a less dynamic sagittal plane knee flexion-extension moment, to maintain knee stability as a result of the high demands of the early part of stance (41,43,44). Given perceptions of instability are found during gait; perhaps altered mechanics are a reflection of strategies adopted by individuals with knee OA to maintain stability or function. The challenge however is that the common method for understanding instability in individuals with knee OA is through self-report surveys.

2.3 Knee Instability

2.3.1 The Knee Outcome Survey

In order for individuals with knee OA to navigate their environment safely, it is possible that they utilize changes in gait patterns to maintain stability. Self-reported knee instability is described as a sudden loss of postural support during weight bearing as a result of buckling, shifting or giving way of the knee joint (29). In individuals with knee OA, self-reported knee instability is described in approximately 60-80% of patients (26,27,29,31), and interferes with their ability to participate in activities and function independently (27,42).

The KOS gives patients an opportunity to report how knee symptoms affect their ability to perform daily activities, as well as how their knee condition affects their capability to perform functional tasks. Each item is scored from 0-5, with 5 indicating “no difficulty” and 0 indicating “unable to perform”. The KOS has demonstrated consistency, validity and reliability within a population of 397 individuals with ligamentous or meniscal injury, patellofemoral pain and degenerative OA (109).

A question of the KOS addresses the self-reported instability of the knee joint, and will be used to address Objective 1a and 2a. The sensation of buckling or giving way of the knee joint is common in individuals with knee OA (29,110), and may be associated with how an individual will respond to a dynamic challenge to stability. Table 2-1 illustrates the question used in the KOS aiming to interpret how confident an individual is in the stability of their knee joint.

Table 2-1: Question pertaining to stability or buckling of the knee joint on the Knee Outcome Survey.

6. To what degree does buckling of your knee affect your daily activity level?	
5	I never have buckling of my knee.
4	I have buckling of my knee, but it does not affect my daily activity level.
3	Buckling affects my activity slightly.
2	Buckling affects my activity moderately.
1	Buckling affects my activity severely.
0	Buckling of my knee prevents me from performing all daily activities.

The current method for understanding stability in individuals with knee OA is the questionnaire described above, having been used for over two decades for this purpose. More recently, there has been a focus of research to understand how their self-reported episodes relate to quantifiable function through gait and proprioception testing.

2.3.2 Gait and Stability

Measures of self-reported knee instability are associated with activity limitations (26), higher levels of pain (8,29), and increase falling rates (29) demonstrating the importance of this outcome for understanding mobility. It is imperative to discover links between subjective, self- reported metrics and objective characteristics of joint function we can measure during walking.

Gustafson et al. (53) looked at the variability of knee joint motion during decline gait between individuals with knee OA with self-reported stable knees (median KL 3) and unstable knees (median KL 4). The stable OA group demonstrated reduced knee joint motion variability compared to unstable group (53). Alongside this reduction in knee joint motion variability was an increase in “stiff knee gait” (53). Gustafson et al. (53) reported that this increase in knee joint motion variability demonstrated by the unstable OA group signifies that the mechanical stability of the knee joint is compromised.

Some studies have looked at linking excessive frontal plane knee motion with instability of the knee joint. Sharma et al. (30) tested the hypothesis that knee confidence and buckling have a relationship with excessive frontal plane ROM during gait and are related to a self-reported score of physical functioning. This group scored self-reported questionnaires to determine overall knee confidence and knee buckling, and compared this to valgus-varus knee motions during gait. No correlations were found between frontal plane movements and both confidence and buckling scores (30). In contrast, Lewek et al. (43) determined that individuals with knee OA demonstrate greater frontal plane motion and instability scores than age-matched healthy individuals, concluding that this excessive motion in the frontal plane exacerbates the degradation of the medial compartment (43) but also requires more control from each of the subsystems involved in stability (36,37), including the neuromuscular system.

As mentioned above, Farrokhi et al. (8) investigated knee stability and its link with gait alterations, finding that individuals who reported unstable knees, walked slower and demonstrated small increases in knee flexion angle. These changes in gait mechanics pose questions that alterations in OA are caused by deficits in systems used to perceive the position of the limbs in space during walking, possibly linking reduced proprioception to reductions of stability in dynamic, weight-bearing activities.

2.3.3 Proprioception and Stability

Proprioception is defined as the ability to consciously and/or unconsciously perceive the spatial position and movements of a joint in space (111–113) and its link with knee OA pathomechanics is not yet fully understood (32,33,112,114,115). It is hypothesized that knee joint proprioception serves to protect against excessive movements, stabilize the joint, provide joint protection, and coordinate movements (112,113,116). Knee proprioception stems from an integration of afferent signals from proprioceptive mechanoreceptors embedded within structures in the knee and signals outside the knee (112). Testing procedures include; a position sense test and a threshold detection test (97). Generally, for a position sense test, the participant must accurately reposition their limb to a criterion angle that was previously established, assessing their ability to sense joint position. In contrast, the threshold detection test involves detecting the onset/offset of passive motion, which focuses on sensing minute joint movements. These tests and slight variations thereof have been used in the knee OA literature to assess proprioception.

To date, studies have hypothesized that dysfunctional mechanoreceptors present in individuals with knee OA, or fatigue may lead to impaired proprioception (113). Interestingly, Bayramoglu et al. (113) indicated no significant differences in knee reposition error were found between an ASYM group and a knee OA group, both before and after lower extremity fatiguing exercises (cycle ergometer). However, after further analysis, they reported that individuals with KL grades of 2 or greater demonstrated larger reposition error compared to individuals with a KL grade of 1, suggesting that rather than fatigue, joint degeneration associated with OA may play a larger role in proprioceptive deficits. While logical, this finding has been challenged. Lund et al. (114) found reduced ability to detect passive, sagittal plane motion on both symptomatic and ASYM knees, as defined by the American College of Rheumatology (ACR) criteria for clinical and radiographic OA, concluding that impaired proprioception due to knee OA is not localized to the symptomatic joint, rather it is a generalized problem affecting the entire system.

Theoretically, proprioception is inherently linked to instability, although associations have not been clear. This is due to the fact that instability is a complex problem, resulting from altered neuromuscular stabilization (neural control/active subsystem), laxity in the capsule and surrounding ligaments (passive subsystem), structural damage to cartilage and bone (passive subsystem) and impaired sensory input (neural control subsystem) (22,37). Chang et al. (117) found that the presence of self-reported knee instability was associated with a failure to provide joint angular stiffness during an open kinetic chain external valgus perturbation, with the unstable subset demonstrating decreased joint stabilization compared to a stable subset and the ASYM controls. In contrast, Kumar et al. (62) demonstrated no differences in knee flexion/extension threshold detection between a group with knee OA and an ASYM control group despite greater frontal plane varus motion and medial joint space narrowing. Knoop et al. (31) concluded that self-reported knee instability was not associated with open kinetic chain knee flexion/extension threshold detection in a population of individuals with knee OA. Together, findings suggest that proprioception testing as employed using threshold detection and position sense are not sufficient to understand why some people feel unstable during functional activities and alter gait mechanics.

The main concern within proprioception literature is regarding the vast variety of results and the inability to confidently link a measure of proprioception with self-reported stability scores. A key limitation of the aforementioned proprioceptive testing, is that these tests are not performed in weight-bearing, and this is where individuals report sensations of buckling and giving way. Our understanding of stability remains reliant on self-reported measures and limitations remain present when studying deficits in proprioception in individuals with knee OA.

2.3.4 Current Limitations in Testing Stability

There are limitations that exist in the measurement of stability through self-reported measures, gait and proprioception testing. Self-report measures of knee function are important to asses an individual's perception on how their knee is working and feeling, however, these results can also be confounded with psychosocial factors that can worsen or better their score. This is a limitation; however, self-reported measures are widely used to understand stability in knee OA populations. Measures of stability with walking assessment, may also provide little information regarding the true function of the knee joint. Traditional walking assessments are completed on stable, secured walking platforms, in controlled laboratory environment and they do not usually provide a challenge to stability beyond natural walking. Measuring stability from comfortable over-ground walking may not provide accurate results of how unstable the joint may be, and may not accurately represent the conditions they experience in daily life. Finally, assessing stability with proprioception also comes with certain limitations. Proprioception testing does not replicate the weight-bearing function of the knee joint. Our usual activities that elicit sensations of instability, most often than not, are activities when the knee joint is in a closed kinematic chain.

Perturbation testing may provide a better understanding of how individuals with knee OA walk. With stability being define above as the way system behaves following a perturbation and the ability of that system to remain within specific boundaries of control. Perturbations tests could provide a methodology for researchers to perturb the system and monitor a response to begin to further understand the strategies used for individuals to walk. Perturbations research is a novel attempt at providing information regarding function of the knee joint as the joint responds to a change.

2.4 Perturbation Research

The study of human movement and gait has been utilized in the research community for decades. However, more recently researchers have been investigating the use of external stimuli (perturbations) to alter the system measuring how individuals respond in order to possibly gain more understanding on how individuals with knee OA walk. Perturbations can occur in the frontal or sagittal plane and are used in healthy and pathological gait to understand an individual's response to a challenge, and if it differs as a result of a pathology.

In the sagittal plane, perturbations have been utilized in a variety of research disciplines. Ilmane et al. (65) used sagittal plane perturbations to compare self-rated balance difficulty between perturbed and non-perturbed gait in a group of healthy individuals. A speed change of one treadmill belt during the swing phase of the gait cycle was used to perturb the participants gait (65). Ferber et al. (118) utilized the sagittal plane perturbations during gait and measured its effects on joint motions, moments and muscle activation patterns in healthy adults. The subjects walked at a self-selected walking speed along a 5m walkway, which was capable of moving anteriorly and posteriorly 10cm upon heel contact (118). This study found after the perturbation, participants reduced knee flexion during stance, increased and delayed the peak knee flexion moment, demonstrated a decreased peak knee extension moment and showed significant increases in tibialis anterior, vastus lateralis and biceps femoris activity. The sagittal plane perturbations in each of the studies all follow the concept outlining the aforementioned definitions of stability; utilizing a perturbation to determine if the system can maintain within its confines of control. These studies attempt to challenge the motion in the sagittal plane and see how ASYM individuals and individuals with pathologies respond. The literature demonstrates that both ASYM individuals and individuals with pathologies elicit responses, specifically changing spatiotemporal and gait mechanics.

Frontal plane perturbations follow the same concept, and have been used to examine the efficacy of evaluating fall recovery and compensatory actions with gait (67,119). Peterson et al. (119) recruited ten healthy individuals who were asked to walk across a treadmill belt with an embedded force plate. The walkway would then translate the loaded stance foot medially or laterally to interrupt the gait cycle (119). Spatiotemporal gait characteristics and electromyography were measured, and they demonstrated that significant gait alterations after medial and lateral perturbations occurred in order for participants to regain walking stability (119). Specifically, step length decreased, step width and step duration increased after the perturbation occurred.

Kim et al. utilized a custom instrumented sandal designed to perturb gait during single leg stance to compare the age effects of spatiotemporal responses. During stance, the unloaded midfoot abruptly inverted (medial perturbation) or everted (lateral perturbation) (67). The results demonstrated that older adults did not significantly alter kinematics of their first recovery step, where younger individuals did. Frontal plane perturbations adequately align with the definition of stability, challenging the system to maintain control. However, frontal plane perturbations challenge the system in a different way from the sagittal plane. From the proprioception literature Chang et al. (117) found threshold detection deficits with varus/valgus perturbations but Knoop et al. (31) and Kumar et al. (62), using sagittal plane testing did not. Also the OA disease process commonly alters the medial/lateral loading distribution of the tibiofemoral joint, which authors have purported, will affect joint stability in that direction. Gait perturbations provide information regarding the ability to walk and the ability of the joint to maintain control while walking.

To date, little has been done to study the biomechanical response to frontal plane perturbations in healthy individuals and also in a group of individuals with medial compartment knee OA. It is understood that with OA, the knee joint has altered its function, and these alterations are thought to be a product of maintaining stability to safely navigate an environment. With walking perturbations, we can challenge an individual, similar to what they experience day-to-day, and measure how their response, providing information regarding the functional abilities of the knee joint that are not present during stable walking conditions.

2.5 Walking Perturbations and Knee Osteoarthritis

Walking perturbations in a population with knee OA can potentially provide valuable information regarding knee function. If we provide mechanical stress to the joint, through the use of frontal plane perturbations, we can learn about knee OA functioning as a result of their response that is not possible using currently employed methodologies of stable environment gait analyses.

Two studies have investigated the perturbation methodologies in the knee OA population. The first study aimed to investigate the influence of knee instability on muscle activation strategies in response to perturbations (63). Individuals with isolated medial knee OA were recruited and classified into two groups, based on self-reported knee instability scores from the KOS (Table 2). The participants walked at a self-selected speed across a 13-m walkway with a custom-built moveable platform, with three-dimensional motion analysis system monitoring kinematic movement (63). When unlocked, the platform translated laterally 5.8cm (0.4m/s) at initial contact. All subjects completed 20 trials, (10 lateral trials and 10 locked trials) with the subjects unaware of which trial they were going to experience the perturbation, although subjects knew that the perturbation could only happen when their foot was on the plate. Subjects rated instability during perturbation trials (0 = extreme instability, 10 = no instability). Both groups demonstrated similar severities of medial knee OA (KL grades II, III, IV), and the unstable group did report greater knee instability after experiencing the perturbation.

In terms of knee motions, no differences were observed in sagittal plane excursion and frontal plane excursion between the unstable and stable group (63). During perturbation trials both groups utilized relatively similar joint kinematics, but muscular activation strategies elicited differences (63). Higher medial quadriceps-hamstring co-contraction were found in the unstable group compared to the stable group in preparation for, during and after perturbations (63). The unstable groups utilized higher co-contraction, yet achieved similar sagittal and frontal plane knee excursion compared to the stable group suggesting the neuromuscular system is making adjustments to preserve joint function. From previous literature, higher co-contractions are associated with less ROM experienced in the sagittal plane (45). The major limitation of the study is the lack of variability within the perturbation protocol. The participants were aware of the perturbation, and were informed that it was either going to occur or not. They were aware of the direction and the distance, and could have developed preparation responses. This is evident in the fact that higher medial quadriceps and hamstring co-activation was evident in preparation for a perturbation (63). Increase the variability of perturbations (i.e. different distances and directions) may reduce the preparation response and improve the disturbed walking protocol.

The second study aimed to compare adaptations in muscle activation and joint motions in response to repeated lateral perturbations (62). The justification for the study (62) was that due to damage to joint structures and neural deficits, the ability of the neuromuscular system to execute appropriate movements in response to challenges to stability would be impaired (120). However, it is unknown whether individuals with knee OA are able to respond to perturbations in a manner similar to an ASYM group. Thirty-eight individuals with diagnosed medial knee OA and twenty-three individual without walked at self-selected walking speed over a 13m walkway (62). Researchers collected kinematics and electromyography for each individual. A 5.8cm lateral perturbation

(0.4m/s) would occur at initial contact and movement trials were blinded to the participant, the participants were allowed to view the perturbation, and could request a practice trial for safety purposes (62). The participants were asked to complete 10 normal walking trials, after which participants were notified the perturbation protocol would begin. The platform moved randomly for the first perturbation on one of the first five walking trials, after which the subjects were informed that the platform would translate on the following five trials to measure an adaptation response.

Kumar et al. (62) found that despite the pathological symptoms and activity limitations of the OA group, they responded with similar proactive and reactive responses to perturbations that challenged their walking. In regards to kinematics, both groups responded to the novel lateral perturbations with decreased sagittal plane knee motion during the loading response and mid-stance phase of the gait cycle (62). This was accompanied with an generalized increase in muscle activity in the medial and lateral quadriceps, hamstrings and gastrocnemii (62). After subsequent perturbations, knee motion increased and muscle activity decreased during the mid-stance of the gait cycle, giving evidence of an short-term adaptive response during mid-stance (62). However, no significant results were found between the ASYM and knee OA groups. The limitations of this study are similar to Schmitt and Rudolph (63). The participants were aware that either the perturbation was going to occur or not. Also, Kumar et al. (62) only reported sagittal plane kinematics, and did not indicate if differences occurred in the frontal plane (i.e. direction of perturbation) or if differences occurred in frontal or sagittal plane moments. Kinematics alone, provide an outcome for a comprehensive assessment based on current biomechanical theory of the pathomechanics involved in knee OA, however, a combination of joint moments and kinematics will provide the best representation of the underlying mechanical joint function.

Both studies investigated the response of a lateral perturbation as a challenge to walking in individuals with medial compartment knee OA. While not discussed in the papers, a lateral perturbation is thought to destabilize the medial compartment, using an unnatural movement direction during stance, and creating a compressive force on the lateral compartment and stretching the medial compartment. The perturbation protocol for the proposed study will include both lateral and medial perturbations, however, we have decided to focus on medial perturbations. Medial perturbations are thought to mimic a more natural movement direction during stance, further loading the medial compartment of the knee joint, typical in knee OA gait. Medial perturbations also reduce the body's base of support (BOS) putting increased stress on our ability to maintain stability.

The results of perturbation testing can provide important information regarding the function of the knee, which can provide evidence-based changes to how we treat OA and understand knee function in the clinical realm. Perturbation testing could also be used to validate clinical treatments that focus on improving stability, to better realize our understanding of the role of stability and walking mechanics. Understanding knee joint function in response to a disturbed walking paradigm can provide clinicians with information on knee OA joint function, possible to better understanding an individuals physical abilities and functional limitations.

2.6 Clinical Significance in Osteoarthritis

Clinical reasoning often takes the roll of understanding the function of an organ by monitoring its response to a known stress. For example, if an individual presents chest pain, an electrocardiogram is used to measure heart function while stress (exercise) is applied to the system. As a result, clinicians are able to approach treatment and patient care with comprehensive information. This “stress test” challenges the individual and provides an objective measure of a response. In orthopaedic practice, stress tests for lower extremity joint function are far from developed. Decades of work have been performed to understand joint function (biomechanics and electromyography) in individuals with knee OA. We have yet however, to significantly deviate from self-selected walking in controlled environments, limiting our understanding of how knee joint function may change when walking is challenged. Our current treatments are designed to improve knee stability with strategies including bracing, manual therapy and strengthening, but we don’t know if these treatments are making a positive impact on how individuals maintain joint function.

As mentioned above, clinicians and researchers are aware that individuals with knee OA present self-reported instability along with altered gait mechanics. This has provided some information into how the joint functions, but these results are under safe, controlled, short duration walking. Perturbations provide challenges to the joint itself by creating a short-term unstable environment, similar to what individuals experience day-to-day. The responses that are measured are possible compensatory gait alterations that can provide insight into the functional capabilities of the joint. Before the challenged walking paradigm can be implemented as a stress test, research is needed to investigate how the joint is functioning. By investigating biomechanical responses to perturbations and determining if these responses are different between ASYM individuals and individuals with knee OA, we may be able to provide data on how the joint functions when challenged.

Chapter 3 - General Methodology

The methodology was developed as a pilot study to investigate Objectives 1 and 2 described in the Chapter 1. Recruitment, instrument selection, analysis procedures and statistical analysis have been carefully selected with reference to the Nova Scotia Health Authority (NSHA) Research Ethics Board (REB) [NSHA RS 2015-137 and ROMEO No. 1028025] to effectively examine the research goals.

3.1 Subject Recruitment

3.1.1 Participants with Moderate Knee OA

A Development and Innovation Nova Scotia Health Research Foundation (NSHRF) grant (MED-DI-2014-9558) and a NSHA REB [NSHA RS 2015-137 and ROMEO No. 1028025] was obtained to complete this study on a group of individuals with MOA. Data was collected from June 2015 to January 2016, in which the author took the role of research assistant aiding with laboratory set-up, participant set-up and various components of the data collection, processing and all analysis pertaining to the thesis.

Individuals with MOA were recruited from Dr. William Stanish at the Orthopaedic and Sports Medicine Clinic of Nova Scotia. Participants were identified through direct referral from Dr. Stanish. All individuals with MOA were diagnosed using the ACR guidelines (121). The ACR classification includes knee pain, plus one of the following criteria; (1) crepitus on active movement (2) osteophyte formation (3) stiffness less than 30 minutes (4) age greater than 50 years (121). Dr. Stanish approached eligible patients with a standardized introduction to the walking study research and was given a letter pertaining to the perturbation study. Any immediate questions from the patients were answered at that time. The participant then consented to a transfer of contact information, and the participants were contacted by telephone using a standardized script to determine final eligibility for the study. The script was utilized to determine cardiovascular, respiratory and neurological health status, age, and the presence of isolated knee OA. The patient was then asked to self-report their functional capabilities to walk one city block, jog five meters, climb or descend stairs in a reciprocal fashion and ability to walk for 30 minutes continuously. This was used to help define the MOA population (61). All participants were required to meet certain inclusion criteria, which includes no history of sprain or strain in the last year and demonstrate the ability to walk independently without the use of a walking aid. All participants in the MOA group were receiving non-surgical treatment strategies and were not scheduled for a TKA. Once eligibility was determined, details of walking study, including expectations, directions to the Joint Action Research laboratory and monetary compensation were discussed.

3.1.2 Asymptomatic Participants

An NSHA REB [ROMEO No. 1028025] was obtained in order to collect an asymptomatic group for the study. This data was collected from January to April 2016, in which the author took the role of research assistant to coordinate participant recruitment and aid with laboratory and participant set-up and various components of the data collection, processing and all analysis pertaining to the thesis.

Asymptomatic individuals, age-matched to the MOA group, were recruited from the local area using social media, email and poster advertisements. Interested individuals were sent a letter outlining the details of the study. Upon final confirmation of interest, individuals were contacted via telephone, using a standard script to determine the participant's eligibility in the study. The studies inclusion criteria are:

- Over the age of 50 years
- Unilateral symptomatic knee pain
- Radiographic evidence of knee OA
- Have not been deemed a candidate for a total knee replacement surgery
- No cardiovascular disease (high blood pressure OK if controlled)
- No neurological disease
- No musculoskeletal disease or injury other than knee OA
- No lower limb surgery within the past year
- Ability to walk independently without the use of an ambulatory aid
- Functional standard for moderate knee OA
    - Able to jog 5 meters
    - Able to walk more than a city block unaided
    - Able to climb stair in a reciprocal fashion (i.e one foot over the other)

If the individual was deemed eligible, the participant was then provided details of the walking study, including directions to the Joint Action Research laboratory, contact information, and attire.

3.1.3 Sample Size

Given the developmental approach to the objectives and the information from other perturbation studies that have used group sizes between 5 and 23 participants (62,63,118,119) to detect significant differences in knee mechanics, an n of 12 individuals per group was selected. The group sizes fall within the range of sample sizes used in similar studies and made recruitment feasible over a short duration. Given the unknown ability of participants with knee OA to tolerate 30 minutes of walking while perturbations are being delivered, the sample size was limited until tolerance and feasibility could be determined.

Previous studies have detected significant differences in knee flexion range of motion between 3˚ and 5˚ (Standard Deviation = 6˚) when investigating the effects of perturbations during walking (62,63) and it has been reported that the error in calculating the knee flexion angle was less than 2˚ (122). The change in knee flexion angle was chosen because of the relevance within the literature investigating perturbations in an OA population. Beta (ß) was set at 20 percent, indicating the probability of a false positive of the null hypothesis. Power was set to 80% (Power = 1-ß) to calculate the sample size required to safely reject the null hypothesis. The power and sample size calculation was completed using a paired t-test, from the hypothesis regarding a change in knee flexion angle before and after a perturbation.

From previous literature,

Difference in knee flexion angle during loading = 5˚

Standard Deviation for knee flexion angle = 6˚

Paired t-Test
Testing mean paired difference = 0 (versus not = 0)
Calculating power for mean paired difference = difference
α = 0.05 Assumed standard deviation of paired difference = 6

Difference	Sample Size	Target Power	Actual Power
5	14	0.8	0.821565

A sample size of 14 subjects is required in each group based on a paired t-test calculation. Power and sample size calculations were performed in Minitab™ v.17.

3.2 Procedures

3.2.1 Participant Preparation

All testing was completed in the Joint Action Research laboratory within the School of Physiotherapy at Dalhousie University. Upon arrival, all participants were introduced to the laboratory setting and collection equipment. Appropriate ethical and informed consent documentation was completed and the study objectives were reviewed.

Before completing treadmill walking, the participants were asked to complete the KOS and the Knee Injury and Osteoarthritis Outcome Score (KOOS). Scores for the Western Ontario and McMaster Universities Arthritis Index (WOMAC) were calculated from the KOOS. The KOS is a self-reported survey that queries participants about how their knee symptoms and conditions affect their ability to perform general daily activities and specific functional tasks (109). The KOS demonstrates high test-retest reliability and validity (109).

The participants were then instructed to remove footwear and change into tight fitting shorts and t-shirt. Standard anthropometric measurements were taken including height, weight, and waist, hip, thigh, and shank circumferences.

Participants were asked to walk back-and-forth across the GAITRite™ portable pressure sensitive walkway approximately 15-20 times at a self-selected speed. Five walking trials were randomly recorded. These trials were used to establish the appropriate self-selected walking speed for the instrumented treadmill. The GAITRite™ pressure sensitive walkway system has demonstrated excellent reliability (ICC=0.91) and validity in measuring gait speed in older adults (123,124). Figure 3-1 is an image illustrating both the GAITRite™ walkway and the R-Mill, dual-belt instrumented treadmill.

Figure 3-1: GAITRite™ portable pressure sensitive walkway and the R-Mill dual-belt instrumented treadmill.

Passive, retro-reflective skin surface markers were then affixed to each participant. Fixed on rigid bodies (foot, shank, thigh pelvis, thorax) were clusters of four markers. Both individual markers and rigid clusters were placed bilaterally. Individual markers were placed over boney, anatomical landmarks including, the lateral aspect of the shoulders below the acromion, spinous process of the 7th cervical vertebra, greater trochanters, lateral and medial femoral and tibial epicondyles, lateral and medial malleoli, head of the 1st and 5th metatarsal, atop the 2nd metatarsal, and posterior heels. An illustration of the markers used in this study protocol is given in Figure 3-2.

