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EVALUATING THE CHANGES IN HIP FUNCTION IN EXPECTANT MOTHERS BEFORE AND AFTER DELIVERY: CORRELATION BETWEEN HIP FUNCTION AND DELIVERY OUTCOME

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BY

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ABSTRACT

INTRODUCTION: Worldwide, approximately 800 women die *daily* from preventable maternal causes of death (COD). These CODs (e.g. prolonged labor, hemorrhage) are frequently connected to biomechanical limitations during childbirth. There is increased risk for complications/death during labor/delivery if pelvis/hip anatomy does not biomechanically change enough. Monitoring pelvic/hip biomechanical changes throughout pregnancy may help detect complications that arise during or prior to labor/delivery.

METHODS: Sixteen females (10 nulligravid female control participants, 6 gravid female participants) were enrolled. All participants performed walking, stair ascent, and stair descent while lower extremity optical motion capture and electromyography data (bilateral hip/knee flexors/extensors) were captured. Controls were assessed once, while gravid participants completed 5 timepoints (1 x T1, 1 x T2, 2 x T3, 1 x postpartum). Outcome variables included 3D peak pelvis/hip joint angles, neuromuscular features (peak EMG magnitude and dominant frequency), and post-partum patient reported outcome measures (PROMs). A Pearson's Correlation evaluated associations between peak joint angles/EMG magnitude and post-partum PROMs.

RESULTS: There was a significant impact of pregnancy status and gestation cycle timepoint on peak pelvis and hip joint angles in the sagittal plane during walking and stair descent. Kinematics changed significantly throughout pregnancy and returned towards pre-pregnancy values after parturition ($p<0.05$). While gestation cycle timepoint was not significantly connected with EMG variables, the dominant frequency of the gluteus maximums was significantly different between the control cohort and pregnant

cohort (p=-0.026). Additionally, kinematic values were significantly correlated with postpartum outcomes during walking. Specifically, it was found that hip transverse plane motion (i.e. internal/external rotation) was significantly correlated to Birth Satisfaction Scale scores (r>0.98, p<0.02). Additionally, hip extension was significantly correlated with active pushing time during labor (r=0.97, p=0.03).

DISCUSSION: Biomechanics are significantly impacted by pregnancy, mostly in the sagittal plane. More critically, these changes are correlated to clinical delivery outcomes, implying there may be a direct link between how the pelvis/hips biomechanically prepare for labor and intra-/post-partum outcomes. This result indicates there is the possibility for developing better screening and treatment modalities to reduce complications during labor and delivery.

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DEDICATION

For all mothers. For all women.

"There is no limit to what we, as women, can accomplish."

- Michelle Obama

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CHAPTER 1

INTRODUCTION

1.1 Background

Human childbirth is substantially more biomechanically challenging compared to the same process in other primate species (e.g. apes, monkeys, etc.).[1] Unlike other non-human primates where the fetal dimensions (e.g. head, shoulders, etc.) are significantly smaller than the maternal birth canal, the human maternal birth canal and fetal dimensions are closely matched in size.

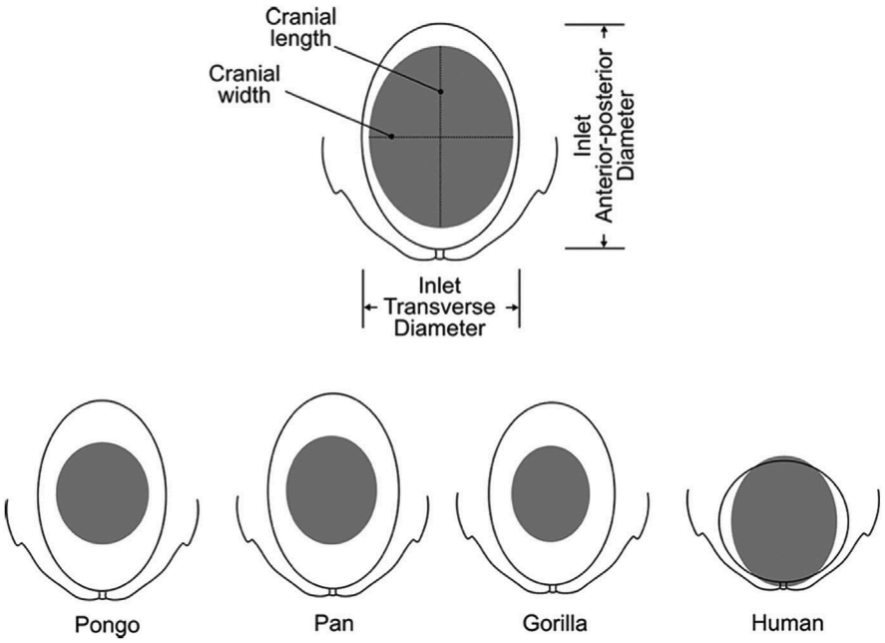


Figure 1. *Comparison of cephalopelvic proportions across related primates: orangutan (Pongo), chimpanzee (Pari), gorilla (Gorilla), and modern humans (from Pavličev, Am J Obstet Gynecol 2020.)*[1]

This is in part due to the encephalization (i.e. increasing brain size) of humans during evolution as humans adopted bipedalism (i.e. walking on two limbs).[2] During this adaptation, the pubic symphysis may have become more constrained while the fetal cranial dimensions increased. In contrast in non-human primates, the pubic symphysis is

often more flexible because of the quadruped position they typically assume, especially during the birth process.[1] Additionally, there is some evidence that there may be a reduced need for the non-human primate pelvis/pelvic floor to support a greater total mass as well as the reproductive and digestive organs compared to humans.[1] In contrast, the pelvic floor in humans is responsible for creating a horizontal support system for the abdominopelvic organs. Thus it has been suggested that a relatively smaller pelvic outlet enhances this support function.[1] While a wider and more flexible pubic symphysis (i.e. larger birth canal) would potentially be advantageous for a quick delivery, it has also been implicated in pelvic floor disorders.[1] Pelvic floor disorders are common complications associated with the gestation cycle and parturition itself, especially obstructed labor. Most commonly, they result from the strain to muscles and connective tissues that results from a widening pelvis that accommodates a heavy fetus. These disorders are also linked to craniopelvic disproportion and obstructed labor.[1] Thus, while a controversial topic in evolutionary biology/anthropology, developing bipedalism and encephalization may have resulted in the narrowing and stiffening of the human pelvis, and therefore the maternal birth canal.[1–3]

Despite a narrower and stiffer pelvis than other primates likely increasing the biomechanical difficulty of the progression of labor and delivery, it also may have several biomechanical advantages. One advantage is improved support for the weight of the viscera and human fetus during gestation.[1] Due to this evolutionary alteration, it is likely that a significantly different birth canal than other primates was sculpted which may not have accounted for the increased relative human brain size.[1] As a result of the matched pelvic outlet and fetal head size, human childbirth can result in complications during or

after birth, such as severe maternal morbidity (SMM; unexpected outcomes of labor and delivery resulting in significant consequences to a woman's health) and even maternal mortality.[1, 4, 5]

According to the World Health Organization, in 2020 approximately 800 women died *every day* worldwide from preventable maternal causes of death (COD).[6] Critically, the predominant CODs (hemorrhage, obstructed labor, protracted labor) can all be connected to prolonged or obstructed labor.[2, 5] Moreover, these CODs are in part connected to the biomechanical implications described previously. Additionally, the increase in cesarean sections performed in the US from 20.7% in 1996 to 32.1% in 2021 may be partially linked to biomechanical complications during pregnancy.[7] Critically, Cesarean sections are also associated with increased SMM risk and factors connected to maternal mortality (hemorrhage, hematoma, infection, subsequent surgical intervention).[2, 7, 8]

To aid in a safe progression of labor and potentially minimize the risks of SMM/maternal mortality, humans produce a hormone known as *relaxin*. *Relaxin* is responsible for creating laxity in ligaments including those found in the pelvis (sacroiliac and pubic symphysis).[9, 10] This is thought to facilitate widening of the birth canal in preparation for parturition. Unfortunately, many of the described CODs (hemorrhage, obstructed labor, protracted labor) are linked to narrower pelvic outlets.[2, 3, 5, 8] In other words, while increased *relaxin* concentration has been linked to pelvic ligament laxity and birth canal widening, there are occasions where pelvic anatomy alterations are not significant enough to accommodate the larger fetus size without risk of SMM and maternal mortality. This implies there may be an increased risk for complications during

labor and delivery if the pelvis anatomy does not change in the necessary magnitude. Therefore, if the pelvis and hips do not change enough biomechanically to accommodate fetal descent through the birth canal, there may be increased risk of complications during labor and delivery.

Accordingly, monitoring biomechanical changes in the pelvis and hips throughout pregnancy may help healthcare providers, patients, and scientists detect complications that could arise during or in advance of labor and delivery. To monitor these changes, biomechanics techniques/technology can be used to quantify kinematics, kinetics, and neuromuscular activity of the pelvis and lower extremities to anticipate and reduce SMM risks and maternal mortality. Though limited, emerging research has attempted to characterize biomechanical changes throughout pregnancy.[9, 10] Notably, these observed changes are not well understood or quantified. In particular, the change of pelvis and hip joint kinematics and kinetics are not well described and are often conflicting. According to previous studies by Mei et al. (2018) and Branco et al. (2013), peak hip flexion and extension in the sagittal plane are significantly reduced in the third trimester, but evidence is conflicting about frontal plane changes (i.e. hip adduction/abduction).[9, 11, 12] In another study conducted by Branco et al. (2015), the authors concurred that peak hip flexion and extension are reduced throughout pregnancy, but do not address any significant conclusions about the changes in the frontal and transverse planes.[9, 10] This inconsistency can be attributed to discrepancies between each study's measurement techniques. For example, some studies used the pregnant participant as their own baseline, while others used non-pregnant controls.[13, 15–18]

1.2 Statement of the Problem

The United States (US) has a maternal mortality rate almost 300% higher than any other global counterpart[13] despite having one of the most extensive and expensive healthcare systems.[14] While the US allots more money toward healthcare in comparison to the rest of the globe, maternal healthcare does not reap these benefits.[5, 13, 14] From 1900 to 1986, there was an impressive decline in the maternal mortality rate, from 850 to 7.4 deaths per 100,000 live births.[15] However, since then, the US has seen a reversal of this trend, with maternal mortality numbers increasing nearly five-fold since the 1980s[15] up to 32.9 deaths per 100,000 live births.[6] Today, over 1,200 American women die while pregnant or within 42 days from the end of that pregnancy annually. Moreover, about 60,000 experience near-fatal complications, otherwise known as severe maternal morbidity (SMM).[13, 14] Furthermore, disparities between geographical region, hospital location, and medical management strategies have been found.[14] Perhaps most critically, areas of low income, rural locations, and not-for-profit government-based management strategies are all factors that have been linked with significantly increased risk of childbirth complications compared to wealthier, urban areas, and for-profit hospitals.[16] In conjunction, race/ethnicity have also been linked to disparities in maternal outcomes and increased complication risk[6, 16] with non-Hispanic Black women dying 2.6x more frequently than non-Hispanic White women (69.9 vs. 32.9 deaths per 100,000 live births).[6]

Currently, the US healthcare system monitors potential pregnancy risks and complications during gestation, labor, and delivery using a traditional disease-based model. Typically, monitoring consists of screening for conditions like preeclampsia,

gestational diabetes, high blood pressure, and preterm labor[17] that require a healthcare professional to diagnose and treat. Unfortunately, due to the aforementioned disparities, access to early and regular prenatal care for detection and care for these complications is imperative but not always feasible for every expectant mother. As a national call for improvements on maternal care standards and research into maternal mortality and labor/delivery complications grows stronger, alternative techniques for finding indications of a high-risk pregnancy and potential labor/delivery complications are beginning to emerge. Specifically, while currently in its infancy, a focus has been placed on research into pregnancy biomechanics, and the implications these changes could have on clinical outcomes.

In addition to psychological and social influences, the success of pregnancy and labor/delivery relies upon biomechanical processes.[18] These biomechanical processes rely on physiological and anatomical changes to occur in order to minimize risk to both the mother and fetus. Specifically during pregnancy, numerous musculoskeletal biomechanical changes occur that anatomically alter the pelvis.[9] As previously stated, this includes an endocrinological influence on the muscles and ligaments that usually constrain the pelvis and its organs.[19] This typically yields pelvic anatomy changes in order to expand the birth canal as needed to allow the fetus to descend. As a result of this changing anatomy, the musculoskeletal biomechanics corresponding change.

Although these anatomical and biomechanical changes occur, few researchers have attempted to quantify them throughout the entire gestation duration and postpartum. Perhaps most critically, any connection that may exist between biomechanical changes that occur throughout pregnancy and post-partum outcomes has not been characterized.[9,

[16, 20] To develop better ante-partum screening protocols and improved decision-making during childbirth, further research is needed to explore biomechanical changes in the pelvis and hips throughout the course of pregnancy. Doing so could lead to standardized practices that begin narrowing current disparities (e.g. socioeconomic, geographic, racial) experienced throughout childbirth.

To our knowledge, no studies have connected any alterations to lower extremity biomechanics to labor/delivery outcomes. Additionally, no studies have examined each trimester of pregnancy vs. postpartum vs. nulligravid controls. Finally, neuromuscular measurements on pregnant mothers are not well researched. Accordingly, we propose quantifying how the kinematics and neuromuscular features of the pelvis and hips change through each trimester of pregnancy and postpartum using optical motion capture and electromyography. Additionally, we propose quantifying postpartum outcomes in order to establish if there are any correlations between labor/delivery outcomes and biomechanical changes throughout pregnancy.

Specific Aims & Hypotheses

Aim 1: Evaluate the 3D kinematic (i.e. joint angles) changes of the pelvis and hip joint and neuromuscular (i.e. electromyography [EMG]) changes in the gluteus maximus and rectus femoris muscles throughout pregnancy, postpartum, and in non-pregnant participants during activities.

Hypothesis 1.1: Expectant mother peak hip joint angles will change significantly at each pre-parturition visit in the frontal and transverse planes, but not the sagittal plane during activities.

Hypothesis 1.2: Expectant mother neuromuscular activity (peak EMG magnitude and dominant EMG frequency), in both the bilateral gluteus maximus and rectus femoris, will not change significantly throughout pregnancy during activities.

Hypothesis 1.3: At the postpartum visit, all variables will not be significantly different from nongravid control subjects.

Aim 2: Evaluate the correlation between pelvis and hip biomechanical function and post-partum outcomes (delivery room statistics and clinical psychological survey results).

Hypothesis 2.1: There will be a significant correlation between changes in peak joint angles in the frontal plane and positive postpartum outcomes (i.e., delivery ease, delivery perception, etc.).

Hypothesis 2.2: There will not be significant correlations between changes in neuromuscular features and postpartum outcomes (i.e., delivery ease, delivery perception, etc.).

CHAPTER 2

LITERATURE REVIEW

2.1 The Problem

Limited literature is available concerning biomechanical and neuromuscular changes throughout pregnancy. Even less is known about the correlations to postpartum outcomes. By examining the changes in biomechanics and neuromuscular activity throughout pregnancy as well as capturing postpartum outcomes, our study will establish any connections between biomechanical/neuromuscular changes throughout pregnancy with clinical outcomes.

2.2 Maternal Mortality

Maternal mortality is a prevalent issue globally. To date, there is a global ratio of 400 maternal deaths per 100,000 live births with an estimated 529,000 women dying from pregnancy-related causes annually.[13] The CDC defines pregnancy-related deaths as the death of a woman during or within one year of pregnancy that was considered to be caused by a pregnancy complication, a chain of events initiated by pregnancy, or an aggravation of another condition by the physiological effects of pregnancy.[4, 21] Although the definition of pregnancy-related death differs between countries making data monitoring challenging, the CDC estimates the risk of dying from a pregnancy-related complication is much higher in the US than most European or other high-income countries.[5, 21] Further estimates indicate approximately 1,200 women in the US die annually during pregnancy or childbirth and more than 60,000 women suffer from near-fatal complications each year.[14] Not only are maternal mortality rates (MMR) in the US

higher than other high-income countries, but there has also been a reversal of positive trends the past two decades.

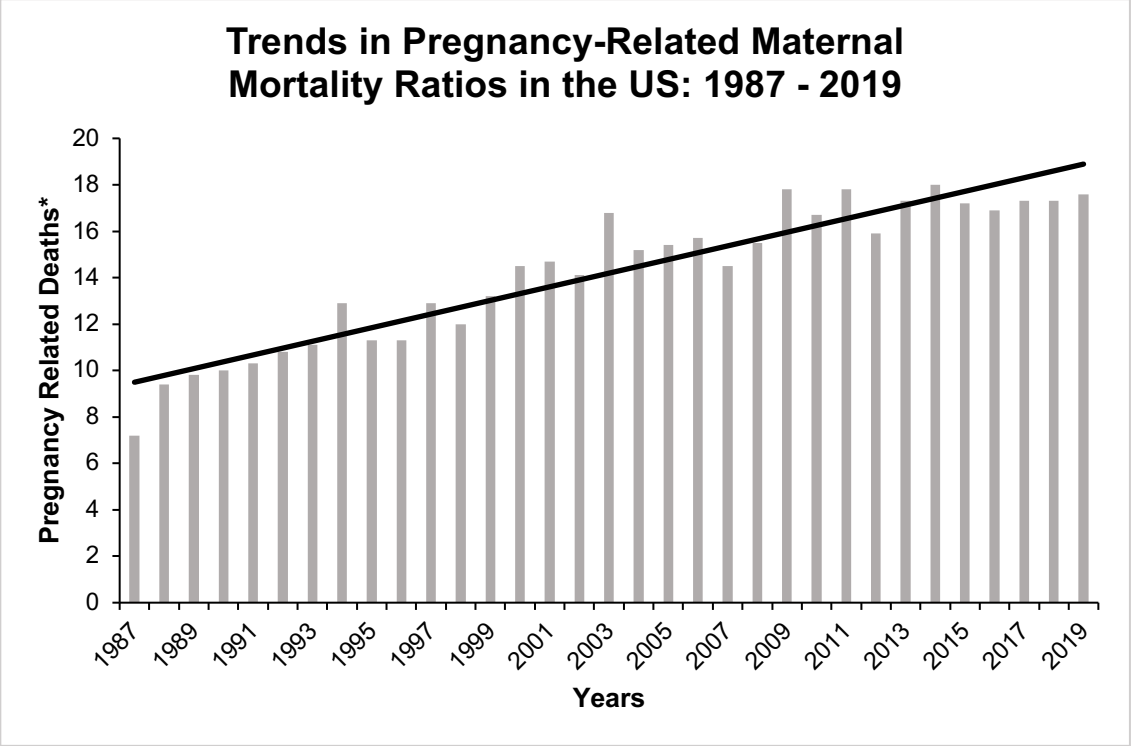


Figure 2. *Trends in pregnancy-related maternal mortality in the United States from 1987-2019. *Number of pregnancy-related deaths per 100,000 live births per year. Data from Centers for Disease Control and Prevention.*[22]

The average MMR across the continental 48 states is estimated to have risen by almost 27% from 18.8 to 23.8 maternal deaths per 100,000 live births since the year 2000. In 2019, 754 pregnancy-related deaths were reported, whereas in 2021, this statistic rose to 1,205 women.[6, 15] This trend stands in stark contrast to other high-income countries who have seen consistent improvements to their MMR and SMM statistics.[5, 23]

In investigating the causes of maternal mortality or SMM, various factors have been identified, including disease-specific (e.g. hemorrhage), management specific (e.g. interventions to prevent diseases), and organ-system dysfunction.[14, 21] Hemorrhage and infection (disease-specific criteria) as well as cardiovascular conditions (organ-system

criteria) are estimated to cause 50% of all pregnancy-related deaths.[23] Looking deeper at cardiovascular conditions, instances of cardiogenic shock have increased 3-fold since the year 2000.[21, 23] Typically, cardiogenic shock occurs when the body cannot pump enough blood to meet the body's needs. This generally occurs as a result of severe obstetric hemorrhage during the childbirth process. Critically, obstetric hemorrhage that results in maternal mortality has been directly linked to obstructed labor.

2.2.2 Obstructed Labor

Obstructed labor, or the failure of the fetus to descend fully in the birth canal despite having adequate uterine contractions, is one of the most common causes of maternal death.[24, 25] Obstructed labor frequently leads to maternal and fetal mortality and morbidity mainly due to detrimental side effects, such as infection and severe hemorrhage.[24] The most common cause of obstructed labor is believed to be craniopelvic disproportion (CPD), or a fetal head that is larger or very close in size to the birth canal or pelvic inlet of the mother.[25, 25, 26] Compared to other primates the human fetal head size relative to the pelvic inlet size is a significantly greater than the same dimensions in non-human primates.[26, 27] Thus, the likelihood of CPD, and therefore obstructed labor, is significantly greater in modern humans than other primate species.[26, 28]

In current clinical practice, to avoid morbidity and mortality, the timing and likelihood of obstructed labor is predicted.[29, 30] Specifically, predictions of obstructed labor assess cervical ripening and evaluations of the bony anatomy of the pelvis in preparation for labor.[29, 31] Historically, bony anatomy evaluations have been done via radiographic pelvimetry in order to measure pelvic inlet size and/or screen for bony

prominences that could obstruct labor.[31] However, clinical pelvimetry has played a reduced role in modern obstetric practice given x-rays are unsafe for the developing fetus. Pelvimetry was also unreliable for measuring the anatomical disproportion between the fetal head size compared to the pelvic inlet size.[1, 26, 31, 32] While pelvic inlet size could be significant for determining the route of delivery in the future, limited evidence suggests that these measurements alone, are enough to predict obstructed labor.[32] In other words, relying exclusively on evaluation of pelvis bony anatomy limits the possibility that other structures that also change throughout gestation could contribute to obstructed labor as well.[29]

Although a matched fetal head size and pelvic inlet dimension are known to increase the likelihood of obstructed or prolonged labor, these variables are only one factor involved in explaining obstetrical challenges.[1] While a smaller pelvis is believed to be better for upright stability and a stronger pelvic floor, there is a need to understand how the pelvis changes anatomically and biomechanically throughout pregnancy.[19] For example, there are other biomechanics factors at play like the hips widening, additional kinematic/kinetic consequences on the lower extremity, and neuromuscular alterations.[33] Considering a broader perspective that includes the simultaneous contributing factors to anatomical and morphological changes in pregnancy is paramount to understanding abnormal or obstructed labor.[1, 29] Therefore, a new paradigm, where labor is recognized as a fundamentally biomechanical process, is necessary. By understanding the biomechanical changes that occur throughout pregnancy, especially during locomotion, better prediction models for obstructed labor could be developed to personalize

interventions for women who need support or are at greater risk for morbidity/mortality during childbirth.[1]

2.3 Biomechanics in Pregnancy

Currently, biomechanics in typically developing, healthy humans is well understood. In the past, there has been an attempt to understand how biomechanics may change or deviate throughout pregnancy. Typically, these pregnancy-induced changes have been characterized during walking by measuring various joint kinematics/kinetics as well as some neuromuscular activity using EMG.[34–36] This has resulted in colloquial terms for gait during pregnancy, such as "the pregnancy waddle."