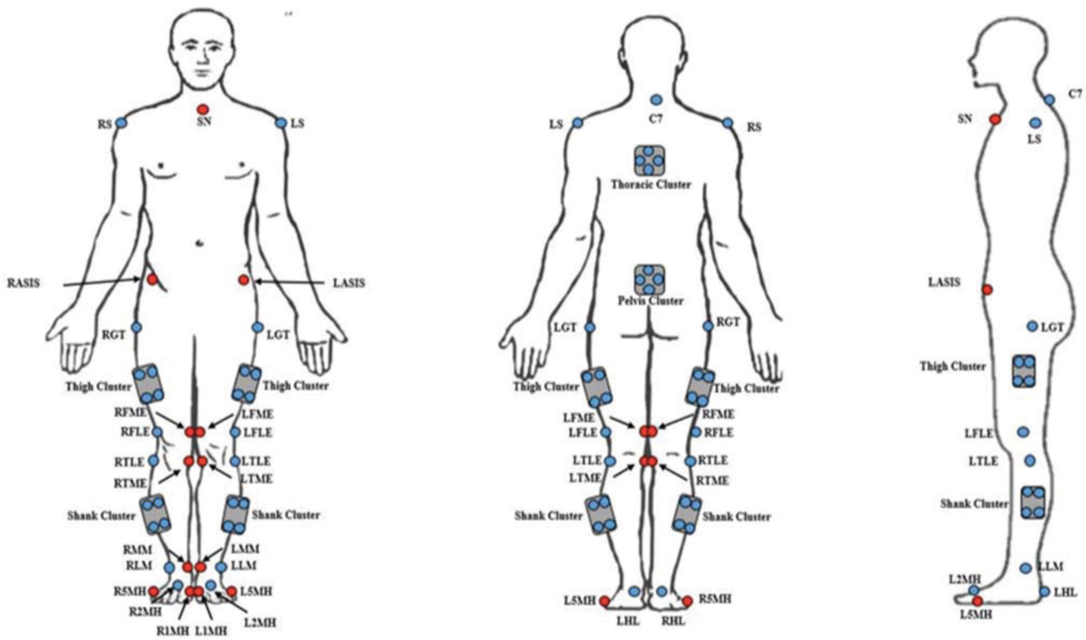

Figure 3-2: Skin surface marker set utilized for this study. Clusters are indicated by grey squares with four blue balls, virtual point markers are represented by red balls, and individual markers placed on bony landmarks are represented by blue balls.

3.2.2 Walking Protocol

For the walking protocol, participants walked barefoot on the R-Mill (Motekforce Link, Culemborg, the Netherlands) dual-belt instrumented treadmill, at the speed determined by the GAITRite™. Retro-reflective marker motion was sampled at 100Hz using eight Qualisys® OQUS 500 (Qualisys®, Gothenburg, Sweden) motion analysis cameras, while three-dimensional ground reaction forces (GRF) and moments were sampled at 2000Hz from the two force plates of the R-Mill aligned that were aligned with the motion capture system. All analog signals were acquired, analog-to-digital converted (16bit, +/-5V) and synchronized using Qualisys Track Manager V2.10.

3.2.2.1 Calibration

Following the placement of the markers, subjects stood on the treadmill with their feet shoulder width apart and knees as straight as possible while a standing trial was collected. After the standing trial, greater trochanter, femoral medial epicondyle, tibial medial and lateral epicondyle, medial malleoli and the 1st and 5th metatarsal markers were removed.

Virtual point trials were then collected to define anatomical landmarks on the sternal notch, and the left and right anterior superior iliac spines (ASIS) using a pre-calibrated digitizer wand. The position of each individual marker, rigid cluster and virtual point is represented in Figure 3-2.

3.2.2.2 Warm-Up

Prior to walking, participants were instructed to remain in the middle of the treadmill and to walk with one foot on one plate and one foot on the other plate. Participants were also harnessed to the ceiling using a rope and upper torso harness system to allow unimpeded movement of the lower extremities to occur. To acclimatize to the level of exercise, the marker set and the conditions of the treadmill, the participants walked for six minutes as recommended in ASYM adults (125,126). After acclimatization, the participants were informed the perturbation protocol will commence. They were also informed the goal is to keep walking, placing the right foot on the right plate, left foot on the left plate to the best of their ability and refrain from holding onto the railings unless absolutely necessary.

3.2.2.3 Perturbation Protocol

The perturbation protocol contained a block of eight unexpected, medial and lateral translations of the treadmill and occurred during the single leg stance, calculated as the time between contralateral toe-off and contralateral heel strike. The translation was triggered at toe-off of the contralateral leg and occurred randomly on both the left and right legs at distances of 1cm and 3cm. The rate of translation was set at 0.1m/s. The perturbations were separated by at least 40 unperturbed strides. Twenty seconds of data were recorded per perturbation, where the perturbation was triggered at ~10s to ensure at least three strides before and three strides after the perturbation could be recorded. This block of eight perturbations was repeated three times, and is illustrated in Table 3-1. The participants were blinded to occurrence, direction, and magnitude of the perturbation. The investigators did not interact with the participants during the testing.

Table 3-1: Perturbation protocol: A series of eight perturbations, unknown to the participants, that are repeated three times.

Series	Leg	Direction	Magnitude (cm)
1	Left	Lateral	1
2	Right	Medial	3
3	Right	Lateral	1
4	Left	Medial	3
5	Right	Lateral	3
6	Left	Lateral	3
7	Left	Medial	1
8	Right	Medial	1

After the participant completed all of the perturbation trials, the treadmill speed was then reduced briefly for a cool down period, which ended the walking protocol. If participants completed the protocol, a total of 24 perturbation walking trials were expected to be recorded during the testing.

3.3 Data Processing

3.3.1 Spatiotemporal Characteristics

Using motion and GRF data, stride time, stance time, swing time, step time, step length, step width, and FPA were calculated as compensatory spatiotemporal characteristics for Objective 1. Stride time, stance time, swing time and step time were calculated using the kinematic heel-strike and toe-off indicators. The heel-strike and toe-off events were calculated by determining the events in which the vertical GRF passed above or below a 30N threshold, and if those events were associated with a kinematic heel-strike or toe-off event as described by Zeni et al. (127). Kinematic heel-strike was defined as the largest distance between the heel marked and the sacrum, while toe-off was described as the largest distance between the 2nd metatarsal marker and the sacrum (127). Stride time was defined as the time between heel-strike and ipsilateral heel-strike. Stance time was defined as 1st heel-strike to ipsilateral toe-off and swing time was defined as ipsilateral toe-off to the following ipsilateral heel-strike. Stance time and swing time were then normalized to the stride time and represented as percentage of the gait cycle. Step time was calculated as the time between an ipsilateral heel-strike and a contra-lateral heel-strike (i.e. Right step time is from the left heel strike to the next right heel strike).

Step length and step width were defined as the distance between a toe-off and a contralateral heel-strike. Step length used the markers on the 2^{nd} metatarsal and the heel marker on contralateral feet to calculate the distance in the positive x direction. Step width used the heel markers on contralateral feet to determine the distance in the y direction. Foot progression angle was defined as the angle created between the forward x direction and the vector created by the 2^{nd} metatarsal and the heel and calculated at 50% of stance. A positive FPA represents an increase in toe-out. T1 represented the first spatiotemporal event to occur immediately after the perturbation, while T3 represented the third. The spatiotemporal event (i.e. FPA) occurring in the each of the three strides before the perturbation occurred were averaged and denoted as T0.

3.3.2 Kinematics

Eight Qualisys® OQUS 500 (Qualisys®, Gothenburg, Sweden) motion analysis sensors captured the movement of passive retro-reflective skin surface markers attached to the body [Figure 3-1]. Since the camera coordinate system and the force plate system would not align once a perturbation occurred, all kinematic data were transformed to the treadmill coordinate system using equation 3-1.

$$P_{LOCAL} = [T_{TREADMILL}]^{-1} * P_{GLOBAL} \qquad [3\text{-}1]$$

P_{LOCAL} = Point in the local coordinate system
$T_{TREADMILL}$ = Transformation matrix of the Treadmill coordinate system
P_{GLOBAL} = Point in the global coordinate system

All kinematic data were low pass filtered (Butterworth 4^{th} order, 6Hz - recursive) and processed using pre-programmed software (JAR v3.1) written in MatLab Ver. R2015a (The Mathworks Inc., Massachusetts, USA). From this data, local and technical anatomical bone embedded coordinate systems for the pelvis, thigh, shank and foot were derived from skin markers, rigid clusters and virtual points. Joint angles were calculated using Cardan/Euler rotations (34) with order Flexion/Extension, Abduction/Adduction, Internal Rotation/External Rotation. The primary flexion/extension axis of the hip and knee were oriented in a medio-lateral direction defined by a vector embedded between the ASIS and medial and lateral femoral epicondyles, respectively. For the thigh, the medial-lateral axis was fixed, the anterior-posterior and distal-proximal axis were a result of the cross product to define an orthonormal coordinate system, based on the original axes from the greater trochanter to the lateral epicondyle of the femur. For the shank, the distal-proximal axis was fixed and the anterior-posterior and medial-lateral axis were crossed, based on the original axes from the lateral to medial malleolus of the shank. For the pelvis, the axis between the ASIS was fixed, an all other axes were crossed. Flexion, abduction and internal rotation about the knee and hip joint were described as positive motion. Joint angles were described as the distal segment moving about a fixed proximal segment (34)

Heel strike and toe-off events were determined using a method described in *3.3.1 Spatiotemporal Characteristics*. A gait cycle began with participant heel strike and terminate with a second heel strike of the ipsilateral leg. Angle waveforms were time normalized to 100% of the gait cycle.

3.3.3 Kinetics

Each of the force plates embedded on the walking surface contains 6 sensors that provide, using a calibration matrix (Motekforce Link, Culemborg, the Netherlands), three-dimensional GRF and moments. Ground reaction forces and moments were low-pass filtered (recursive Butterworth 4th order, 30Hz) and processed on pre-programmed software (JAR v3.1) written in MatLab Ver. R2015a (The Mathworks Inc., Massachusetts, USA).

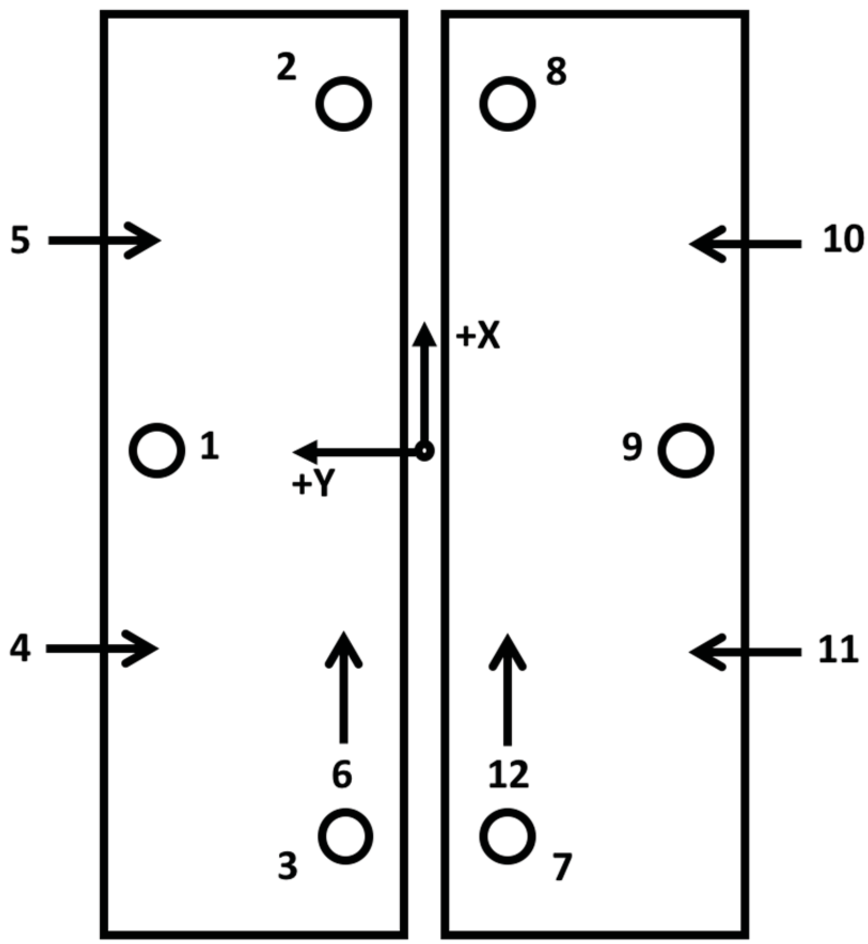

Figure 3-3: Schematic of the R-Mill treadmill with force places and orientation of the positive x and y directions. The numbers indicated the force transducers associated with each plate.

Ground reactions forces, kinematics, subject anthropometrics and inertial properties were used to derive external joint moments using an inverse dynamics approach (128).

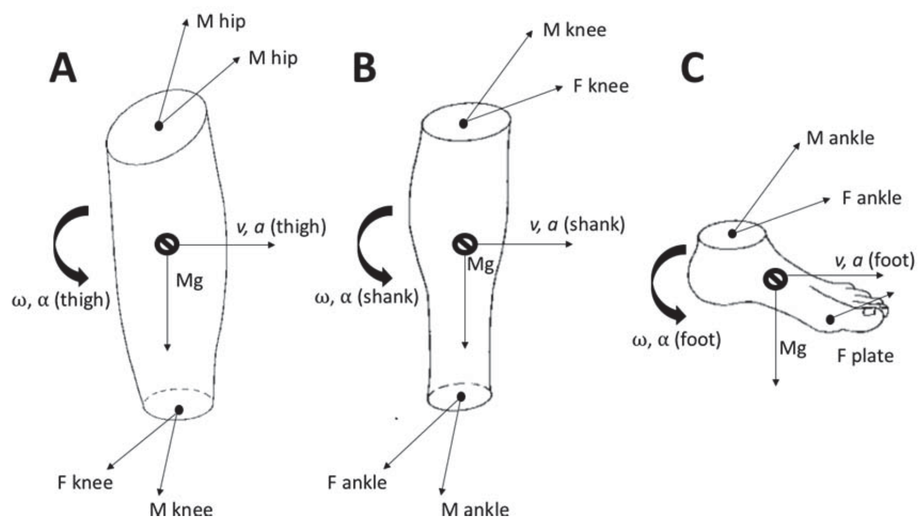

Figure 3-4: General free body diagrams demonstrating external moments (M) and forces (F) calculated through segment modeling of the lower extremity. Three-dimensional forces and moments are represented in the X, Y and Z dimensions. Mg represents the mass of the segment multiplied by the acceleration due to gravity. Fplate represents the three-dimensional resultant force from the plate. Acceleration terms are also demonstrated for the thigh, shank and foot. Modified from Vaughan's Gait Book (128).

To calculate forces and moments, free body diagrams were established for each body segment, as seen in Figure 3-3, and a summation of the external forces and moments acting about each segments centre of gravity were used to calculate segments rate of change of linear and angular momentum (128). Along with a direct application Newton's Laws of Motion, three-dimensional joint forces and moments were calculated and expressed in terms of a joint specific-based coordinate system (34,48). Three-dimensional joint forces and moments were expressed in the orientation described for kinematic assessment, however, there was a floating axis created in order to project the moments into the joint coordinate system (129) . Moments were low-pass filtered (recursive Butterworth 4th order, 10Hz) and normalized to body mass (Nm/kg). Moments were time normalized to 100% of the stance phase.

3.4 Data Analysis

The symptomatic leg was chosen for the MOA group, while a random leg was chosen from the ASYM group. Three strides before (T0) the perturbation occurred were averaged to represent baseline strides and two individual strides after the perturbation were obtained to represent the response of the spatiotemporal characteristics, the knee and hip motions and knee moments. The first and third (T1, T3) stride were represented by individual waveforms.

Discrete variable analysis has been previously implemented in OA literature to investigate three-dimensional joint mechanics (40,41,47,49,86,96). Using kinematic data, peaks and ranges of motion previously tested in OA literature will be extracted (41,130,131). Metrics from the knee kinematics included i) knee angle at initial contact ii) knee flexion range from initial contact to peak flexion during stance and iii) the range between peak knee flexion during stance to peak extension in late stance v) total frontal plane knee ROM during the stance phase of the gait cycle (30,130). From hip kinematics, the total hip ROM range during stance were extracted from each the sagittal and frontal plane. From frontal and sagittal plane knee moments, peaks and ranges were extracted from the sagittal plane and peaks from the frontal plane. Metrics from the sagittal plane include i) peak KFM ii) peak knee extension moment and iii) the range between the peak flexion and peak extension moment. From the frontal plane, the peak KAM were used for statistical analysis (35,130).

3.5 Statistical Analysis

This section provides the details of the statistical analysis for Objectives 1 & 2. Student's t-test was used to determine significant differences between groups for subject demographics and walking speed. Assumptions of equal variance and normality were examined using Kolmogorov-Smirnov and Levene's test for all continuous variables (α=0.05). For each perturbation magnitude, a two-way, mixed model Analysis of Co-variance (ANCOVA) was utilized to test the null hypotheses of Objectives 1 and 2, adjusted for differences in walking velocity as has been previously employed (42,43,63,92). The assumptions of the ANCOVA are as follows: (1) For each independent variable, the relationship between the covariate and the dependent variable is linear (2) There is homogeneity of the regression slopes (3) The covariant and independent variables are independent. If the assumptions of the ANCOVA or if walking velocity was not a significant addition to the model, an Analysis of Variance (ANOVA) was conducted. Bonferonni's post-hoc testing ($p<0.05$) were used for all significant effects. Since this study is an exploratory investigation, borderline significant effects ($p=0.05$ to $p=0.1$) were also highlighted. Figure 3-4 illustrates an example of the between (ASYM and MOA) and within (T0, T1, T3) group comparisons that were made in each perturbation magnitude.

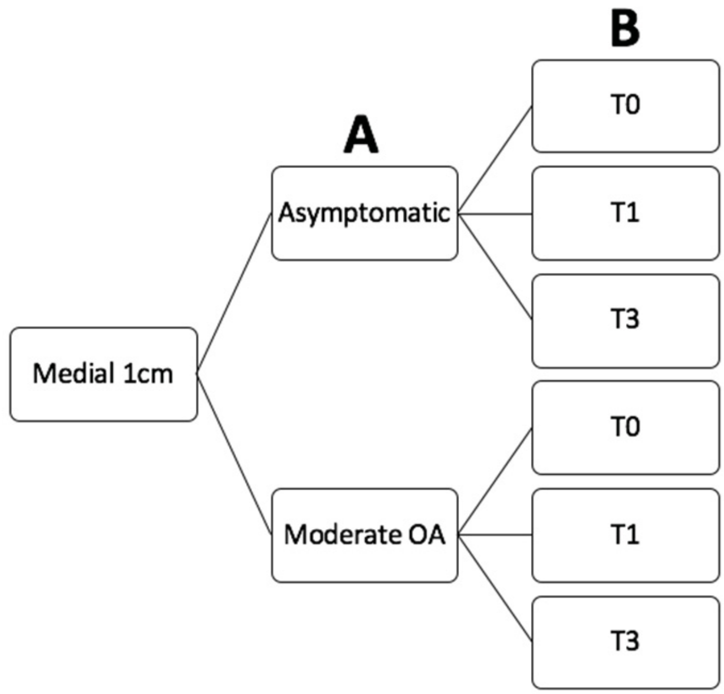

Figure 3-5: Representation of the (A) between group and (B) within group comparisons used for the medial 1cm perturbation direction and magnitude during statistical analysis for each variable if interest.

Spearman's correlations were completed between subjective stability scores measured on the KOS for the MOA group against statistically significant group by time interactions determined in Objectives 1a and 2a. All statistics were performed in Minitab™ v.17 (Minitab Inc., Pennsylvania, USA).

Chapter 4 - Spatiotemporal Response

4.1 Introduction

Stability is understood as the way a system behaves following a perturbation, and if the state of that system remains within specific boundaries of control (58–60). This definition originates in physics, but has recently been adopted to understand knee joint stability. Using spatiotemporal parameters, we can begin to develop an understanding of how individuals walk after a perturbation aimed at challenging stability. Peterson et al. (119) studied a group of ten young adults investigating spatiotemporal contributions to fall recovery after perturbations. They reported that step length and step duration both decreased after a medial perturbation, while no changes were evident in step width (119). A second study by Kim et al. (67) utilized perturbations to understand the effects of age on perturbation response, specifically investigating step width and step length. Kim et al. demonstrated that after perturbations, both older and young individuals reacted similarly; decreasing step length and increasing step width (67). This response came at different times, with the younger group responding on the immediate stride after perturbations and the older group responding on the following stride (67). Both studies are investigating a challenged walking paradigm, but neither is interested in the abilities of individuals who self-report instabilities and a lack of confidence in their joint. How individuals who report unstable joints respond to perturbations, could provide information towards day-to-day walking of individuals with knee OA.

4.1.1 Objective 1

To determine if spatiotemporal gait characteristics (stride time, step width, FPA, etc.) are altered in response to unexpected 1 and 3cm medial walking surface translations of the symptomatic limb during stance in individuals with MOA compared to an ASYM control group.

a. To determine if self-reported measures of stability, specifically question 6 of the KOS which outlines sensations of buckling, shifting or giving-way are related to spatiotemporal outcomes during dynamic perturbation testing.

4.1.2 Hypothesis

For Objective 1, it is hypothesized that medial 3cm walkway translations will alter the spatiotemporal characteristics of both the MOA and ASYM groups. Immediately after the perturbation, there will be a decrease in stride time, stance time, swing time and step time. A decrease in step length will be accompanied by an increase in step width and an increase in FPA in both groups. Medial 1cm walkway translations will not alter spatiotemporal characteristics in either group.

a. A significant positive relationship will exist between self-reported measures of stability from the KOS and spatiotemporal characteristics measured during dynamic gait.

4.3 Results

4.2.1 Group Demographics

All subjects were able to complete the gait analysis protocol. Table 4-1 illustrates demographics, anthropometrics, gait velocity, self-report scores and perturbations outcomes for both groups. Kellgren-Lawrence grades were included in Table 4-1 for the MOA group. No significant differences were found between participants' age and height in each group. Significant differences were found between mass ($p<0.001$), BMI ($p<0.001$) and walking velocity ($p=0.02$), demonstrating that the MOA group walked slower and was heavier then the ASYM group. Significant differences were found in all KOOS ($p<0.001$), and WOMAC ($p<0.001$) self-report scores as well as KOS stability score ($p<0.001$). A low score indicates greater level of impairments on the KOOS and KOS, while a low score on the WOMAC indicates greater functional capabilities and less impairment. Graded radiograph scores demonstrate that the MOA group showed KL grades ranging from KL I to III, with the majority [7] at KL II. The ASYM group did not have radiographs for scoring. A successful perturbation trial is defined as the individual responding to the perturbation without holding onto hand rails and the individuals was able to keep their right foot on the right plate and their left foot on the left plate.

Table 4-1: Mean (Standard Deviation) participant demographics, anthropometrics, and self report scores and radiographic grades for asymptomatic and moderate knee OA groups.

Variable	Asymptomatic	Moderate OA
n	12	12
Sex (M:F)	6:6 (50% Male)	8:4 (67% Male)
Age (years)	61 (8)	60 (8)
Height (m)	1.69 (0.09)	1.71 (0.08)
Mass (kg)	65.2 (12.0)*	87.6 (13.2)*
BMI (kg/m^2)	22.7 (3.0)*	29.9 (4.2)*
Walking Velocity (m/s)	1.19 (0.13)*	1.06 (0.12)*
KOS Stability Score (n/5)	(12) 5	(4)5, (3)4, (1)3, (3)2, (1)1
KOOS	-	-
Symptoms (n/100)	99.4 (2.1)*	58.3 (11.8)*
Pain (n/100)	100 (0)*	64.1 (19.6)*
Activities of Daily Living (n/100)	100 (0)*	65.8 (19.8)*
Quality of Life (n/100)	100 (0)*	42.7 (19.3)*
WOMAC	-	-
Pain (n/20)	0 (0)*	6.6 (4.2)*
Stiffness (n/8)	0 (0)*	3.5 (1)*
Physical Functioning (n/68)	0 (0)*	23.3 (13.5)*
Radiographic grade (n)	-	-
KL 0	-	0
KL I	-	4
KL II	-	7
KL III	-	1
KL IV	-	0
Successful Perturbations	-	-
Medial 1cm (n/72)	67	69
Medial 3cm (n/72)	54	56
Total (n/144)	121	125

→ * denotes significant differences between groups

Walking velocity differences were significant between the two groups (p=0.02), with the MOA group on average walking 0.13m/s slower then the ASYM group. Pearson correlations were used to determine if walking velocity was associated with biomechanical variables. Walking velocity correlated with initial contact to peak flexion sagittal plane knee ROM (r=0.368, p=0.001), sagittal plane hip ROM during stance (r=0.341, p=0.003), sagittal plane knee peak extension moment (r=-0.259, p=0.028) and the sagittal plane knee flexion-extension moment range (r=0.420, p<0.001).

4.2.2 Medial Perturbations

Table 4-2 provides average spatiotemporal characteristics for each group at T0, T1 and T3 for a medial 1cm perturbation. No group differences were found in swing time, step length, step width or FPA between the ASYM and MOA groups (p>0.10). Significant group effects were found in stride time (p=0.004), stance time (p=0.001), and step time (p=0.003). These results demonstrate that the MOA group generally have a longer stride time and spend more time in stance compared to the ASYM group. The MOA group also demonstrates a longer step time than the ASYM group.

Time main effects were found in stance time (p=0.013), step width (p=0.005), and FPA (p=0.029). These results demonstrate that both groups responded to 1cm perturbation with a shorter stance time and more toed-in FPA immediately after the perturbation (T1) compared to before (T0) and returned to baseline by the third stride (T3). Both groups also demonstrated an increase in step width on the third stride after a perturbation (T3) compared to before (T0) and immediately after (T1). There were no significant group by time interactions in any reported spatiotemporal characteristics for medial 1cm perturbations.

Table 4-2: Mean (Standard Deviation) spatiotemporal characteristics of both moderate knee OA and asymptomatic groups before (T0), immediately after (T1), and the third stride after (T3) a medial 1cm perturbation.

Medial 1cm	**Group Effects**		
	Asymptomatic		**Moderate OA**
Stride Time (s)	1.02 (0.05)		1.11 (0.08)
Stance Time (%GC)	60.1 (1.7)		62.2 (1.7)
Step Time (s)	0.51 (0.03)		0.55 (0.04)
	Time Effects		
	T0	**T1**	**T3**
Stance Time (%GC)	61.4 (1.7)	60. (2.3)*	61.6 (1.8)
Step Width (m)	0.18 (0.02)	0.18 (0.03)	0.20 (0.03)*
Foot Progression Angle (˚)	9.8 (4.0)	9.1 (4.4)	10.3 (4.9)

→ * represents significant time effects different from T0 (p<0.10)

Table 4-3 provides average spatiotemporal characteristics for each group at T0, T1 and T3 for a medial 3cm perturbation. Consistent with medial 1cm perturbations, no group differences were found in step length, step width or FPA (p>0.10) between ASYM and MOA groups, however no group differences were also found in stance time (p=0.449) and swing time (p=0.104). Significant group effects were found in stride time (p=0.006) and step time (p=0.004), which are similar to results found in medial 1cm perturbation. These results demonstrate that the MOA group had a longer stride time and step time compared to the ASYM group.

Consistent with medial 1cm perturbations, time effects were found in stride time (p=0.007), stance time (p<0.001) and step width (p<0.001), however, medial 3cm perturbations demonstrated time effect in swing time (p<0.001) and step time (p<0.001). No time affects were found in step length (p=0.116). These results show that both groups demonstrated a shorter stride time, stance time, swing time, step time and a more toed in FPA immediately after (T1) the perturbation, and responses returned to baseline (T0) by the third stride (T3). In terms of step width, both groups responded with a wider step immediately (T1) and three strides after the perturbation (T3) compared to baseline (T0).

Table 4-3: Mean (Standard Deviation) spatiotemporal characteristics of both moderate knee OA and asymptomatic groups before (T0), immediately after (T1), and the third stride after (T3) a medial 1cm perturbation.

Medial 3cm	**Group Effects**					
	Asymptomatic			**Moderate OA**		
Stride Time (s)	1.01 (0.06)			1.10 (0.08)		
Step Time (s)	0.50 (0.03)			0.55 (0.05)		
	Time Effects					
	T0		**T1**		**T3**	
Stride Time (s)	1.06 (0.08)		1.04 (0.09)*		1.05 (0.08)	
Stance Time (%GC)	61.4 (1.7)		60.4 (2.3)*		61.6 (1.8)	
Swing Time (s)	0.41 (0.03)		0.37 (0.05)*		0.41 (0.03)	
Step Time (s)	0.53 (0.04)		0.50 (0.06)*		0.53 (0.04)	
Step Width (m)	0.18 (0.02)		0.21 (0.03)*		0.22 (0.04)*	
	Group* Time Interactions					
	Asymptomatic			**Moderate OA**		
	T0	*T1*	*T3*	*T0*	*T1*	*T3*
Foot Progression Angle (˚)	10.2 (5.2)	6.4 (5.2)X	10.3 (5.5)	9.5 (3.5)	8.4 (3.8)	9.4 (4.1)

→ * represents significant time effects
→ X depicts a group by time interaction

A significant group by time interaction was found for FPA (p=0.008) after a medial 3cm perturbation, which is inconsistent with results from medial 1cm perturbations. Both groups toed-in at T1 compared to T0, however, the ASYM group responded to a medial 3cm perturbation (T1) with a higher amount of toed in FPA than individuals with MOA.

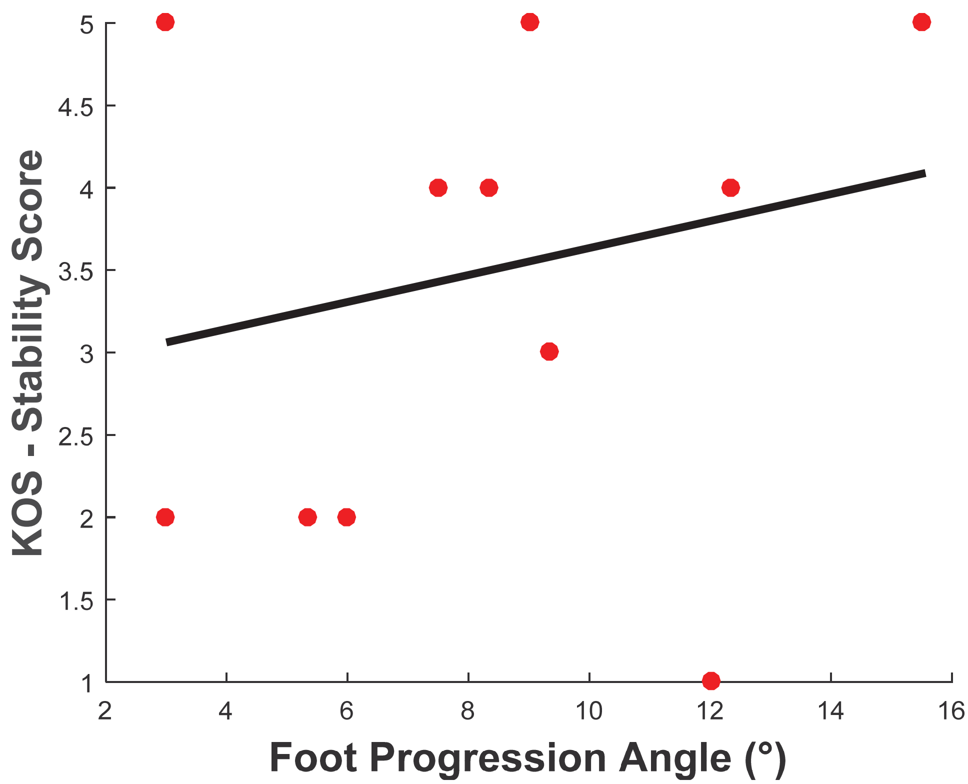

Figure 4-1:Spearman's ranked correlation of the moderate OA groups foot progression angle (˚) by self-reported KOS stability score (n/5).

A Spearman ranked correlation was used to test associations between FPA and KOS self-reported stability scores recorded in the MOA group. Figure 4-1 illustrates this association. A lower score on the KOS indicated a higher sensation of buckling, shifting or giving way of the knee joint. No association was demonstrated between the self-reported stability score and the FPA (r=0.194, p=0.546). Only group by time interactions were tested for an association with KOS self-report stability scores using Spearman ranked correlation.

In summary, this study demonstrated that individuals with MOA walk with shorter stride times, step times, longer time spent in stance and shorter time spent in swing compared to an age-matched, ASYM group. However, when responding to both medial 1cm and medial 3cm perturbations, both groups had a similar response. After medial 1cm perturbations, both groups responded with a shorter time in stance at T1 and a wider step width at T3. After medial 3cm perturbations, both groups demonstrated shorter stride times, step times, shorter time in stance and shorter time in swing at T1 and a wider step width at T1 and T3. The FPA demonstrated the only group by time interaction, where the MOA group responded with smaller toed-in angle at T1 compared to the ASYM group. This group difference was not explained by KOS self-report stability score, as no association was determined by Spearman ranked correlations.

Spatiotemporal parameters provide information regarding functional capabilities of individuals with knee OA, but do not provide information on underlying pathomechanics of the involved joint. Joint biomechanics is used to understand a deeper piece of the puzzle.

Chapter 5 – Joint Level Biomechanical Response

5.1 Introduction

To gain an understanding between joint structural and functional impairments and limitations (i.e. walking), a biomechanical gait assessment serves as an important tool. During dynamic tasks, the knee aims to balance between stability and mobility, which while minimizing loading, have been shown to be difficult for individuals with knee OA (9,38–40). From a physics perspective, stability is defined as the way a system behaves following a perturbation, and if the state of that system remains within specific boundaries of control (58–60). Therefore, to further understand how individuals with sensations of instability walk, we must challenge the system and record how they respond. Only two studies have employed perturbation protocols in individuals with knee OA (62,63). In both studies, a 5.8cm (0.4m/s) lateral perturbation of the symptomatic limb on an instrumented over ground platform was used. Schmitt and Rudolph investigated two groups of individuals with knee OA who were separated into self-reported stable and unstable groups (63) and monitored sagittal plane mechanics. Kumar et al. investigated a group of individuals with knee OA and compared them to a healthy cohort, focussing on sagittal plane mechanics (62). Results were confounding, Schmitt and Rudolph found no differences between groups in knee flexion range during stance as a result of the perturbation(63), while Kumar found a reduction in knee flexion range during stance after the perturbation, but this response was evident in both groups (62).

Currently, literature in this area of study is limited. But, it is understood, that individuals with knee OA face challenges to maintaining knee stability day-to-day.

Therefore, understanding the responses to unexpected medial perturbations in both healthy and populations with knee OA is important and it is possible to stress the mechanisms that work to maintain joint function and stability during walking?

5.1.1 Objective 2

To determine if unexpected 1cm and 3cm medial walking surface translations to the symptomatic leg during stance will result in immediate alterations in:

- Sagittal and frontal knee motions during gait in individuals with MOA compared to an ASYM control group.

- Sagittal and frontal hip motions during gait in individuals with MOA compared to an ASYM control group.

- Sagittal and frontal knee moments during gait in individuals with MOA compared to an ASYM control group.

a. To determine if self-reported measures of stability, specifically question 6 of the KOS which outlines sensations of buckling, shifting or giving-way are related to biomechanical outcomes during dynamic perturbation testing.

5.1.2 Hypothesis

For Objective 2, the null hypothesis include:

- No changes will occur in frontal plane knee motions in both MOA and ASYM groups immediate after a 1cm and 3cm medial walkway translations. No changes will occur in the sagittal plane knee motions after a 1cm medial walkway translation. Immediately after a medial 3cm walkway translation significant difference will be found, with both groups striking in more flexion at initial contact and peak flexion during stance, however, going through similar range from initial contact to peak flexion and from peak flexion to peak extension.

- No changes will occur in frontal plane hip motions in both MOA and ASYM groups immediately after 1cm and 3cm walkway translation. No changes will occur in sagittal plane hip motions after a 1cm medial walkway translation. Immediately after medial 3cm walkway translation a significant difference will be found in total hip ROM during stance in both groups.

- No changes will occur in frontal plane knee moments in both MOA and ASYM groups immediately after 1cm and 3cm walkway translations. No changes will occur in the sagittal plane knee moments after a 1cm medial walkway translation. Immediately after medial 3cm walkway translation, the dynamic sagittal plane moment range (peak flexion to peak extension moment) will be reduced in both groups.

a. A significant relationship will exist between self-reported measures of stability from the KOS and biomechanical outcomes measured during dynamic gait.

5.2 Results

5.2.1 Knee Kinematics

Sagittal plane knee motions corresponding to medial 1cm perturbations for both groups and times before (T0) and immediately after (T1) perturbations are shown in Figure 5-1.

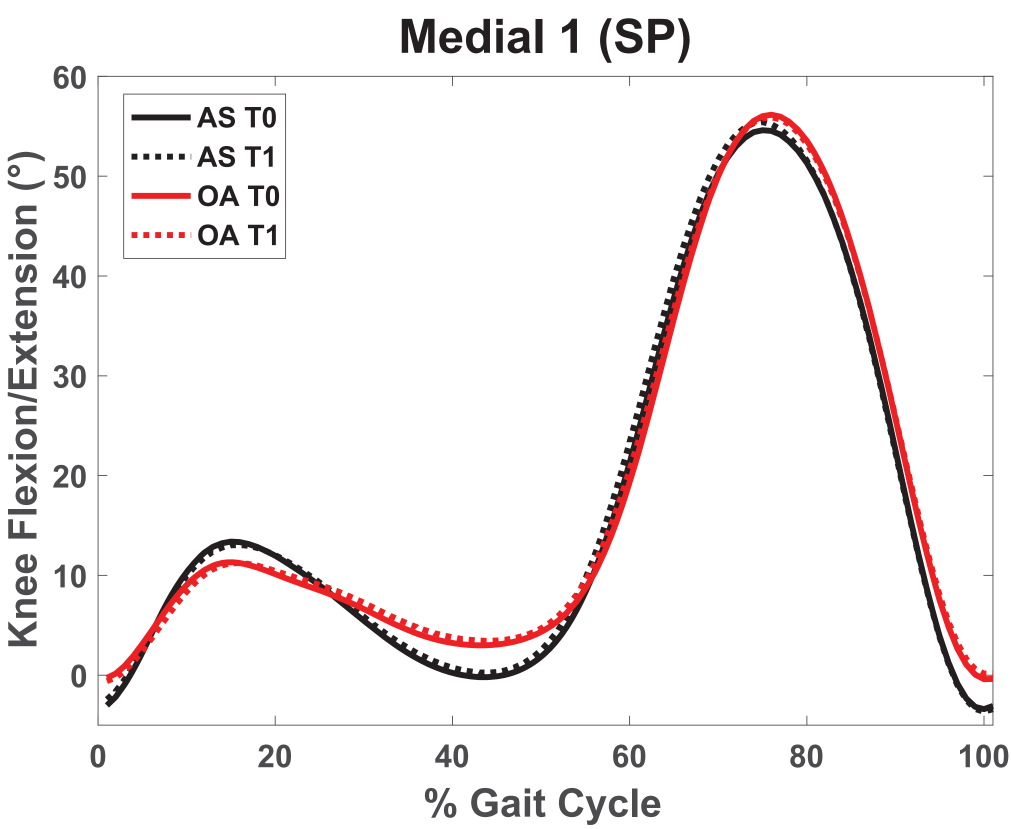

Figure 5-1: Sagittal plane (SP) knee kinematics for medial 1cm perturbations. The moderate OA group is represented by red curves and the asymptomatic groups are represented by black curves. Before the perturbation (T0) is represented by the solid line and the first stride after the perturbation (T1) is represented by the dotted line.

No significant sagittal plane motion group effects were found for initial contact (p=0.250), however a group effect was found for the range from peak flexion to peak extension during stance (p=0.025) and a borderline group effect was found for the range from initial contact to peak flexion (p=0.054) where individuals with MOA go through less ROM during late stance compared to the ASYM group. No time or group by time interactions were found (p>0.10). The data is found in Table 5-1.

Table 5-1: Mean (Standard Deviation) knee kinematic response of both moderate knee OA and asymptomatic groups before (T0), immediately after (T1), and the third stride after (T3) a medial 1cm perturbation.

Medial 1cm	**Group Effects**	
	Asymptomatic	**Moderate OA**
Initial Contact to Peak Flexion (˚)	16.1 (4.1)	12.0 (5.7)
Peak Flexion to Peak Extension [0-60%] (˚)	13.5 (4.6)	8.7 (4.9)

→ shaded rows depicts a group effect
→ * depicts a time effect
→ Positive angle represents flexion and negative angle represents extension

In Figure 5-2, sagittal plane knee motions corresponding to medial 3cm perturbations for both groups and times before (T0) and immediately after (T1) perturbations are shown.

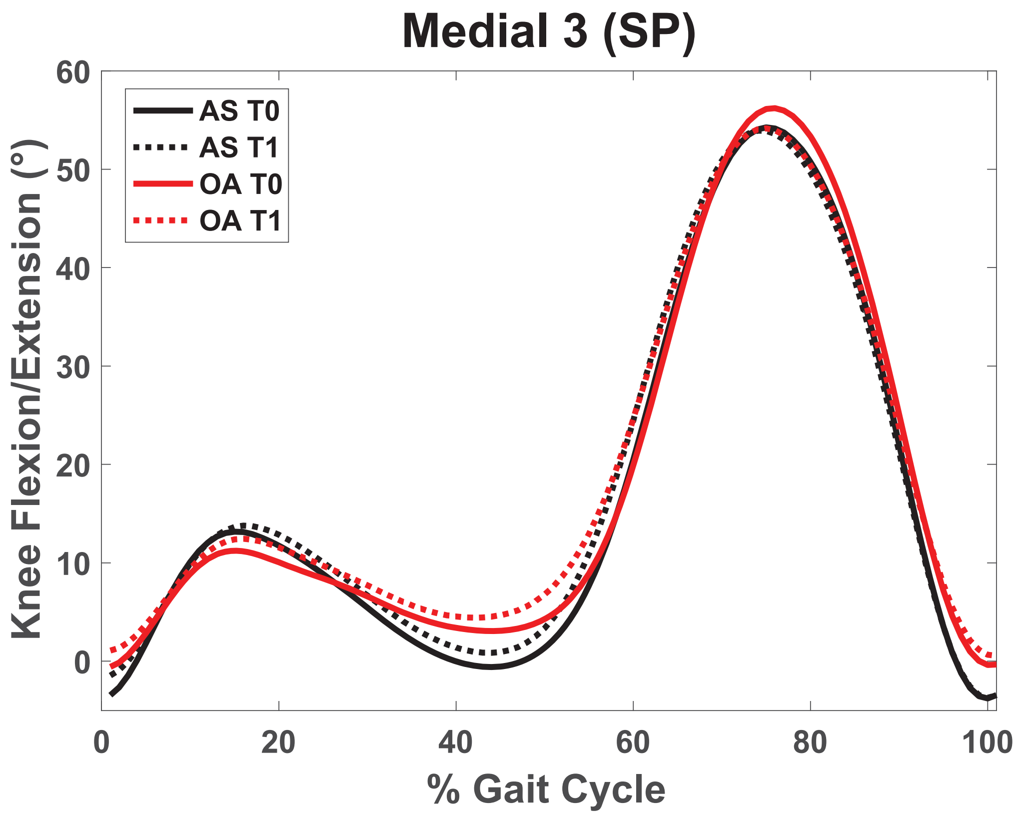

Figure 5-2: Sagittal plane (SP) knee kinematics for the medial 3cm perturbations. The moderate OA group is represented by red curves and the asymptomatic groups are represented by black curves. Before the perturbation (T0) is represented by the solid and the first stride after the perturbation (T1) is represented by the dotted line.

Consistent with medial 1cm, no group effects were found for initial contact and after a medial 3cm perturbation, significant group effects were evident for the range from initial contact to peak flexion (p=0.029) and the range from peak flexion to peak extension (p=0.016) showing that individuals with MOA demonstrate less knee ROM throughout stance phase compared to the ASYM group. No time affects were found for the ranges from initial contact to peak flexion and the range from peak flexion to peak extension, which was similar to medial 1cm perturbation. A significant time effect for initial contact (p=0.003) was demonstrated after a medial 3cm perturbation showing that both groups responded to a medial 3cm perturbation by immediately (T1) striking in more knee flexion at initial contact, but returning to baseline (T0) by the third stride (T3). The data is found in Table 5-2.

Table 5-2: Mean (Standard Deviation) knee kinematic response of both moderate knee OA and asymptomatic groups before (T0), immediately after (T1), and the third stride after (T3) a medial 3cm perturbation.

Medial 3cm	**Group Effects**		
	Asymptomatic	**Moderate OA**	
Initial Contact to Peak Flexion (˚)	16.1 (4.2)	11.7 (5.2)	
Peak Flexion to Peak Extension [0-60%] (˚)	13.7 (4.9)	8.8 (4.8)	
	Time Effects		
	T0	**T1**	**T3**
Initial Contact (˚)	-2.0 (5.2)	-0.2 (6.1)	-1.6 (4.8)

→ shaded rows depicts a group effect
→ * depicts a time effect
→ Positive angle represents flexion and negative angle represents extension

In the frontal plane, neither group nor time effects were found after medial 1cm or 3cm perturbations (p>0.10). No group by time interactions were demonstrated from sagittal and front plane knee kinematic variables.

5.3.2 Hip Kinematics

Sagittal plane hip motions corresponding to medial 1cm perturbations for both groups and times before (T0) and immediately after (T1) perturbations are shown in Figure 5-3.

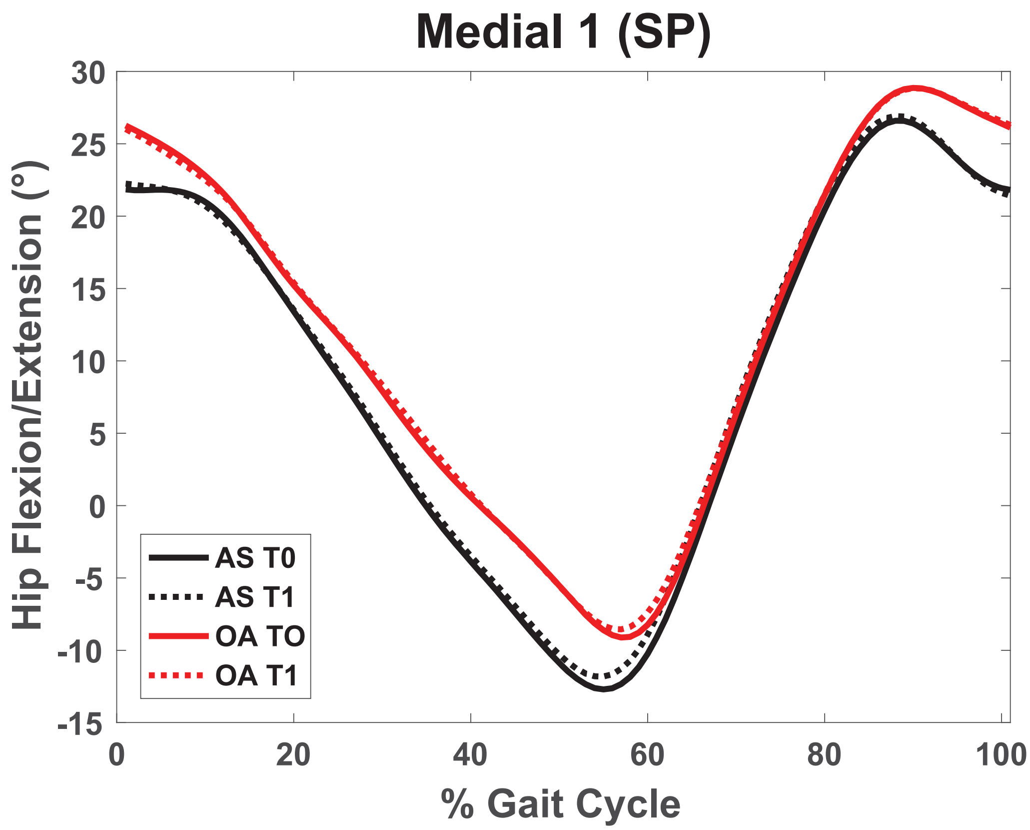

Figure 5-3: Sagittal plane (SP) hip kinematics for medial 1cm perturbations. The moderate OA group is represented by red lines and the asymptomatic groups are represented by black lines. Before the perturbation (T0) is represented by the solid and the first stride after the perturbation (T1) is represented by the dotted line.

No sagittal or frontal plane group, time main effects or group by time interactions were evident in medial 1cm ($p>0.10$).

In Figure 5-4, sagittal plane hip motions corresponding to medial 3cm perturbations for both groups and times before (T0) and immediately after (T1) perturbations are shown.

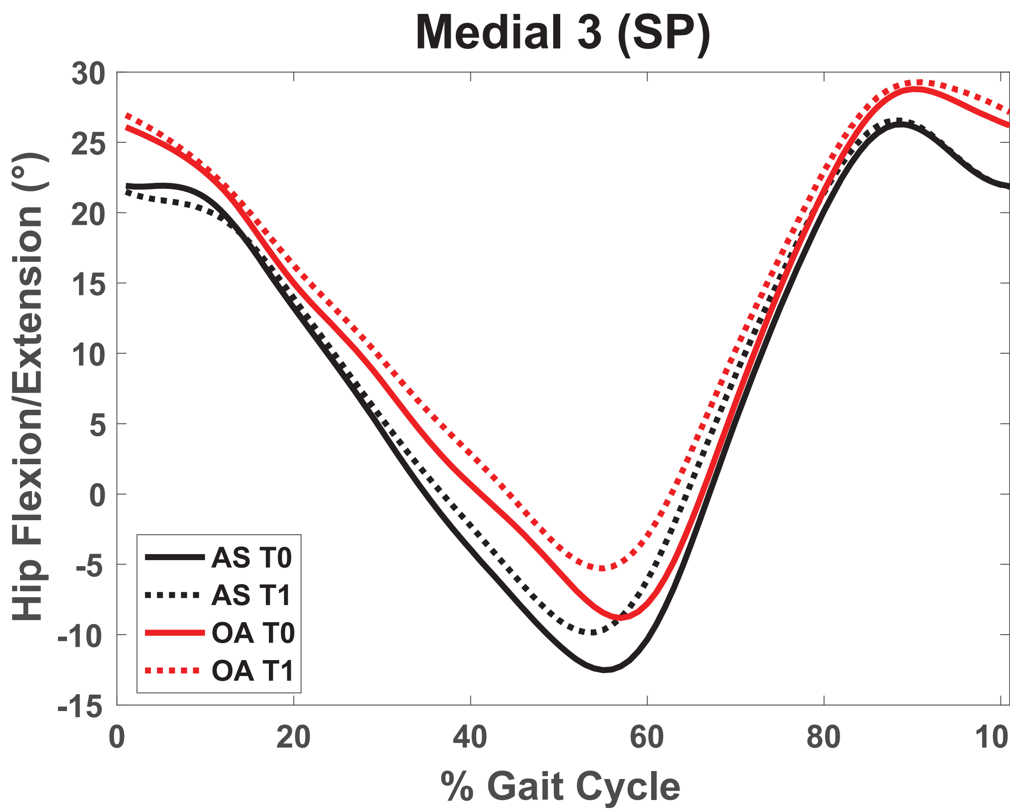

Figure 5-4: Sagittal plane (SP) hip kinematics for medial 3cm perturbations. The moderate OA group is represented by red curves and the asymptomatic groups are represented by black curves. Before the perturbation (T0) is represented by the solid and the first stride after the perturbation (T1) is represented by the dotted line.

Consistent with medial 1cm perturbation, no group effects were demonstrated after medial 3cm perturbations ($p>0.10$). A time effect was evident in total sagittal plane ROM ($p<0.001$), where both MOA and ASYM groups demonstrated less hip ROM in the sagittal plane immediately after (T1) the perturbation compared to baseline (T0) and the third stride after (T3). Similar to medial 1cm, no time effect was evident in total frontal plane hip ROM during stance ($p=0.112$). No group by time interaction was demonstrated in hip motions ($p>0.10$). The data is shown in Table 5-4.

Table 5-3: Mean (Standard Deviation) hip kinematic response of both moderate knee OA and asymptomatic groups before (T0), immediately after (T1), and the third stride after (T3) a medial 3cm perturbation.

Medial 3cm	**Time Effects**		
	T0	**T1**	**T3**
Sagittal Plane Range [0-60%] (°)	35.4 (4.0)	32.3 (4.7)	35.1 (4.3)

→ shaded rows depicts a group effect
→ * depicts a time effect
→ Positive angle represents flexion and negative angle represents extension

5.3.3 Knee Kinetics

Sagittal plane knee moments corresponding to medial 1cm perturbations for both groups and times before (T0) and immediately after (T1) perturbations are shown in Figure 5-5.