2.3.1 Kinematic Adaptations During Pregnancy

The kinematics of this pregnancy induced "waddle" gait has been studied by a number of investigators. Foti et al. (2000) were one of the first research groups to study gait adaptations throughout gestation. This study aimed to evaluate the gait deviations associated with pregnancy by performing a three-dimensional gait analysis during walking at a self-selected speed in the second half of the third trimester and again one year postpartum.[37] They hypothesized they would observe increased hip range of motion (ROM) given there are substantial hormonal changes (*relaxin*) throughout pregnancy that have been linked to increased ROM of the pelvis.[37, 38] Compared to postpartum, maximum anterior pelvic tilt increased by an average of 4 degrees during the third trimester. Maximum hip flexion and hip adduction during stance phase of gait during the third trimester was increased as well, but no other kinematic parameters were

significantly different between the two time points.[37] However, because they only measured 1 timepoint in late pregnancy and 1 timepoint postpartum, there may not be enough data to significantly draw conclusions about gait adaptations throughout pregnancy.

Forczek et al. (2018) also attempted to evaluate gait adaptations during pregnancy via participants' walking mechanics during a self-selected speed before pregnancy and at the end of Trimester 1. Given *relaxin* levels peak during the first trimester, they expected changes in mechanics during pregnancy due to increased joint laxity.[39, 40] They performed a kinematic gait analysis of the pelvis and hips because these are the structures most directly connected with the location of the developing fetus.[39, 41] Their findings were consistent with previous literature, failing to observe significant changes between pre-pregnancy and Trimester 1 measures.[37, 39] Therefore, they concluded peak *relaxin* levels do not coincide with observed changes in mechanics during pregnancy.

Branco et al. (2013) also conducted a longitudinal study to explore the kinematics and kinetics of gait during pregnancy in Trimesters 2 and 3. They noted growth of the fetus is primarily biomechanically carried in the abdominal/pelvic region, where an additional 50% increase of fetal weight can be observed in Trimester 3 alone.[12, 39, 41] These changes typically lead to an increase in the overall body weight of the mother and can result in superior shifts in the center of gravity.[12, 42] This study primarily aimed to capture the effects of increased fetal weight on pregnancy gait by quantifying the lower extremity kinematics and kinetics, comparing these measurements to those of nulligravid participants (never been pregnant).[12] Significant differences were present in the first hip abduction peak during walking between non-pregnant control participants and pregnant

participants at Trimester 2.[12] In the other lower extremity joints, no significant changes were found throughout pregnancy. These results highlight that the hip joint kinematically changes more in response to pregnancy than other lower extremity joints.

To our knowledge, few studies exist assessing the biomechanics of expectant mothers throughout the entire temporal continuum of pregnancy. However, Hagan & Wong (2010) completed a longitudinal case series on 2 pregnant participants to study lower extremity changes through all three trimesters of pregnancy and postpartum. Participants were assessed during walking at a self-selected speed at five time points: pre-pregnancy, near the end of Trimester 1, Trimester 2, and Trimester 3, and 12-16 weeks postpartum (PP).[43] They found that anterior pelvic tilt increased by more than 5 degrees from Trimester 1 to Trimester 3 during stance phase of gait for both participants, aligning with previous studies.[37, 43] Anterior pelvic tilt during gait at PP returned to that found during Trimester 1.[43] They also found average hip flexion decreased by at least 5 degrees from Trimester 3 to PP during gait.[43] This study suggests that pregnancy alters gait kinematic of the hip and pelvis most significantly in the sagittal plane.[37, 43] However, their investigation was only a small case series, and therefore should not be generalized to other larger populations.

In another longitudinal investigation conducted by Branco et al. (2015), they assessed gait kinematics/kinetics to discover the effect pregnancy has on biomechanical patterns and dynamics changes of walking.[10] Eleven pregnant participants performed a 10-meter walk test at a self-selected speed during Trimesters 1, 2, Trimester 3, and post-partum. Hip flexion increased while extension decreased between both Trimester 2 and PP, and Trimester 3 and PP. From Trimester 1 to Trimester 3, hip adduction decreased

slightly while internal rotation increased.[10] As such, they concluded kinematic parameters in all 3 planes of motion are influenced by the progression of pregnancy. Moreover, pelvic kinematics were consistent with published literature showing anterior pelvic tilt increases, coinciding with morphological changes that occur throughout pregnancy.[10, 37, 43]

Mei et al. (2018) also conducted a longitudinal study on adaptions and alterations that occur throughout pregnancy and postpartum during gait. The purpose of this study was to connect gait biomechanics before parturition to changes in the postpartum period.[10, 11] Sixteen pregnant participants were analyzed during self-selected speed walking during Trimester 2, Trimester 3, and PP. Peak anterior pelvis tilt during the third trimester was greater than Trimester 2, consistent with findings of previous studies.[10, 11, 37, 43] They also found both peak hip flexion and extension were significantly greater in PP than in Trimesters 2 and 3. Peak external hip rotation was also greater in Trimester 3. Larger peak hip adduction was discovered post-partum compared to Trimester 2 and Trimester 3, consistent with the findings of Branco et al..[10, 11] They believe, these alterations are biomechanical mechanisms pregnant women adopt for increased stability needed with the increasing fetal weight.[11, 12, 39, 41]

Few studies have attempted to capture biomechanical adaptations throughout pregnancy of any other activity or physical function task besides walking. Gilleard et al. (2008) conducted a longitudinal investigation that aimed to study the effect of pregnancy on rising to stand from a chair.[44] They compared lower extremity kinematics of 9 pregnant participants to 12 nulliparous control participants during a sit-to-stand test. Each pregnant participant was seen once in Trimester 1, once in Trimester 2, twice in

Trimester 3, and once PP.[44] They found that at PP, pelvic anterior tilt was significantly less than controls. However, no other significant kinematic changes were found as pregnancy progressed compared to controls. They argued that while kinematics were similar to the control group in early pregnancy, there were still biomechanics changes in other joints that exceeded those accounted for by natural variability.[44] It was also found that there were relatively large standard deviations, indicating significant variability between pregnant women. These changes suggest there are adaptations during pregnancy to minimize movement obstructions and increase stability during rising from a chair.[44] Given few studies exist evaluating longitudinal changes induced by pregnancy during non-gait functional tasks, further investigation is needed to focus on other activities across a broader spectrum of timepoints throughout pregnancy.

2.3.2 Neuromuscular Adaptations During Pregnancy

The relationship between neuromuscular adaptations of the lower extremity and pregnancy have not been extensively studied. Similar to previous literature on kinematic adaptations throughout pregnancy, studies that do attempt to establish a relationship between muscle activity and pregnancy typically do so through walking gait only. Electromyography, which is used to measure neuromuscular activity, could potentially provide additional information on how muscles or muscle groups are activated during pregnancy. Thus, this information may elucidate musculoskeletal changes during or after pregnancy. These changes may be insightful to understanding how the body prepares for parturition and what neuromuscular demands are placed on the mother.[35]

In most previous literature, only the static and dynamic biomechanical adaptations of the lower extremity and gait pattern changes throughout pregnancy were studied. It has been found that while most literature on walking gait patterns throughout pregnancy have similar conclusions,[11, 12, 20, 37, 39, 43–45] little is known about the neuromuscular adaptations of walking gait throughout pregnancy.[46] However, from previous literature on biomechanics in pregnancy, it is clear that biomechanical changes promote some muscular overloads on the lower limbs[46] that could lead to injury during pregnancy or postpartum.

A study conducted by Bagwell et al. (2020) aimed to show a difference of lower extremity kinetics and muscle activation during gait between nulliparous females and pregnant females. The purpose was to understand how neuromuscular activity changes throughout pregnancy during walking gait.[34, 35] The researchers argued that comparing pregnant participants to nulliparous controls is important because it is unknown if pregnancy has an effect on neuromuscular activity.[35, 46] In this longitudinal study, 23 pregnant participants and 23 nulliparous participants completed 7 trials of a 16-meter walkway at a self-selected speed. Pregnant participants were captured during Trimester 2, Trimester 3, and postpartum, totaling 3 sessions.[35] The researchers found pregnant participants showed a smaller peak gluteus maximus amplitude and reduced peak hip extension in Trimester 2. For the first time, this study showed that pregnant females show a difference in lower extremity muscle activation compared to nulliparous females. Additionally, they confirmed reduced use of the hip, exemplified by the reduced sagittal plane movement and gluteus maximus amplitude.[35]

Previously, an association between pregnancy related pelvic girdle pain and altered kinematic, kinetic, and motor control of the pelvis has been explored.[40] In a study conducted by Bagwell et al. (2022), the researchers attempted to establish a correlation between biomechanics and muscle activation in pregnant females with reports of pelvis girdle pain during and after pregnancy. They studied 20 pregnant participants with data collections occurring once in Trimester 2, Trimester 3, and PP during self-selected speed overground walking. While they found no significant interactions with respect to peak kinematics, they did find that gluteus maximus peak amplitude was smaller during Trimester 2 compared to Trimester 3.[34] They also discovered increased activity in the rectus femoris.[42, 48] Although the level of evidence for the association was moderate, this evidence supports that muscle activity changes in lower extremities of pregnant women. These findings were consistent with previous studies that have found that there is reduced use of the hip during pregnancy and indicates a clinical need to better prepare pregnant mothers for changing joint loading and muscular demands.[34, 35]

2.4 Postpartum Outcome Measures

The association between postpartum outcome measures and biomechanics in pregnancy is not one that has been studied before. No previous literature has examined the relationship between any biomechanical variable, including kinematics, neuromuscular features, or their respective changes, and postpartum outcomes and/or clinical measures of delivery. However, measuring delivery and postpartum outcomes is an important aspect of the clinical care of expectant mothers.

Delivery room statistics and clinical surveys are used to measure the "ease" of parturition in the delivery room.[49] Dystocia, or difficult labor that is slow and not progressing, has been linked to increased cesarean delivery rates in the US.[50] Typically, mothers who experience dystocia are likely to have longer total labor durations.[50–52] If labor duration surpasses 14 hours for primiparous and 20 hours for multiparous mothers, thus defined as "prolonged labor", then the mother is more at-risk for a caesarean section.[53] Typically, mothers who experience prolonged labor are likely to also experience both a delay and increased duration of active pushing during labor.[51, 53, 54] Prolonged active push time, which is part of the active stage of labor, has been linked to adverse maternal outcomes after delivery.[54, 55] Adverse maternal outcomes are considered to be compilations related to cesarean sections (i.e, hemorrhage, massive blood loss, sepsis, etc.[19, 27]), pelvic injury, or maternal and/or neonatal mortality.[50, 55, 56]

It has also been found that delivery room statistics have a connection with mental health outcomes after delivery. Clinically, it is important to measure how satisfied a mother feels with her delivery and her postpartum adjustment since the outcome of these variables have been found to be influenced by poor delivery room statistics.[51, 53, 57–61] Mothers who experience increased risks and complications due to dystocia and/or unplanned caesarean section are more likely to be less satisfied with their delivery, more prone to postpartum depression, and experience challenges bonding with their baby.[59, 62] By measuring these variables, clinicians aim to understand the impact of caesarean section and delivery complications on mothers and their adjustment into the postpartum period.

Several surveys have been developed and validated to measure the mental and psychological wellbeing of a mother after delivery. The Birth Satisfaction Scale (BSS) is validated survey used to measure how satisfied a mother is with her delivery experience.[63–65] Higher scores on the BSS, which means a mother is more satisfied with their delivery experience, are associated with less medical interventions during delivery, feelings of less stress during delivery, and spontaneous, vaginal births.[64] The Mother-Infant Bonding Scale (MIBS) is another validated survey[66] that measures the perceived bond between a mother and baby after delivery. It has been found that emergency caesarean sections have been linked with significantly higher scores on the MIBS, indicating that the mother feels less bonded with her baby.[61] It has also been thought that these feelings of decreased bonding originate in feelings like sadness and disappointment from an unplanned or mentally and physically traumatic delivery experience.[61] The Edinburgh Postnatal Depression Scale (EPDS) is the most commonly used validated screening tool for women who might be depressed after delivery.[67–69] Women who experience emergency caesarean section tend to score higher on the EPDS, meaning they are more likely to be depressed after delivery.[60] Depression after delivery has been associated with feelings of resentment towards their baby, a feeling of inadequacy, and increased anxiety during caretaking.[59, 60, 63]

As previously mentioned, there is a need to understand how pelvis and hip biomechanics change throughout pregnancy because of the theoretical relationship between biomechanical pregnancy changes, craniopelvic disproportion, and, therefore, caesarean sections.[30, 31, 35] Since it is recognized that dystocia and the subsequent health risks and complications, such as caesarean section, can lead to adverse delivery room and

postpartum outcomes,[51, 70] it is important to investigate if an association between biomechanical changes throughout pregnancy and delivery/postpartum outcomes exists.

Critically, our current understanding of the biomechanical and neuromuscular changes throughout pregnancy and postpartum is limited, particularly in connecting biomechanics changes to postpartum outcomes. Existing literature has primarily focused on lower extremity kinematic changes through walking gait, with less attention given to neuromuscular activity changes. Moreover, existing studies have inconclusive or conflicting findings regarding the quantification of kinematic/neuromuscular changes that occur as a result of pregnancy. Thus, there is a gap in the literature regarding the impact of pregnancy on biomechanical and neuromuscular changes throughout pregnancy *and* postpartum during physical function tasks.

Additionally, there is a significant gap connecting these biomechanical and neuromuscular changes through pregnancy to clinical outcomes during and after labor/delivery. To address these gaps, our study will specifically explore the kinematic changes of pregnant participants over 5 visits (Trimester 1 (T1), Trimester 2 (T2), early Trimester 3 (T3.1), late Trimester 3 (T3.2), and $\geq$ 4 weeks postpartum (PP)) during self-selected walking, stair ascent, and stair descent. We will also track delivery room and postpartum outcomes of both the mother and baby. By examining the correlation between kinematic and neuromuscular changes and delivery/postpartum outcomes, we aim to fill these gaps and gain a better understanding of how the pelvis and hips prepare for parturition and if this preparation has any impact on postpartum outcomes.

The conclusions from this research have the potential to contribute to the quantification of what normal musculoskeletal changes during pregnancy should be and

what is considered abnormal. They may also be able to establish a correlation between biomechanics and clinical outcomes for parturition. This may aid in early detection of abnormal labor and contribute to the development of more effective screening and prediction tools for obstructed labor. Through this work, we hope to take the first step toward a novel approach for reducing maternal mortality and morbidity rates by developing novel diagnostics and interventions for parturition support earlier in pregnancy. Ultimately, our study aims to provide valuable knowledge that can improve clinical care for pregnant women and enhance our understanding of the biomechanics of pregnancy.

CHAPTER 3

METHODOLOGY

3.1 Study Design

This study was a prospective, longitudinal, case-controlled study. Eligible participants were separated into two groups: a nulliparous control cohort and a pregnant cohort. The control cohort was required to complete one data capture visit to the University of Rhode Island Biomechanics and Wearables Laboratory (BWL). The pregnant cohort completed 5 visits total, consisting of one visit in Trimester 1 (T1; $\leq$ 13 weeks pregnant) and 2 (T2; 14-27 weeks pregnant), two visits during Trimester 3 (T3.1; 28-32 weeks pregnant and T3.2; 33-27 weeks pregnant), and one visit postpartum (PP; > 4 weeks after delivery), totaling five data capture visits in the BWL.

3.2 Study Population

Pregnant mothers (n=6) and non-pregnant, nulligravid females (n=12), both aged 18-35 years and considered healthy, were recruited from Southern New England via flyers, social media, and advertisement at local birthing centers and public community spaces. Interested individuals contacted a member of the research team via email. They were provided an online pre-screening questionnaire to determine eligibility. Specific inclusion and exclusion criteria for both cohorts of participants are displayed and explained in Table 1.

Table 1. *Study inclusion and exclusion criteria.*

Pregnant Participants:	**Control Participants:**
INCLUSION CRITERIA	
Healthy pregnant woman Within 1st trimester of pregnancy Aged 18-35 years old Able to climb stairs for 1 minute Able to walk without the use of assistive devices Able to read, speak, and understand English Secure transportation to URI Be cleared to perform minimally strenuous physical activities	Healthy non-pregnant woman Aged 18-35 years old Not currently pregnant and has never been pregnant or given birth previously Able to climb stairs for 1 minute Able to walk without the use of assistive devices Able to read, speak, and understand English Secure transportation to URI Be cleared to perform minimally strenuous physical activities
EXCLUSION CRITERIA	
Diagnosis of chronic condition that affects balance and/or taking medications that affect balance History of hip surgery or hip replacement or significant hip injury Inability to walk for 5–10-minute periods	Diagnosis of chronic condition that affects balance and/or taking medications that affect balance History of hip surgery or hip replacement or significant hip injury Inability to walk for 5–10-minute periods

3.3 Study Protocol

Pre-screened, eligible participants were invited to an onsite visit where eligibility was confirmed again via identical paper-based eligibility screening (see Appendix 1). Following paper-based eligibility screening, informed consent was completed via paper form. After written consent was obtained, a urine-based pregnancy test was completed to ensure participants were grouped correctly based on active pregnancy status.

Following urine-based pregnancy test, all participants regardless of cohort completed a series of paper surveys including the Edinburgh Handedness, Waterloo Footedness, Visual Analog Scale of Pain, PROMIS Physical 10a, PROMIS Physical 10b, and PROMIS Life Satisfaction 5a surveys (see Appendix 2-7). Next, anthropometrics were captured including height, weight, limb length, and fundal height. A standard

stadiometer and platform scale were used to measure height and weight respectively. Limb length, using a soft-cloth tape measure, was measured in 2 segments: greater trochanter to lateral epicondyle of the femur and lateral epicondyle of the femur to lateral malleolus of the ankle. Fundal height was also measured with a soft-cloth tape measure between the public symphysis and top of the uterus. Goniometric range of motion (ROM) was then captured bilaterally on the hip joint in all three planes of motion.

Afterwards, all participants were fitted with retroreflective motion-capture markers placed on specific anatomical landmarks (full lower limb set and pelvis cluster) and electromyography sensors. All data captures took place on a force plate instrumented treadmill. Non-gravid (control) participants completed this data capture process once. Expectant mothers returned for the identical data capture process four additional times (5 total data capture visits).

3.4 Data Collection Modalities

3.4.1 Optical Motion Capture

Optical motion capture systems are used to track the motion of humans, animals, or objects by digitizing the position of reflective markers for kinematic analyses. Reflective spherical markers (optical MOCAP markers) were placed on specific anatomical landmarks that were tracked in three dimensions via infrared light-based cameras. These 3D positions were then compiled into a model of the underlying skeleton of each specific subject to describe their movements in detail.

Specifically, herein, kinematic data were collected using 8 infrared cameras (Miqus M3, Qualisys AB, Göteborg, Sweden; f_s=100 Hz). The cameras were calibrated

via manufacturer's recommendations using the standard 300mm wand and oriented via L-frame. Calibration was accepted only if the standard deviation of the wand length measured below 0.5mm.

Figure 3. *Lower extremity marker set.*

Figure 4. *Sacral cluster.*

3D marker positions for all trials were stored via Qualisys Track Manager (QTM). Optical MOCAP markers were placed on anatomical landmarks on the pelvis and lower extremities according to a predefined marker set (Figure 3). This marker set was developed and validated by Cappozzo et al. (1999) for the lower limb segments and CODA pelvis (Charnwood Dynamics, Ltd., Leicestershire, UK).[71] Due to the progression of pregnancy and development of a significant fundal distance, instead of using the traditional 4 separate pelvis markers (bilateral anterior superior iliac spines, bilateral posterior superior iliac spines), a sacral cluster was attached to the posterior sacral surface via using gauze wrap (Figure 4). Four separate static calibration files were captured using a virtual marker creation wand to virtually create four pelvis markers referring back to the sacral cluster and monitor the motion of the pelvis. Additional individual markers were

placed on relevant anatomical landmarks (bilaterally on the lateral and medial femoral epicondyles, lateral and medial malleoli, 1st metatarsal head, 5th metatarsal head, and calcaneus) using tape adhesive and Cover Roll. Marker clusters were placed on bone segments (bilaterally on the midshaft of the thigh and shank) using gauze wraps. All MOCAP data was stored in QTM and post-processed in QTM and Visual3D.

3.4.2 Electromyography

The primary objective of EMG technology is to obtain neuromuscular electrical activity. This information is then used to detect any patterns or irregularities that may occur during a movement or activity. The specific modality utilized herein was surface EMGs (sEMGs). sEMGs were placed directly on the skin via adhesives and the EMG sensors captured the magnitude and frequency of the electrical signals that a specific muscle produced when activated.

In this study, sEMGs (Delsys Trigno Wireless EMG System, Delsys Inc., Natick MA; f_s=1000Hz) were placed bilaterally on the participant's *gluteus maximus* and *rectus femoris* to measure muscular activity of the primary hip extensors (*gluteus maximus*) and flexors (*rectus femoris*), respectively. Each sEMG sensor was wirelessly connected and temporally synchronized with the QTM software for data capture. Prior to placement of each sEMG sensor, the skin was lightly abraded via small Brillo pad and sterilized via alcohol wipe at the site of the sEMG. All sEMG sensors were placed at the belly of the muscle oriented with the long axis of the muscle fibers. Specifically, the sEMG sensor on the *gluteus maximus* was positioned half-way between the sacral vertebrae and the greater trochanter of the femur. The *rectus femoris* sEMG was placed 50% of the distance

between the anterior superior iliac spine and the superior part of the patella. See Figure 5 for example placement location for each sensor. After all sEMG sensors were placed appropriately, maximum voluntary contraction files and motion files were collected (see below for more detailed description). All EMG data was stored in QTM and post-processed in Visual3D.

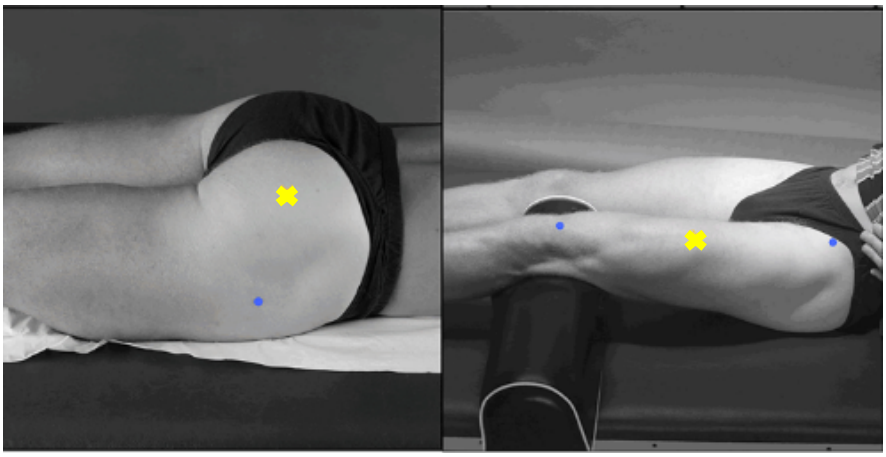


Figure 5. *EMG placement.*

3.4.3 Force Plate Instrumented Treadmill

A Bertec force plate instrumented treadmill (Bertec Corp., Columbus, OH; f_s=1000Hz) was used to assess the ground force reactions during all activities. The force plates measure the force that is exerted by the ground in opposition to the weight placed on it. Force plate data was temporally synchronized with all other data, stored in QTM, and processed in Visual3D to evaluate when walking steps occurred during ambulatory tasks.

3.5 Data Collection

Once participants were fitted with all sensing modalities (optical MOCAP markers and wireless EMG sensors), data capture began with maximal voluntary

contractions (MVCs) for EMG normalization. For MVCs, 4 total measurements were taken to assess the EMG activity of the bilateral hip flexors and hip extensors. This was accomplished by fixing one portion of the limb and applying a force to the free portion of the limb to which the participant resisted (see Figure 6 for reference positions). Specifically, this involved the subject performing the primary planar motion for the muscle of interest (i.e. hip flexion and hip extension, respectively) and a research team member resisting that motion. Four distinct files were collected for each respective motion on both legs facilitating EMG signal normalization across subjects and across days (i.e. first data capture, second data capture, etc.).