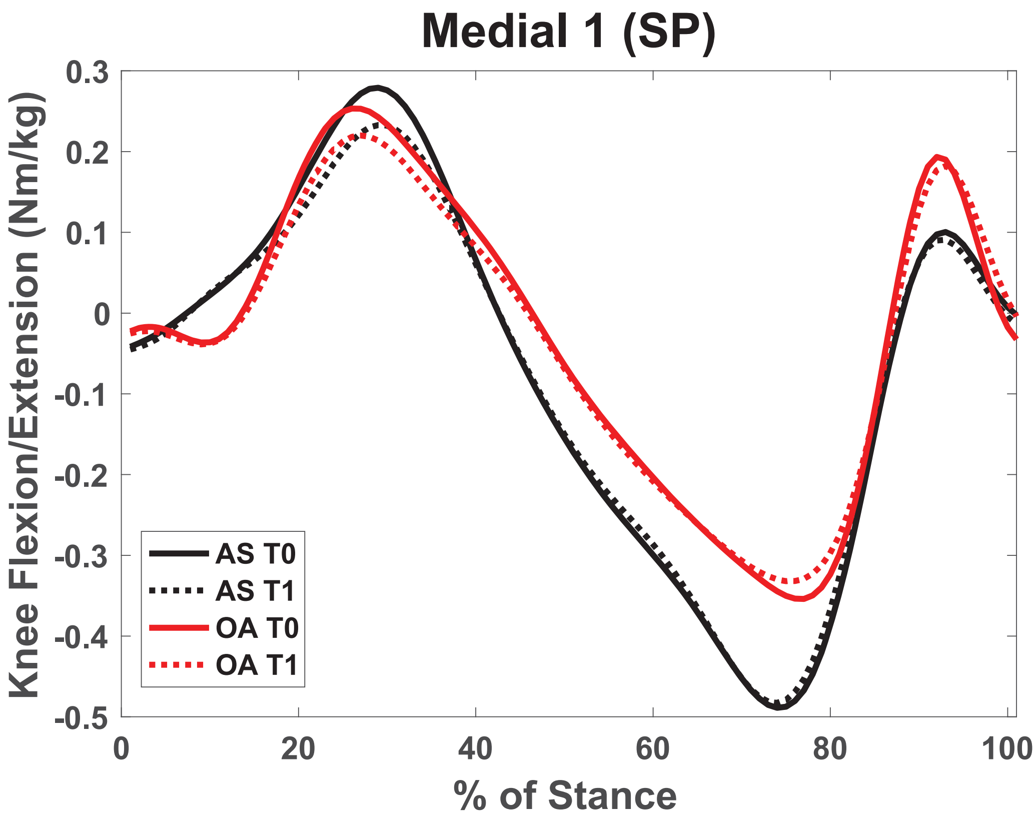

Figure 5-5: Sagittal plane (SP) flexion/extension moment for medial 1cm perturbations. The moderate OA group is represented by red curves and the asymptomatic groups are represented by black curves. Before the perturbation (T0) is represented by the solid and the first stride after the perturbation (T1) is represented by the dotted line.

After medial 1cm perturbations, no group effects were found in the peak extension moment (p=0.118), peak flexion moment (p=0.829), or the range from peak flexion to peak extension (p=0.118). No time effects were found in peak flexion moment (p=0.143), however, a significant time effect was demonstrated in the range from peak flexion to peak extension (p=0.022) and a borderline significant time effect was evident in peak extension moment (p=0.051). These results show that both groups respond to medial 1cm perturbations with a less dynamic flexion-extension moment and a borderline reduced peak extension moment immediately after a perturbation (T1) compared to baseline (T0), and return to baseline by the third stride (T3). No group by time interactions were demonstrated from sagittal plane knee moment variables. This data is found in Table 5-5.

Table 5-4: Mean (Standard Deviation) knee kinetic response of both moderate knee OA and asymptomatic groups before (T0), immediately after (T1), and the third stride after (T3) a medial 1cm perturbation.

Medial 1cm	Time Effects		
	T0	**T1**	**T3**
Peak Extension (Nm/kg)	-0.43 (0.21)	-0.42 (0.22)	-0.44 (0.22)
Peak Flexion to Peak Extension (Nm/kg)	0.72 (0.25)	0.67 (0.24)	0.72 (0.26)

→ shaded rows depicts a group effect
→ * depicts a time effect
→ Positive represents a flexion moment and negative represents extension moment

No group or time main effects occurred after medial 1cm perturbations for peak KAM values. Furthermore, no group by time interactions were present. Means and standard deviations are recorded in Table 5-5 and Figure 5-6 represents frontal plane knee moment corresponding to medial 1cm perturbations for each group and time.

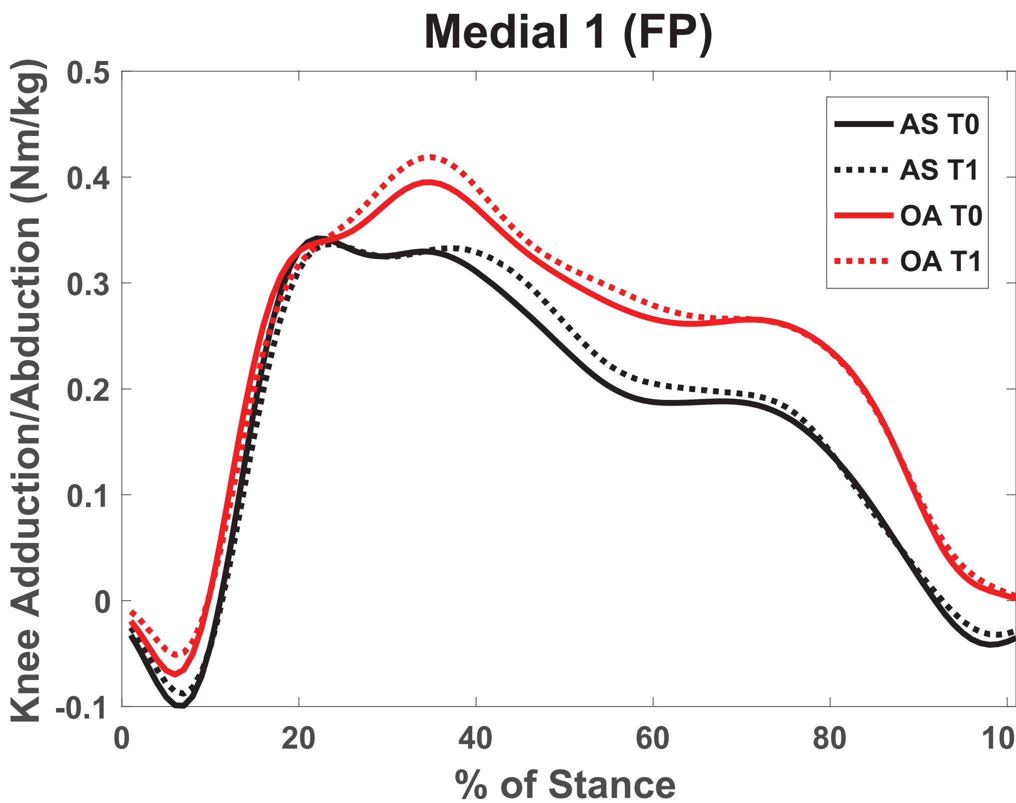

Figure 5-6: Frontal Plane (FP) knee adduction moment (KAM) for medial 1cm perturbations. The moderate OA group is represented by red curves and the asymptomatic groups are represented by black curves. Before the perturbation (T0) is represented by the solid and the first stride after the perturbation (T1) is represented by the dotted line.

Sagittal plane knee moments corresponding to medial 3cm perturbations for both groups and times before (T0) and immediately after (T1) the perturbations are shown in Figure 5-7.

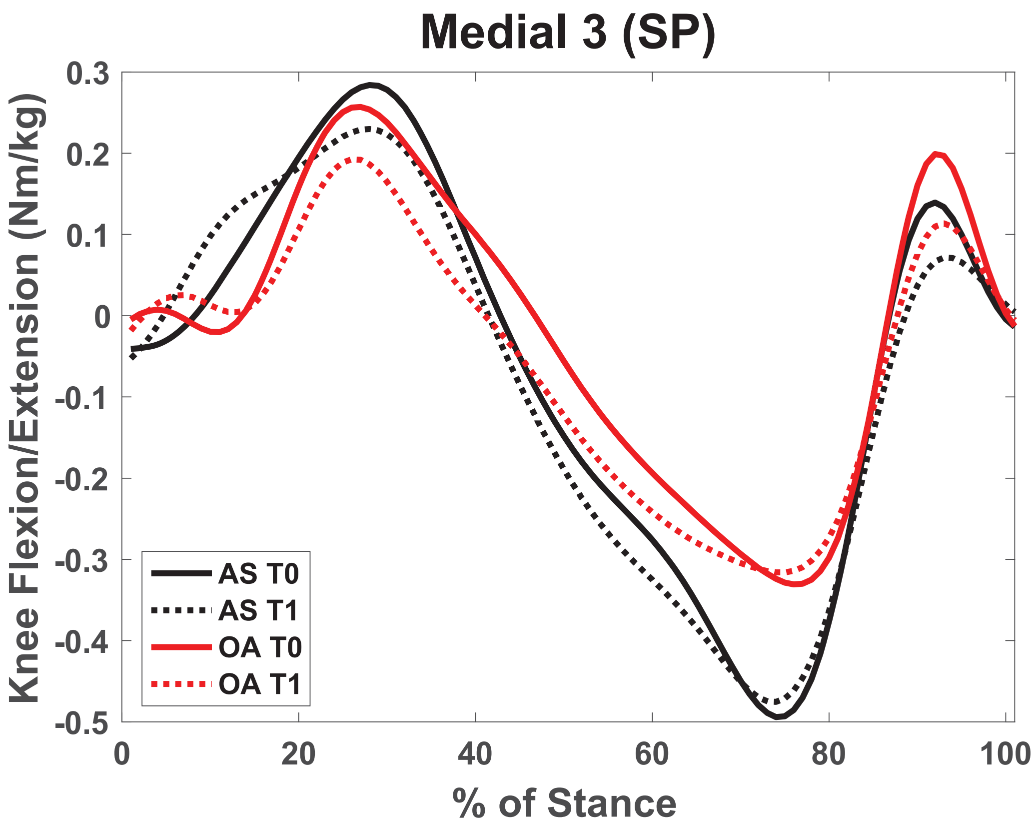

Figure 5-7: Sagittal plane (SP) flexion/extension moment for medial 3cm perturbations. The moderate OA group is represented by red curves and the asymptomatic groups are represented by black curves. Before the perturbation (T0) is represented by the solid and the first stride after the perturbation (T1) is represented by the dotted line.

Consistent with medial 1cm perturbations, no group effects were found in the peak flexion moment (p=0.734). After medial 3cm perturbations, a significant group effect was demonstrated in the range from peak flexion to peak extension (p=0.046) and a borderline significant group effect was demonstrated in the peak extension moment (p=0.072). These results show that individuals with MOA walk with a less dynamic flexion-extension moment, and a reduced peak extension moment compared to the ASYM group. Similar to medial 1cm perturbations, no time effects were found in peak flexion moment (p=0.159), however, in addition, no time effect was found for peak extension moment (p=0.142) or the range from peak flexion to peak extension (p=0.106). These results demonstrate that both groups are walking with a less dynamic flexion-extension moment after a 3cm perturbation. No group by time interactions were demonstrated from sagittal plane knee kinematic variables, which is consistent with medial 1cm perturbations. This data is found in Table 5-6.

Table 5-5: Mean (Standard Deviation) knee kinetic response of both moderate knee OA and asymptomatic groups before (T0), immediately after (T1), and the third stride after (T3) a medial 3cm perturbation.

Medial 3cm	**Group Effects**	
	Asymptomatic	**Moderate OA**
Peak Flexion to Peak Extension (Nm/kg)	0.80 (0.24)	0.61 (0.21)

→ shaded rows depicts a group effect
→ * depicts a time effect
→ Positive represents a flexion moment and negative represents extension moment

Consistent with medial 1cm perturbations, no group or time main effects occurred and no group by time interaction was shown after a medial 3cm perturbation for the peak KAM. Figure 5-8 represents frontal plane moment corresponding to medial 3cm perturbation.

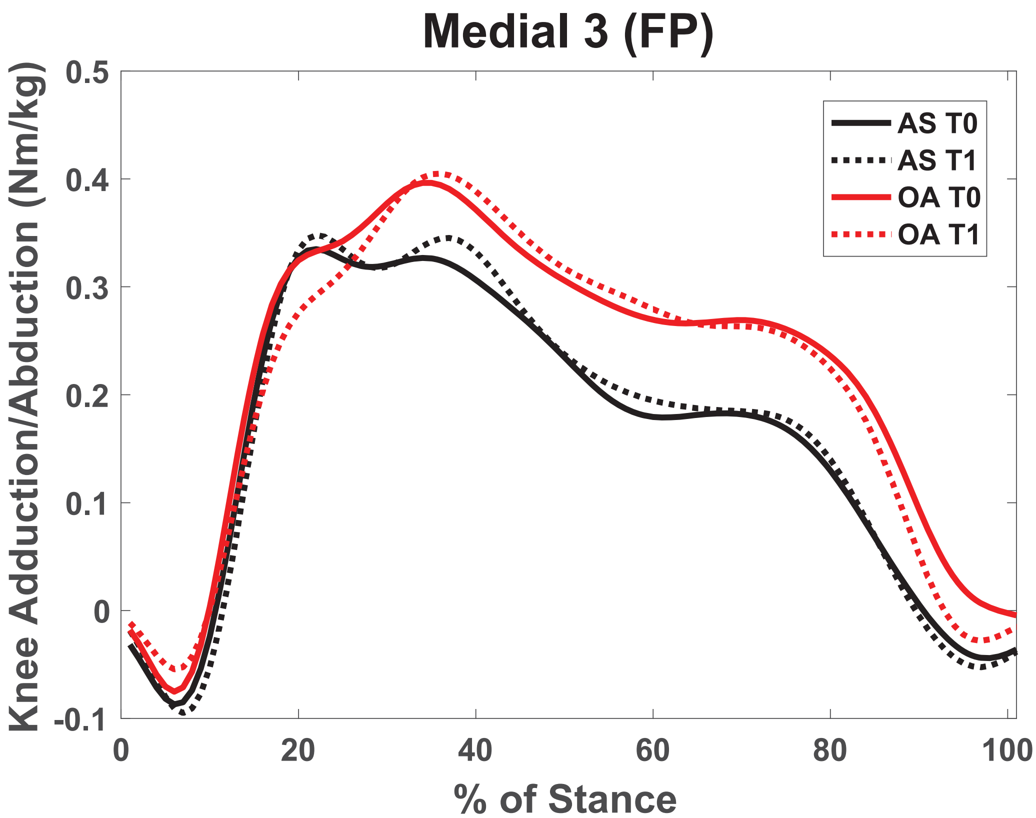

Figure 5-8: Frontal Plane (FP) knee adduction moment (KAM) for medial 3cm perturbations. The moderate OA group is represented by red curves and the asymptomatic groups are represented by black curves. Before the perturbation (T0) is represented by the solid and the first stride after the perturbation (T1) is represented by the dotted line.

Due to no biomechanical group by time interactions in this study, Objective 2a was not pursued.

In summary, individuals with MOA walk with less sagittal plane knee ROM during stance, lower peak extension moment, and an overall less dynamic flexion-extension moment compared to the ASYM group. Both groups tended to respond similarly in terms of biomechanics to perturbations. After medial 1cm perturbations, both groups did not alter motions at the knee and hip joints, however, both groups demonstrated a reduced peak extension moment as well as a less dynamic flexion-extension moment. While for medial 3cm perturbations, both groups struck the ground in more flexion at initial contact, experienced less sagittal plane ROM at the hip joint, and, similar to medial 1cm perturbations, tended to experience a less dynamic flexion-extension moment immediately after the perturbation.

Chapter 6 - Discussion

Currently, our understanding of how individuals with MOA respond to unexpected medial perturbations, that may mimic challenges day-to-day, is narrow and unclear. Of individuals with medial compartment knee OA, 60-80% self-report instabilities (26,27,132) and this population is constantly responding to altered adduction moments that load the medial compartment and may cause lateral compartment lift off (51). In order to maintain and preserve joint function, mechanical and neuromuscular factors contribute to the response (36,37). In order for knee OA stability research to progress, a novel approach of challenging individuals with perturbations that may increase medial compartment load and further induce lateral compartment lift-off is appropriate. The focus of this thesis has been on mechanical responses to medially directed perturbations, concentrating on the spatiotemporal characteristics, knee and hip motions and knee joint moments. Currently, the understanding of how individuals respond to perturbations is limited. During everyday activity, individuals experience unexpected challenges to the knee joint that may impact physical function. Given the high prevalence of instability, and its relationship to physical functioning, how individuals with moderate medial compartment knee OA respond to these perturbations may provide information on knee function that traditional gait testing (stable walking environments) cannot obtain.

In order to understand if this study achieved a population with MOA, it is important to firstly examine group differences that were present and if these differences are commonly reported in similar populations.

6.1 Group Differences

This study set out to determine spatiotemporal and joint-level biomechanical response to medial 1cm and 3cm perturbations on individuals with moderate medial compartment knee OA compared to a group of individuals without lower extremity pathology. To address the main objectives of this thesis, a novel gait analysis protocol was developed. The methodology employed the use of a dual-belt instrumented perturbation treadmill, an approach to gait analysis in knee OA populations that has not been widely utilized. Previously, gait mechanics in a MOA population has been understood using over ground walking. It is important to understand if this study is collecting data and acquiring general patterns and group differences (between ASYM and MOA) that are similar to data collected over the past two decades. Magnitudes and general patterns will be discussed in the ASYM group to help justify that data collected in this study is similar to data collected in previous literature. Similarly, given the novelty of treadmill walking in the study of knee OA gait mechanics and the designation of a MOA sub group in the current study, group differences found in this study and how these differences relate to previous literature are discussed below.

In order for this study to remain confident in the ability to capture appropriate motions and moments, the magnitudes and general patterns demonstrated by the ASYM group are compared to previous over-ground and treadmill walking studies. Sagittal plane knee motions collected in this study have similar patterns and magnitudes to those collected in previous over ground studies (34,35). Figures 5-1 and 5-2 demonstrate sagittal plane knee motion patterns and the peak flexion magnitude during stance and swing are approximately 15˚ and 55˚, respectively. Figure 2-2 is an example of sagittal plane knee motions reported by Astephen et al. (35) and demonstrate similar patterns and magnitudes of approximately 15˚ for peak flexion during stance and 60˚ for peak flexion during swing. In comparison to over ground walking, this study demonstrated small pattern and magnitude differences in sagittal plane knee moments compared to previous studies (34,35,102). Figure 2-4, 5-5 and 5-7 all demonstrate a biphasic sagittal plane net external knee moment which is consistent with previous literature (34,35,102), however sagittal plane knee moments are shifted toward extension in this study. Peak flexion and peak extension moments in this study are 0.31 Nm/kg and -0.50 Nm/kg, respectively. Over ground walking studies report peak flexion moments ranging from 0.5 to 0.7 Nm/kg and peak extension moments ranging from -0.2 to -0.4Nm/kg. Lee et al. (133) reported similar differences peak flexion/peak extension moments when comparing treadmill and over ground walking in healthy individuals. Treadmill walking seems to lower the peak flexion moment, and cause a larger peak extension moment (133). This is thought to occur because during treadmill walking individuals allow the momentum of the belts to carry their leg back into extension, rather then actively moving their leg towards extension. The peak KAM in this study follows the general pattern demonstrated in both over ground and treadmill walking study, evident in Figures 2-3, 5-6 and 5-8. Both demonstrate a first peak, followed by an unloading (midstance minimum) and a second peak. Lee et al. (133) reported that treadmill walking does not result in a pronounced mid-stance unloading when compared to over ground walking in healthy individuals which supports differences evident in this study compared to previous literature on over ground walking.

Individuals with knee OA in this study were classified as moderate. A MOA group was targeted to provide information regarding moderate stage knee OA in an attempt to reduce the overall burden of OA, increase quality of life, increase physical activity levels, and ultimately, reduce stress on health care systems by changing the way clinicians manage OA and identify TKA candidates. In previous studies, radiographic scores (KL I-III) have been used to classify individuals with MOA (40) which demonstrates consistency with data from Table 4-1. Yet, to classify those with MOA, this study has categorized individuals using functional abilities. To be classified as MOA, individuals must not be a candidate for a TKA and must be able to walk a city block, jog 5m and climb stairs in a reciprocal fashion (61). The MOA group in this study demonstrates similar subject demographics, radiographic scores, functional scores and gait characteristics to MOA groups in other studies (34,35,61,134,135).

This study reported an average age of 60 years, a mass of 87.6kg and a BMI of 29.9 kg/m^2 for the MOA group. Astephen et al. (35) reported similar group demographics, with an average age of 58 years, a mass of 93.6kg and a BMI of 30.9kg/m^2. In terms of subject demographics, participants with MOA were heavier and had a higher BMI than the ASYM group and that is consistent with findings in the literature (34,35,61,93,113).

This study collected radiographic scores for the MOA groups symptomatic knee. Kellgren-Lawrence grades of I-III were reported, with 4 (33%) individuals with KL-1, 7 (58%) individuals with KL-II and one (9%) individuals with KL-III. Hubley-Kozey et al. (61) reported a similar MOA group, with 2 (5%) individuals with KL-I, 23 (58%) individuals with KL-II and 15 (37%) individuals with KL-III. Similar to this study, the majority of MOA individuals in Hubley-Kozey et al. (61) demonstrated scores of KL Grade II, however, our group presented less severe radiographic OA, with more individuals with KL-I, fewer individuals with KL-III and no individuals with KL IV.

The MOA group in this study reported a WOMAC pain score of 6.6, a stiffness score of 3.5 and a function score of 23.3. This is similar to the moderate OA WOMAC scores in other studies (35,61,135). Rutherford et al. (135), reported a pain score of 6.6, a stiffness score of 3.8 and function score of 21.2. Knee Outcome Survey stability scores reported by this studies MOA population, averaged 3.5, with 42% of individuals reporting a score of 5, 25% of individuals reporting a score of 4 and 33% of individuals reporting a score of below 4. This was similar to Kumar et al. (62), who reported 40% of individuals reporting a score of 5, 18% of individuals reporting a score of 4 and 42% of individuals reporting a score below 4.

The ASYM group walked faster then the MOA group which is consistent with the literature (34,35,86). However, both groups tended to walk slower than previously reported. Self-selected walking speeds in those with MOA range from 1.13m/s to 1.30m/s (34,35,42,49) while ASYM individuals ranged from 1.22m/s to 1.38m/s (34,35,42,49). The methodology to obtain walking velocity in this study may have resulted in an overall speed decrease in both MOA and ASYM groups. Participants were instructed to walk barefoot, back and forth along the pressure sensitive walkway 15-20 times at a leisurely pace, where in traditional walking studies, individuals walk from point A to point B, returning to point A for the next trial. This difference in walking velocities may be a result of different methodologies. Due to significant group difference, walking velocity was considered as a covariate for the study. Variables were tested using an ANCOVA with walking velocity as a covariate. Velocity was either not a significant addition to the model, or the model demonstrated the same significant results as without the covariate. Given these results, walking velocity was not considered as a covariate in the final statistical analyses given the concerns of this statistical adjustment to understand knee OA gait mechanics (136).

Astephen et al. (35) and Zeni and Higginson (42) reported that individuals with MOA demonstrated longer stride times, while Elbaz et al. (88) reported longer step times. Previous studies have also reported that individuals with MOA walked with a longer percentage of time in stance (34,35,88) and a shorter percentage of time in swing (88). The findings of this study are comparable to those previously reported (34,35,42,88). Spending more time in stance coupled with longer stride times, extends the amount of time the medial compartment of the knee joint is exposed to compressive loads. Despite these group differences, stride length, step width and FPA were consistent between MOA and ASYM groups as shown in Table 4.2 and 4.3. Regarding FPA, these results are consistent with Rutherford et al. (93) also reporting no differences between MOA and ASYM. Longer stride and step times were group main effects that were evident in both medial 1cm and 3cm perturbations, however, time spent in stance and swing were only significant in medial 1cm perturbations. These results are thought to be affected by larger variability in medial 3cm perturbations and the inability to pick out significant group effects reported in medial 1cm and expected in medial 3cm perturbations.

From a biomechanical perspective, we expected to demonstrate similar group differences reported in the literature between an MOA and ASYM population. Knee motions in this study demonstrated group differences in the range from initial contact to peak flexion and range from peak flexion to peak extension. Previous literature confirms this finding, showing individuals with MOA walk with less knee flexion range during stance (34,35,40,86) compared to ASYM groups. At the hip joint, no significant differences were found between sagittal plane ROM, which is consistent with previous findings (92,137). In terms of knee kinematics, previous studies have reported that individuals with MOA demonstrate lower peak flexion and peak extension moments, resulting in a less dynamic flexion-extension moment, compared to ASYM groups (34,35,52,61). This study determined that a group difference was evident in the sagittal plane range from peak knee flexion to peak knee extension moment. However, only a borderline difference was evident in the peak extension moment and no significant difference were found in the peak flexion moment. Demonstrating that only in combination, small reductions in the peak flexion and peak extension moments, a significant difference in knee flexion-extension moment range occurs. Only a borderline group main effect was identified in the peak extension moment with a difference between the MOA and ASYM group being 0.16Nm/kg. This borderline difference could be explained by the study sample size. For a power of 80%, a sample size of 26 individuals would be needed to detect a group difference of 0.16Nm/kg in the peak extension moment given the variability found in this study.

Group main effects were trending towards significance for the range from initial contact to peak flexion angle and the range from peak flexion to peak extension moment. The flexion-extension moment range was significant and the range from initial contact to peak flexion was borderline significant after medial 1cm perturbations. However, after medial 3cm perturbations, the flexion-extension moment range was borderline significant and the range from initial contact to peak flexion was significant. These equivocal findings could be a result of the studies pilot nature, specifically the sample size. If the sample size was to increase, from various power calculations, group main effects would be consistently identified between both perturbation magnitudes. For example, with 80% power, a sample size of 34 for medial 1cm and 26 for medial 3cm perturbations would need to be recruited in order to identify differences in peak extension moments. Consistent group main effects were demonstrated for both medial 1cm and medial 3cm perturbation for peak flexion to peak extension ROM in sagittal plane knee flexion range, with the MOA group reporting less range during stance from peak flexion to peak extension compared to the ASYM group.

The KAM has aided researchers in understanding loading that occurs at the medial compartment of the knee joint (34,47,49,96,101,106). Previous literature has reported contradictory results around the peak KAM, some studies publishing increasing an increase in peak KAM (34,49,105) and others reported no change (47,95,100) when comparing OA and ASYM groups. This study reported no difference in the peak KAM between the two groups, however, the MOA groups peak KAM was 0.43Nm/kg, higher than the ASYM group, which was 0.37Nm/kg.

This study targeted a MOA group to help understand walking mechanics by using these techniques to evaluate treatments and to understand the mechanical factors in progression. Because the novel nature of perturbation research, this study did not want to test individuals with severe reductions in function who may not be able to tolerate perturbations and longer distance treadmill walking. The results of this study, and comparisons to other studies help to support that the moderate OA population this study recruited, are in fact individuals with MOA. These individuals have similar age, mass and BMI (34,35,61,134,135), similar radiographic (61) and WOMAC scores (35,61,135), and similar spatiotemporal (34,35,42,88) and biomechanical (34,35,40,47,52,86,92,95) differences then other groups investigating moderate OA populations. With identifying these group differences, it is appropriate in moving to a perturbation protocol to attempt to challenge individuals walking.

6.2 Spatiotemporal Responses to Perturbations

The primary objective of this study was to understand how individuals with MOA and ASYM individuals responded to medial 1cm and 3cm perturbations. The first objective was to specifically understand spatiotemporal responses and if they differ between the two populations. Table 4-2 and 4-3 illustrates data from this response.

This study looked at spatiotemporal parameters to get an understanding of functional capabilities of both groups and a general overview of responses to walking perturbations. Other studies have recorded spatiotemporal response to perturbations (67,119). The complexity of the spatiotemporal parameter is less than biomechanical responses, therefore making responses, if different, more applicable to a wider audience. These functional differences are also more applicable in a clinical sense. Responses (i.e. wider step width, faster step time, increased FPA) provide clinicians with information that they can use in treatment plans.

6.2.1 Medial 1cm

This study demonstrated that individuals with MOA responded with similar spatiotemporal parameters to the ASYM group after medial 1cm perturbations. In this study, baseline walking was determined by averaging three strides before the perturbation. The response was determined by looking at the first (T1) and third (T3) strides after the perturbation. The hypothesis for this objective stated that we would see no response from medial 1cm perturbations in both groups. The findings do not support this hypothesis as small spatiotemporal responses are evident as a result of this 1cm perturbation. Both ASYM and MOA groups responded to medial 1cm perturbation by decreasing the percentage of time spent in stance and decreasing FPA in the first stride after the perturbation. A reduction in stance time may indicate that, while adjusting their gait in response to the perturbation, this causes individuals to spend less time on the perturbed leg, perhaps as an indicator of challenged stability. Medial perturbations bring the perturbed leg closer to the unperturbed leg, reducing the BOS. In addition, both groups increased their step width by their third stride. An increased step width, as a response to a perturbation increases the BOS for strides after a perturbation, which would theoretically have positive impact on stability. Previous literature has reported that step width is increased after a medial perturbation and this response is delayed past the first stride (138) and the step width increases with perturbation intensity (64). To date, the author is unaware of studies to investigate FPA angle or percentage of time in stance as direct metrics for perturbation outcomes.

Previous perturbation literature has only implemented larger (5.8cm) perturbations (62,63), while 1cm perturbations have not been studied. Small magnitude perturbations, as observed in this study, do not always elicit visual responses. But, as demonstrated by the measurements, spatiotemporal changes are occurring and could provide information on appropriate perturbation intensities for certain populations.

6.2.2 Medial 3cm

As Hak et al reported, when perturbation intensity increased, responses to the perturbation demonstrated a larger change (64). This study supports this result. This hypothesis stated that after a medial 3cm perturbation a decrease in stride time, step time, percentage of stance and percentage of swing would be accompanied by an increased in step width and an increased FPA. This hypothesis was partially supported. After a medial 3cm perturbation, stride time decreased, percentage of stance decreased, swing time decreased, step time decreased, and step width increased immediately after the perturbation, with only step width remaining increased after the third stride, similar to results of medial 1cm perturbations. Step length remained unchanged after the perturbation, which was unexpected, and not supported by previous studies (64,67,119). A toed out FPA was expected, because it was thought that a more toed out position would provide a wider BOS, and thus increasing sensations of stability. Instead individuals responded in the first stride after the perturbation, with a more toed-in FPA. It is possible that this might be a contribution of treadmill walking. Participants were aware that in order to continue walking, and remain stable, they must continue progressing forward, it is possible that they may be turning their foot towards the direction of walking to maintain this forward progression. Only one group by time interaction occurred in this study; the MOA group differed in FPA response to a perturbation from the ASYM group.

The MOA group, as seen in Table 4-3, responded with 2˚ less toed-in angle in T1, with both groups returning to baseline by T3. Some literature has reported that reduced proprioception in individuals with knee OA, specifically in the ability of sensing the position of a limb in space (114,116,117). Reduced proprioception could affect the MOA group's ability to equal toed-in angles measured in the ASYM group. Similarly, the MOA group in this study reported higher self-reported stiffness scores on the WOMAC compared to the ASYM group, which could result in the inability to achieved a higher toed-in angle. An increase in dynamic stiffness has also been reported in previous literature (52,132,139), but does not correlate well with self-reported stiffness (52).

A subsection of Objective 1 was, if a group by time interaction occurred, meaning a difference between MOA and ASYM groups was evident, was this difference associated with the MOA groups self-reported KOS stability scores. The KOS was developed to understand the symptoms and functional limitations that occur as a result of knee pathologies and impairments (109). A majority of studies have used the KOS, specifically the question regarding stability [Table 2-1], to understand objective metrics that relate to subjective KOS scores. Dynamic stiffness, knee flexion angle, knee biomechanics have all been studied with their relation to the KOS in populations with knee OA (43,44,132). It was hypothesized that if a group by time interaction occurred, differences in self-reported stability would significantly contribute to this result. A Spearman ranked correlation was used to determine the association [Figure 4-1], which was not significant. There was no association of self-reported KOS stability scores with differences in FPA.

6.2.3 Summary

From both medial 1cm and medial 3cm perturbations, this study showed that ASYM and MOA groups respond with an increased step width, that either is a delayed response (only occurring at T3) or a maintained response (occurring at T1 and T3). Although there is no previous literature looking at the response in MOA populations, studies have reported an increased in step width in ASYM groups occurring after medial perturbation (64,67,119). Medial directed perturbations reduced the BOS and therefore, individuals widen strides in order to improve sensations of stability. FPA decreased at T1 for medial 1cm and 3cm perturbations for both ASYM and MOA groups. To the authors knowledge, there is no literature discussing FPA findings as a perturbation response. This response could be a result of individuals turning their foot toward the axis of progression in order to continue to make forward progress on the treadmill. The study did show that after medial 3cm perturbations, ASYM individuals were 2˚ more toed in than the MOA group. An impaired joint has been associated with decreased proprioception and increased general stiffness, which could impair the ability of an individual with knee OA to respond with a similar toed-in response to an ASYM individual. The Spearman rank correlation demonstrated that there was no association between self-reported instability at the objective measures of gait testing in this study, as previously hypothesized.

Medial 3cm perturbations elicited a different response in some spatiotemporal parameters. A decrease in stride time, step time and percentage of stance and swing were demonstrated in Table 4-3. This was not the case after medial 1cm perturbations. It is thought that this increase in perturbation intensity, affecting sagittal plane spatiotemporal characteristics are a results of “stiff knee strategy” (39,45) beginning at the knee joint to provide knee stability. A decrease in stride time and step time, could result from a faster stride to assist the participants in continuing to walk after the perturbation. Due to an unchanged step length, this convolutes this possible reasoning for the change in some spatiotemporal characteristics. It is possible that the perturbation response for both ASYM and MOA individuals is an attempt to quicken the stride and stiffen the joint to remain stable and continue walking.

Spatiotemporal characteristics come with limitations, especially in understanding the capabilities of lower extremity joints and joint function. Biomechanical responses, if different between the groups, could provide information on how walking challenges can elicit alterations to the joint pathomechanics. It is important to keep in mind, that these spatiotemporal responses provide a small piece of the puzzle in understanding joint function, but can help strengthen and support biomechanical results.

6.3 Joint-Level Biomechanical Responses to Perturbations

The second study objective was to determine how individuals with MOA and ASYM individuals respond biomechanically to medial 1cm and 3cm perturbations applied during the stance phase of the gait cycle, and if there are group differences. Tables 5-1 to 5-8 illustrate results of discrete metric analysis of knee kinematics and kinetics as well as hip kinematics. It was hypothesized that both MOA and ASYM individuals would respond in a similar manner. Medial 1cm perturbation would provoke no biomechanical difference, while a more intense, medial 3cm perturbation would demonstrate alterations in the sagittal plane hip and knee motions and knee moments between T0 and T1, but frontal plane mechanics would not change.

It was thought that these biomechanical differences potentially provide valuable information to support spatiotemporal differences that occurred above. These differences could elucidate pathomechanical information that informs on knee joint function during gait and how individuals with moderate medial compartment knee OA respond to walking challenges in everyday life.

6.3.1 Medial 1cm

To date only two studies have looked at kinematic response of perturbations on a population of individuals with knee OA, both studies looked at larger magnitude, 5.8cm lateral walkway translations (62,63). These studies demonstrated equivocal results, one indicating no biomechanical changes (63) and the other demonstrating that OA and ASYM groups responded with similar reductions in sagittal plane knee motions (62). The purpose of Objective 2 was to investigate biomechanical responses of small magnitude (1cm) medial perturbations, and if different responses occurred between the two groups. The hypothesis of Objective 2 was that no biomechanical alterations would be evident in both groups after medial 1cm perturbations. Results of this study partially supported this hypothesis. After medial 1cm perturbations, no significant alterations occurred in T1 or T3 for sagittal or frontal plane knee or hip motions. In general, from Tables 5-1 and 5-3 and Figure 5-1 and 5-3, it is evident that participants in both groups tend to experience less knee and hip ROM in the sagittal plane at T1 compared to T0 and T3. With this trend evident, it is possible that individuals altered their gait by reducing motion immediately after small (1cm) medial perturbations. However, this trend was not significant. This study did demonstrate that after a medial 1cm perturbation both MOA and ASYM individuals demonstrate a smaller range from peak flexion moment to peak extension moment. A less dynamic flexion-extension moment has been reported in the literature, and has been specifically associated with knee OA gait. Some studies have defined this result, alongside less knee flexion angle during stance as a “stiff knee strategy” to improve joint stability (39,45). Reduction in knee flexion-extension moment range has been reported in literature as a combination of reduced peak knee flexion and peak knee extension moment, however, in this study the majority of this result was driven from a reduction in the flexion moment, which is inconsistent with previous stiff knee gait literature.

In summary, these results are indicating that after medial 1cm perturbations individuals are possibly utilizing a “stiff knee strategy” in order to maintain joint stability. Along with small spatiotemporal results that are occurring, specifically faster stride, step, stance and swing times, this study is demonstrating the possibility that medial 1cm perturbation are causing a challenge to joint stability as both groups have altered their gait patterns as a result. This is an interesting finding, as individuals often reported that they could identify if the medial 1cm perturbations had occurred. Even though many participants could not detect the movement occurring, this study is identifying changes in knee biomechanics occurring in order to continue walking. Previous studies reported that responses to perturbations, specifically in regards to spatiotemporal parameters, increased with increasing magnitude. Results of medial 3cm perturbations will be discussed below.

6.3.2 Medial 3cm

Medial 3cm perturbations were also tested in Objective 2, to determine effects of larger (3cm) medial perturbations. Previous literature has looked at large (5.8cm) lateral perturbations in knee OA populations. Medial 3cm perturbations were chosen in this study as large magnitude perturbations. The maximal rate of translation for the R-Mill is 0.1m/s, and perturbations were applied during mid-stance. Applying a perturbation larger than 3cm, increases the chances that the treadmill is still translating when the contralateral foot strikes the ground. For medial 3cm perturbations, it was hypothesized that decrease sagittal plane knee and hip ROM, would be coupled with a less dynamic flexion-extension moment at T1, but this response would return to baseline by T3. No changes in frontal plane hip or knee motions would be present, similar to the hypothesis of medial 1cm perturbations. It was hypothesized that both MOA and ASYM groups would response with similar biomechanics. This hypothesis was supported. After medial 3cm perturbations, both groups struck the ground in more knee flexion at initial contact at T1 compared to T0 and T3. Based on Figure 5-4, this reduction in hip ROM was mainly a result of decreased hip extension during terminal stance. Concomitantly, the knee also did not reach the same amount of extension during terminal stance [Figure 5-2]. Anatomically, it is understood that ROM potential at the knee and hip joint are associated, meaning that if less ROM is experienced at the knee joint, then the hip will not experience its full ROM. Decrease knee flexion ROM was supported by the results of Kumar et al (62). Both studies indicated no difference between OA and ASYM groups, but both groups responded to perturbations with reduced knee flexion ROM. However, Kumar's study did not report hip motions or knee moments, which provide more information on the effects of perturbations on lower extremity joint function.

These results also support the "stiff knee strategy" theory mentioned above. In this case, this perturbation intensity demonstrates definite difference in ROM in the hip and knee joint, however, in medial 3cm perturbations, only a borderline significant difference was evident in the range from peak flexion to peak extension moment. This could be a result of sample size, as increasing the number of individuals in the study to 23 per group, based on previous power calculations, would have provided sufficient power to detect a difference in dynamic sagittal plane moment range. Again, the "stiff knee strategy" has been described in the literature as gait alterations that occur to improve knee joint stability (45).

This study, and others from previous literature, demonstrated a reduction in knee ROM and knee moment range in individuals with OA compared to ASYM. Despite the group difference discussed in section 6.1, these results suggest that both ASYM and MOA groups are responding in a similar way, same direction and a pattern of a "stiff knee strategy", which has been reported as a way to maintain joint stability and protection (45). Perhaps, individuals with knee OA, altering their walking day-to-day, in the same manner as an individual in this study altering their walking in response to a perturbation.

6.3.3 Summary

The purpose of Objective 2 was to investigate biomechanical responses to medial 1cm and 3cm perturbations, and if their responses were different between MOA and

ASYM groups. The hypothesis of Objective 2 was partially supported. Medial 1cm perturbations did elicit a biomechanical response, however, only in sagittal plane knee moments. The response of medial 1cm was similar to, but smaller than medial 3cm perturbations, however, due to increased variability in medial 3cm perturbations, only borderline significant reductions were found in the sagittal plane knee moment range after medial 3cm perturbations.

Previous research has reported that individuals with OA walk with a “stiff knee strategy” (39,45), that may be utilized to maintain stability in the knee joint. Both medial 1cm and 3cm tend to elicit a “stiff knee gait” as demonstrated from data in this study, but the results from medial 3cm perturbations tend to be consistently significant. Immediately after perturbations (T1), both groups tend to strike the ground in more flexion, demonstrate less hip ROM, and the knee flexion-extension moment range is decreased. After medial 1cm perturbations the sagittal plane knee moment range decreased, and generally, the knee and hip motions decreased. After medial 3cm perturbations, the knee and hip motions decrease, and generally, the flexion-extension moment range is decreased. A “stiff knee strategy” has been discussed in the literature as a tactic to keep the knee joint stable (39,45). “Stiff knee gait” is occurring in both ASYM and MOA groups, but is also commonly reported in OA populations (45). Therefore, it may be that overtime, individuals with knee OA, as they work to maintain knee function and respond to challenges to walking day-to-day, these patterns of reduce knee flexion-extension moment range and less ROM at the hip and knee, become habitual.

Similar to spatiotemporal parameters, there are limitations to biomechanical measurements. In terms of knee stability, from the works of Panjabi and Solomonow, it is understood that three subsystems contribute to knee joint stability (36,37). Neuromuscular contributions are a major componenet to stability as they provide active responses to walking challenges. The biomechanical responses that are occurring, specifically the “stiff knee strategy” have be reported in the literature to be accompanied by increased neuromuscular contributions (45).

Chapter 7 - Conclusion

In conclusion, this study demonstrated that other then a small change in the FPA after medical 3cm perturbations, both ASYM and MOA groups responded in a similar manner in terms of spatiotemporal and biomechanical parameters. The difference of FPA between groups could be a result of increased stiffness in the knee joint reported in the MOA group. This group demonstrates a biomechanical “stiff knee gait” after a perturbation by decreasing knee and hip ROM and demonstrating a less dynamic flexion-extension moment. This stiffness evident in MOA gait in combination with higher self-reported WOMAC stiffness scores prior to perturbation testing, could be the result of alterations in the FPA after medial perturbations between ASYM and MOA groups. It is difficult interpret this result, as there is no mention of FPA in current perturbation research.

For spatiotemporal characteristics, both ASYM and MOA groups tended to walk with a wider stride after perturbation (T1), which continues through to the third stride (T3). This is understood as a response to increase stability by means of a wider BOS. It is important to note, that although a increased step width is evident at T3, baseline step width values (T0) were similar between individual perturbation blocks [Table 3-1], suggesting that over a number of strides, step width returned to baseline (T0). No differences between any baseline metrics before each perturbation occurred in this study. Increased step width is coupled with faster stride, stance, swing and step times. This indicates that individuals are quickening their stride in attempts to stay in double support more often to return to stable gait.

Spatiotemporal results are supported by biomechanical differences that are occurring as a result of perturbations. A faster stride time and step time could be supported by less sagittal plane ROM at the knee and hip joint. These results are either significant or borderline significant after medial 1cm and 3cm perturbations. This study is demonstrating that individuals are striking at initial contact with more knee flexion, and passing through less overall ROM during stance at the knee and hip joint. In combination, spatiotemporal and biomechanical responses lead to support the understanding that a "stiff knee strategy" is occurring in the lower extremity to maintain joint function and stability (39,61). This is supported by significant and borderline significant smaller flexion-extension moment range that is demonstrated after medial 1cm and 3cm perturbations.

Utilizing a "stiff knee gait" is commonly reported in OA populations, of which, 60-80% of individuals self-report sensations of buckling, shifting and giving way of the knee joint (31,140,141). It may be, that due to responding to challenges to walking each and every day, individuals with knee OA adapt to this gait pattern of less ROM at the hip and knee and less dynamic flexion-extension range to maintain knee joint function. This "stiff knee strategy" is occurring in both ASYM and MOA groups. Strengthening the argument that after perturbations, both MOA and ASYM groups, tend to stiffen their knee joint in order to remain stable and within the confines of control.

7.1 Limitations

This study is a novel investigation of medial perturbations and spatiotemporal and biomechanical responses in MOA and ASYM populations. However, due to the pilot nature, limitations to the study were evident.

Due to smaller group sizes, this study had difficulties identifying group and time main effects from the data. Significant results have been found in the literature with smaller group differences and similar variability. As shown in Figures 5-1 to 5-8, group differences were evident that previously have been detected as significant. Many p-values ranged between 0.05 and 0.15, suggesting that this study may be underpowered to detect these differences. For example, the peak KAM differences in this study are 0.06Nm/kg and was not determined as a group main effect in this study. However, Gok et al. (86), with similar groups sizes (13 OA, 13 ASYM) determined a significant difference (p=0.01) between the groups with differences of 0.09Nm/kg.

Secondly, perturbations in this study were limited to a maximum of 3cm. As mentioned above, due to a maximal rate of translation of the R-Mill of 0.1m/s, in order to reduce the chance of the contralateral foot striking the ground, this study limited perturbation length to 3cm. Previous perturbation studies, looking at knee motions performed 5.8cm perturbations at a rate of 0.4m/s. This limits the ability of our study to compare directly to previous literature as Hak et al. (64) reported that increased responses are evident with increased perturbation intensities.

Thirdly, a person's ability to respond to perturbations may be rely on individual level of fitness. This study did not control for fitness level, which may influence the results. Individuals who are less fit may demonstrate altered biomechanics during perturbation testing compared to those that have a higher level of fitness.

Finally, another limitation is the possibility that an individual learns from subsequent perturbations and responds by altering gait patterns during baseline trials. Since, this study has not examined neuromuscular contributions, it is possible that learning has occurred. However, in order to minimize the response of learning, we randomized perturbations and participants did not see nor experience a perturbation prior to the study. The authors also examined if differences were evident between baseline trials. In terms of biomechanics, no differences were evident between baseline trials, therefore, this study can conclude no biomechanical alterations occurred as a result of learning for the period of perturbation testing.

7.2 Recommendations for Future Research

This thesis brought a novel and comprehensive approach to the study of gait perturbations in people with MOA, but many aspects of walking perturbations and knee instability require further exploration. The findings of this thesis lay the groundwork for further research in the following areas:

1. This study is demonstrating in combination, that a possible "stiff knee strategy" is occurring in the lower extremity to maintain joint function. In order to confirm this hypothesis, it is important to study neuromuscular contributions to gain an understanding of how the active subsystem plays a role in joint stability.
2. This study investigates the effects of medial perturbations on the symptomatic leg and measures a response. After the perturbation, we generally see short step times, meaning the asymptomatic leg makes first contact with the ground after the perturbation. Future studies could look at the effects of perturbing the asymptomatic leg, and measuring how individuals respond with their symptomatic leg.

3. This study focused on the effects of medial perturbations due to the familiar tibial loading that occurs at the knee as a result. Previous literature has focused on lateral perturbations, possibly looking to destabilize the medial compartment of the joint. Future studies could look at lateral perturbations, how smaller magnitude perturbations related to previous studies and if medial or laterally directed perturbations elicit different responses at the knee and hip.
4. This study investigated biomechanical responses to medial perturbations by focusing on the strides after the perturbation occurred. Some valuable information, however, may be occurring during the perturbation. Future studies should look at the biomechanical and neuromuscular response to perturbations as the translation is occurring.

Appendix

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Appendix B: Gait Waveforms

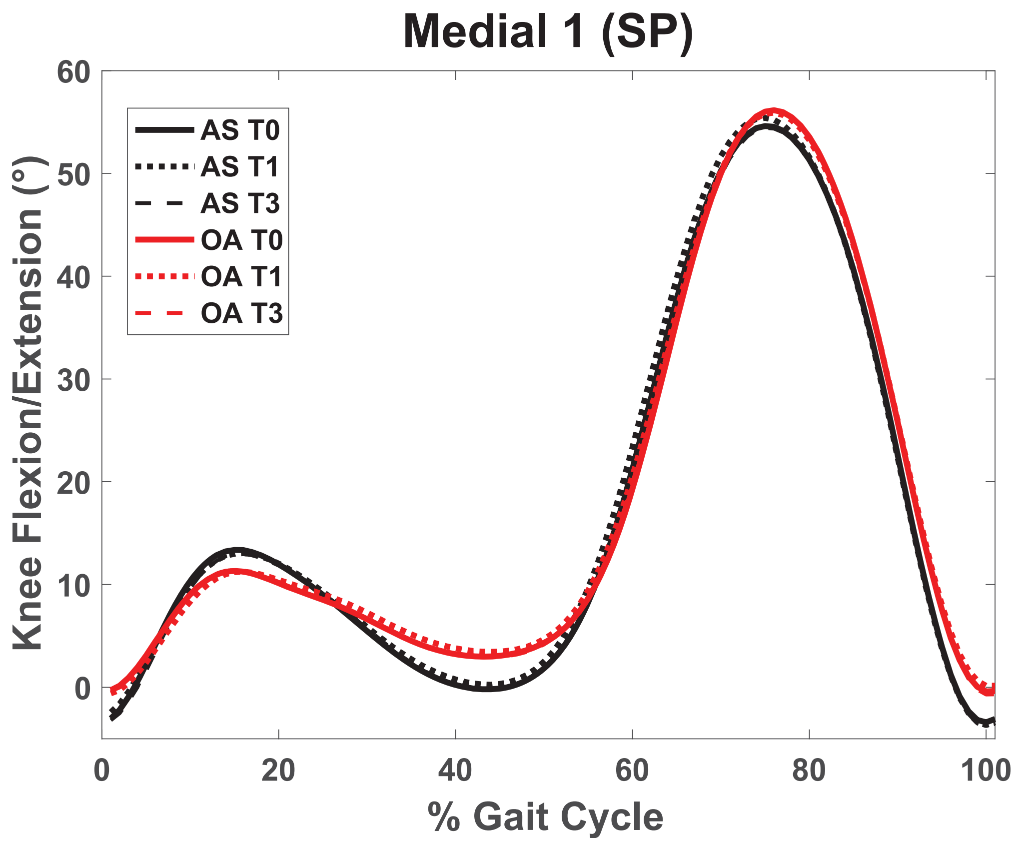

Figure A1: Sagittal plane knee flexion/extension angle for medial 1cm perturbations. The moderate OA group is represented by red curves and the asymptomatic groups are represented by black curves. Before the perturbation (T0) is represented by the solid, the first stride after the perturbation (T1) is represented by the dotted line and the third stride after the perturbation (T3) is represented by the dashed line.