Figure 6. *MVC contraction positions for hip flexion (left) and hip extension (right), respectively.*

To calibrate each participant's skeleton within the motion capture system, a static calibration, four pelvis static calibrations, and a dynamic calibration were captured via MOCAP cameras. The static calibration was a brief capture of the participant standing stationary on the treadmill, one foot on each belt, for 10 seconds. The pelvic static calibrations also required the subject to remain stationary in view of the MOCAP cameras with the addition of a researcher placing the pelvis pointer wand on each of the

four pelvis points (L/R ASIS and PSIS). The static and four pelvis static pointer trials were used to construct the baseline skeleton for each subject during each data capture session. The dynamic calibration required the participant to perform 5 repetitions of the following motions: squat, single leg raise to 90/90 position, and hip circumduction (see Figure 7). This dynamic calibration file was utilized to automatically identify the associated markers in all other movement trials.

Figure 7. *Dynamic calibration movements including squat (left), standing knee bend (middle), and hip circumduction (right), respectively.*

Table 2. *Activities measured during data collection session for each visit.*

Activities	Speed/Amount	Trials
Normal Walking	Self-selected pace	3, 30s each
Stair Ascent	3 steps	3
Stair Descent	3 steps	3

Lastly, subjects performed three activities while all measurement equipment simultaneously captured data (Table 2). Activities performed included walking at a self-selected speed, stair ascent, and stair descent. These specific activities reflected common physical tasks that pregnant mothers encounter in everyday life. They were also chosen for easy replication in the lab and translatability to normal daily activities. Additionally,

self-selected speed walking has been selected in previous studies pertaining to pregnancy biomechanics.[12–14, 16–18] Three repetitions of each activity were captured, stored, and processed offline.

Participants in the pregnant cohort re-completed this data capture process (excluding eligibility, informed consent, and handedness/footedness surveys) once during Trimester 2, twice during Trimester 3, and once postpartum at least 4 weeks after they delivered their baby. During their postpartum data capture session, pregnant cohort participants completed all surveys from pre-parturition visits T2-T3.2, as well as provided delivery room statistics (i.e., hours of total labor duration, hours of active push time, total blood loss, etc.) and completed clinical psychological surveys, including the Birth Satisfaction Scale (BSS), the Edinburgh Postnatal Depression Scale (EPDS), and the Mother-Infant Bonding Scale (MIBS).

The BSS has been developed and validated by Hollins Martin and Marin (2014) as a means for screening for delivery satisfaction (see Appendix 8).[65] It contains 30 statements about feelings during the delivery process and postpartum. For example, Statement 1 is *'I coped well during my birth.'* The participant is asked to choose one of 5 possible responses, such as, *'Strongly Agree', 'Agree', 'Neither Agree or Disagree', 'Disagree',* and *'Strongly Disagree'* for each statement. Each statement is then scored of 1 to 5 and scores are totaled. Therefore, the range is 30 to 150, with higher scores indicating more satisfied feelings.

The EPDS was developed and validated by Cox et al. (1987) to screen patients for postpartum depression (see Appendix 9).[68] It consists of 10 statements about feelings within the past week (previous 7 days). Item 1, for example, is *'I have been able to laugh*

and see the funny side of things.' The participant is then asked to select one of four possible responses, such as, *'As much as I always could', 'Not quite so much now', 'Definitely not so much now',* or *'Not at all'.* Each item is then scored from 0 to 3 and then the scores are totaled. The range is 0 to 30 with higher scores indicating more negative feelings.

The MIBS was developed and validated by Brockington et al. (2001) to detect for mother and baby bonding disorders (see Appendix 10).[66] It has 25 statements pertaining to the feelings a mother has towards her baby postpartum. Statement 1, for example, is *'I feel very close to my baby'.* The participant is asked to select one of six responses ranging from *'Always'* to *'Never'.* The responses are scored from 0 to 5 and then the scores are summated with a range of 0 to 125. Higher scores indicate less bonded feelings and an increased likelihood of bonding pathology.

All data was captured in the same manner to pre-partum and control participant data collection sessions.

3.6 Location

All aspects of the study and data collection took place in the Biomechanics and Wearables Laboratory at Independence Square in the Department of Kinesiology at the University of Rhode Island.

3.7 Data Analysis

A variety of biomechanics software was used to assess pelvis and hip function throughout pregnancy. After each file was captured (static, pelvic static, and dynamic

calibrations; all activities) in QTM, all motion capture markers were identified and tracked to ensure a complete marker set was present throughout each trial. EMG and force were evaluated qualitatively for completeness within QTM prior to export. Once all sensing modalities were tracked and confirmed, each trial was exported as a C3D file for use in Visual3D (V3D).

3.7.1 QTM

Raw motion capture marker data were initially unlabeled and untracked. Accordingly, we initially labeled the static calibration files with the appropriate markers (3 sacral cluster markers, 4 thigh cluster markers per leg, 4 shin cluster markers per leg, 2 knee markers per leg, 2 ankle markers per leg, and 3 feet markers per foot). Within QTM, this file was used to generate an Automatic Identification of Markers (AIM) static model. The AIM static model was then applied to the four pelvic static calibration files. These four files had the same anatomical markers labeled as the original static calibration file with the addition of the proximal and distal pelvis pointer wand markers. If any markers remained unlabeled/untracked, those markers were labeled and tracked manually. Finally, all 5 static calibration files were exported as C3D files for use in V3D.

The AIM static model was then applied to the dynamic calibration file. If there were markers that the static AIM model was unable to identify, the remaining unidentified marker trajectories were manually labeled appropriately. Once the dynamic calibration file was fully tracked and labeled, within QTM the file was leveraged to generate a dynamic AIM model for use on activity files. This dynamic calibration file and

dynamic AIM model were intended to mimic the movements expected during activities. In doing so, it facilitated rapid data tracking, labeling, editing, and analysis.

Finally, each activity file was processed within QTM. The dynamic AIM model was applied to each respective activity file and labeled automatically. If motion capture markers remained untracked/unlabeled, all unidentified marker trajectories were tracked and labeled manually. This was completed for all files and all markers until any gaps between marker trajectories were less than or equal to 10 frames (0.1s of total data). These gaps were edited and interpolated later in V3D. Once all activity files were tracked and labeled, all files were exported from QTM as a C3D file for analysis in V3D**.**

3.7.2 Visual 3D

Motion Capture

Using V3D Professional software (C-Motion, Inc., Boyds, MD), a full skeleton of the participant was constructed to visualize the motion data collected in QTM (Figure 8). First, static calibration C3D file and the four pelvic static calibration files were imported. These files built and scaled the model to each specific subject. Using the tracked MOCAP marker data, the pelvis was constructed by first computing the virtual marker positions of the four pelvic anatomic landmarks (L/R ASIS and PSIS). These four virtual markers then referred to the 3 sacral cluster markers in every subsequent file. As such, as the sacral cluster translated and rotated, the four virtual pelvis markers moved in conjunction. Additionally, these four markers built the pelvis portion of the skeletal model including the acetabulum and the center of the hip joints.

Next, the bilateral femur, shank, and foot were created. First, the femur was built using the newly created hip joint centers in the acetabulum and all markers adhered to the upper leg. The femur length was determined by starting proximally at the acetabulum hip joint center and moving distally to the markers on the lateral and medial femoral epicondyle. These distal markers were also responsible for defining the knee joint. The four markers on the thigh clusters were then responsible for the dynamic tracking of the 3D femur motion during all subsequent motion files. The bilateral tibias were then created beginning proximally from the two femoral epicondyle markers and terminated distally at the two ankle markers (medial and lateral malleoli). These two markers were also responsible for creation of the ankle joint. The four shank cluster markers were then used in subsequent motion files for tracking the 3D shank motion. Finally, the bilateral feet were created using the 3 markers adhered to the feet (calcaneus, first and fifth metatarsal head) rotating proximally about the ankle joint.

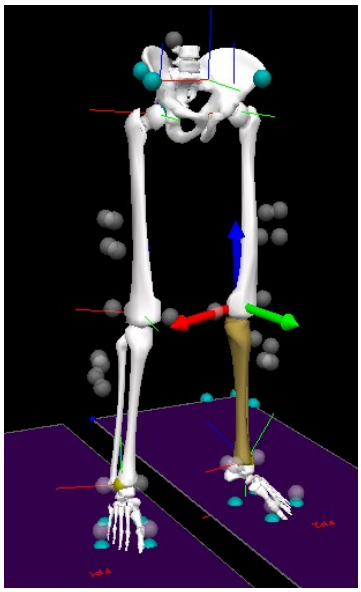


Figure 8. *Example V3D skeletal model and associated optical MOCAP markers.*

All bony segments utilized a local coordinate system as described by the International Society of Biomechanics.[72] Specifically, each bony segment had a medial-lateral axis that generally pointed positive to the right, an anterior-posterior axis that pointed positive to the front, and an inferior-superior axis that pointed positive up. These axes were defined in V3D utilizing the previously described motion capture markers and subject-specific skeletons. In detail, rotating the pelvis about its own local coordinate system provided 3D pelvic angles (*sagittal: anterior/posterior tilt, frontal: left/right tilt, transverse: left/right turn*). Additionally, rotating a distal segment about a proximal segment allowed computation of the relative joint angles at any point in time. In specific, rotating the femur about the pelvis' local coordinate system provided 3D hip joint angles (*sagittal: flexion/extension, frontal: AB-/AD-duction, transverse: internal/external rotation*). In a similar manner, rotating the tibia about the femur's local coordinate system quantified 3D knee joint angles (*sagittal: flexion/extension, frontal: varus/valgus, transverse: internal/external rotation*) and rotating the foot about the tibia's local coordinate system allowed computation of 3D ankle angles (*sagittal: dorsi-/plantar-flexion, frontal: inversion/eversion, transverse: internal/external rotation*).

After skeleton creation, all motion C3D files were imported into V3D and the previously created skeletal model was applied to those files. All motion capture marker data were low pass filtered (Butterworth LPF, f_c=6Hz) and interpolated to fill any gaps less than or equal to 10 frames (Max. Gap: 10, Nu. Fit: 3, Polynomial Order: 3). Following filtration and interpolation, the relative orientation of each bony segment was computed to output relative 3D joint angles (pelvis, hip, knee, ankle). For each motion trial, this was done for the entire duration of that trial. For walking trials, the relative joint

angles were averaged as a percent of the gait cycle using the force plate data on respective feet as described below. Relative joint angles normalized with respect to gait cycle percent were then be exported to Excel. For non-treadmill gait trials, relative joint angles throughout the entire trial were exported to Excel.

Force Instrumented Treadmill

Force data was also contained in the C3D files imported into V3D. This data was captured continuously throughout each motion trial. For all motion trials, 3D ground reaction force (GRF) were computed throughout the entire trial. For all activities, force plate data was low-pass filtered (Butterworth LPF, f_c=25Hz). For each walking trial, force data was used to differentiate each stride as the moment each respective foot contacts the force plate. Each stride was defined as the beginning at the first moment the respective plate exceeds 20N of force (heel strike) and terminating when the force plate returned below 20N of force (toe-off). Subsequently, all metrics (joint angles, joint moments, center of pressure, and EMG) were expressed as a percent of the gait cycle and averaged across all strides. For non-walking trials, force data (GRF, center of pressure, joint moments) was exported as the entire trial.

Electromyography

In a similar manner to the kinematic data, all EMG signals were imported into V3D. Since the data were still in their raw form, all EMG data (MVCs and all activity trials) were low pass filtered (Butterworth LPF, f_c=25Hz). Following filtration, the amplitude of each muscle's MVCs was quantified. This was done by finding the peak-to-peak amplitude of each MVC.

Subsequently, each motion file was rectified by taking the absolute value of the entire signal. Using the rectified data, the motion files were then normalized to a percentage of the MVC file. Peak EMG magnitude for all muscles during activity trials was computed. Finally, time-based EMG signals were passed through a Fast Fourier Transform via MATLAB to extract the dominant frequency content of each EMG signal during all activity trials.

3.8 Statistical Analysis

Descriptive statistics (mean, standard deviation, and range as appropriate) were used to characterize the participants. A multivariate analysis of variance (MANOVA) was utilized to evaluate differences between the groups (*Hypothesis 1.3:* controls vs. pregnant participants), the impact of time (*Hypothesis 1.1* and *1.2*: gestational time), and the interaction between the two factors with the α set to 0.05. Finally, Pearson's Correlations were conducted to analyze the strength of association between peak joint angles, peak EMG magnitude, peak EMG frequency content, and all post-partum outcomes (*Hypothesis 2.1* and *2.2*). Microsoft Excel (Version 16.83, Microsoft Corp., Redmond, WA), MATLAB (R2023b Update 3, MathWorks Inc., Natick, MA), and SPSS (Version 29.0.1.0, IBM Corp., Armonk, NY) software were used for statistical analysis.

CHAPTER 4

RESULTS

4.1 Participants

Following IRB approval, 12 nulligravid and 6 pregnant individuals volunteered to participate and gave informed consent (see Table 3 for participant characteristics). Two nulligravid control participant's data were excluded due to equipment malfunctions. The remaining ten nulligravid control participants were 25.8±3.2 years old with a height of 165.1± 4.6 cm and a mass of 66.8±20.0 kg. All control participants presented with no history of musculoskeletal or neuromuscular dysfunction that would impact their movements. All control participants reported never being pregnant (nulligravid).

At the time of enrollment, the six pregnant participants were 30.5±4.0 years (range=22-35 years). All pregnant participants reported no history of musculoskeletal or neuromuscular pathologies that impacted their ability to complete movement tasks. Five pregnant participants were first-time expectant mothers (primigravid) while one was pregnant for the second time (multigravida).

On the day of enrollment (T1: first laboratory visit), pregnant participants were at 9.1±2.3 weeks of gestation, a height of 167.2±7.8 cm, and a mass of 64.6±10.0 kg. They returned to the lab (T2) at 19.6±3.0 weeks of gestation with a mass of 67.7±7.2 kg. At their third visit (T3.1: first visit during third trimester), participants were 28.3±1.7 gestational weeks with a mass of 76.8±2.5 kg. At their last pre-parturition visit (T3.2: second visit during third trimester), pregnant participants presented to the laboratory at 32.7±1.2 gestational weeks with a mass of 81.9±1.4 kg. Throughout 23.6 weeks of pregnancy that elapsed from first to last pre-parturition visit, participant mass increased by

17.3kg representing an average mass change of 0.73kg per week on average. Follow parturition, participants in the pregnant cohort presented for their final visit (PP) at 4.3 weeks postpartum with a mass of 71.9kg. Two participants delivered via vaginal route and two participants delivered via caesarean section.

Table 3. *Participant age, height, weight, and parity status at time of enrollment. Null=never pregnant before, Primi=first time pregnancy, Multi=at least 1 previous pregnancy.*

PARTICIPANT	AGE (yrs)	HEIGHT (cm)	WEIGHT (kg)	PARITY STATUS
PP01	20	166.0	76.65	Primi
PP02	31	160.0	67.59	Primi
PP03	31	175.0	68.60	Primi
PP04	35	167.5	68.27	Multi
PP05	29	157.5	50.80	Primi
PP06	30	177.0	58.51	Primi
Control Avg.	25.8±3.2	165.1± 4.6	66.8±20.0	Nulli

4.2 Walking

The kinematics of the pelvis and hip were analyzed for each participant in three planes of motion (sagittal, frontal, transverse) during each visit in both cohorts during a walking trial at a self-selected pace. Preliminary analyses showed all data to be normally distributed, as assessed by a Shapiro-Wilk test. Some outliers were identified but were within 3 standard deviations of the mean value and were included in the analysis.

4.2.1 Walking - Joint Kinematics

Kinematic traces for the pelvis and hips throughout walking at a self-selected speed are displayed in three dimensions in Figures 9, 11, and 13. For each joint and

plane, maximum and minimum values were extracted and are displayed in Tables 4, 5, and 6. Additionally, change scores were computed by subtracting the first visit performance for each variable from subsequent visits. These values are contained in Figures 10, 12, and 14.

4.2.1.1 Walking - Sagittal Plane

Exploring the impact of pregnancy status on pelvis and hip kinematics revealed several significant findings. Comparing across cohorts (pregnant vs. controls), showed pregnancy status had a significant interaction with peak sagittal plane joint angles of the pelvis. A significant difference was seen in peak anterior pelvic tilt (Figure 9, $F_{1, 436.652}$=6.898, n^2=0.216, p=0.015) and peak posterior pelvic tilt (Figure 9, $F_{1, 498.642}$=7.006, n^2=0.219, p=0.014) between cohorts. More specifically, peak anterior pelvic tilt angles were significantly different (p=0.042) between control participants (16.2±14.3°) and pregnant participants at their final pre-parturition visit (25.7±5.6°). During the final pre-parturition visit, like peak anterior pelvic tilt angle, peak posterior tilt angles for the control participants (26.0±8.5°) were significantly different (p=0.024) than those of the pregnant participants (30.3±5.5°). A similar analysis for the hips showed that pregnancy status and left peak hip extension angles were statistically significantly different ($F_{1, 432.05}$=4.356, n^2=0.148, p=0.047).

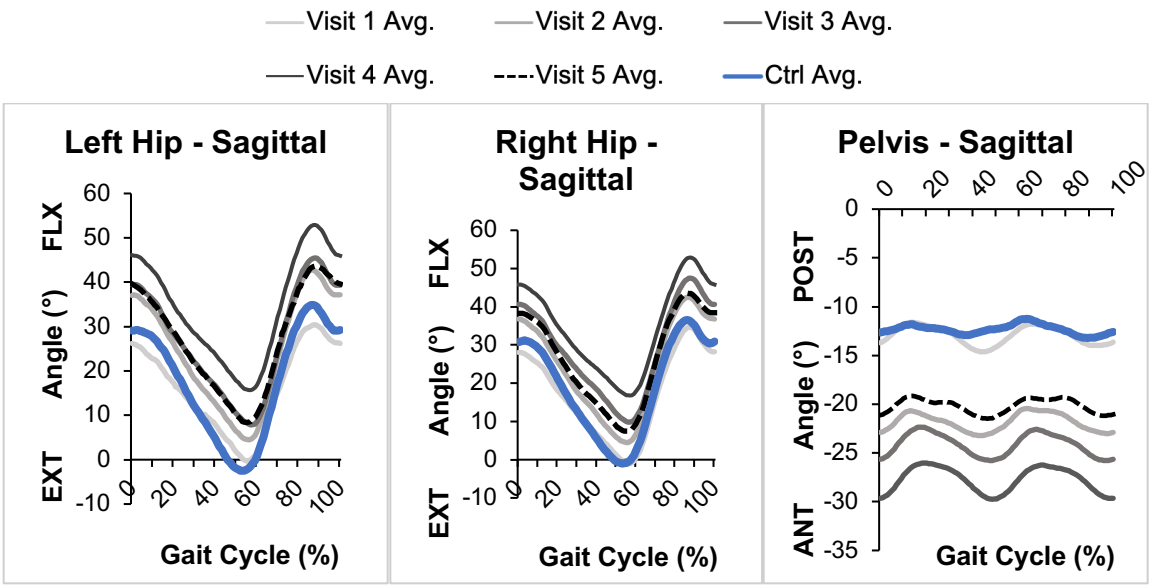


Figure 9. *Kinematic pattern of walking gait in the sagittal plane of the* ***A)*** *left hip,* ***B)*** *right hip, and* ***C)*** *pelvis during each laboratory visit.*

Table 4. *Average peak sagittal plane pelvis and hip joint angles (degrees) during each laboratory visit during walking. FLX=hip flexion, EXT=hip extension, ANT=anterior pelvic, and POST=posterior pelvic tilt.*

	Left Hip		Right Hip		Pelvis	
	FLX	**EXT**	**FLX**	**EXT**	**ANT**	**POST**
Controls	35.2±7.7	2.8±9.8	35.2±7.4	2.8±9.00	10.7±7.7	13.7±7.3
Pregnant Visit 1	31.7±8.5	0.6±4.8	31.7±8.6	0.6±3.3	11.5±5.3	14.3±4.5
Pregnant Visit 2	42.9±9.8	4.2±7.4	42.9±9.3	4.2±6.1	19.9±7.8	23.1±6.9
Pregnant Visit 3	45.6±12.0	7.6±8.9	45.6±11.7	7.6±9.9	22.2±9.3	26.5±7.8
Pregnant Visit 4	53.0±13.9	15.2±6.8	53.0±12.6	15.2±7.7	25.7±6.2	30.3±5.0
Post-Partum	43.8±15.1	8.2±10.1	43.8±14.2	8.2±11.9	18.7±9.9	19.5±9.0

A MANOVA conducted to explore the interaction of gestational time and pelvis and hip kinematics, also revealed several significant findings. Specifically, there was a significant effect of pregnancy timepoint on peak posterior pelvic tilt ($F_{3,\ 583.211}$=3.530, n^2=0.449, p=0.046) and peak anterior pelvic tilt ($F_{3,\ 461.350}$=3.398, n^2=0.44, p=0.05). Peak pelvis anterior tilt angles were 11.5± 5.3°, 19.9±7.8°, 22.2.9±9.3°, 25.7±6.2°, and 18.7±9.9° during T1, T2, T3.1, T3.2, and PP visits respectively. Peak pelvis posterior tilt angles were 14.3±4.5°, 23.1±7.8°, 26.5±7.8°, 30.3±5.0°, and 19.5±9.0° during T1, T2, T3.1, T3.2, and PP visits respectively.

For the hip, the same analysis revealed left peak hip flexion was significantly different across gestational times ($F_{3, 955.404}$=4.876, n^2=0.529, p=0.017). Left peak hip flexion angles were 31.7±8.5°, 42.9±9.8°, 45.6±12.0°, 53.0±19.0, and 43.8±15.1° during respective pre-parturition and PP visits.

A separate analysis comparing postpartum values for pregnant participants to control participants was conducted to evaluate return to a non-pregnant set of biomechanics. The peak joint angles for both the pelvis and hip in the sagittal plane for the control cohort were not statistically significantly different from postpartum visit of the pregnant cohort (p=0.053). As seen in Table 4, the peak joint angles in most PP visit returned to values similar to those of T1 of the pregnant participants or closer to the values of the control cohort. A lack of statistical significance indicates that after delivery, pregnancy status does not interaction with peak joint angles in the pelvis and hips.

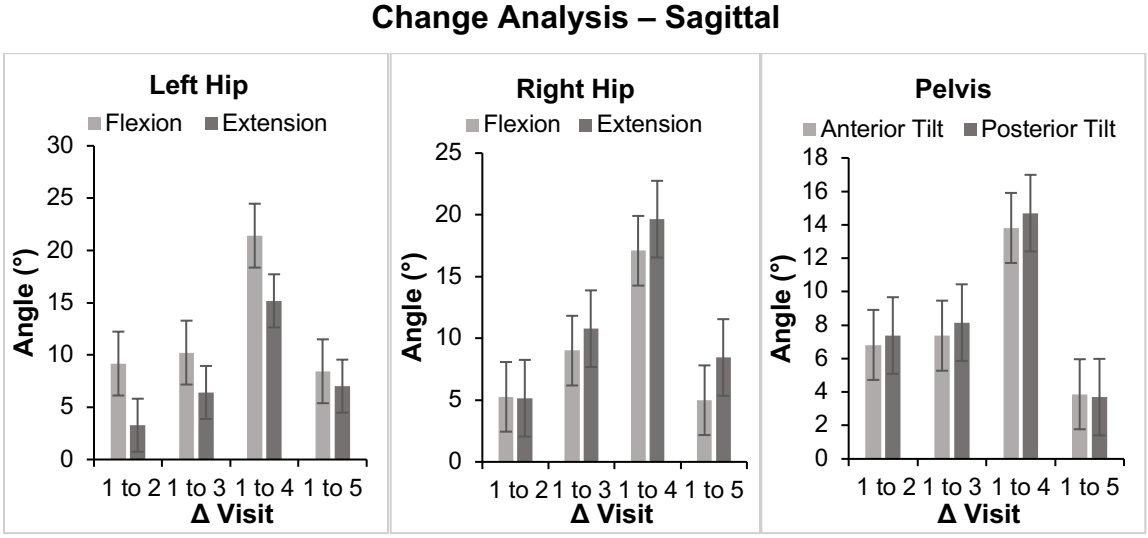


Figure 10. Change analysis of sagittal plane kinematics during walking of the **A)** left hip, **B)** right hip, and **C)** pelvis from Visit 1 to each subsequent laboratory visit. (1=T1, 2=T2, 3=T3.1, 4=T3.2, 5=Postpartum)

A change analysis between each visit for the pregnant cohort was done to observe the impact that pregnancy has over time on frontal plane motion. The change analysis is

displayed in Figure 10. Despite changes observed, no change scores were found to be significantly different from any other timepoint throughout pregnancy.

4.2.1.2 Walking - Frontal Plane

Frontal plane kinematic data during walking are contained in Figure 11 and Table 5. When comparing across cohorts (pregnant vs. controls), the analysis showed no significant differences were noted between control participants and pregnant participants. This indicates that pregnancy status does not have an interaction with peak frontal joint angles of the pelvis.

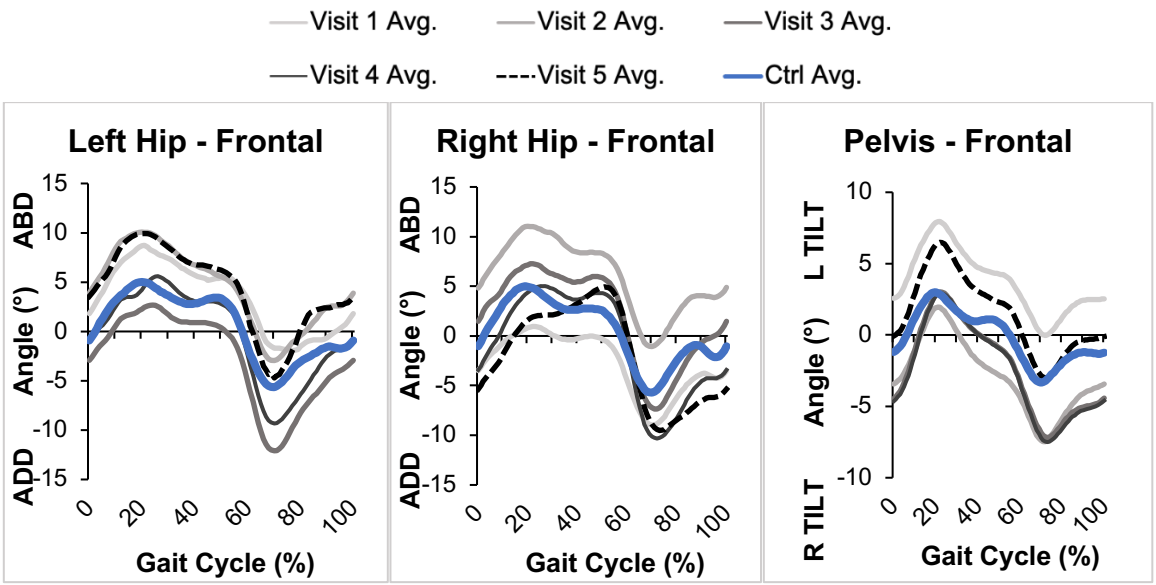


Figure 11. *Kinematic pattern of walking gait in the frontal plane of the **A)** left hip, **B)** right hip, and **C)** pelvis during each laboratory visit.*

The MANOVA conducted to explore the impact of gestational time on pelvis and hip kinematics revealed no significant findings in the frontal plane during walking. This analysis indicates that there is no significant effect of pregnancy timepoint on left or right pelvis tilt or hip abduction or adduction (Figure 11). Additionally, the peak joint angles for both the pelvis and the hip in the frontal plane for the control cohort were not statistically

significantly different from the postpartum visit of the pregnant cohort. A lack of statistical significance indicates that after delivery, pregnancy status does not interact with frontal peak joint angles in the pelvis and hips.

Table 5. *Average peak frontal plane pelvis and hip joint angles (degrees) during each laboratory visit during walking. ABD=hip abduction, ADD=hip adduction, L TILT=left pelvic tilt, and R TILT=right pelvic tilt.*

	Left Hip		Right Hip		Pelvis	
	ABD	**ADD**	**ABD**	**ADD**	**L TILT**	**R TILT**
Controls	5.6±5.5	6.4±5.4	5.6±6.5	6.4±6.6	3.1±5.8	3.5±5.0
Pregnant Visit 1	9.1±8.7	3.3±5.8	9.1±9.1	3.3±7.4	8.0±6.6	0.1±5.7
Pregnant Visit 2	10.6±7.5	3.2±6.4	10.6±11.2	3.2±9.8	2.0±11.6	7.5±8.9
Pregnant Visit 3	3.0±3.6	12.1±1.6	3.0±3.7	12.1±1.5	3.1±3.6	7.2±2.4
Pregnant Visit 4	5.8±7.9	9.5±3.3	5.8±4.3	9.5±0.2	3.0±5.9	7.6±2.0
Post-Partum	7.5±5.4	6.4±2.8	7.5±10.9	6.4±5.8	4.2±5.8	5.3±3.4

A change analysis between each visit for the pregnant cohort was done to observe the impact that pregnancy has over time. The change analysis is displayed in Figure 12. Because there were no significant changes observed in the frontal plane, no change scores were found to be significantly different from any other timepoint throughout pregnancy.

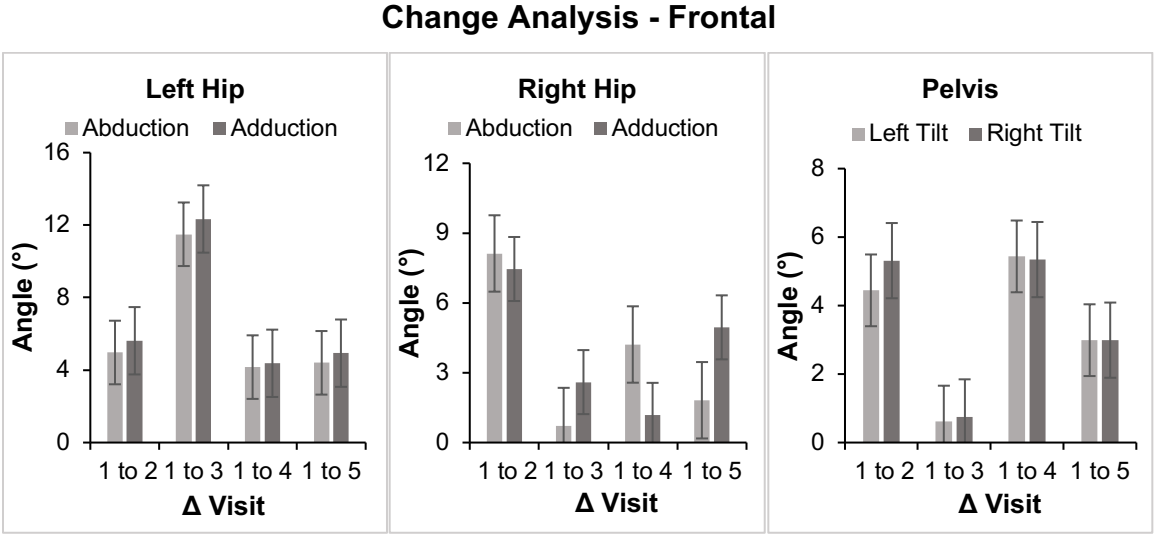


Figure 12. *Change analysis of the frontal plane kinematics during walking of the **A)** left hip, **B)** right hip, and **C)** pelvis from Visit 1 to each subsequent laboratory visit. (1=T1, 2=T2, 3=T3.1, 4=T3.2, 5=Postpartum)*

4.2.1.3 Walking - Transverse Plane

Transverse plane kinematic data during walking are displayed in Figure 13 and Table 6. When comparing across cohorts (pregnant vs. controls), the analysis showed no significant differences between cohorts. This indicates that pregnancy status does not have an interaction with peak transverse joint angles of the pelvis during walking.

The MANOVA conducted to explore the impact of gestational time on pelvis and hip kinematics revealed no significant findings in the transverse plane during walking. This analysis indicates that there may not be any significant effect of pregnancy timepoint on forward or backwards pelvis rotation or hip internal or external rotation (Figure 13).

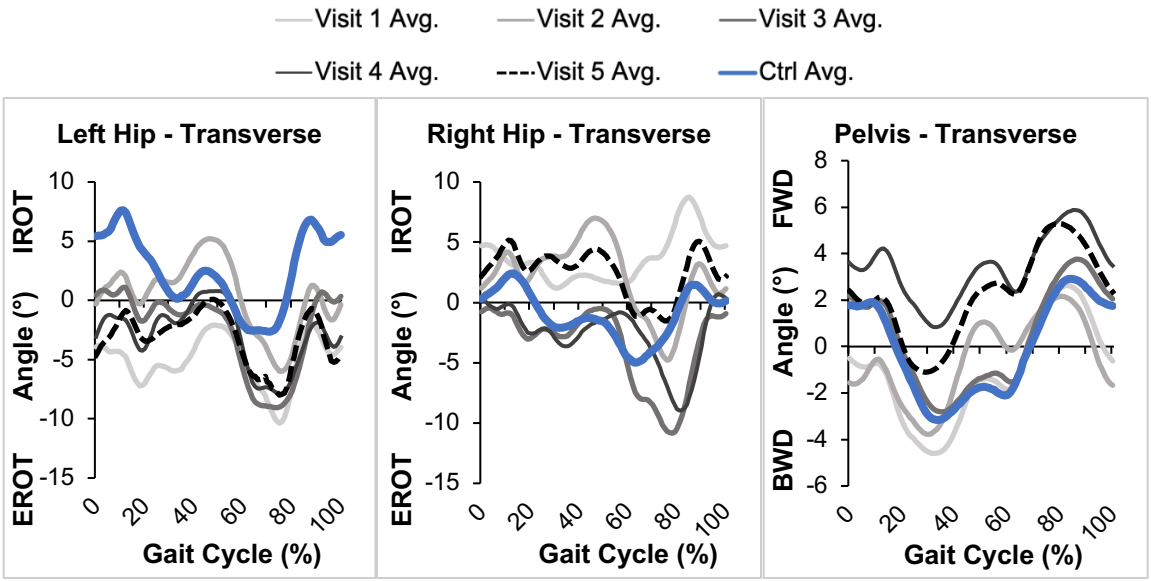


Figure 13. *Kinematic pattern of walking gait in the transverse plane of the* ***A)*** *left hip,* ***B)*** *right hip, and* ***C)*** *pelvis during each laboratory visit.*

Additionally, the peak joint angles for both the pelvis and the hip in the transverse plane for the control cohort were not statistically significantly different from the postpartum visit of the pregnant cohort. A lack of statistical significance indicates that

after delivery, pregnancy status may interact with transverse peak joint angles in the pelvis and hips.

Table 6. *Average peak transverse plane pelvis and hip joint angles (degrees) during each laboratory visit during walking. IROT=hip internal rotation, EROT=hip external rotation, F ROT= forward pelvic rotation, B ROT=backwards pelvic rotation.*

	Left Hip		Right Hip		Pelvis	
	IROT	**EROT**	**IROT**	**EROT**	**F ROT**	**B ROT**
Controls	9.8±8.8	4.8±10.1	5.0±9.3	6.8±6.5	4.1±3.5	4.0±2.1
Pregnant Visit 1	12.5±6.2	0.9±3.3	12.0±10.6	2.6±6.8	2.9±8.5	4.9±3.1
Pregnant Visit 2	6.8±4.2	8.1±2.6	8.5±13.5	6.0±9.0	2.7±9.0	3.9±5.7
Pregnant Visit 3	4.2±10.8	11.5±3.6	4.2±10.1	11.5±4.0	3.9±3.8	3.1±2.0
Pregnant Visit 4	3.4±13.4	9.9±3.3	3.4±15.4	10.0±7.2	6.4±6.8	0.3±4.1
Post-Partum	7.3±14.4	7.1±9.3	7.7±14.1	7.0±7.4	3.7±6.7	3.3±2.5

A change analysis between each visit for the pregnant cohort was done to observe the impact that pregnancy has over time. The change analysis is displayed in Figure 14. Because there were no significant changes observed in the transverse, no change scores were found to be significantly different from any other timepoint throughout pregnancy.

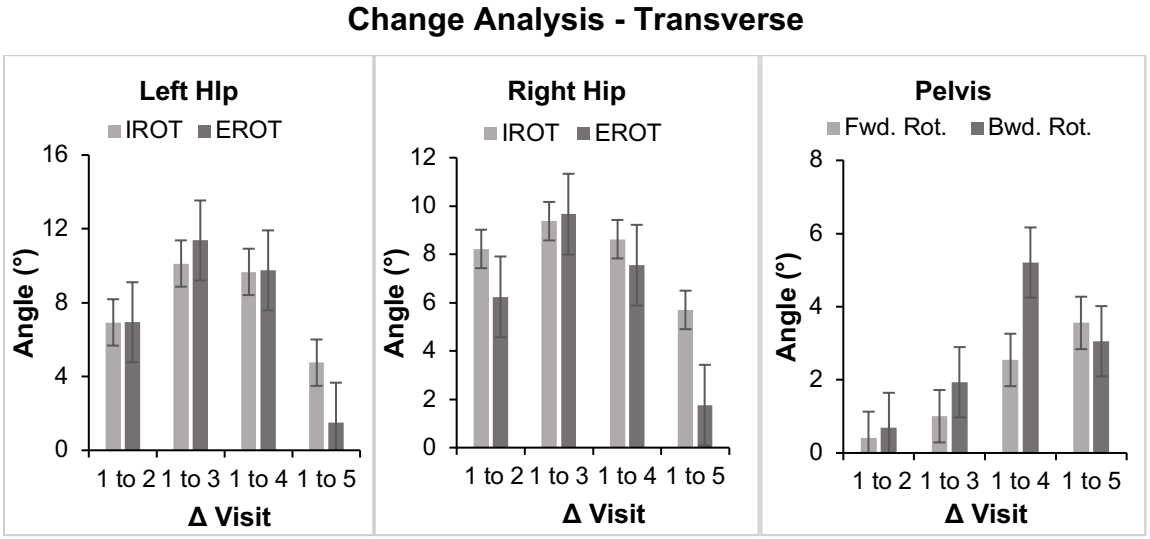


Figure 14. *Change analysis of the transverse plane kinematics during walking of the A) left hip, B) right hip, and C) pelvis from Visit 1 to each subsequent laboratory visit. IROT=hip internal rotation and EROT=hip external rotation. (1=T1, 2=T2, 3=T3.1, 4=T3.2, 5=Postpartum)*

4.2.2 Walking - Neuromuscular Activity

The neuromuscular analysis of walking gait for all evaluated muscles is presented in Figure 15. Specifically shown for each muscle are peak magnitude and dominant frequency values. Additionally, change scores were computed by subtracting the first visit performance for each variable from subsequent visits. These values are displayed in Table 7.

4.2.1.1 Walking Neuromuscular Activity Analysis

A MANOVA conducted to explore the impact of pregnancy status on hip neuromuscular activity revealed several significant findings. Comparing across cohorts (pregnant vs. controls), there was a main effect of pregnancy status on dominant frequency. Specifically, there was a significant impact on left gluteus maximus (Figure 15, $F_{1, 1014.546}$=13.872, n^2=0.387, p=0.001), left rectus femoris (Figure 15, $F_{1, 1625.812}$=8.279, n^2=0.263, p=0.009), and right gluteus maximus dominant frequency (Figure 15, $F_{1, 3192.639}$=18.828, n^2=0.461, p=0.0002). However, peak magnitude in all muscles was not significantly different between control and pregnant participants.

The MANOVA, which explored the interaction of gestational time on pelvis and hip neuromuscular activity during walking, revealed no significant findings. Specifically, this analysis revealed that there was not a significant effect of pregnancy timepoint on peak EMG activity or dominant frequency. Moreover, the neuromuscular activity, both peak magnitude and dominant frequency, for the control cohort were not statistically significantly different from postpartum visit of the pregnant cohort. The peak magnitude and dominant frequency show no patterned or measurable changed between the two

groups. A lack of statistical significance indicates that after delivery, pregnancy status does not interaction with neuromuscular activity of the pelvis and hips during walking.

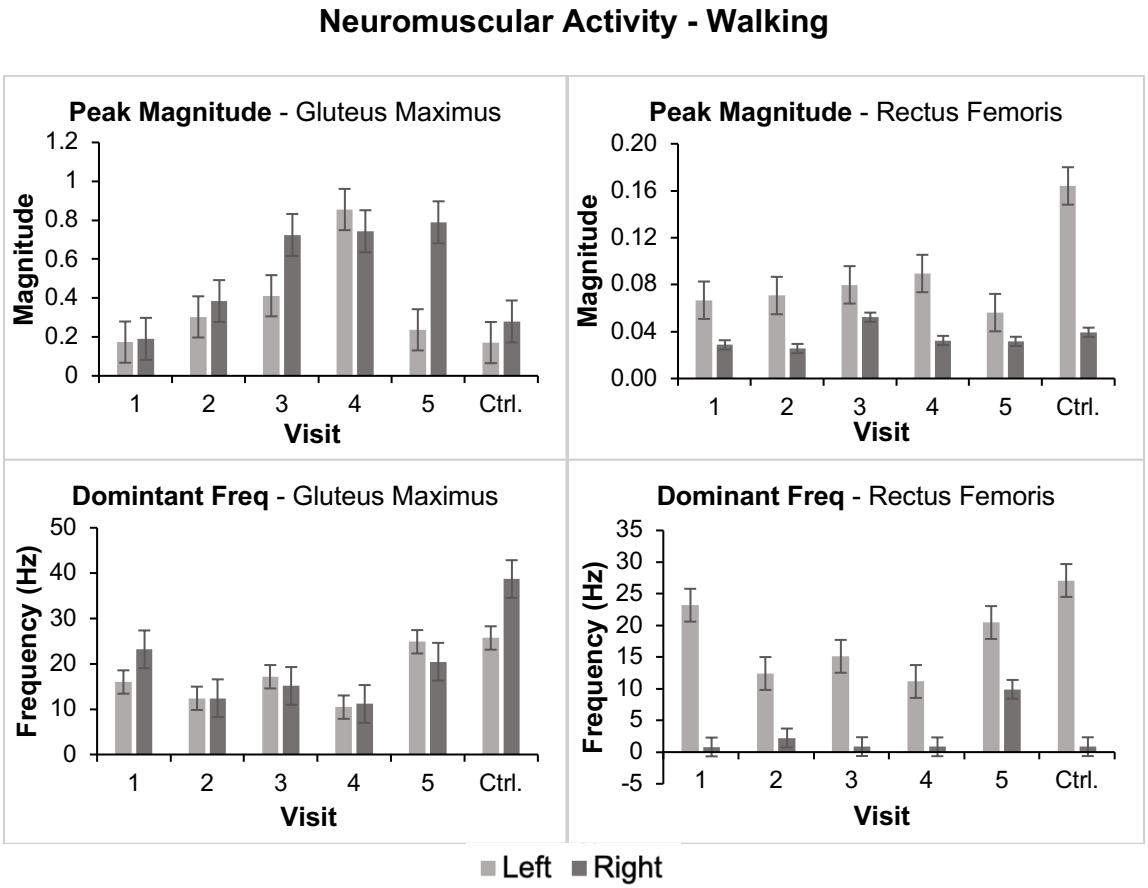


Figure 15. *Neuromuscular activity of the bilateral hip flexors (rectus femoris) and extensor (gluteus maximus), respectively, during walking.*

A change analysis between each visit for the pregnant cohort was done to observe the impact that pregnancy has over time. The change analysis is quantified and displayed in Table 7. Despite some significant changes observed in walking neuromuscular activity, no change scores were found to be significantly different from any other timepoint throughout pregnancy.

Table 7. *Change analysis of pelvis and hip neuromuscular activity from Visit 1 to each subsequent laboratory visit during walking.*

	Δ Peak EMG Magnitude			
	Left		**Right**	
	Gluteus Max.	**Rectus Fem.**	**Gluteus Max.**	**Rectus Fem.**
Δ Visit 1 to 2	0.1445±0.36	0.0156±0.02	0.2517±0.44	0.0004±0.02
Δ Visit 1 to 3	0.1901±0.33	0.0208±0.02	0.5289±0.14	0.0264±0.03
Δ Visit 1 to 4	0.7360±0.74	0.0368±0.12	0.5223±0.63	0.0021±0.01
Δ Visit 1 to 5	0.1178±0.29	-0.0028±0.01	0.3965±0.91	0.0058±0.02
	Δ Dominant Frequency			
	Left		**Right**	
	Gluteus Max.	**Rectus Fem.**	**Gluteus Max.**	**Rectus Fem.**
Δ Visit 1 to 2	0.15±15.8	9.4±6.1	15.2±16.6	1.7±3.7
Δ Visit 1 to 3	5.9±16.7	1.0±7.2	2.3±5.0	0.3±0.5
Δ Visit 1 to 4	4.5±12.8	7.0±7.7	6.0±2.1	0.0±0.0
Δ Visit 1 to 5	11.4±11.8	4.2±9.9	0.6±8.7	9.1±12.2

4.3 Stair Ascent

The kinematics of the pelvis and hip were analyzed for each participant in three planes of motion (sagittal, frontal, transverse) during each visit in both cohorts during a 3-step stair ascent activity. Preliminary analyses showed all data to be normally distributed, as assessed by a Shapiro-Wilk test. Some outliers were identified but were within 3 standard deviations of the mean value and were included in the analysis.

4.3.1 Stair Ascent - Joint Kinematics

Peak kinematic data for the pelvis and hips throughout stairs ascent are displayed in three dimensions in Figures 16, 17, and 18. Additionally, change scores were computed by subtracting the first visit performance for each variable from subsequent visits. These values are contained in Tables 8, 9, and 10.

4.3.1.1 Stair Ascent – Sagittal

When comparing across cohorts (pregnant vs. controls), no significant differences were found between cohorts (p>0.121 for all other variables tested). This indicates pregnancy status did not have an interaction with peak sagittal joint angles of the pelvis or hips during stairs ascent. Sagittal plane peak data is displayed in Figure 16.

The MANOVA conducted to explore the interaction of gestational time on pelvis and hip kinematics during stair ascent revealed no significant findings in the sagittal plane (p>0.088 for all other variables tested). This analysis indicates that there is no significant effect of pregnancy timepoint on left or right pelvis tilt or hip abduction or adduction (Figure 16).