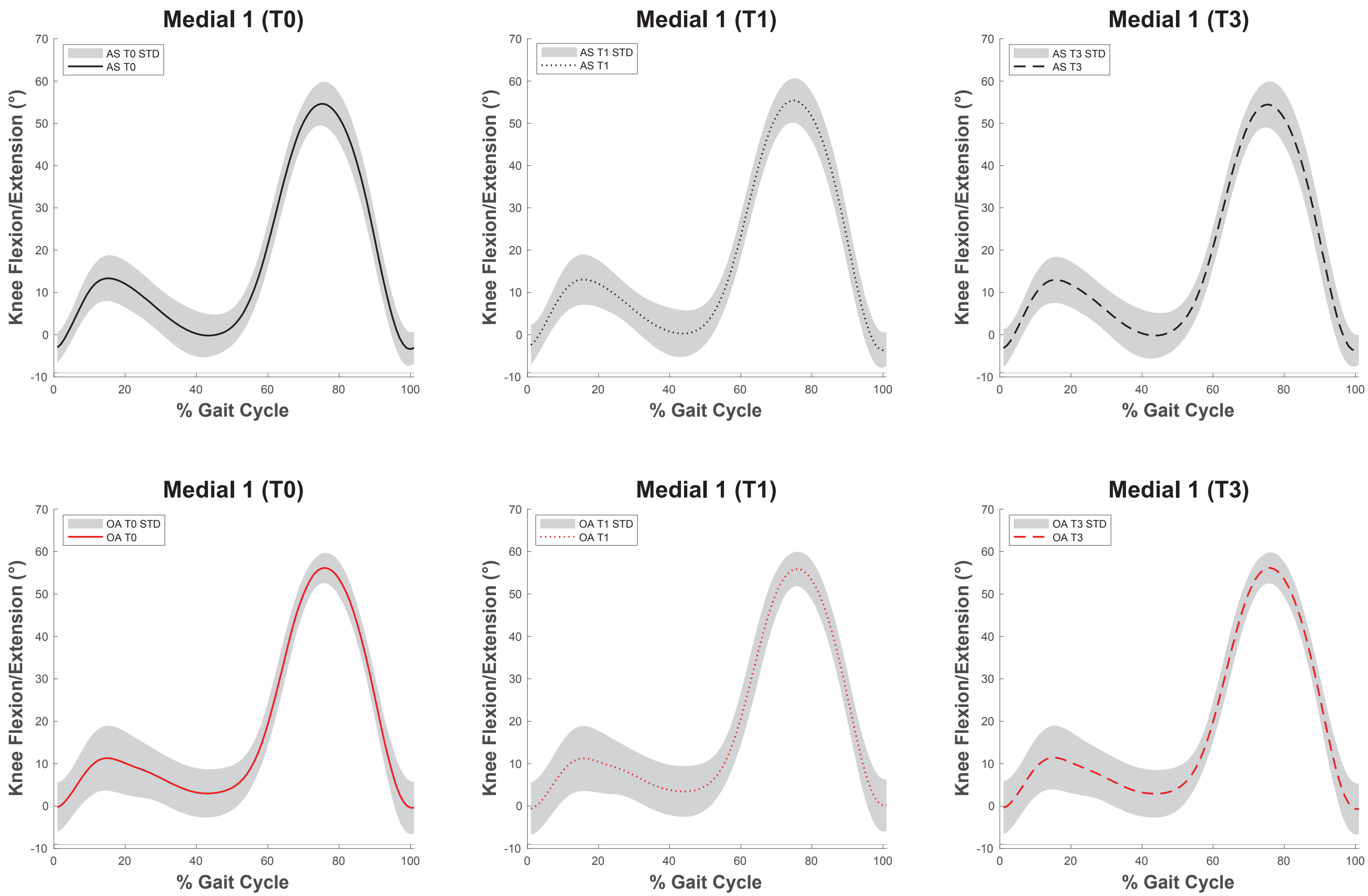

Figure A2: Sagittal plane knee flexion/extension angle for medial 1cm perturbations. Shaded area represents +/- one standard deviation about the mean for each time point (T0, T1, T3).

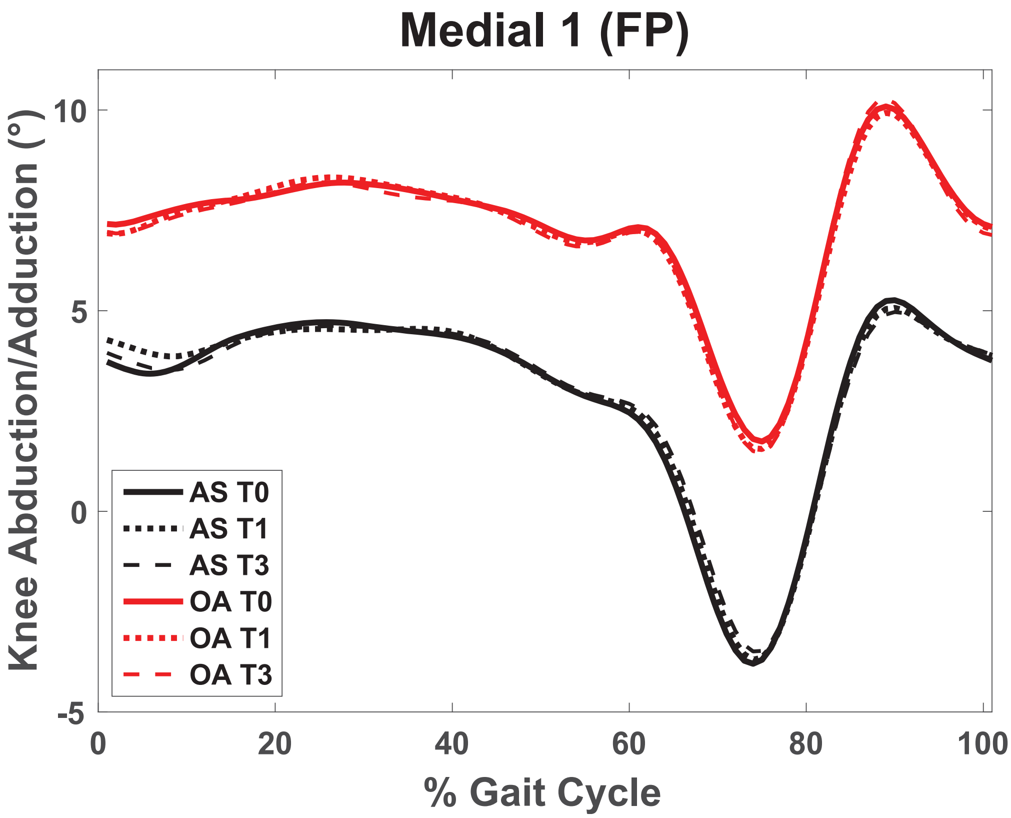

Figure A3: Frontal plane knee abduction/adduction angle for medial 1cm perturbations. The moderate OA group is represented by red curves and the asymptomatic groups are represented by black curves. Before the perturbation (T0) is represented by the solid, the first stride after the perturbation (T1) is represented by the dotted line and the third stride after the perturbation (T3) is represented by the dashed line.

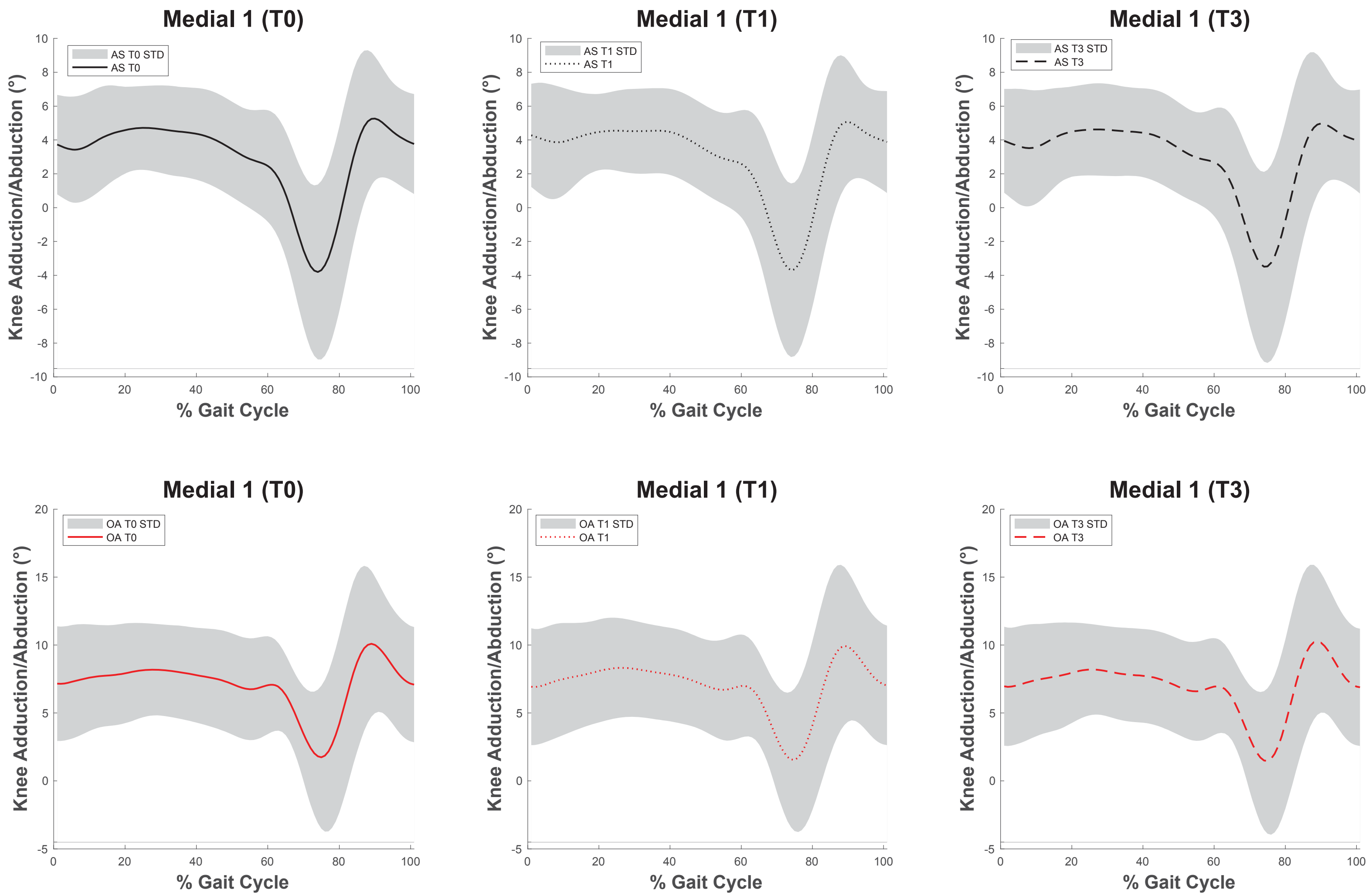

Figure A4: Frontal plane knee adduction/abduction angle for medial 1cm perturbations. Shaded area represents +/- one standard deviation about the mean for each time point (T0, T1, T3).

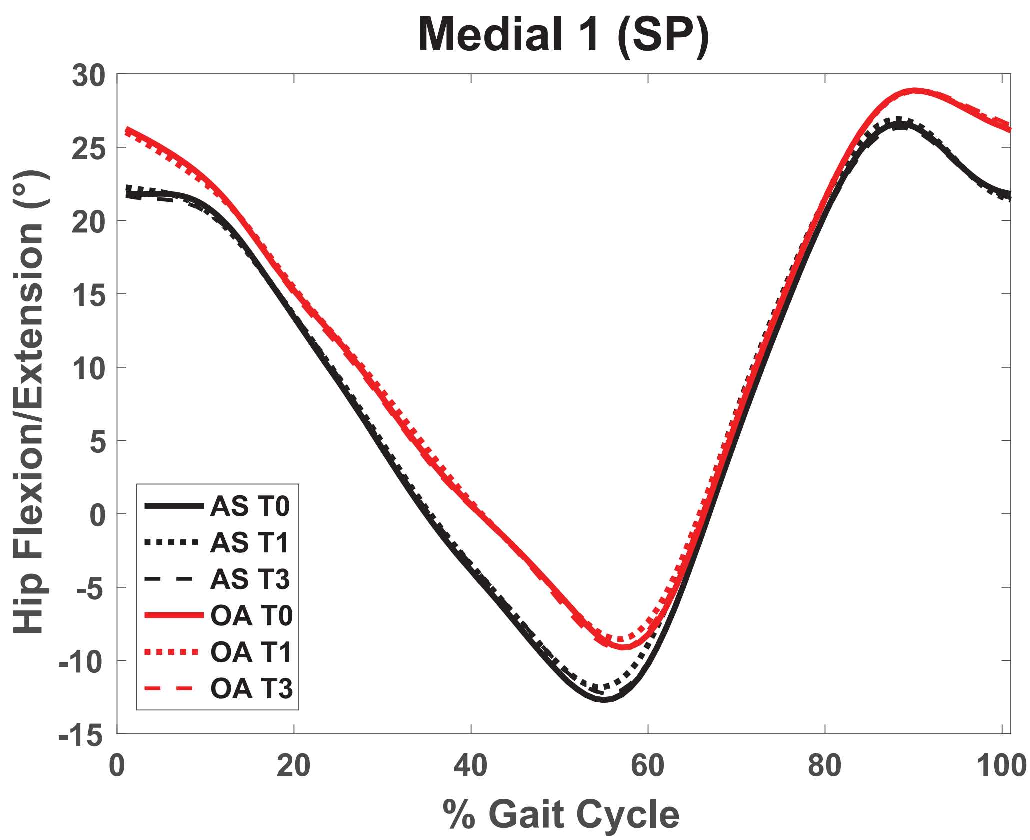

Figure A5: Sagittal plane hip flexion/extension angle for medial 1cm perturbations. The moderate OA group is represented by red curves and the asymptomatic groups are represented by black curves. Before the perturbation (T0) is represented by the solid, the first stride after the perturbation (T1) is represented by the dotted line and the third stride after the perturbation (T3) is represented by the dashed line.

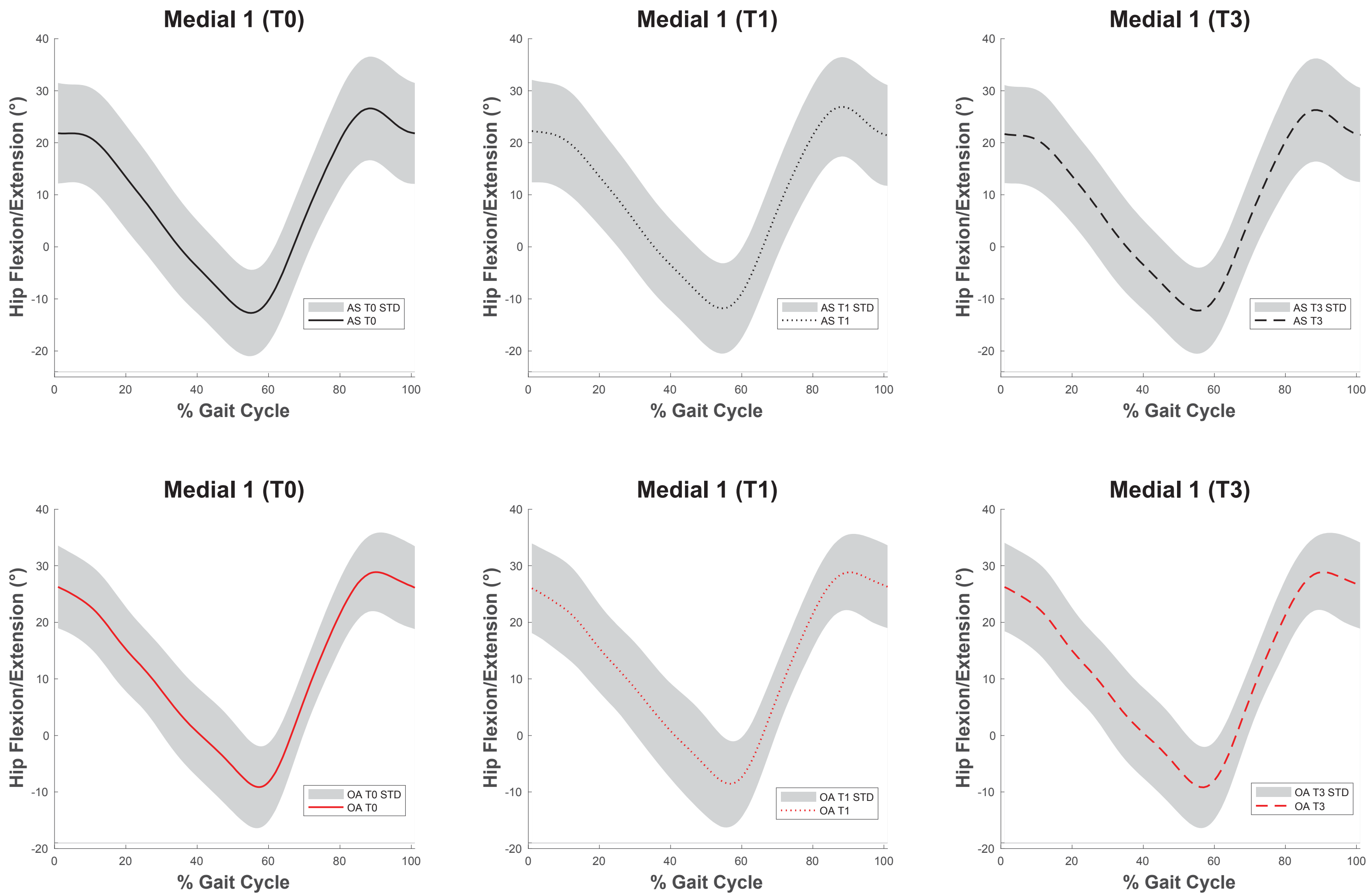

Figure A6: Sagittal plane hip flexion/extension angle for medial 1cm perturbations. Shaded area represents +/- one standard deviation about the mean for each time point (T0, T1, T3).

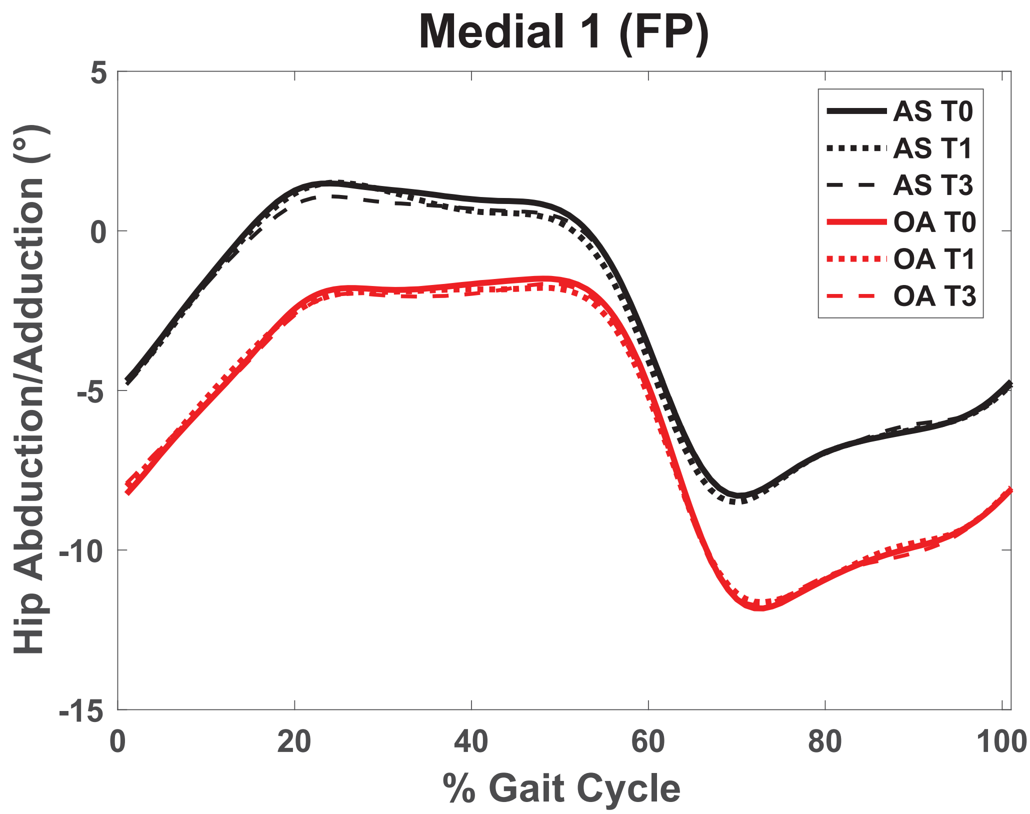

Figure A7: Frontal plane hip abduction/adduction angle for medial 1cm perturbations. The moderate OA group is represented by red curves and the asymptomatic groups are represented by black curves. Before the perturbation (T0) is represented by the solid, the first stride after the perturbation (T1) is represented by the dotted line and the third stride after the perturbation (T3) is represented by the dashed line.

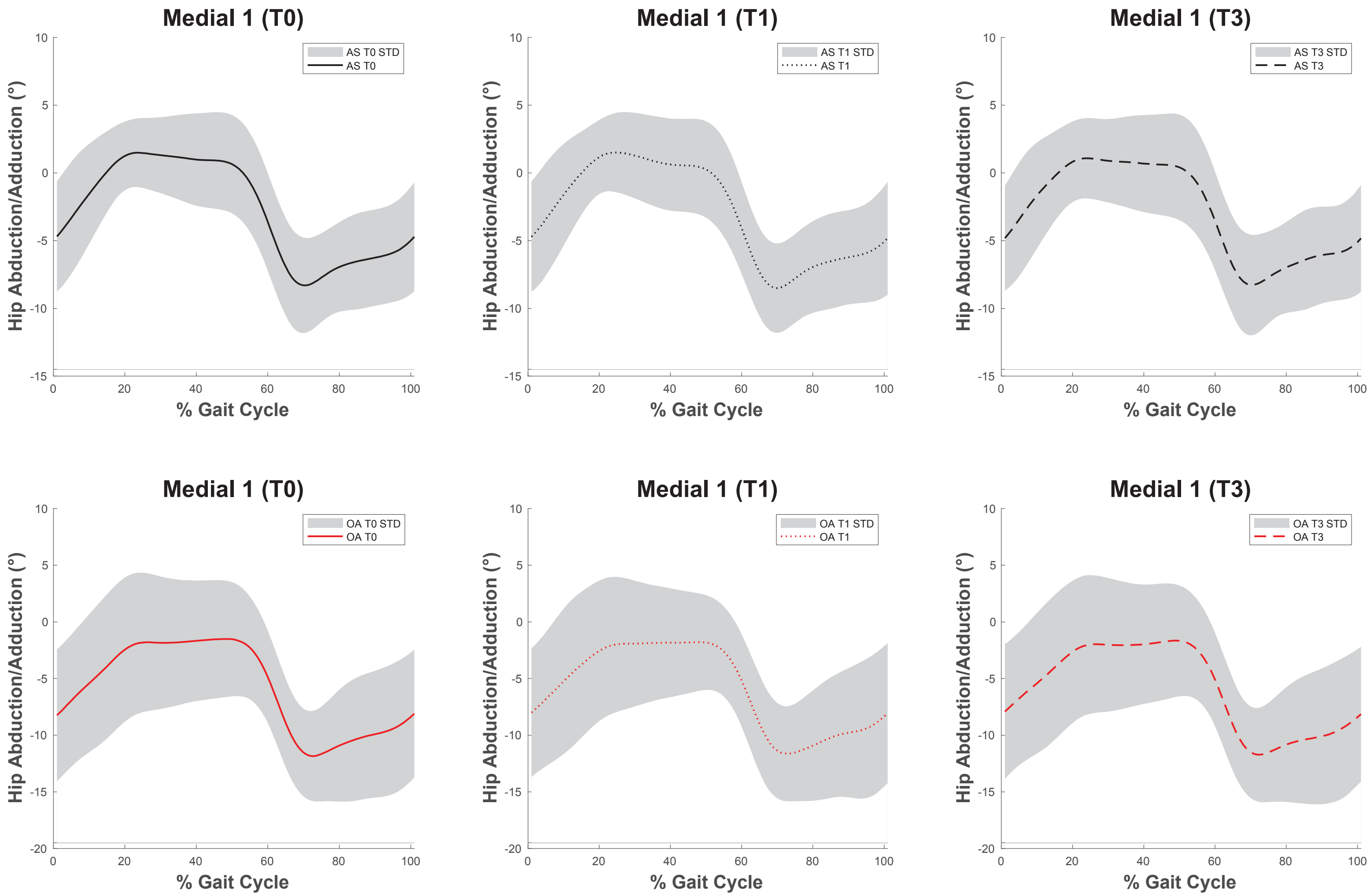

Figure A8: Frontal plane hip adduction/abduction angle for medial 1cm perturbations. Shaded area represents +/- one standard deviation about the mean for each time point (T0, T1, T3).

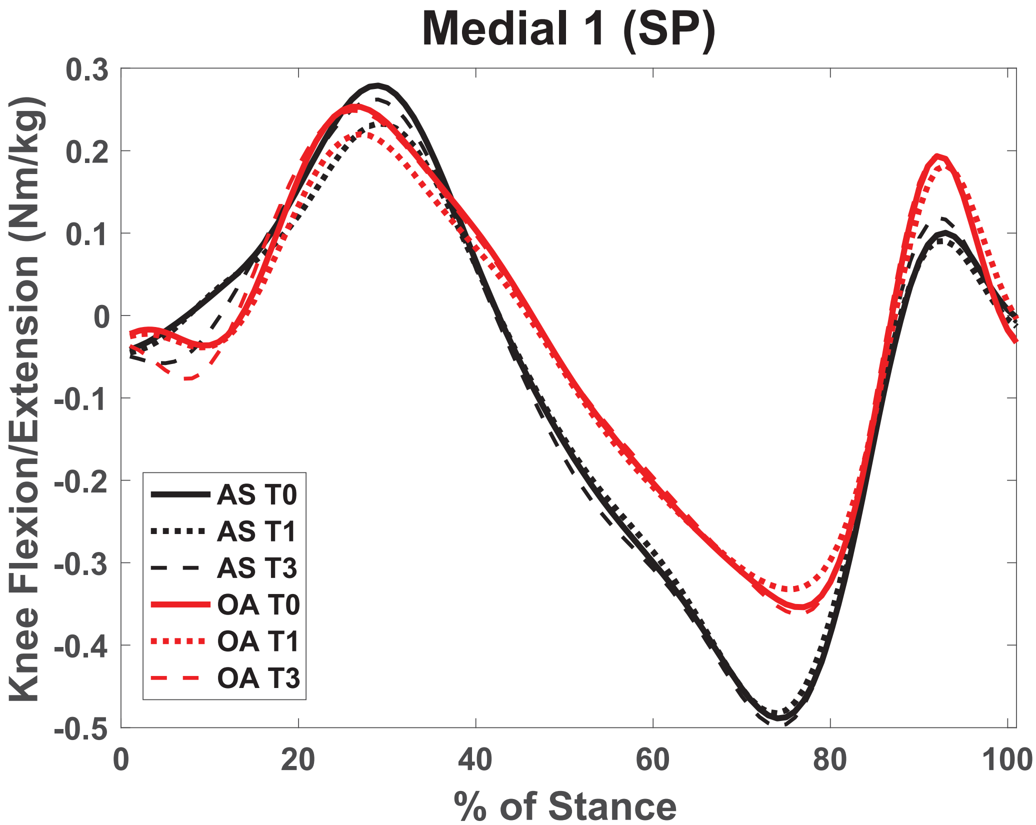

Figure A9: Sagittal plane knee flexion/extension moment for medial 1cm perturbations. The moderate OA group is represented by red curves and the asymptomatic groups are represented by black curves. Before the perturbation (T0) is represented by the solid, the first stride after the perturbation (T1) is represented by the dotted line and the third stride after the perturbation (T3) is represented by the dashed line.