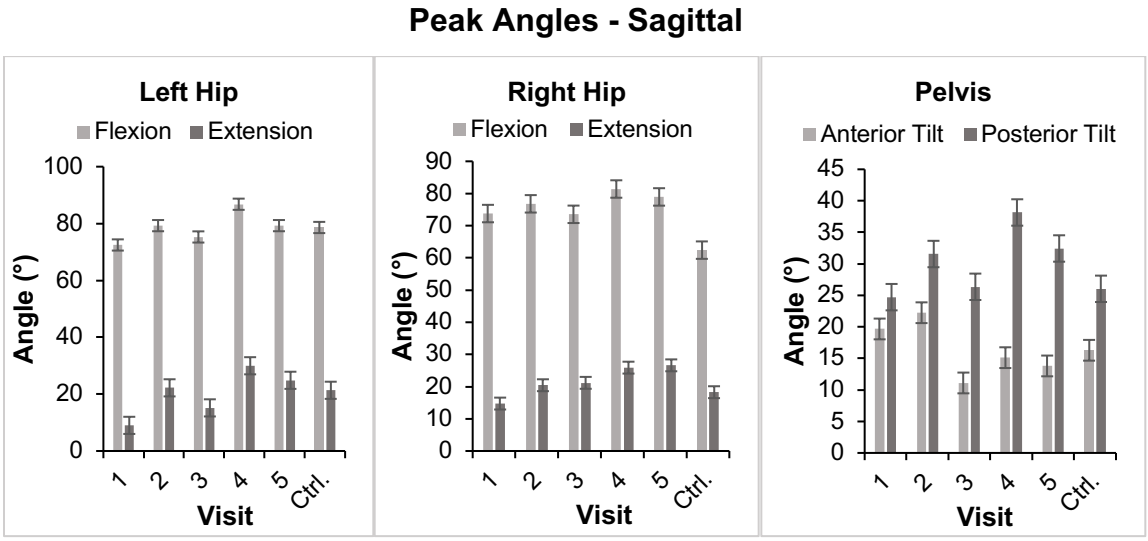


Figure 16. *Peak sagittal plane kinematics during stair ascent of the **A)** left hip, **B)** right hip, and **C)** pelvis for each laboratory visit. (1=T1, 2=T2, 3=T3.1, 4=T3.2, 5=Postpartum)*

Additionally, the peak joint angles for both the pelvis and the hip in the frontal plane for the control cohort were not statistically significantly different from the postpartum visit of the pregnant cohort (p>0.065 for all other variables tested). A lack of

statistical significance suggests that after delivery, pregnancy status does not interact with sagittal peak joint angles in the pelvis and hips.

A change analysis between each visit for the pregnant cohort was done to observe the impact that pregnancy has over time. The quantified change analysis data is displayed in Table 8. No change scores were found to be significantly different from any other timepoint throughout pregnancy.

Table 8. *Change analysis from Visit 1 to each subsequent laboratory visit for the pelvis and hip kinematics in the sagittal plane of motion during stair ascent. FLX=hip flexion, EXT=hip extension, ANT=anterior pelvic, and POST=posterior pelvic tilt.*

	Left Hip		**Right Hip**		**Pelvis**	
	FLX	**EXT**	**FLX**	**EXT**	**ANT**	**POST**
Δ Visit 1 to 2	6.8±14.9	13.2±15.1	6.8±7.8	13.2±11.6	2.6±8.1	6.8±8.4
Δ Visit 1 to 3	2.5±12.4	8.8±9.9	2.5±5.3	8.8±15.6	5.7±12.5	2.0±14.5
Δ Visit 1 to 4	16.2±12.1	23.9±17.1	16.2±13.4	23.9±26.0	4.8±12.9	13.5±16.9
Δ Visit 1 to 5	1.6±14.8	12.9±13.9	1.6±11.2	12.9±22.7	10.4±9.5	9.7±8.6

4.3.1.2 Stair Ascent – Frontal

Frontal plane kinematics during stair ascent are displayed in Figure 17. When comparing across cohorts (pregnant vs. controls), no significant differences were noted between cohorts during stair ascent in the frontal plane ($p>0.158$ for all other variables tested). This indicates pregnancy status does significantly interact with peak frontal joint angles of the pelvis or hips during ascending stairs.

The MANOVA conducted to explore the interaction of gestational time on frontal plane pelvis and hip kinematics revealed no significant interaction between gestational time and frontal plane angles during stairs ascent. This analysis indicates that there is no significant effect of pregnancy timepoint on left or right pelvis tilt or hip abduction or adduction. Additionally, the peak joint angles for both the pelvis and the hip in the frontal plane for the control cohort were not statistically significantly different from the

postpartum visit of the pregnant cohort. A lack of statistical significance indicates that after delivery, pregnancy status does not interact with frontal peak joint angles in the pelvis and hips.

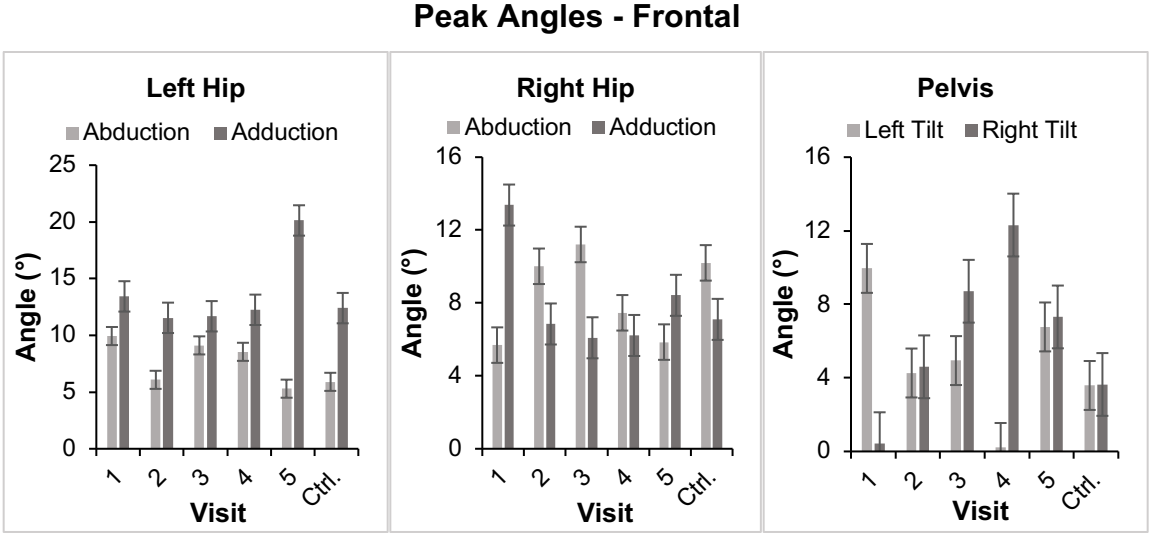


Figure 17. *Peak frontal plane kinematics during stair ascent of the A) left hip, B) right hip, and C) pelvis for each laboratory visit. (1=T1, 2=T2, 3=T3.1, 4=T3.2, 5=Postpartum)*

A change analysis between each visit for the pregnant cohort was done to observe the impact that pregnancy has over time. The change analysis is quantified data is displayed in Table 9. Because there were no significant changes observed in the frontal plane, no change scores were found to be significantly different from any other timepoint throughout pregnancy.

Table 9. *Change analysis from Visit 1 to each subsequent laboratory visit for the pelvis and hip kinematics in the frontal plane of motion during stair ascent. ABD=hip abduction, ADD=hip adduction, L TILT=left pelvic tilt, and R TILT=right pelvic tilt.*

	Left Hip		**Right Hip**		**Pelvis**	
	ABD	**ADD**	**ABD**	**ADD**	L TILT	**R TILT**
Δ Visit 1 to 2	5.0±10.2	5.6±11.2	8.1±4.8	7.5±7.5	4.4±5.7	5.3±10.2
Δ Visit 1 to 3	11.5±12.0	12.3±11.8	0.7±14.4	2.6±17.4	0.6±9.9	0.7±12.6
Δ Visit 1 to 4	4.2±10.7	4.4±13.2	4.2±8.9	1.2±4.1	5.4±3.2	5.3±9.7
Δ Visit 1 to 5	4.4±13.2	5.0±10.8	1.8±13.7	5.0±23.5	3.0±19.0	3.0±19.0

4.3.1.3 Stair Ascent – Transverse

Transverse plane kinematics of the pelvis and hip during stair ascent are displayed in Figure 18. When comparing across cohorts (pregnant vs. controls), the analysis showed no significant differences (p>0.166 for all other variables tested) between cohorts. This indicates that pregnancy status does not have an interaction with peak transverse joint angles of the pelvis or hips during stair ascent.

The MANOVA conducted to explore the interaction of gestational time with pelvis and hip kinematics revealed no significant interaction of gestational time on the transverse plane kinematics during stair ascent. This analysis indicates that there is no significant effect of pregnancy timepoint on forward or backwards pelvis rotation or hip internal or external rotation (Figure 18).

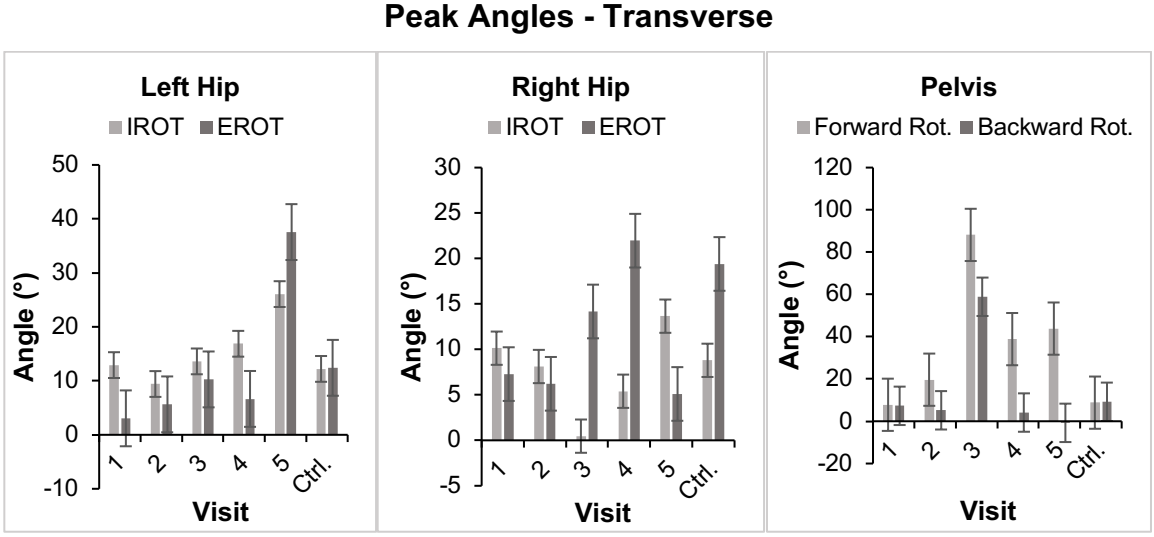


Figure 18. *Peak transverse plane kinematics during stair ascent of the A) left hip, B) right hip, and C) pelvis for each laboratory visit. IROT=hip internal rotation and EROT=hip external rotation. (1=T1, 2=T2, 3=T3.1, 4=T3.2, 5=Postpartum)*

Additionally, the peak joint angles for the pelvis and hip in the transverse plane for the control cohort were not statistically significantly different from the postpartum

visit of the pregnant cohort. This indicates that post-delivery, forward pelvis rotation remains changed from pre-pregnancy values.

Table 10. *Change analysis from Visit 1 to each subsequent laboratory visit for the pelvis and hip kinematics in the transverse plane of motion during stair ascent. IROT=hip internal rotation, EROT=hip external rotation, F ROT= forward pelvic rotation, B ROT=backwards pelvic rotation.*

	Left Hip		**Right Hip**		**Pelvis**	
	IROT	**EROT**	**IROT**	**EROT**	**F ROT**	**B ROT**
Δ Visit 1 to 2	3.9±11.1	1.9±13.2	3.9±14.3	1.9±5.2	11.9±5.6	2.1±5.1
Δ Visit 1 to 3	9.5±14.0	2.9±28.3	9.5±12.6	2.9±8.7	60.6±0.8	36.5±5.1
Δ Visit 1 to 4	5.0±2.8	0.3±12.1	5.0±18.7	0.3±14.7	30.9±5.8	4.3±10.0
Δ Visit 1 to 5	12.6±13.7	11.6±43.0	12.6±13.1	11.6±10.8	28.2±28.5	6.6±5.1

A change analysis between each visit for the pregnant cohort was done to observe the impact that pregnancy has over time. The change analysis is quantified data is displayed in Table 10. Because there were no significant changes observed in the frontal plane, no change scores were found to be significantly different from any other timepoint throughout pregnancy.

4.4 Stair Descent

The kinematics of the pelvis and hip were analyzed for each participant in three planes of motion (sagittal, frontal, transverse) during each visit in both cohorts during a stairs descent activity. Preliminary analyses showed all data to be normally distributed, as assessed by a Shapiro-Wilk test. Some outliers were identified but were within 3 standard deviations of the mean value and were included in the analysis.

4.4.1 Stair Descent - Joint Kinematics

Peak kinematic data for the pelvis and hips throughout stair descent are displayed in three dimensions in Figures 19, 20, and 21. Additionally, change scores were computed by subtracting the first visit performance for each variable from subsequent visits. These values are contained in Tables 12, 12, and 13.

4.4.1.1 Stair Descent – Sagittal

Sagittal plane kinematics during stair ascent are displayed in Figure 19. When comparing across cohorts (pregnant vs. controls), the analysis showed no significant differences (p>0.203 for all other variables tested) between cohorts for sagittal kinematics. This indicates that pregnancy status did not have an interaction with peak sagittal joint angles of the pelvis or hips during stairs descent.

The MANOVA conducted to explore the interaction between gestational time and pelvis and hip kinematics yielded only one significant finding. In the sagittal plane, gestational timepoint was found to significantly interact with right peak hip flexion ($F_{3, 3334.411}$=6.059, n^2=0.602, p=0.009). This indicates there is a significant effect of pregnancy timepoint on right hip flexion, but not on pelvis kinematics or any other hip motion (Figure 19).

Additionally, the peak joint angles for both the pelvis and the hip in the sagittal plane for the control cohort were not statistically significantly different from the postpartum visit of the pregnant cohort. A lack of statistical significance indicates that after delivery, pregnancy status does not interact with sagittal peak joint angles in the pelvis and hips.

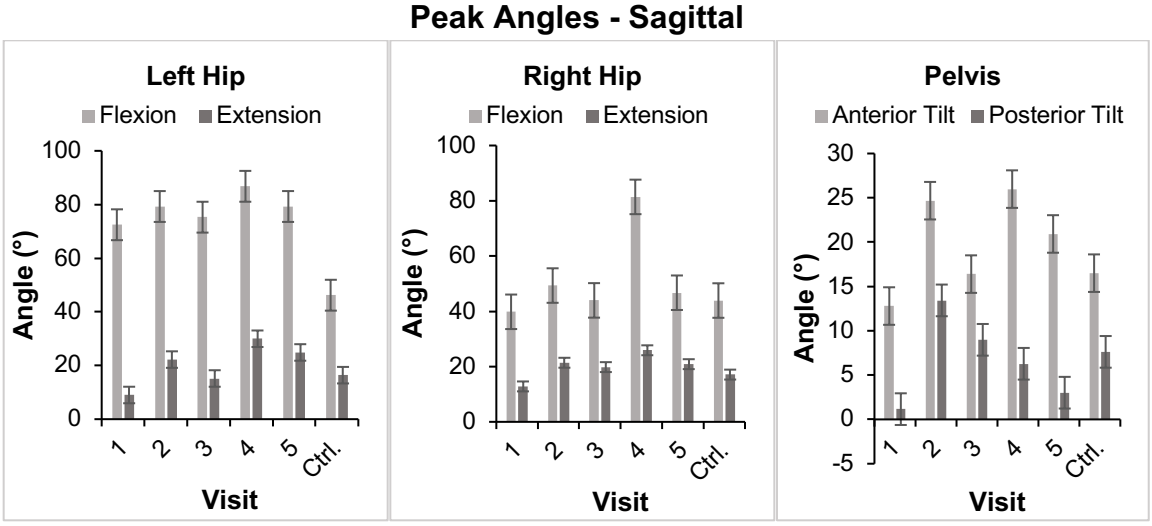


Figure 19. *Peak sagittal plane kinematics during stair descent of the* ***A)*** *left hip,* ***B)*** *right hip, and* ***C)*** *pelvis for each laboratory visit. (1=T1, 2=T2, 3=T3.1, 4=T3.2, 5=Postpartum)*

A change analysis between each visit for the pregnant cohort was done to observe the impact that pregnancy has over time. The quantified change analysis data is displayed in Table 11. Because there were no significant changes observed in the frontal plane, no change scores were found to be significantly different from any other timepoint throughout pregnancy.

Table 11. *Change analysis from Visit 1 to each subsequent laboratory visit for the pelvis and hip kinematics in the sagittal plane of motion during stair descent. FLX=hip flexion, EXT=hip extension, ANT=anterior pelvic, and POST=posterior pelvic tilt.*

	Left Hip		**Right Hip**		**Pelvis**	
	FLX	**EXT**	**FLX**	**EXT**	**ANT**	**POST**
Δ Visit 1 to 2	4.3±25.5	1.5±10.8	2.8±30.0	3.2±15.3	5.7±12.6	8.9±12.6
Δ Visit 1 to 3	2.1±28.6	1.1±36.1	1.4±19.0	15.2±19.4	1.0±19.6	7.9±23.9
Δ Visit 1 to 4	3.9±29.0	17.1±19.4	43.6±11.3	15.1±24.3	13.1±19.2	7.4±9.4
Δ Visit 1 to 5	5.5±19.4	9.5±12.9	2.5±17.2	14.7±12.6	1.0±16.6	0.3±14.6

4.4.1.2 Stair Descent – Frontal

Frontal plane kinematics are displayed in Figure 20 for stair descent for the bilateral hips and pelvis. When comparing across cohorts (pregnant vs. controls), the

analysis showed no significant findings (p>0.099 for all other variables tested). This indicates that pregnancy status does not have an interaction with peak frontal joint angles of the pelvis or hips during walking.

The MANOVA conducted to explore the interaction between gestational time with pelvis and hip kinematics revealed no significant findings about the frontal plane during stairs ascent. This analysis indicates that there is no significant effect of pregnancy timepoint on left or right pelvis tilt or hip abduction or adduction during stair descent.

Additionally, the peak joint angles for both the pelvis and the hip in the frontal plane for the control cohort were not statistically significantly different from the postpartum visit of the pregnant cohort. A lack of statistical significance indicates that after delivery, pregnancy status does not interact with frontal peak joint angles in the pelvis and hips during stair descent.

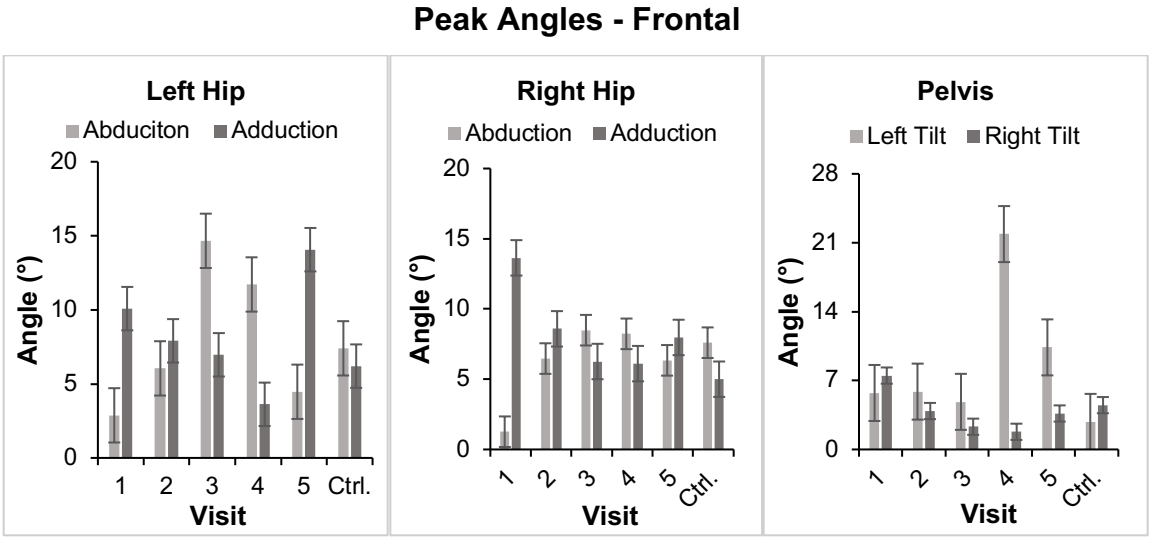


Figure 20. *Peak frontal plane kinematics during stair descent of the* ***A)*** *left hip,* ***B)*** *right hip, and* ***C)*** *pelvis for each laboratory visit. IROT=hip internal rotation and EROT=hip external rotation. (1=T1, 2=T2, 3=T3.1, 4=T3.2, 5=Postpartum)*

A change analysis between each visit for the pregnant cohort was done to observe the impact that pregnancy has over time. The change quantified data are

displayed in Table 12. Because there were no significant changes observed in the frontal plane, no change scores were found to be significantly different from any other timepoint throughout pregnancy.

Table 12. *Change analysis from Visit 1 to each subsequent laboratory visit for the pelvis and hip kinematics in the frontal plane of motion during stair descent. ABD=hip abduction, ADD=hip adduction, L TILT=left pelvic tilt, and R TILT=right pelvic tilt.*

	Left Hip		**Right Hip**		**Pelvis**	
	ABD	**ADD**	**ABD**	**ADD**	**L TILT**	**R TILT**
Δ Visit 1 to 2	1.66±8.1	4.2±12.0	5.6±5.8	7.2±7.9	1.3±7.4	4.6±5.8
Δ Visit 1 to 3	1.3±21.0	6.0±17.8	4.8±20.6	1.9±16.5	7.1±6.4	0.8±6.9
Δ Visit 1 to 4	5.9±6.7	4.4±9.7	5.1±5.8	6.2±7.7	11.3±13.2	7.8±7.2
Δ Visit 1 to 5	11.0±22.3	12.1±18.9	5.5±21.6	5.4±21.2	4.5±8.5	1.5±9.1

4.4.1.3 Stair Descent – Transverse

Transverse plane kinematics during stair descent are displayed in Figure 21. When comparing across cohorts (pregnant vs. controls), the analysis showed no significant findings (p>0.236 for all other variables tested). This indicates that pregnancy status does not have an interaction with peak transverse joint angles of the pelvis or hips during walking.

The MANOVA conducted to explore the effect of gestational time on pelvis and hip kinematics revealed no significant findings about the transverse plane during stair descent. This analysis indicates that there is no significant effect of pregnancy timepoint on forward or backwards pelvis rotation or hip internal or external rotation (Figure 21).

Additionally, the peak joint angles for both the pelvis and the hip in the frontal plane for the control cohort were not statistically significantly different from the postpartum visit of the pregnant cohort. A lack of statistical significance indicates that after delivery, pregnancy status does not interact with transverse peak joint angles in the pelvis and hips during stair descent.