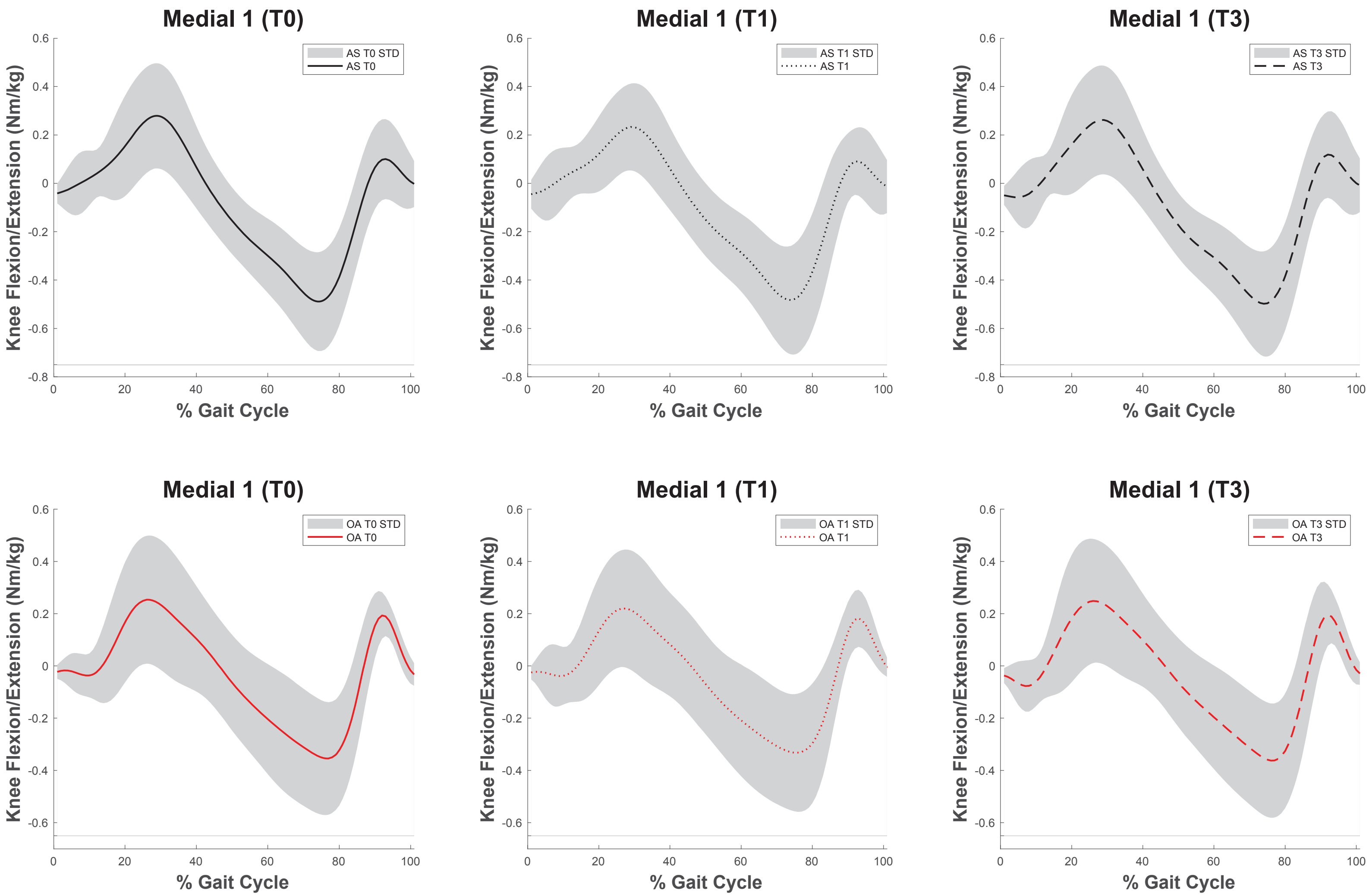

Figure A10: Sagittal plane hip flexion/extension moment for medial 1cm perturbations. Shaded area represents +/- one standard deviation about the mean for each time point (T0, T1, T3).

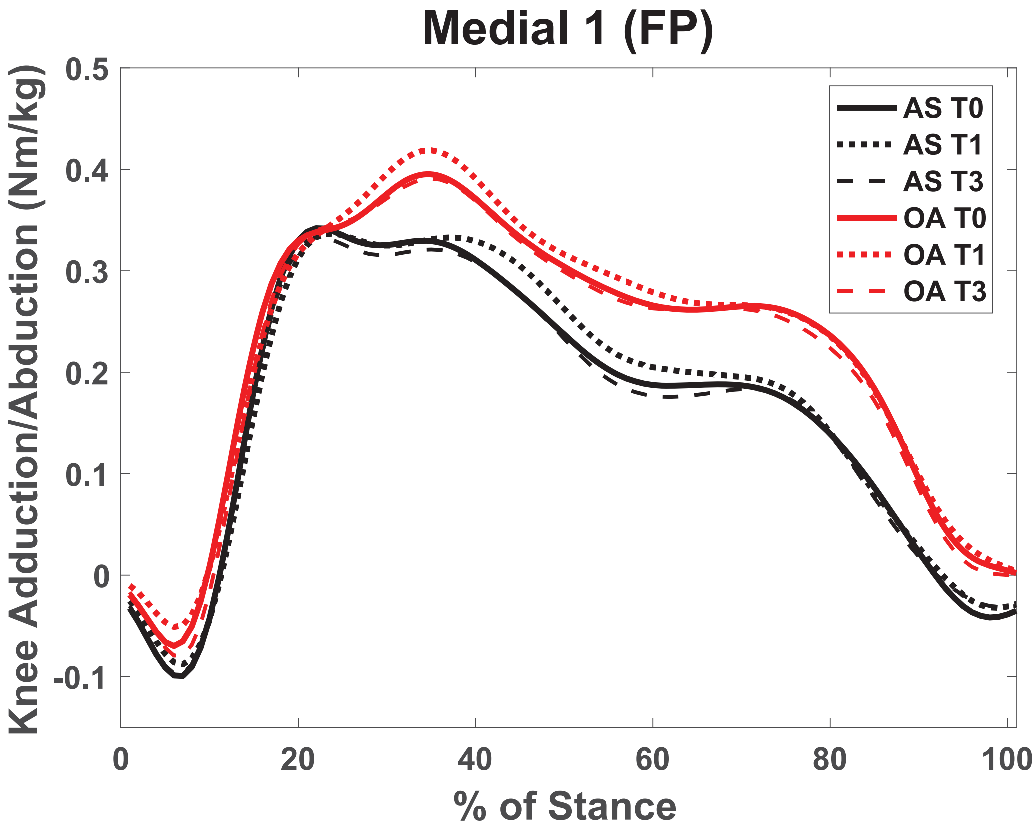

Figure A11: Sagittal plane knee flexion/extension moment for medial 1cm perturbations. The moderate OA group is represented by red curves and the asymptomatic groups are represented by black curves. Before the perturbation (T0) is represented by the solid, the first stride after the perturbation (T1) is represented by the dotted line and the third stride after the perturbation (T3) is represented by the dashed line.

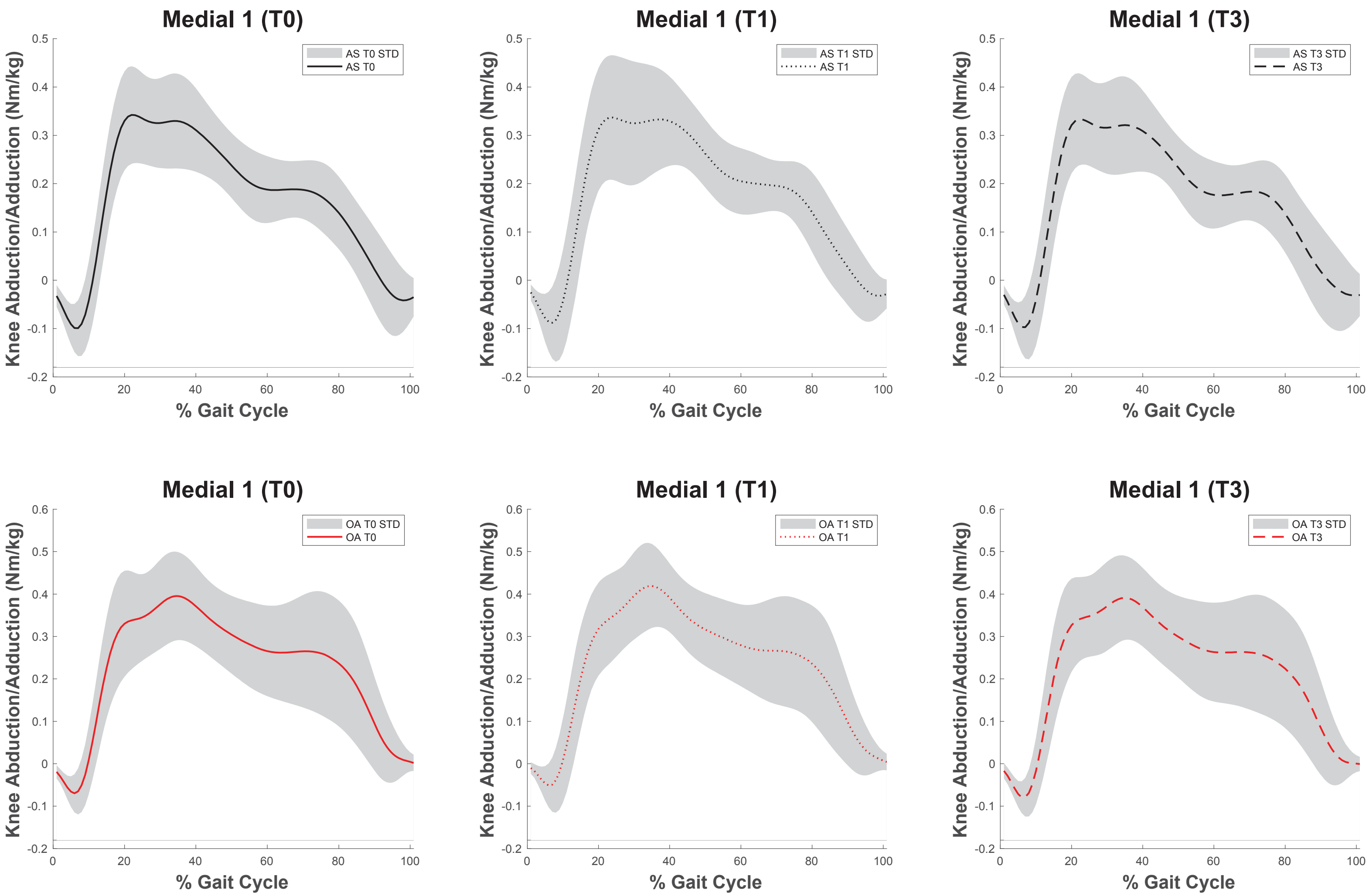

Figure A12: Frontal plane knee adduction/abduction moment for medial 1cm perturbations. Shaded area represents +/- one standard deviation about the mean for each time point (T0, T1, T3).

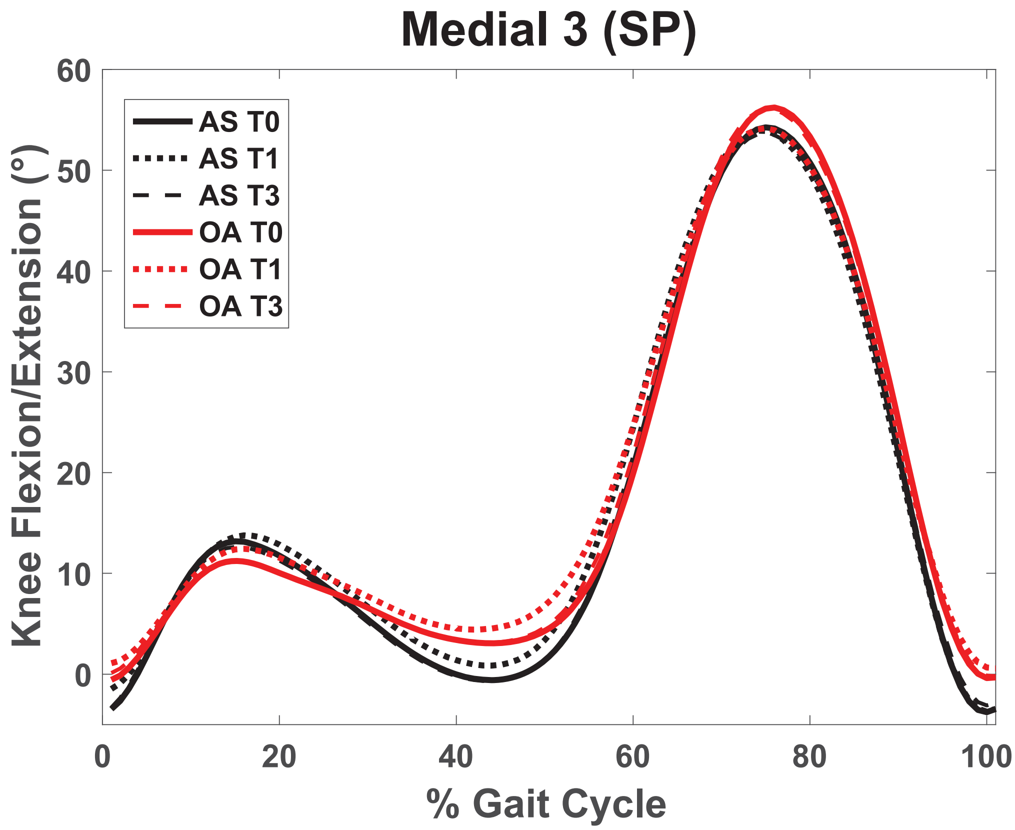

Figure A13: Sagittal plane knee flexion/extension angle for medial 3cm perturbations. The moderate OA group is represented by red curves and the asymptomatic groups are represented by black curves. Before the perturbation (T0) is represented by the solid, the first stride after the perturbation (T1) is represented by the dotted line and the third stride after the perturbation (T3) is represented by the dashed line.

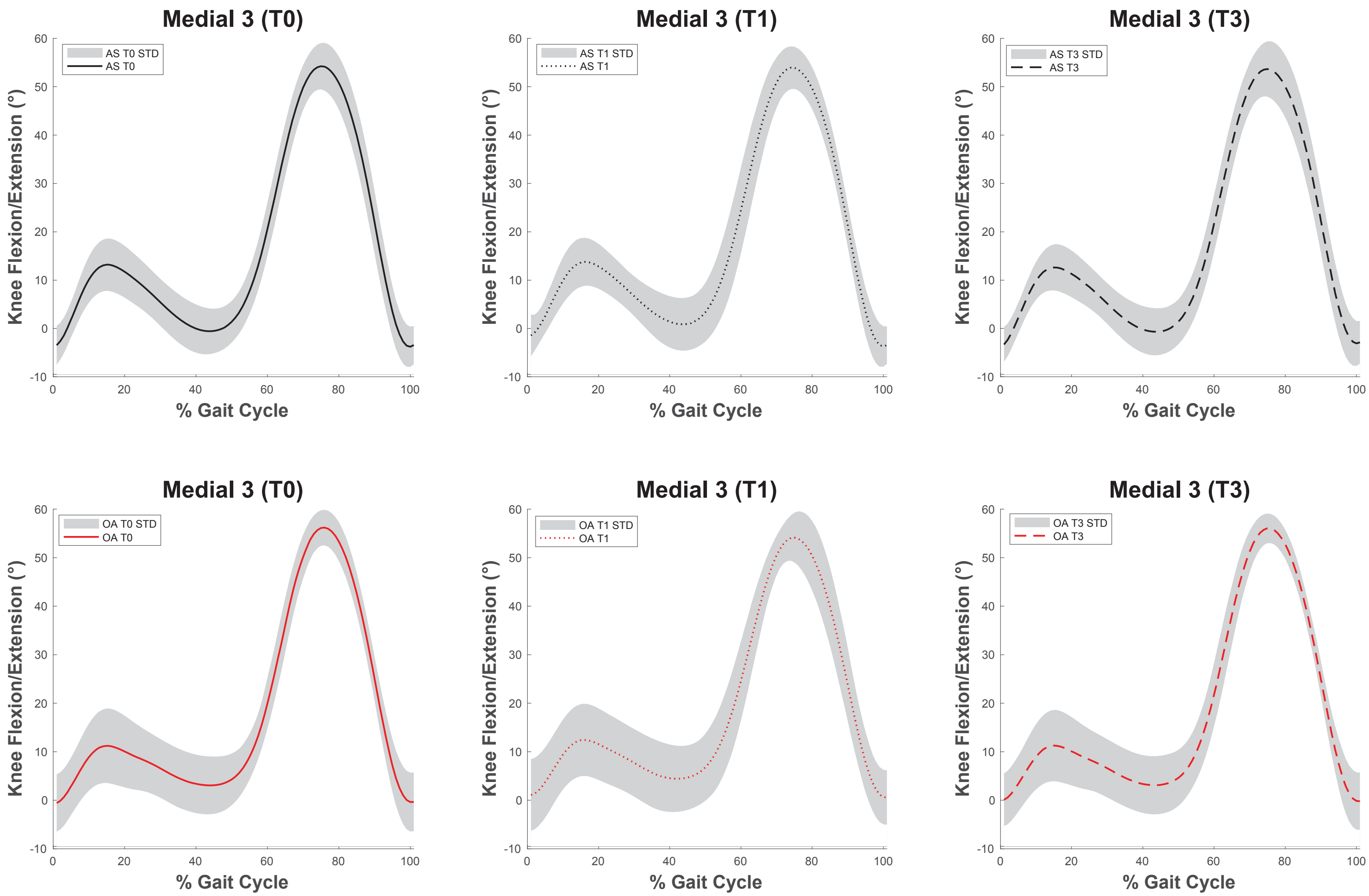

Figure A14: Sagittal plane knee flexion/extension angle for medial 3cm perturbations. Shaded area represents +/- one standard deviation about the mean for each time point (T0, T1, T3).

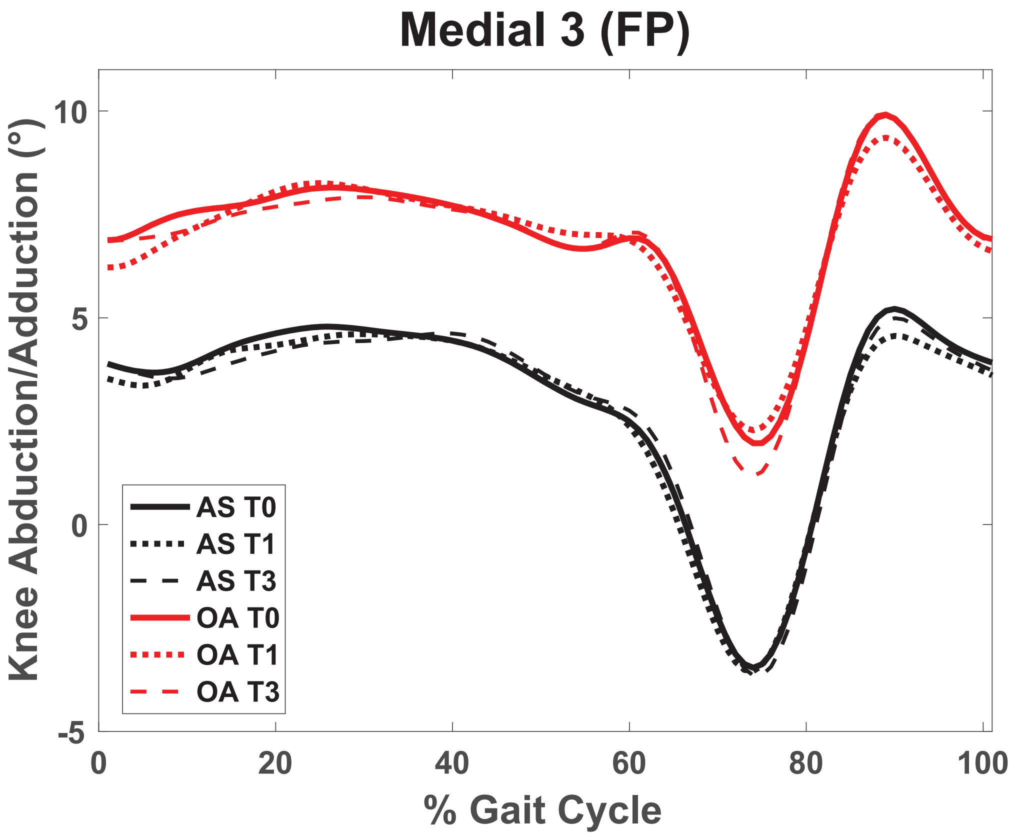

Figure A15: Frontal plane knee abduction/adduction angle for medial 3cm perturbations. The moderate OA group is represented by red curves and the asymptomatic groups are represented by black curves. Before the perturbation (T0) is represented by the solid, the first stride after the perturbation (T1) is represented by the dotted line and the third stride after the perturbation (T3) is represented by the dashed line.

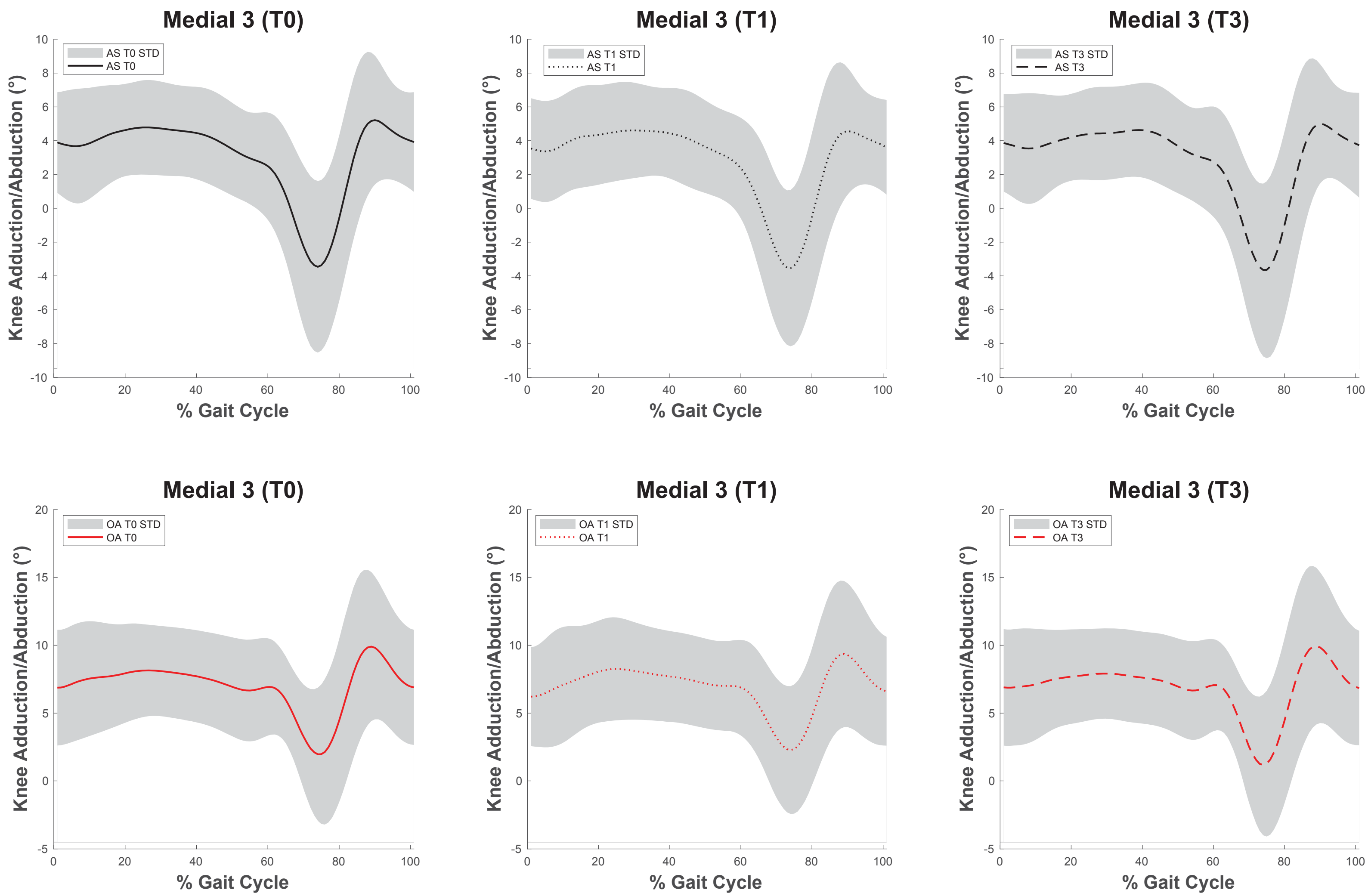

Figure A16: Sagittal plane knee adduction/abduction angle for medial 3cm perturbations. Shaded area represents +/- one standard deviation about the mean for each time point (T0, T1, T3).

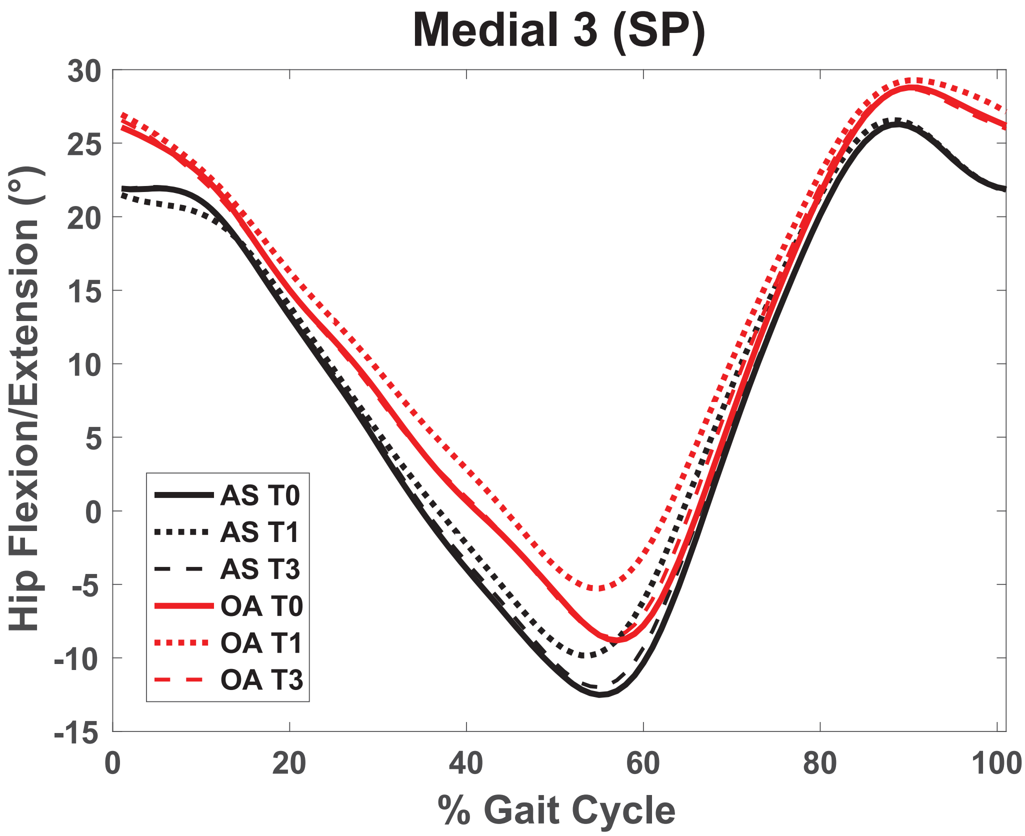

Figure A17: Sagittal plane hip flexion/extension angle for medial 3cm perturbations. The moderate OA group is represented by red curves and the asymptomatic groups are represented by black curves. Before the perturbation (T0) is represented by the solid, the first stride after the perturbation (T1) is represented by the dotted line and the third stride after the perturbation (T3) is represented by the dashed line.