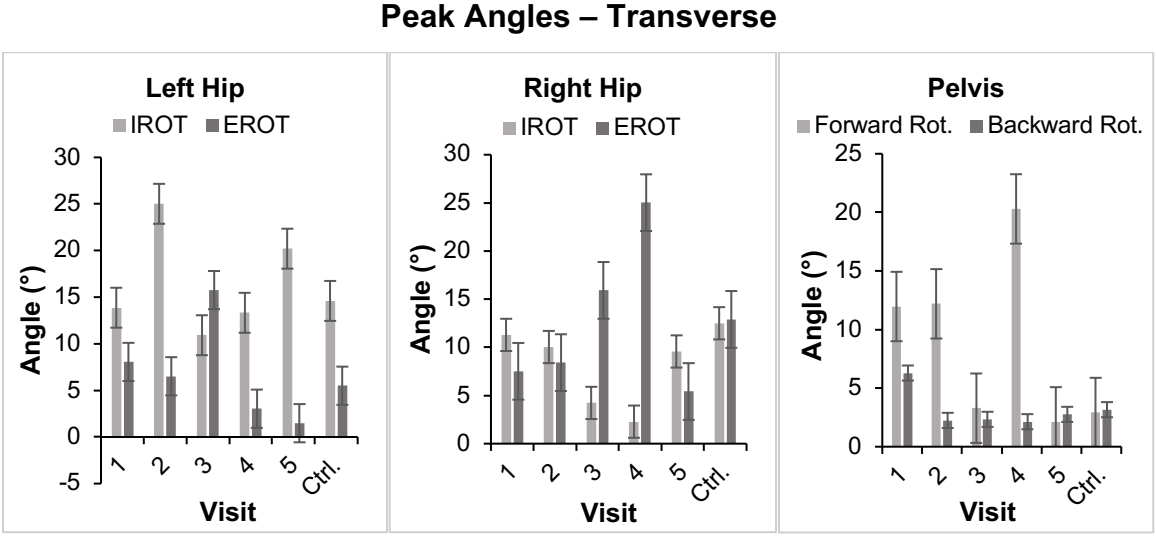


Figure 21. *Peak transverse plane kinematics during stair descent of the **A)** left hip, **B)** right hip, and **C)** pelvis for each laboratory visit. (1=T1, 2=T2, 3=T3.1, 4=T3.2, 5=Postpartum)*

A change analysis between each visit for the pregnant cohort was done to observe the impact that pregnancy has over time. The change analysis is quantified data is displayed in Table 13. Because there were no significant changes observed in the transverse plane, no change scores were found to be significantly different from any other timepoint throughout pregnancy.

Table 13. *Change analysis from Visit 1 to each subsequent laboratory visit for the pelvis and hip kinematics in the transverse plane of motion during stair descent. IROT=hip internal rotation, EROT=hip external rotation, F ROT= forward pelvic rotation, B ROT=backwards pelvic rotation.*

	Left Hip		**Right Hip**		**Pelvis**	
	IROT	**EROT**	**IROT**	**EROT**	**F ROT**	**B ROT**
Δ Visit 1 to 2	4.9±23.6	3.2±4.3	3.8±12.7	1.2±4.2	2.8±5.7	8.0±2.1
Δ Visit 1 to 3	1.3±7.8	0.4±27.6	19.1±28.0	4.6±10.4	6.5±5.4	0.3±14.6
Δ Visit 1 to 4	2.7±1.6	4.9±6.7	11.9±15.0	13.5±15.3	7.8±9.6	2.7±12.5
Δ Visit 1 to 5	5.1±19.0	0.2±13.6	11.9±26.9	4.2±8.7	9.9±3.7	3.4±9.4

4.5 Stairs – Neuromuscular Activity

The neuromuscular analysis of stairs ascent and descent for all evaluated muscles is displayed in Figure 22. Additionally, change scores were computed by subtracting the

first visit performance for each variable from subsequent visits. These values are contained in Table 14.

The MANOVA, which explored the effect of gestational time on pelvis and hip neuromuscular activity, revealed no significant findings. Specifically, this analysis revealed that there was not a significant effect of pregnancy timepoint on peak EMG activity or dominant frequency.

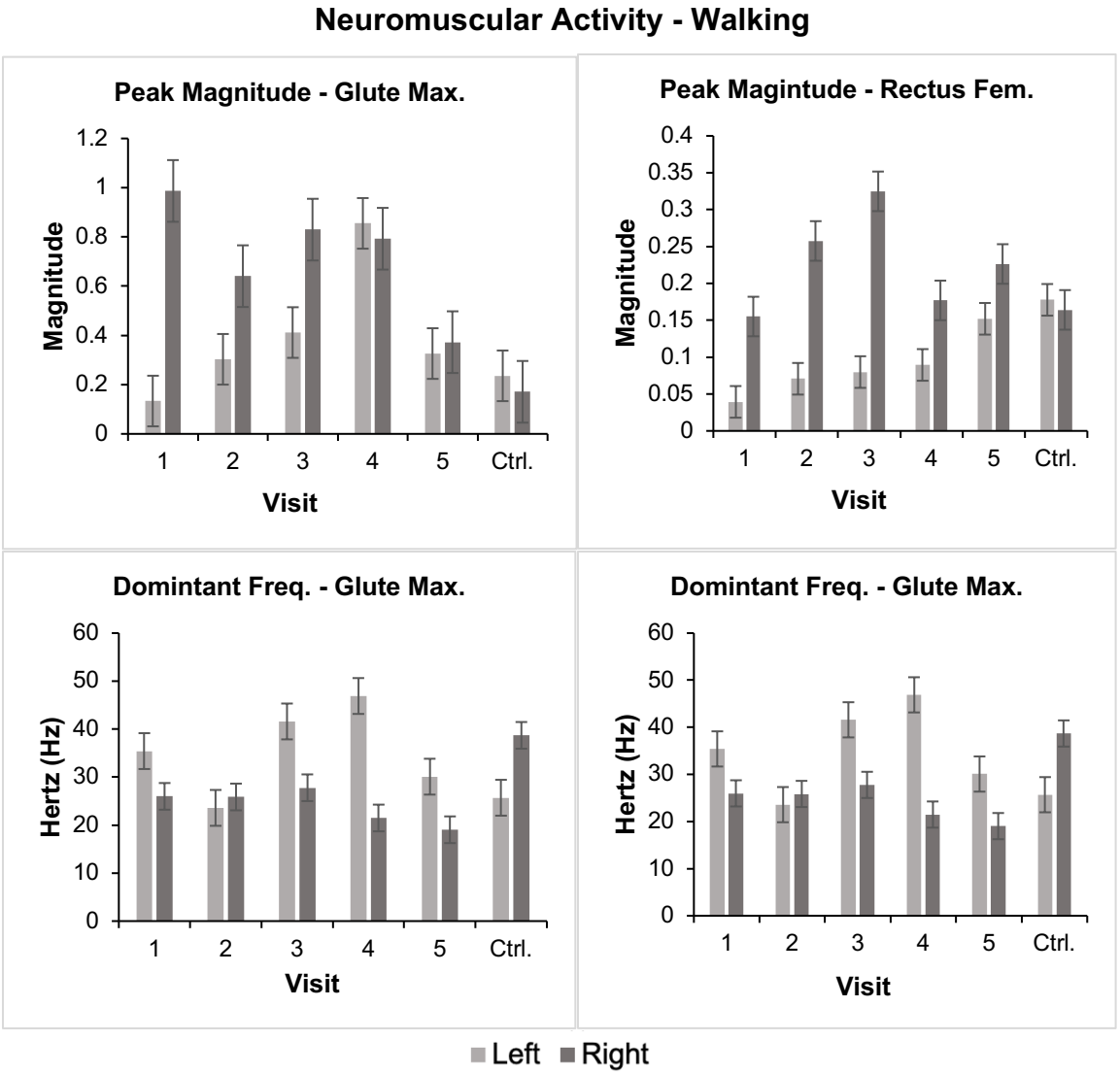


Figure 22. *Neuromuscular activity of the bilateral hip flexor and extensor (rectus femoris and gluteus maximus respectively) during stairs activity.*

A MANOVA was conducted to explore the interaction of pregnancy status and pelvis and hip neuromuscular activity and revealed several significant findings. Comparing across cohorts (pregnant vs. controls), there was a main effect of pregnancy status on dominant frequency. Specifically, there was a significant interaction with right gluteus maximus dominant frequency (Figure 22, $F_{1,\ 218.896}$=5.626, n^2=0.197, p=0.026). However, the peak magnitude in the bilateral gluteus maximus and bilateral rectus femoris have shown no significant interactions between non-pregnant controls and the pregnant cohort.

Moreover, the neuromuscular activity for peak magnitude for the control cohort was not statistically significantly different from postpartum visit of the pregnant cohort. There was a statistically significant difference of dominant frequency between the control cohort and postpartum visits. The analysis revealed that postpartum status significantly effects right gluteus maximus dominant frequency (Figure 22, $F_{1,\ 401.093}$=15.254, n^2=0.560, p=0.002).

Table 14. *Change analysis of pelvis and hip neuromuscular activity from Visit 1 to each subsequent laboratory visit during stairs activities.*

	Δ Peak EMG Magnitude			
	Left		**Right**	
	Gluteus Max.	**Rectus Fem.**	**Gluteus Max.**	**Rectus Fem.**
Δ Visit 1 to 2	0.1447±0.36	0.0156±0.01	0.4607±1.99	0.0914±0.02
Δ Visit 1 to 3	0.1901±0.34	0.0208±0.02	0.3639±1.81	0.1358±0.09
Δ Visit 1 to 4	0.7360±0.4	0.0368±0.11	0.7246±0.92	0.0064±0.07
Δ Visit 1 to 5	0.2076±0.38	0.0930±0.13	0.6136±1.23	0.0373±0.06
	Δ Dominant Frequency			
	Left		**Right**	
	Gluteus Max.	**Rectus Fem.**	**Gluteus Max.**	**Rectus Fem.**
Δ Visit 1 to 2	13.8±17.3	1.4±11.9	1.2±11.3	21.1±11.9
Δ Visit 1 to 3	19.2±31.2	6.4±10.0	12.9±13.4	1.6±31.6
Δ Visit 1 to 4	17.1±25.8	4.9±5.4	1.7±7.5	7.2±9.9
Δ Visit 1 to 5	2.2±16.4	7.9±7.2	4.4±8.7	11.3±30.6

A change analysis between each visit for the pregnant cohort was done to observe the effect that pregnancy has over time. The change analysis is quantified data is displayed in Table 14. Despite some significant changes observed in walking neuromuscular activity, no change scores were found to be significantly different from any other timepoint throughout pregnancy.

4.6 Correlations

A Pearson's product-moment correlation was conducted to assess the association between pelvis/hip kinematic and neuromuscular data during all activities and delivery outcomes in the pregnant cohort. Preliminary analyses showed the association to be linear with all variables normally distributed, assessed by Shapiro-Wilk test ($p>0.05$). There were multiple outliers determined to be 3 or more standard deviations above the mean, specifically in the stairs (both ascent and descent) kinematics, and EMG analysis. These outliers were then excluded from the data and the analyses proceeded.

Specific correlations conducted were the change in each kinematic/EMG variable from visit one (Trimester 1) through the final pre-parturition visit (late Trimester 3). When examining the Pearson's correlation between the magnitude of change in walking kinematics and delivery outcomes, there were strong, significant correlations (Pearson's $r > 0.5$) found in the sagittal and transverse planes. In the transverse plane, it was found that the change in left hip internal rotation (r=0.985, p=0.015) and external rotation (r=0.981, p=0.019) were strongly, significantly correlated to Birth Satisfaction Scale (BSS) scores. Specifically, we found that higher BSS scores (i.e. more satisfied with the

labor/delivery experience) were associated with increased magnitude of change in transverse plane hip motion (Figure 23).

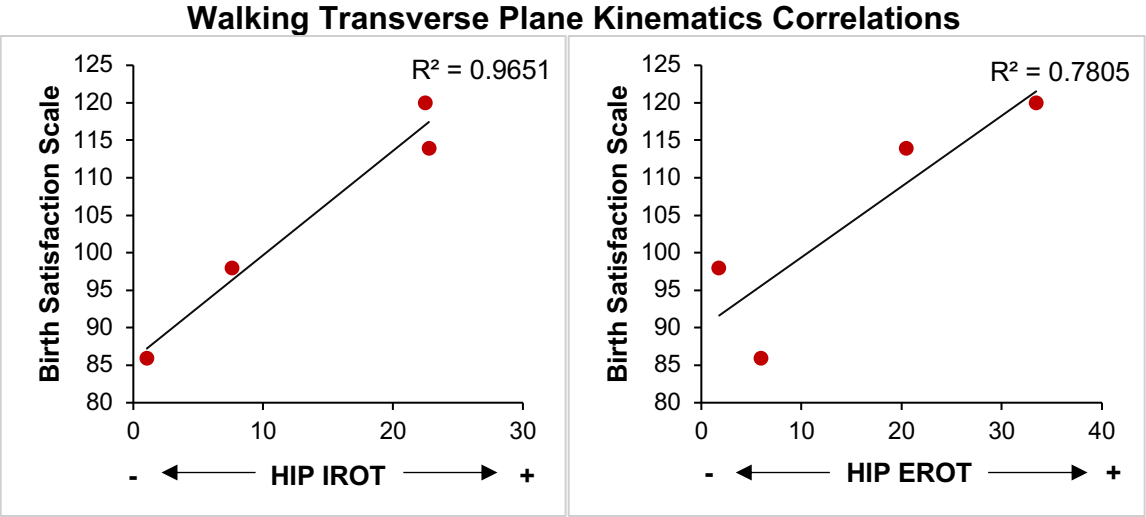


Figure 23. *Pearson's Correlation between walking transverse plan left hip kinematics and delivery outcomes. The black line represents the line of best fit.*

Additionally, in the sagittal plane, we observed that there was a strong, significant correlation between left hip extension and reduced active pushing time (Figure 24, r=-0.971, p=0.029). In other words, with greater change in extension, less time was spent actively pushing during labor. No other significant correlations were noted during walking.

The Pearson's correlation between the magnitude of change in stairs ascent and descent kinematics and delivery outcomes did not result in any significant associations between the variables. No correlations between peak magnitude or dominant frequency for both walking and stairs ascent/descent were observed. This indicates that stairs kinematics and EMG activity did not have an association with delivery outcomes.

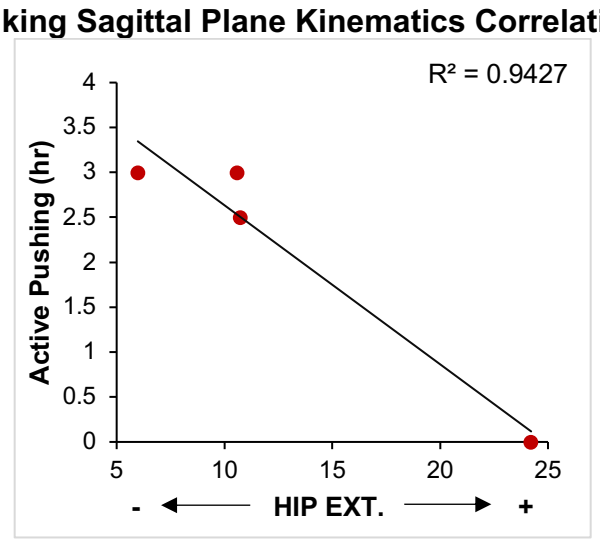


Figure 24. *Pearson's Correlation between walking sagittal plane left hip kinematics and delivery outcomes. The black line represents the line of best fit.*

CHAPTER 5

DISCUSSION

5.1 Aim 1

The overarching objective of the present study was to evaluate pelvis and hip kinematics as well as neuromuscular activity throughout pregnancy in order to evaluate how those changes relate to delivery outcomes. Our first aim was to evaluate the kinematic and neuromuscular changes of the pelvis and hip throughout pregnancy and postpartum during a series of activities (walking, stair ascent, and stair descent). It was hypothesized that: peak hip joint angles of expectant mothers will change significantly throughout pregnancy in the frontal and transverse planes (*Hypothesis 1.1*); neuromuscular activity of expectant mothers will not change significantly throughout pregnancy (*Hypothesis 1.2*); and postpartum variables will not be significantly different from nongravid controls (*Hypothesis 1.3*).

Contrary to Hypothesis 1.1, it was determined that the peak pelvis and peak hip joint angles in the sagittal plane were impacted by gestational timepoint. These changes were large enough in magnitude and different enough that they cannot be attributed to natural variability between participants. The changes in the sagittal plane, which mostly increased in peak angle as each trimester progresses, coincide with morphological adaptations that the body makes to in response to increased *relaxin* levels and to support an increasing fetus size through development.[10, 36, 39, 43] Generally, these findings align with previous literature[11, 36, 38, 42] that reported increased anterior pelvic tilt angles in Trimester 3 when compared with an earlier pregnancy timepoint, pre-pregnancy timepoint, or nongravid control subjects. Previous literature has shown that from

Trimester 2 to Trimester 3, there is a decrease in posterior pelvic tilt[10, 12] however these studies did not compare nonpregnant controls or early pregnancy[43] to late pregnancy. Moreover, these investigators also only saw the participants at 1 timepoint in Trimester 3. This implies analyzing kinematics in the late stages of Trimester 3 is valuable to more fully understanding the biomechanical changes that occur in pregnancy.

For the hip, peak hip extension and flexion angles were significantly increased by visit T3.2. This indicates that there are changes peak hip joint angles throughout pregnancy. These results show that in the later stages of pregnancy, specifically at the late stages of Trimester 3, expectant mothers experience a larger magnitude of hip extension and flexion. Our findings are consistent with previous findings that show an increase in hip flexion and extension by Trimester 3.[10, 11, 42] Much like the changes in pelvis, the hip flexion findings support the necessary accommodations made by the body to support an increasing fetus size and still achieve locomotion successfully.[10, 36, 39, 43]

Understanding the motion of the pelvis and hip adaptations adopted to accommodate these changes throughout pregnancy may be important clinically as an expectant mother prepares for labor/delivery.[28, 33] Specifically, determining normative values for the magnitude of change expected for these joints and planes of motion could be another tool in predicting preparedness for the parturition process.[28] Currently, pelvimetry tools that measure anatomic disproportion have not fully elucidated all variables that may influence labor preparedness. The work presented herein implies there are a biomechanical factors and other musculoskeletal structures (muscles, ligaments, etc.) that also may play a significant role in this process.[28, 30] Therefore, examining biomechanics throughout pregnancy and the changes necessary for successful

labor/delivery (e.g. peak pelvic tilt, peak hip sagittal angles) likely provides a better understanding of successful preparation for labor and delivery.

In contrast to the results herein regarding Hypothesis 1.1, our findings partially supported Hypothesis 1.2 that neuromuscular activity for expectant mothers would not change significantly throughout pregnancy. The analysis showed that despite large changes in kinematics, there were no significant changes for peak magnitude of the bilateral gluteus maximus or bilateral rectus femoris. However, there was a significant change in dominant frequency between the nongravid controls and pregnant participants observed during walking gait. The control cohort had an overall higher dominant frequency in the left and right gluteus maximus and left rectus femoris. This indicates that the muscle activation patterns of expectant mothers change as a result of pregnancy. While there are likely several explanations for why this occurred, some include potentially resultant from increased fatigue due to an increased body mass or adjusting motor control patterns to compensate for muscles that weaken throughout gestation.

Previous studies have shown inconsistent results regarding gluteus maximus and rectus femoris muscle activity in expectant mothers compared to nongravid controls.[33–35] Most literature concerning pregnancy neuromuscular adaptations is scarce and often present conflicting results, with several studies showing increased muscle activity[33, 34, 46] while others present no changes.[33, 45] Specifically, Bagwell et al. (2020) found that peak gluteus maximums amplitude was reduced in pregnant participants than nongravid controls. However, in another study by the same research group, they found the opposite to be true. Only one study to our knowledge has explored rectus femoris activity,[34] with no other studies available confirming their findings. The results herein show that

neuromuscular adaptations may not change enough throughout pregnancy to have a relationship to the biomechanical changes observed.

Despite only observing a few changes in neuromuscular features, mostly of dominant frequency, our findings still contribute to the understanding of the relationship between neuromuscular adaptations and pregnancy. The lack of change in peak magnitude could be attributed, in part, to accommodating for an increased mass of both the expectant mother and developing fetus.[10, 36, 39] Since expectant mothers show an increase in mass over time and the fetus also gains mass over the duration of pregnancy,[10, 40] the lower extremity muscles may change muscle recruitment throughout pregnancy to still achieve locomotion with the additional mass. Because of the increase in carrying mass, their muscles may fatigue faster than pre- or early pregnancy values, in which we would more likely see a change in dominant frequency. Whereas peak magnitude is more likely to be associated with a change of strength or intensity of a muscle contraction, which was shown to not be in the case in our analysis. Therefore, the dominant frequency is the more likely variable to experience changes throughout pregnancy.

Furthermore, the peak pelvis joint angles and peak hip joint angles in all planes of motion for the nongravid controls were not significantly different from the postpartum visit for pregnant participant. This supports Hypothesis 1.3 that postpartum variables will not be significantly different from nongravid controls. In terms of significant findings, it was found that, in the pelvis, peak anterior tilt, posterior tilt, and forward rotation angles were found to be significantly decreased in PP compared to T3.2. In the hip, peak flexion and extension angles were also significantly decreased in PP compared to T3.2. These

results support the idea that biomechanical changes developed during pregnancy are due to an accommodation for the increase of mass and these kinematic measures return to pre-pregnancy or early pregnancy values after delivery. In previous literature, similar results have been found. Specifically, there has been an observed decrease of hip extension from both T2 and T3 to PP,[10] indicating that earlier to middle timepoints in pregnancy also show significant increases in hip joint angles compared to the PP timepoint. Other literature has also shown no difference between T1 kinematic measurements and PP kinematic measurements, which could be evidence that PP kinematics will return to similar values as early pregnancy, where few biomechanical adaptations have occurs due to little increases in mass and fetus size.[10, 35, 38, 43, 45] Our results specifically begin to fill a gap in our understanding of how pregnancy adaptations diminish after delivery.

Our study revealed several kinematic changes in the hip sagittal plane during walking and stair ascent and pelvis transverse plane during stairs ascent, but no significant changes during stairs descent or in the frontal plane during any activity. We also found significant differences in dominant frequency during walking, but no other neuromuscular adaptations were found. Overall, these results insinuate that biomechanics do change thought the gestation cycle. It can be concluded that she changes occur to maintain normal locomotion, while adapting to an increased carrying mass around the lower abdomen and pelvic region.

5.2 Aim 2

The second specific aim of the present study was to evaluate any connections between biomechanics changes that occur throughout pregnancy ***and*** labor/delivery outcomes. Our results revealed some significant correlations between hip kinematics during walking in the sagittal and transverse planes and delivery outcomes. Though, our results did not agree with our initial hypothesis that there will be a significant correlation between changes in peak joint angles in the frontal plane and postpartum outcomes (*Hypothesis 2.1*). In contrast, the results revealed a significant negative correlation between the change in left hip extension and duration of active pushing time during labor. Our results also yielded a strong, positive correlation between the changes in left hip internal and external rotation and BSS scores. To our knowledge, these are the first results to report any connections between a mother's musculoskeletal biomechanics in advance of labor/delivery and her experience during and immediately following the laboring process.

In more detail, active pushing time is the amount of time that a mother actively attempts to push the fetus out of her body vaginally. This is frequently known as the active second stage of labor. Critically, a longer duration of active pushing time during delivery has been linked to increased instances of hemorrhage and cesarean section,[54, 70] making long active labor times a concern in the delivery room. Moreover, increasing labor duration has been directly linked with birth satisfaction.[73] While there are inconsistent findings about the exact causes of a longer active pushing time, it is strongly correlated with obstructed labor (or labor dystocia) and failure of the fetus to descend in

the birth canal.[31, 38] As previously mentioned, obstructed labor is typically caused by a small pelvic inlet and craniopelvic disproportion.[1, 31] Because of the connection between increased hip extension and reduced active laboring durations found herein, our results suggest that a larger change in hip extension may be linked to significant changes in the pelvis inlet that reduce active pushing durations. However, no previous studies have linked these specific biomechanics variable with any delivery outcomes.