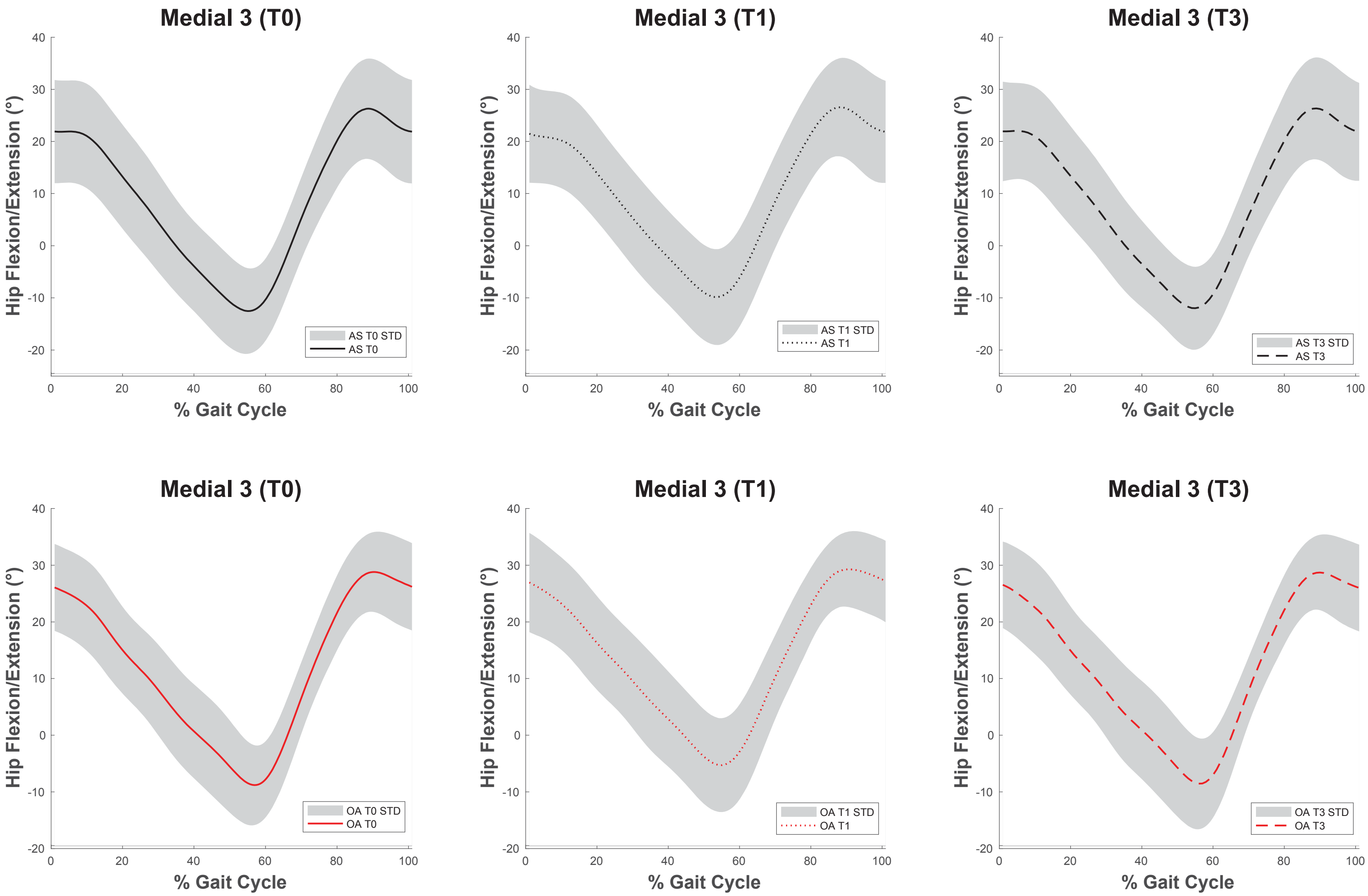

Figure A18: Sagittal plane hip flexion/extension angle for medial 3cm perturbations. Shaded area represents +/- one standard deviation about the mean for each time point (T0, T1, T3).

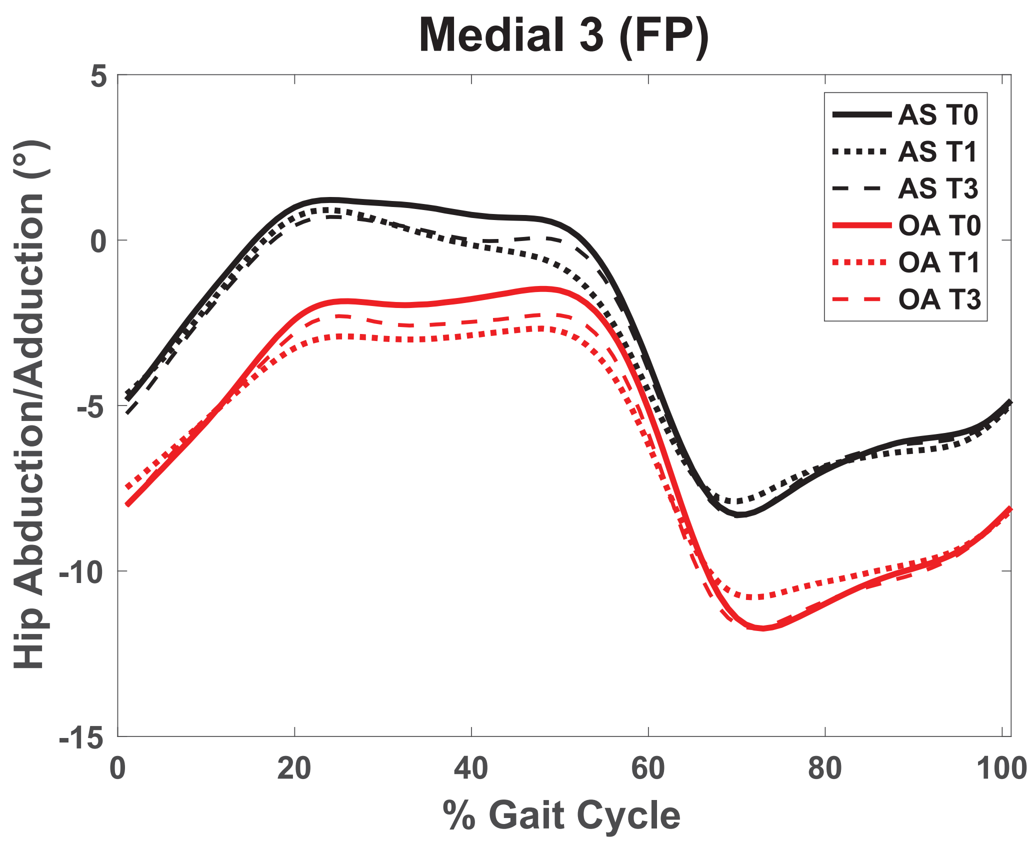

Figure A19: Frontal plane hip abduction/adduction angle for medial 3cm perturbations. The moderate OA group is represented by red curves and the asymptomatic groups are represented by black curves. Before the perturbation (T0) is represented by the solid, the first stride after the perturbation (T1) is represented by the dotted line and the third stride after the perturbation (T3) is represented by the dashed line.

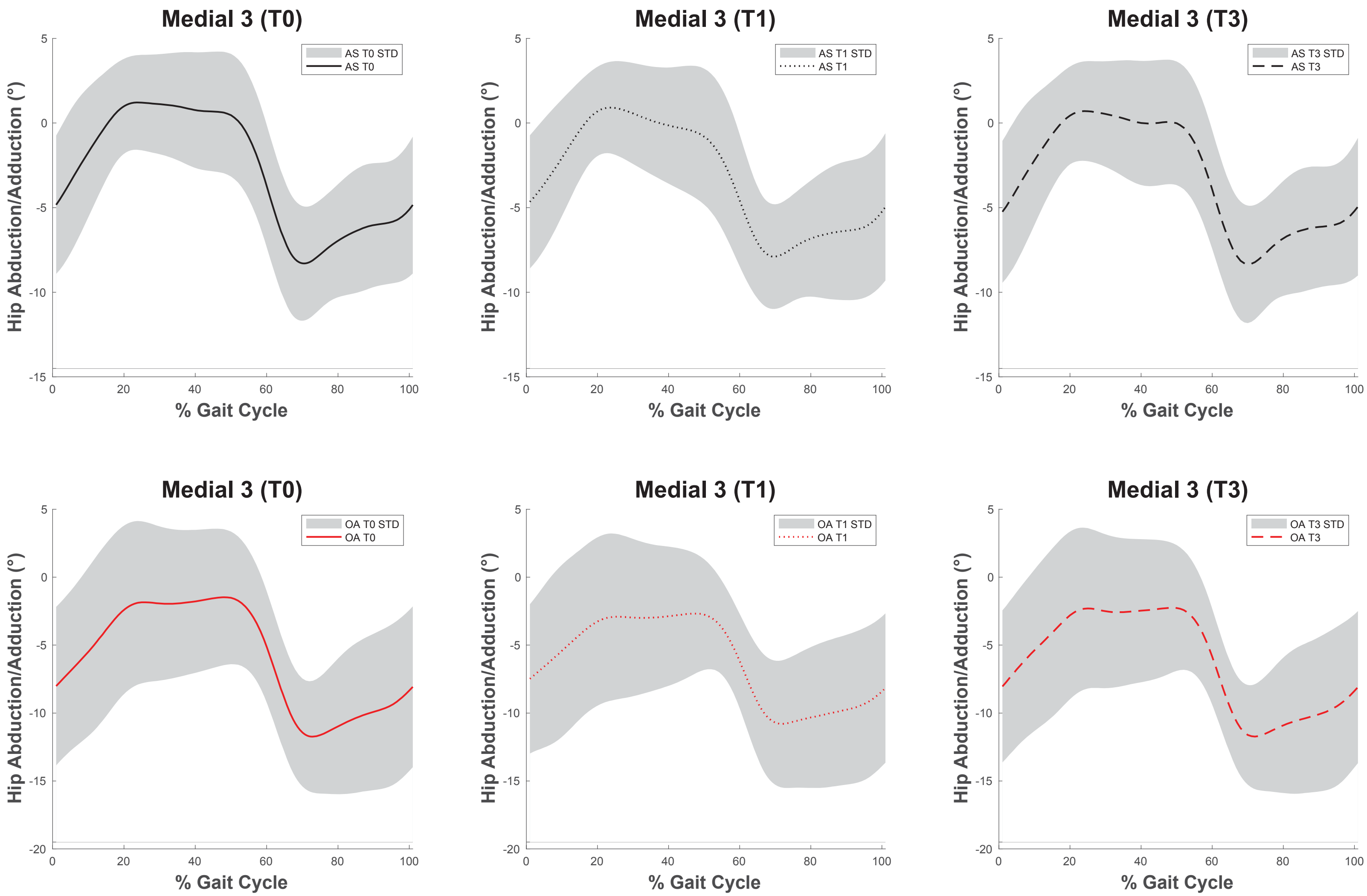

Figure A20: Sagittal plane hip adduction/abduction angle for medial 3cm perturbations. Shaded area represents +/- one standard deviation about the mean for each time point (T0, T1, T3).

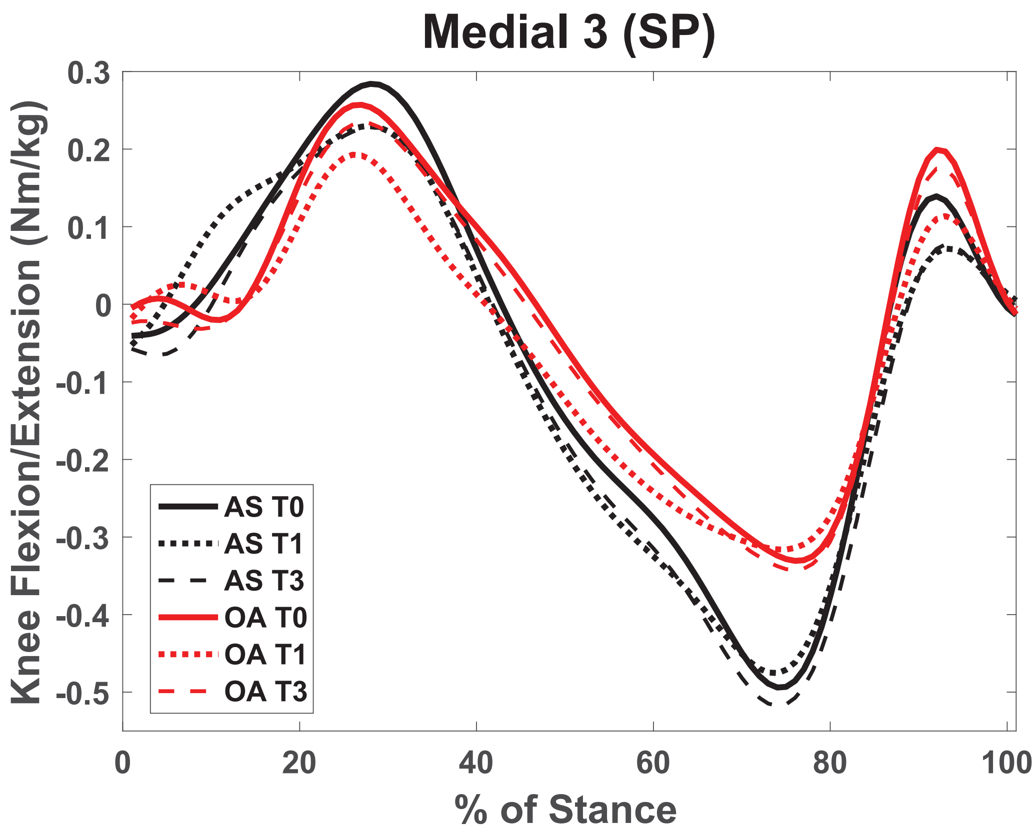

Figure A21: Sagittal plane knee flexion/extension moment for medial 3cm perturbations. The moderate OA group is represented by red curves and the asymptomatic groups are represented by black curves. Before the perturbation (T0) is represented by the solid, the first stride after the perturbation (T1) is represented by the dotted line and the third stride after the perturbation (T3) is represented by the dashed line.

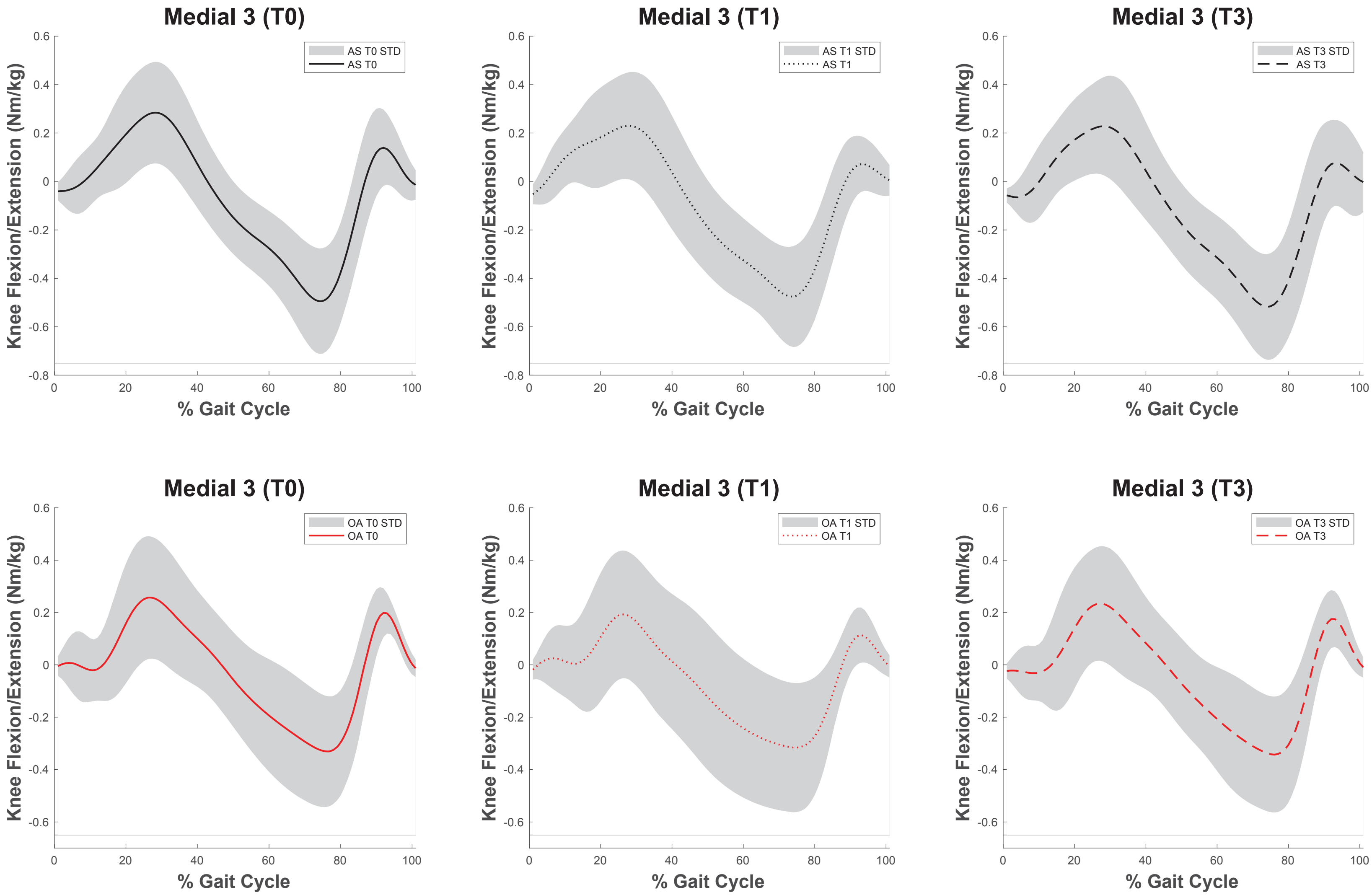

Figure A22: Sagittal plane knee flexion/extension moment for medial 3cm perturbations. Shaded area represents +/- one standard deviation about the mean for each time point (T0, T1, T3).

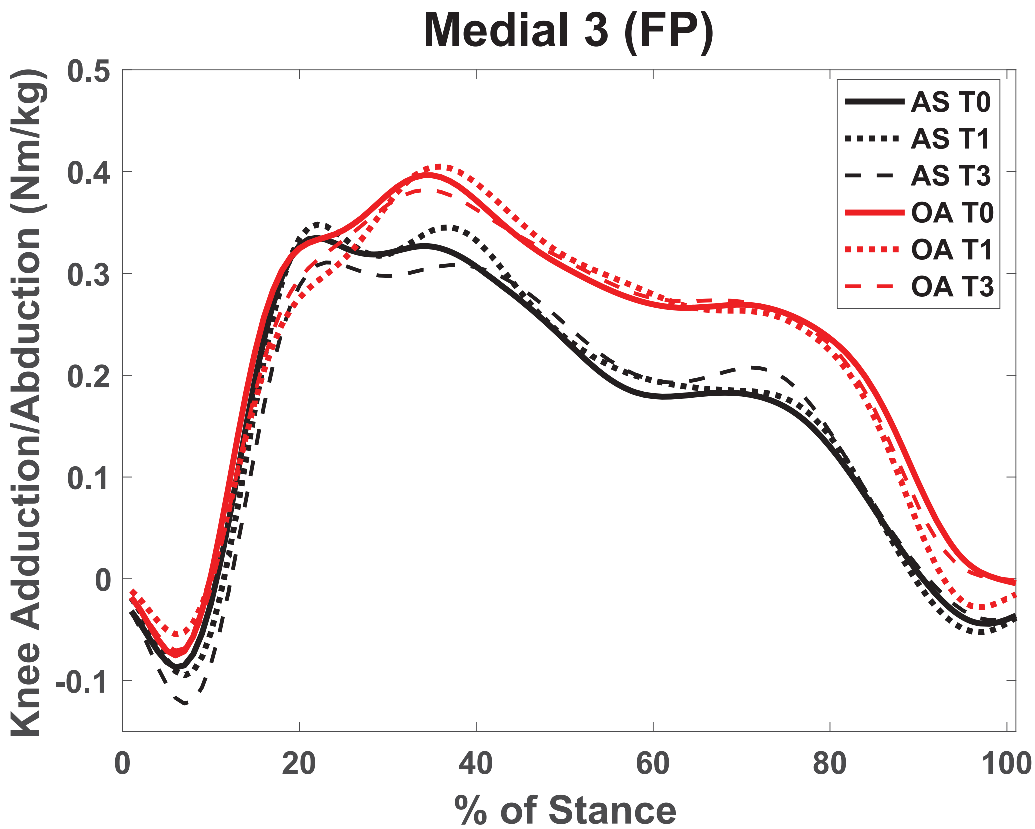

Figure A23: Sagittal plane knee flexion/extension moment for medial 3cm perturbations. The moderate OA group is represented by red curves and the asymptomatic groups are represented by black curves. Before the perturbation (T0) is represented by the solid, the first stride after the perturbation (T1) is represented by the dotted line and the third stride after the perturbation (T3) is represented by the dashed line.

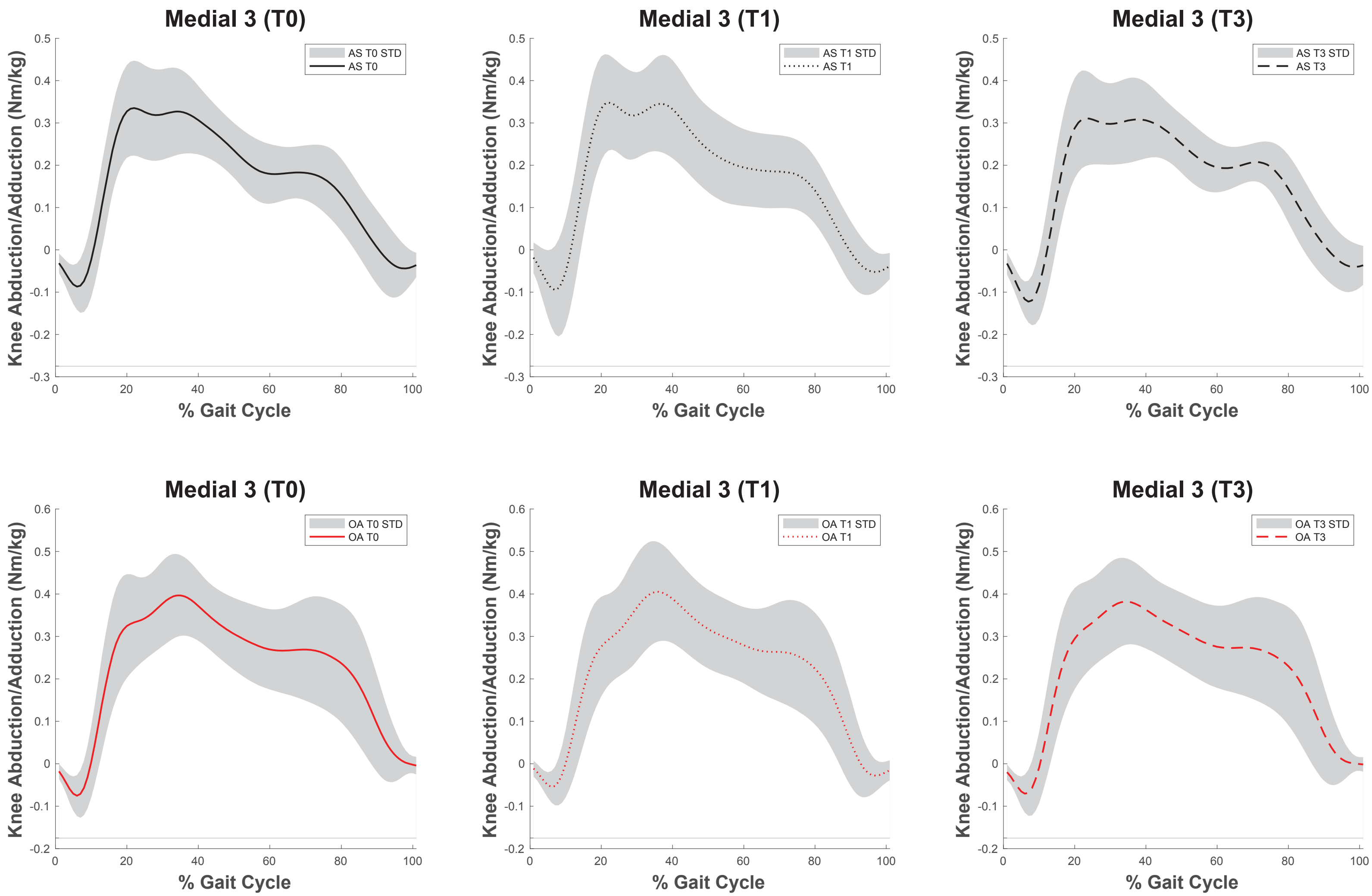

Figure A24: Sagittal plane knee adduction/abduction moment for medial 3cm perturbations. Shaded area represents +/- one standard deviation about the mean for each time point (T0, T1, T3).

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