The Birth Satisfaction Scale (BSS), typically used by clinicians to measure maternal satisfaction within their practice, is scored from 30 to 150 (30=unsatisfied, 150= very satisfied with their birth experience). Many prior studies have linked greater BSS scores with a variety of variables including spontaneous vaginal births compared to women who have more complicated birthing experiences.[49] Thus, BSS scores will be higher, as the birth is less complicated and requires less medical intervention. Our results showed that a greater change in both hip internal and external rotation revealed a correlation with higher satisfaction scores. Biomechanically, it is known that as hip internal rotation increases, the pelvic inlet widens.[49] If internal rotation changes significantly during pregnancy, then the pelvic inlet could widen in preparation for delivery, reducing the complications caused by obstructed labor or craniopelvic disproportion. Additionally, the large changes in external rotation can likely be attributed to necessary adjustments made during walking gait due to the increased carrying mass on the anterior portion of the body.[26, 43] While this is likely a necessary adaptation for safe and efficient ambulation while pregnant, our results also imply that expectant mothers who have larger external rotation changes may have better biomechanical adaptations for labor/delivery resulting in improved BSS scores. However, as previously mentioned,

given the novelty of the present study, our findings are not well supported in the literature.

Our findings of no significant correlation between neuromuscular features and post-partum outcomes supports our second hypothesis for this aim (*Hypothesis 2.2*). Although no association was established, these findings do contribute to our understanding of the relationship between neuromuscular activity and pregnancy. Although limited, neuromuscular adaptations to pregnancy have previously been studied. Bagwell et al. found higher gluteus maximus and rectus femoris activity throughout pregnancy.[40, 42] However, these findings are inconsistent as other studies have found that gluteus maximus activity is lower in pregnant participants or does not change significantly enough to draw a finite conclusion.[41] Our findings support previous literature that has not found a significant change in neuromuscular activity throughout pregnancy and strengthens the argument that pregnant mothers must maintain adequate muscle activity to adapt to resulting biomechanical changes of pregnancy. Nevertheless, our correlational analysis is simply observational data, and it cannot be known whether the associations established here are causal or whether these biomechanical changes avert other adverse outcomes, affecting birth.

5.3 Limitations

The present study has several limitations that may affect the interpretation of the results. The absence of observed simple effects or significant correlations is heavily influenced by a small sample size in the pregnant cohort. Some variables were limited in effect size by the small sample size. While having 6 pregnant participants enrolled, only 3

participants were able to complete all 5 visits to be included in our analysis. One participant delivered early, completing only 3 visits, and 2 participants were still pregnant at the time of completing this thesis document.

Another limitation is that our sample is largely a homogenous cross section of expectant mothers. Specifically, all of our pregnant participants were white, middleclass, relatively healthy adult women. Given the influence of a large swath of socio-demographic variables on maternal mortality/morbidity, this may limit the generalizability of these findings to other demographic groups or populations in different geographical locations. Moreover, as the participants ranged from primigravid to multigravida, this illustrated expectant mothers with varying backgrounds of labor and delivery experience and previous pregnancy-related biomechanical changes. The characteristics of the recruited participants may allow the findings to be applied to healthy menstruation-aged adult women.

Additionally, this study only addressed two activities – walking at a self-selected speed and stairs ascent/descent. While walking and stair climbing are some of the most common physical tasks encountered in general day to day activities, the findings of this study may only be applied to these specific activities. This study also did not track physical activity levels of the participant. Physical activity levels could impact biomechanics not only during pregnancy, but also in both a normal, healthy population and a diseased or disabled population.

In light of its limitations, we should also address the strengths of the current approach and design. The repeated measures design through four timepoints of pregnancy and one timepoint postpartum for each participant in the pregnant cohort allowed for an

analysis of biomechanics through the entire duration of pregnancy and postpartum. Additionally, the research team conducting each trial provided similar procedures and physical cuing for all participants, including the use of a standardized timeline, environment, and approach to all measures, increasing the reliability and validity of the data collected by increasing internal validity. This study also includes activities beyond walking gait and attempts to build an association between pregnancy biomechanics and postpartum outcomes. Lastly, despite not accounting for a larger range of sociodemographic and geographic variables, the analysis from this cohort still provides valuable insight into the role of biomechanical changes among pregnant women. General biomechanics is currently not shown to be impacted by demography, so the role of biomechanics throughout pregnancy can be explored further in a larger more heterogenous sample.

5.4 Future Directions

To overcome these limitations, future studies aiming to access biomechanical changes throughout pregnancy should implement the use of different activities, to determine the adaptations expectant mothers experience through a variety of tasks that they may encounter in daily life. Additional wearable technologies, such as inertial measurement units should be utilized to determine other biomechanical variables beyond joint angles, such as gait and balance parameters. Finally, participants' current and previous physical activity levels should be monitored to determine if physical activity levels during pregnancy change over time in correlation to biomechanical changes.

5.5 Conclusions

Our study revealed significant increases in peak joint angles of the pelvis and hip throughout pregnancy during walking gait in healthy pregnant females, as well as significant differences in dominant EMG frequency between controls and pregnant mothers. There was a correlation between the BSS and hip internal and external rotation, as well as between hip extension and duration of active pushing time during labor. As maternal mortality rates continue to increase each year in the US, there is an increasing need to determine preparedness for labor and delivery before the parturition process has begun. As current obstructed labor prediction methods are limited and obstructed labor can lead to more negative delivery and postpartum outcomes, its essential that another clinical tool for predicting these problems is developed.

APPENDICES

Appendix 1: Online Pre-Screening Questionnaire

Leg Function in Expectant Mothers before and after Labor/Delivery
Inclusion and Exclusion Criteria

1. Have you previously given birth (either vaginally or via Caesarean section)? **Y** **N**
2. Are you between the ages of 18 and 40 years old? **Y** **N**
3. Are you currently pregnant? **Y** **N**
    a. If yes, what week in your pregnancy: _____
4. When is your due date? _____ month _____day _____ year
5. Can you attend:
    a. For expectant mothers: 5 data capture sessions (1 x T1, 1 x T2, 2 x T3, 1 x PP)? **Y** **N**
    b. For non-expectant mothers: 1 data capture session? **Y** **N**
6. Do you have a history of skin irritation from adhesives? **Y** **N**
7. Do you have a terminal illness expected to result in death within 1 year? **Y** **N**
8. Do you have any musculoskeletal disability that impacts your mobility? **Y** **N**
    a. If yes, please explain:
9. Do you have any neuromuscular disability that impacts your mobility? **Y** **N**
    a. If yes, please explain:

Appendix 2: Edinburgh Handedness Inventory

Edinburgh Handedness Inventory[1]

Your participant ID:_____

Please indicate with a one (1) your preference in using your left or right hand in the following tasks.

Where the preference is so strong you would never use the other hand, unless absolutely forced to, put a two (2).

If you are indifferent, put a one in each column (1 | 1).

Some of the activities require both hands. In these cases, the part of the task or object for which hand preference is wanted is indicated in parentheses.

Task / Object	Left Hand	Right Hand
1. Writing		
2. Drawing		
3. Throwing		
4. Scissors		
5. Toothbrush		
6. Knife (without fork)		
7. Spoon		
8. Broom (upper hand)		
9. Striking a Match (match)		
10. Opening a Box (lid)		
Total checks:	LH =	RH =
Cumulative Total	CT = LH + RH =	
Difference	D = RH – LH =	
Result	R = (D / CT) × 100 =	
Interpretation: (Left Handed: R < -40) (Ambidextrous: -40 ≤ R ≤ +40) (Right Handed: R > +40)		

Please stop here

[1] Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsychologia*, *9*, 97-113.

Appendix 3: Waterloo Footedness Questionnaire – Revised

Waterloo Footedness Questionnaire – Revised

Instructions:
Select what foot you would use for all of the following tasks. If you always use one foot to perform the described activity, circle RA or LA for right always or left always, respectively. If you usually use one-foot circle RU or LU, as appropriate. If you use both feet equally often, circle EQ.

Please do not circle an answer for each question, but imagine yourself performing each activity in turn, and then mark the appropriate answer. If necessary, stop and pantomime the activity.

Activities:

a)	Kicking a stationary ball at a target straight in front of you:	**LA**	**LU**	**EQ**	**RU**	**RA**
b)	Standing on one foot:	**LA**	**LU**	**EQ**	**RU**	**RA**
c)	Smoothing sand at the beach:	**LA**	**LU**	**EQ**	**RU**	**RA**
d)	First step up on to a chair:	**LA**	**LU**	**EQ**	**RU**	**RA**
e)	Stomping on a fast moving bug:	**LA**	**LU**	**EQ**	**RU**	**RA**
f)	Balancing on a railway track:	**LA**	**LU**	**EQ**	**RU**	**RA**
g)	Picking up marbles with your toes:	**LA**	**LU**	**EQ**	**RU**	**RA**
h)	Hopping on one foot:	**LA**	**LU**	**EQ**	**RU**	**RA**
i)	Pushing a shovel in to the ground:	**LA**	**LU**	**EQ**	**RU**	**RA**
j)	During relaxed standing, the foot with most of your weight:	**LA**	**LU**	**EQ**	**RU**	**RA**

Additional Questions:

a) Is there any reason (i.e. injury) why you have changed your foot preference for any of the above activities?

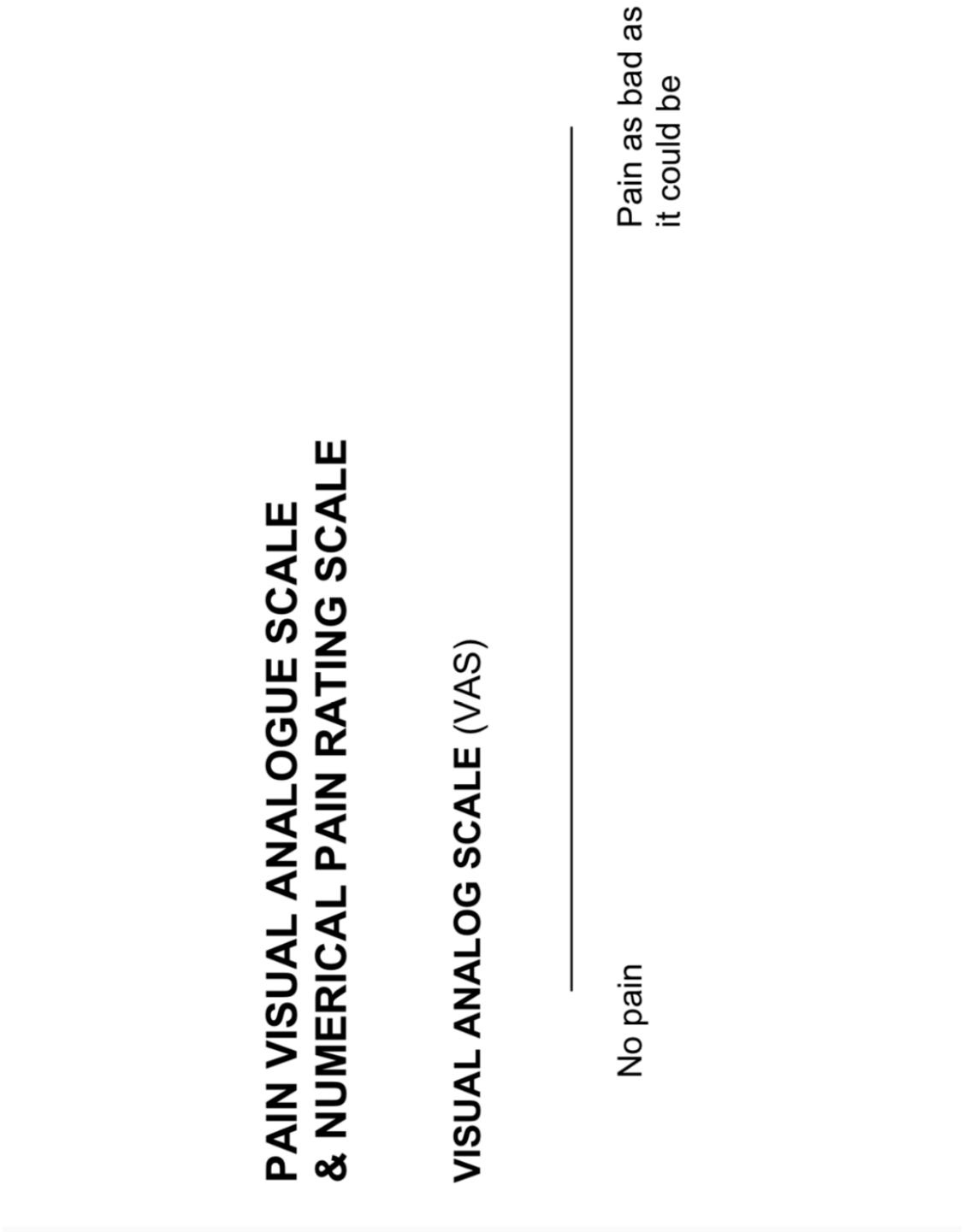
YES **NO**

b) Have you ever been given special training or encouragement to use a particular foot during specific activities?

YES **NO**

c) If you have answered "YES" for either of the additional questions a) or b), please explain:

Appendix 4: Visual Analog Scale of Pain



Appendix 5: PROMIS Physical Function 10a

Physical Function – Short Form 10a

Please respond to each question or statement by marking one box per row.

		Not at all	Very little	Somewhat	Quite a lot	Cannot do
PFA1	Does your health now limit you in doing vigorous activities, such as running, lifting heavy objects, participating in strenuous sports?	☐ 5	☐ 4	☐ 3	☐ 2	☐ 1
PFC36r1	Does your health now limit you in walking more than a mile (1.6 km)?	☐ 5	☐ 4	☐ 3	☐ 2	☐ 1
PFC37	Does your health now limit you in climbing one flight of stairs?	☐ 5	☐ 4	☐ 3	☐ 2	☐ 1
PFA5	Does your health now limit you in lifting or carrying groceries?	☐ 5	☐ 4	☐ 3	☐ 2	☐ 1
PFA3	Does your health now limit you in bending, kneeling, or stooping?	☐ 5	☐ 4	☐ 3	☐ 2	☐ 1
		Without any difficulty	**With a little difficulty**	**With some difficulty**	**With much difficulty**	**Cannot do**
PFA11	Are you able to do chores such as vacuuming or yard work?	☐ 5	☐ 4	☐ 3	☐ 2	☐ 1
PFA16r1	Are you able to dress yourself, including tying shoelaces and buttoning your clothes?	☐ 5	☐ 4	☐ 3	☐ 2	☐ 1
PFB26	Are you able to shampoo your hair?	☐ 5	☐ 4	☐ 3	☐ 2	☐ 1
PFA55	Are you able to wash and dry your body?	☐ 5	☐ 4	☐ 3	☐ 2	☐ 1
PFC45r1	Are you able to sit on and get up from the toilet?	☐ 5	☐ 4	☐ 3	☐ 2	☐ 1

28 March 2017

Appendix 6: PROMIS Physical Function 10b

PROMIS® Item Bank v2.0 – Physical Function – Short Form 10b

Physical Function – Short Form 10b

Please respond to each question or statement by marking one box per row.

		Without any difficulty	With a little difficulty	With some difficulty	With much difficulty	Unable to do
PFA11	Are you able to do chores such as vacuuming or yard work?	☐ 5	☐ 4	☐ 3	☐ 2	☐ 1
PFA56	Are you able to get in and out of a car?	☐ 5	☐ 4	☐ 3	☐ 2	☐ 1
PFA21	Are you able to go up and down stairs at a normal pace?	☐ 5	☐ 4	☐ 3	☐ 2	☐ 1
PFA53	Are you able to run errands and shop?	☐ 5	☐ 4	☐ 3	☐ 2	☐ 1
PFA9	Are you able to bend down and pick up clothing from the floor?	☐ 5	☐ 4	☐ 3	☐ 2	☐ 1
PFB28r1	Are you able to lift 10 pounds (5 kg) above your shoulder?	☐ 5	☐ 4	☐ 3	☐ 2	☐ 1
		Not at all	**Very little**	**Somewhat**	**Quite a lot**	**Cannot do**
PFA1	Does your health now limit you in doing vigorous activities, such as running, lifting heavy objects, participating in strenuous sports?	☐ 5	☐ 4	☐ 3	☐ 2	☐ 1
PFA6	Does your health now limit you in bathing or dressing yourself?	☐ 5	☐ 4	☐ 3	☐ 2	☐ 1
PFB3	Does your health now limit you in putting a trash bag outside?	☐ 5	☐ 4	☐ 3	☐ 2	☐ 1
PFB44	Does your health now limit you in doing moderate activities, such as moving a table, pushing a vacuum cleaner, bowling, or playing golf?	☐ 5	☐ 4	☐ 3	☐ 2	☐ 1

12 June 2018

Appendix 7: PROMIS General Life Satisfaction 5a

PROMIS® Item Bank v1.0 – General Life Satisfaction - Short Form 5a

General Life Satisfaction – Short Form 5a

Please respond to each question or statement by marking one box per row.

	Indicate how much you agree or disagree…	Strongly disagree	Disagree	Slightly disagree	Neither agree nor disagree	Slightly agree	Agree	Strongly agree
PA045m	In most ways, my life is close to perfect	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 6	☐ 7
PA046	If I could live my life over, I would change almost nothing.....	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 6	☐ 7
PA047	I am satisfied with my life.....	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 6	☐ 7
PA048	So far I have gotten the important things I want in life.....	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 6	☐ 7
PA049m	My life situation is excellent	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 6	☐ 7

1 Decebmer 2017

Appendix 8: Birth Satisfaction Scale

Subject ID: _____ Date: _____

Birth Satisfaction Scale

	Strongly Agree	Agree	Neither Agree Or Disagree	Disagree	Strongly Disagree
1. I coped well during my birth.	☐	☐	☐	☐	☐
2. The delivery room staff encourage me to make decisions about how I wanted my birth to progress.	☐	☐	☐	☐	☐
3. I was well prepared for my labor, i.e. read much literature and/or parenthood classes.	☐	☐	☐	☐	☐
4. I found giving birth a distressing experience.	☐	☐	☐	☐	☐
5. I came through childbirth virtually unscathed.	☐	☐	☐	☐	☐
6. I gave birth to a healthy normal baby.	☐	☐	☐	☐	☐
7. During labor I received outstanding medical care.	☐	☐	☐	☐	☐
8. I received much medical intervention, i.e. induction, forceps, c-section, etc.	☐	☐	☐	☐	☐
9. I had a swift and speedy labor.	☐	☐	☐	☐	☐
10. I felt well supported by my partner during labor and birth.	☐	☐	☐	☐	☐
11. I was encouraged to hold my baby for a substantial amount of time after birth.	☐	☐	☐	☐	☐
12. My birth experience was considerable different to what I intended.	☐	☐	☐	☐	☐
13. I had the same midwife throughout the entire process of labor and delivery.	☐	☐	☐	☐	☐
14. I felt that the delivery room was unthreatening and comfortable.	☐	☐	☐	☐	☐
15. I felt very anxious during my labor and birth.	☐	☐	☐	☐	☐
16. I felt out of control during my birth experience.	☐	☐	☐	☐	☐
17. I felt it was better not to know in advance about the processes of giving birth.	☐	☐	☐	☐	☐
18. I was not distressed at all during labor.	☐	☐	☐	☐	☐
19. I felt mutilated by my birth experience.	☐	☐	☐	☐	☐
20. My baby was avoidably hurt during birth.	☐	☐	☐	☐	☐
21. The staff provided me with insufficient medical care during my birth.	☐	☐	☐	☐	☐
22. I had a natural labor, i.e. minimal medical intervention.	☐	☐	☐	☐	☐
23. I thought my labor was excessively long.	☐	☐	☐	☐	☐
24. I felt well supported by staff during my labor and birth.	☐	☐	☐	☐	☐
25. I was separated from my baby for a considerable period of time after my birth.	☐	☐	☐	☐	☐
26. My birth proceeded as I planned it.	☐	☐	☐	☐	☐
27. The staff communicated well with me during labor.	☐	☐	☐	☐	☐
28. The delivery room was clean and hygienic.	☐	☐	☐	☐	☐
29. Giving birth was incredibly painful.	☐	☐	☐	☐	☐
30. Labor was not as painful as I imagined.	☐	☐	☐	☐	☐

Appendix 9: Edinburgh Postpartum Depression Scale

Subject ID: _____ **Date:** _____

Edinburgh Postnatal Depression Scale

As you were pregnant or have recently had a baby, we would like to know how you are feeling. Please check the answer that comes closest to how you have felt *in the pas 7 days*, not just how you feel today.

Here is an example, already completed:

I have felt happy:

☐ Yes, all the time
☒ Yes, most of the time
☐ No, not very often
☐ No, not at all

This would mean: "I have felt happy most of the time" during the past week. Please complete the other questions in the same way.

In the past 7 days:

1. I have been able to laugh and see the funny side of things
   ☐ As much as I always could
   ☐ Not quite so much now
   ☐ Definitely not so much now
   ☐ Not at all

2. I have looked forward with enjoyment to things
   ☐ As much as I ever did
   ☐ Rather less than I used to
   ☐ Definitely less than I used to
   ☐ Hardly at all

3. I have blamed myself unnecessarily when things went wrong
   ☐ Yes, most of the time
   ☐ Yes, some of the time
   ☐ Not very often
   ☐ No, never

4. I have been anxious or worried for no good reason
   ☐ No, not at all
   ☐ Hardly ever
   ☐ Yes, sometimes
   ☐ Yes, very often

5. I have felt scared or panicky for no very good reason
   ☐ Yes, quite a lot
   ☐ Yes, sometimes
   ☐ No, not much
   ☐ No, not at all

6. Things have been getting on top of me
   ☐ Yes, most of the time I haven't been able to cope
   ☐ Yes, sometimes I haven't coped as well as usual
   ☐ Definitely not so much now
   ☐ Not at all

7. I have been so unhappy that I have had difficulty sleeping
   ☐ Yes, most of the time
   ☐ Yes, sometimes
   ☐ Not very often
   ☐ No, not at all

8. I have felt sad or miserable
   ☐ Yes, most of the time
   ☐ Yes, quite often
   ☐ Not very often
   ☐ No, not at all

9. I have been so unhappy that I have been crying
   ☐ Yes, most of the time
   ☐ Yes, quite often
   ☐ Only occasionally
   ☐ No, never

10. The thought of harming myself has occurred to me
    ☐ Yes, quite often
    ☐ Sometimes
    ☐ Hardly ever
    ☐ Never

Appendix 10: Mother Infant Bonding Scale

Subject ID: Date:

Mother-Infant Bonding Scale

	Always	Very Often	Quite Often	Sometimes	Rarely	Never
1. I feel very close to my baby.	☐	☐	☐	☐	☐	☐
2. I wish the old days when I had no baby would come back.	☐	☐	☐	☐	☐	☐
3. I feel distant from my baby.	☐	☐	☐	☐	☐	☐
4. I love to cuddle my baby.	☐	☐	☐	☐	☐	☐
5. I regret having this baby.	☐	☐	☐	☐	☐	☐
6. The baby does not seem to be mine.	☐	☐	☐	☐	☐	☐
7. My baby winds me up.	☐	☐	☐	☐	☐	☐
8. I love my baby to bits.	☐	☐	☐	☐	☐	☐
9. I feel happy when my baby smiles or laughs.	☐	☐	☐	☐	☐	☐
10. My baby irritates me.	☐	☐	☐	☐	☐	☐
11. I enjoy playing with my baby.	☐	☐	☐	☐	☐	☐
12. My baby cries too much.	☐	☐	☐	☐	☐	☐
13. I feel trapped as a mother.	☐	☐	☐	☐	☐	☐
14. I feel angry with my baby.	☐	☐	☐	☐	☐	☐
15. I resent my baby.	☐	☐	☐	☐	☐	☐
16. My baby is the most beautiful baby in the world.	☐	☐	☐	☐	☐	☐
17. I wish my baby would somehow go away.	☐	☐	☐	☐	☐	☐
18. I have done harmful things to my baby.	☐	☐	☐	☐	☐	☐
19. My baby makes me feel anxious.	☐	☐	☐	☐	☐	☐
20. I am afraid of my baby.	☐	☐	☐	☐	☐	☐
21. My baby annoys me.	☐	☐	☐	☐	☐	☐
22. I feel confident when caring for my baby.	☐	☐	☐	☐	☐	☐
23. I feel the only solution is for someone else to look after my baby.	☐	☐	☐	☐	☐	☐
24. I feel like hurting my baby.	☐	☐	☐	☐	☐	☐
25. My baby is easily comforted.	☐	☐	☐	☐	☐	☐

Appendix 11: Dominant Frequency MATLAB Code

```
%% This program was created to run a FFT on raw EMG signals to find the
dominant freuqnecy
%% of sEMG
%%
%%
%% Created by Olivia Greene
%% Janurary 23, 2024
%%
%% Edited by Ryan Chapman, PhD
%% Janurary 24, 2024
%%
%%

%% EMG
% Walking = 30 sec
% fs = 1000 f/s

%% WALKING GAIT
%% 1. Load Raw EMG Data

% load data
WALK_SS_1 = readtable("WALK_SS0001 T_a.xlsx");
WALK_SS_2 = readtable("WALK_SS0002 T_a.xlsx");
WALK_SS_3 = readtable("WALK_SS0003 T_a.xlsx");

% Pull Correct EMG Column for Each Muscle
SS_1_LGM = table2array(WALK_SS_1(6:end,17));
SS_1_LRF = table2array(WALK_SS_1(6:end,15));
SS_1_RGM = table2array(WALK_SS_1(6:end,16));
SS_1_RRF = table2array(WALK_SS_1(6:end,14));

SS_2_LGM = table2array(WALK_SS_2(6:end,17));
SS_2_LRF = table2array(WALK_SS_2(6:end,15));
SS_2_RGM = table2array(WALK_SS_2(6:end,16));
SS_2_RRF = table2array(WALK_SS_2(6:end,14));

SS_3_LGM = table2array(WALK_SS_3(6:end,17));
SS_3_LRF = table2array(WALK_SS_3(6:end,15));
SS_3_RGM = table2array(WALK_SS_3(6:end,16));
SS_3_RRF = table2array(WALK_SS_3(6:end,14));


%% 2. Frequency Metrics
% Compute FFT

% Compute the FFT of the signal SS 1
fs = 1000; % Sampling frequency in Hz
[rows,cols] = size(SS_1_LGM); % Number of samples in the signal
N = rows;
f1 = fs*(0:N/2)/N; % Define the frequency range

FFT_SS_1_LGM = fft(SS_1_LGM);
FFT_SS_1_LGM = abs(FFT_SS_1_LGM/N);
```

```
FFT_SS_1_LGM_New = FFT_SS_1_LGM(1:N/2+1);
FFT_SS_1_LGM_New(2:end-1) = 2*FFT_SS_1_LGM_New(2:end-1);

FFT_SS_1_LRF = fft(SS_1_LRF);
FFT_SS_1_LRF = abs(FFT_SS_1_LRF/N);
FFT_SS_1_LRF_New = FFT_SS_1_LRF(1:N/2+1);
FFT_SS_1_LRF_New(2:end-1) = 2*FFT_SS_1_LRF_New(2:end-1);

FFT_SS_1_RGM = fft(SS_1_RGM);
FFT_SS_1_RGM = abs(FFT_SS_1_RGM/N);
FFT_SS_1_RGM_New = FFT_SS_1_RGM(1:N/2+1);
FFT_SS_1_RGM_New(2:end-1) = 2*FFT_SS_1_RGM_New(2:end-1);

FFT_SS_1_RRF = fft(SS_1_RRF);
FFT_SS_1_RRF = abs(FFT_SS_1_RRF/N);
FFT_SS_1_RRF_New = FFT_SS_1_RRF(1:N/2+1);
FFT_SS_1_RRF_New(2:end-1) = 2*FFT_SS_1_RRF_New(2:end-1);

% Find Max of peaks
[Max_SS1_LGM, Loc_Max_SS1_LGM] = max(FFT_SS_1_LGM_New(2:end));
[Max_SS1_LRF, Loc_Max_SS1_LRF] = max(FFT_SS_1_LRF_New(2:end));
[Max_SS1_RGM, Loc_Max_SS1_RGM] = max(FFT_SS_1_RGM_New(2:end));
[Max_SS1_RRF, Loc_Max_SS1_RRF] = max(FFT_SS_1_RRF_New(2:end));

% Find freq of max peak
DomFreqLGM_1 = f1(Loc_Max_SS1_LGM);
DomFreqLRF_1 = f1(Loc_Max_SS1_LRF);
DomFreqRGM_1 = f1(Loc_Max_SS1_RGM);
DomFreqRRF_1 = f1(Loc_Max_SS1_RRF);

% Compute the FFT of the signal SS 2
fs = 1000; % Sampling frequency in Hz
[rows,cols] = size(SS_2_LGM); % Number of samples in the signal
N = rows;
f2 = fs*(0:N/2)/N; % Define the frequency range

FFT_SS_2_LGM = fft(SS_2_LGM);
FFT_SS_2_LGM = abs(FFT_SS_2_LGM/N);
FFT_SS_2_LGM_New = FFT_SS_2_LGM(1:N/2+1);
FFT_SS_2_LGM_New(2:end-1) = 2*FFT_SS_2_LGM_New(2:end-1);

FFT_SS_2_LRF = fft(SS_2_LRF);
FFT_SS_2_LRF = abs(FFT_SS_2_LRF/N);
FFT_SS_2_LRF_New = FFT_SS_2_LRF(1:N/2+1);
FFT_SS_2_LRF_New(2:end-1) = 2*FFT_SS_2_LRF_New(2:end-1);

FFT_SS_2_RGM = fft(SS_2_RGM);
FFT_SS_2_RGM = abs(FFT_SS_2_RGM/N);
FFT_SS_2_RGM_New = FFT_SS_2_RGM(1:N/2+1);
FFT_SS_2_RGM_New(2:end-1) = 2*FFT_SS_2_RGM_New(2:end-1);

FFT_SS_2_RRF = fft(SS_2_RRF);
FFT_SS_2_RRF = abs(FFT_SS_2_RRF/N);
FFT_SS_2_RRF_New = FFT_SS_2_RRF(1:N/2+1);
FFT_SS_2_RRF_New(2:end-1) = 2*FFT_SS_2_RRF_New(2:end-1);
```

```
% Find Max of peaks
[Max_SS2_LGM, Loc_Max_SS2_LGM] = max(FFT_SS_2_LGM_New(2:end));
[Max_SS2_LRF, Loc_Max_SS2_LRF] = max(FFT_SS_2_LRF_New(2:end));
[Max_SS2_RGM, Loc_Max_SS2_RGM] = max(FFT_SS_2_RGM_New(2:end));
[Max_SS2_RRF, Loc_Max_SS2_RRF] = max(FFT_SS_2_RRF_New(2:end));

% Find freq of max peak
DomFreqLGM_2 = f2(Loc_Max_SS2_LGM);
DomFreqLRF_2 = f2(Loc_Max_SS2_LRF);
DomFreqRGM_2 = f2(Loc_Max_SS2_RGM);
DomFreqRRF_2 = f2(Loc_Max_SS2_RRF);


% Compute the FFT of the signal SS 3
fs = 1000; % Sampling frequency in Hz
[rows,cols] = size(SS_3_LGM); % Number of samples in the signal
N = rows;
f3 = fs*(0:N/2)/N; % Define the frequency range

FFT_SS_3_LGM = fft(SS_3_LGM);
FFT_SS_3_LGM = abs(FFT_SS_3_LGM/N);
FFT_SS_3_LGM_New = FFT_SS_3_LGM(1:N/2+1);
FFT_SS_3_LGM_New(2:end-1) = 2*FFT_SS_3_LGM_New(2:end-1);

FFT_SS_3_LRF = fft(SS_3_LRF);
FFT_SS_3_LRF = abs(FFT_SS_3_LRF/N);
FFT_SS_3_LRF_New = FFT_SS_3_LRF(1:N/2+1);
FFT_SS_3_LRF_New(2:end-1) = 2*FFT_SS_3_LRF_New(2:end-1);

FFT_SS_3_RGM = fft(SS_3_RGM);
FFT_SS_3_RGM = abs(FFT_SS_3_RGM/N);
FFT_SS_3_RGM_New = FFT_SS_3_RGM(1:N/2+1);
FFT_SS_3_RGM_New(2:end-1) = 2*FFT_SS_3_RGM_New(2:end-1);

FFT_SS_3_RRF = fft(SS_3_RRF);
FFT_SS_3_RRF = abs(FFT_SS_3_RRF/N);
FFT_SS_3_RRF_New = FFT_SS_3_RRF(1:N/2+1);
FFT_SS_3_RRF_New(2:end-1) = 2*FFT_SS_3_RRF_New(2:end-1);

% Find Max of peaks
[Max_SS3_LGM, Loc_Max_SS3_LGM] = max(FFT_SS_3_LGM_New(2:end));
[Max_SS3_LRF, Loc_Max_SS3_LRF] = max(FFT_SS_3_LRF_New(2:end));
[Max_SS3_RGM, Loc_Max_SS3_RGM] = max(FFT_SS_3_RGM_New(2:end));
[Max_SS3_RRF, Loc_Max_SS3_RRF] = max(FFT_SS_3_RRF_New(2:end));

% Find freq of max peak
DomFreqLGM_3 = f3(Loc_Max_SS3_LGM);
DomFreqLRF_3 = f3(Loc_Max_SS3_LRF);
DomFreqRGM_3 = f3(Loc_Max_SS3_RGM);
DomFreqRRF_3 = f3(Loc_Max_SS3_RRF);

%% 3. Average the Dominant Frequency

% LGM Avg
```

```
DOMFreq_LGM = [DomFreqLGM_1 DomFreqLGM_2 DomFreqLGM_3];
DOMFreq_Avg_LGM = mean(DOMFreq_LGM);

% LRF Avg
DOMFreq_LRF = [DomFreqLRF_1 DomFreqLRF_2 DomFreqLRF_3];
DOMFreq_Avg_LRF = mean(DOMFreq_LRF);

% RGM Avg
DOMFreq_RGM = [DomFreqRGM_1 DomFreqRGM_2 DomFreqRGM_3];
DOMFreq_Avg_RGM = mean(DOMFreq_RGM);

% RRF Avg
DOMFreq_RRF = [DomFreqRRF_1 DomFreqRRF_2 DomFreqRRF_3];
DOMFreq_Avg_RRF = mean(DOMFreq_RRF);


%% STAIRS ASCENT
%% 1. Load Raw EMG Data

% load data
STAIRS_AS_1 = readtable("STAIRS_AS0001 T_a.xlsx");
STAIRS_AS_2 = readtable("STAIRS_AS0002 T_a.xlsx");
STAIRS_AS_3 = readtable("STAIRS_AS0003 T_a.xlsx");

% Pull Correct EMG Column for Each Muscle
SS_1_LGM = table2array(STAIRS_AS_1(6:end,17));
SS_1_LRF = table2array(STAIRS_AS_1(6:end,15));
SS_1_RGM = table2array(STAIRS_AS_1(6:end,16));
SS_1_RRF = table2array(STAIRS_AS_1(6:end,14));

SS_2_LGM = table2array(STAIRS_AS_2(6:end,17));
SS_2_LRF = table2array(STAIRS_AS_2(6:end,15));
SS_2_RGM = table2array(STAIRS_AS_2(6:end,16));
SS_2_RRF = table2array(STAIRS_AS_2(6:end,14));

SS_3_LGM = table2array(STAIRS_AS_3(6:end,17));
SS_3_LRF = table2array(STAIRS_AS_3(6:end,15));
SS_3_RGM = table2array(STAIRS_AS_3(6:end,16));
SS_3_RRF = table2array(STAIRS_AS_3(6:end,14));


%% 2. Frequency Metrics
% Compute FFT

% Compute the FFT of the signal AS 1
fs = 1000; % Sampling frequency in Hz
[rows,cols] = size(SS_1_LGM); % Number of samples in the signal
N = rows;
f1 = fs*(0:N/2)/N; % Define the frequency range

FFT_SS_1_LGM = fft(SS_1_LGM);
FFT_SS_1_LGM = abs(FFT_SS_1_LGM/N);
FFT_SS_1_LGM_New = FFT_SS_1_LGM(1:N/2+1);
FFT_SS_1_LGM_New(2:end-1) = 2*FFT_SS_1_LGM_New(2:end-1);
```

```
FFT_SS_1_LRF = fft(SS_1_LRF);
FFT_SS_1_LRF = abs(FFT_SS_1_LRF/N);
FFT_SS_1_LRF_New = FFT_SS_1_LRF(1:N/2+1);
FFT_SS_1_LRF_New(2:end-1) = 2*FFT_SS_1_LRF_New(2:end-1);

FFT_SS_1_RGM = fft(SS_1_RGM);
FFT_SS_1_RGM = abs(FFT_SS_1_RGM/N);
FFT_SS_1_RGM_New = FFT_SS_1_RGM(1:N/2+1);
FFT_SS_1_RGM_New(2:end-1) = 2*FFT_SS_1_RGM_New(2:end-1);

FFT_SS_1_RRF = fft(SS_1_RRF);
FFT_SS_1_RRF = abs(FFT_SS_1_RRF/N);
FFT_SS_1_RRF_New = FFT_SS_1_RRF(1:N/2+1);
FFT_SS_1_RRF_New(2:end-1) = 2*FFT_SS_1_RRF_New(2:end-1);

% Find Max of peaks
[Max_SS1_LGM, Loc_Max_SS1_LGM] = max(FFT_SS_1_LGM_New(2:end));
[Max_SS1_LRF, Loc_Max_SS1_LRF] = max(FFT_SS_1_LRF_New(2:end));
[Max_SS1_RGM, Loc_Max_SS1_RGM] = max(FFT_SS_1_RGM_New(2:end));
[Max_SS1_RRF, Loc_Max_SS1_RRF] = max(FFT_SS_1_RRF_New(2:end));

% Find freq of max peak
DomFreqLGM_1 = f1(Loc_Max_SS1_LGM);
DomFreqLRF_1 = f1(Loc_Max_SS1_LRF);
DomFreqRGM_1 = f1(Loc_Max_SS1_RGM);
DomFreqRRF_1 = f1(Loc_Max_SS1_RRF);

% Compute the FFT of the signal AS 2
fs = 1000; % Sampling frequency in Hz
[rows,cols] = size(SS_2_LGM); % Number of samples in the signal
N = rows;
f2 = fs*(0:N/2)/N; % Define the frequency range

FFT_SS_2_LGM = fft(SS_2_LGM);
FFT_SS_2_LGM = abs(FFT_SS_2_LGM/N);
FFT_SS_2_LGM_New = FFT_SS_2_LGM(1:N/2+1);
FFT_SS_2_LGM_New(2:end-1) = 2*FFT_SS_2_LGM_New(2:end-1);

FFT_SS_2_LRF = fft(SS_2_LRF);
FFT_SS_2_LRF = abs(FFT_SS_2_LRF/N);
FFT_SS_2_LRF_New = FFT_SS_2_LRF(1:N/2+1);
FFT_SS_2_LRF_New(2:end-1) = 2*FFT_SS_2_LRF_New(2:end-1);

FFT_SS_2_RGM = fft(SS_2_RGM);
FFT_SS_2_RGM = abs(FFT_SS_2_RGM/N);
FFT_SS_2_RGM_New = FFT_SS_2_RGM(1:N/2+1);
FFT_SS_2_RGM_New(2:end-1) = 2*FFT_SS_2_RGM_New(2:end-1);

FFT_SS_2_RRF = fft(SS_2_RRF);
FFT_SS_2_RRF = abs(FFT_SS_2_RRF/N);
FFT_SS_2_RRF_New = FFT_SS_2_RRF(1:N/2+1);
FFT_SS_2_RRF_New(2:end-1) = 2*FFT_SS_2_RRF_New(2:end-1);

% Find Max of peaks
[Max_SS2_LGM, Loc_Max_SS2_LGM] = max(FFT_SS_2_LGM_New(2:end));
```

```
[Max_SS2_LRF, Loc_Max_SS2_LRF] = max(FFT_SS_2_LRF_New(2:end));
[Max_SS2_RGM, Loc_Max_SS2_RGM] = max(FFT_SS_2_RGM_New(2:end));
[Max_SS2_RRF, Loc_Max_SS2_RRF] = max(FFT_SS_2_RRF_New(2:end));

% Find freq of max peak
DomFreqLGM_2 = f2(Loc_Max_SS2_LGM);
DomFreqLRF_2 = f2(Loc_Max_SS2_LRF);
DomFreqRGM_2 = f2(Loc_Max_SS2_RGM);
DomFreqRRF_2 = f2(Loc_Max_SS2_RRF);


% Compute the FFT of the signal AS 3
fs = 1000; % Sampling frequency in Hz
[rows,cols] = size(SS_3_LGM); % Number of samples in the signal
N = rows;
f3 = fs*(0:N/2)/N; % Define the frequency range

FFT_SS_3_LGM = fft(SS_3_LGM);
FFT_SS_3_LGM = abs(FFT_SS_3_LGM/N);
FFT_SS_3_LGM_New = FFT_SS_3_LGM(1:N/2+1);
FFT_SS_3_LGM_New(2:end-1) = 2*FFT_SS_3_LGM_New(2:end-1);

FFT_SS_3_LRF = fft(SS_3_LRF);
FFT_SS_3_LRF = abs(FFT_SS_3_LRF/N);
FFT_SS_3_LRF_New = FFT_SS_3_LRF(1:N/2+1);
FFT_SS_3_LRF_New(2:end-1) = 2*FFT_SS_3_LRF_New(2:end-1);

FFT_SS_3_RGM = fft(SS_3_RGM);
FFT_SS_3_RGM = abs(FFT_SS_3_RGM/N);
FFT_SS_3_RGM_New = FFT_SS_3_RGM(1:N/2+1);
FFT_SS_3_RGM_New(2:end-1) = 2*FFT_SS_3_RGM_New(2:end-1);

FFT_SS_3_RRF = fft(SS_3_RRF);
FFT_SS_3_RRF = abs(FFT_SS_3_RRF/N);
FFT_SS_3_RRF_New = FFT_SS_3_RRF(1:N/2+1);
FFT_SS_3_RRF_New(2:end-1) = 2*FFT_SS_3_RRF_New(2:end-1);

% Find Max of peaks
[Max_SS3_LGM, Loc_Max_SS3_LGM] = max(FFT_SS_3_LGM_New(2:end));
[Max_SS3_LRF, Loc_Max_SS3_LRF] = max(FFT_SS_3_LRF_New(2:end));
[Max_SS3_RGM, Loc_Max_SS3_RGM] = max(FFT_SS_3_RGM_New(2:end));
[Max_SS3_RRF, Loc_Max_SS3_RRF] = max(FFT_SS_3_RRF_New(2:end));

% Find freq of max peak
DomFreqLGM_3 = f3(Loc_Max_SS3_LGM);
DomFreqLRF_3 = f3(Loc_Max_SS3_LRF);
DomFreqRGM_3 = f3(Loc_Max_SS3_RGM);
DomFreqRRF_3 = f3(Loc_Max_SS3_RRF);

%% 3. Average the Dominant Frequency

% LGM Avg
DOMFreq_LGM = [DomFreqLGM_1 DomFreqLGM_2 DomFreqLGM_3];
DOMFreq_Avg_LGM = mean(DOMFreq_LGM);
```

```
% LRF Avg
DOMFreq_LRF = [DomFreqLRF_1 DomFreqLRF_2 DomFreqLRF_3];
DOMFreq_Avg_LRF = mean(DOMFreq_LRF);

% RGM Avg
DOMFreq_RGM = [DomFreqRGM_1 DomFreqRGM_2 DomFreqRGM_3];
DOMFreq_Avg_RGM = mean(DOMFreq_RGM);

% RRF Avg
DOMFreq_RRF = [DomFreqRRF_1 DomFreqRRF_2 DomFreqRRF_3];
DOMFreq_Avg_RRF = mean(DOMFreq_RRF);


%% STAIRS DESCENT
%% 1. Load Raw EMG Data

% load data
STAIRS_DS_1 = readtable("STAIRS_DS0001 T_a.xlsx");
STAIRS_DS_2 = readtable("STAIRS_DS0002 T_a.xlsx");
STAIRS_DS_3 = readtable("STAIRS_DS0003 T_a.xlsx");

% Pull Correct EMG Column for Each Muscle
SS_1_LGM = table2array(STAIRS_DS_1(6:end,17));
SS_1_LRF = table2array(STAIRS_DS_1(6:end,15));
SS_1_RGM = table2array(STAIRS_DS_1(6:end,16));
SS_1_RRF = table2array(STAIRS_DS_1(6:end,14));

SS_2_LGM = table2array(STAIRS_DS_2(6:end,17));
SS_2_LRF = table2array(STAIRS_DS_2(6:end,15));
SS_2_RGM = table2array(STAIRS_DS_2(6:end,16));
SS_2_RRF = table2array(STAIRS_DS_2(6:end,14));

SS_3_LGM = table2array(STAIRS_DS_3(6:end,17));
SS_3_LRF = table2array(STAIRS_DS_3(6:end,15));
SS_3_RGM = table2array(STAIRS_DS_3(6:end,16));
SS_3_RRF = table2array(STAIRS_DS_3(6:end,14));


%% 2. Frequency Metrics
% Compute FFT

% Compute the FFT of the signal SS 1
fs = 1000; % Sampling frequency in Hz
[rows,cols] = size(SS_1_LGM); % Number of samples in the signal
N = rows;
f1 = fs*(0:N/2)/N; % Define the frequency range

FFT_SS_1_LGM = fft(SS_1_LGM);
FFT_SS_1_LGM = abs(FFT_SS_1_LGM/N);
FFT_SS_1_LGM_New = FFT_SS_1_LGM(1:N/2+1);
FFT_SS_1_LGM_New(2:end-1) = 2*FFT_SS_1_LGM_New(2:end-1);

FFT_SS_1_LRF = fft(SS_1_LRF);
FFT_SS_1_LRF = abs(FFT_SS_1_LRF/N);
FFT_SS_1_LRF_New = FFT_SS_1_LRF(1:N/2+1);
```

```
FFT_SS_1_LRF_New(2:end-1) = 2*FFT_SS_1_LRF_New(2:end-1);

FFT_SS_1_RGM = fft(SS_1_RGM);
FFT_SS_1_RGM = abs(FFT_SS_1_RGM/N);
FFT_SS_1_RGM_New = FFT_SS_1_RGM(1:N/2+1);
FFT_SS_1_RGM_New(2:end-1) = 2*FFT_SS_1_RGM_New(2:end-1);

FFT_SS_1_RRF = fft(SS_1_RRF);
FFT_SS_1_RRF = abs(FFT_SS_1_RRF/N);
FFT_SS_1_RRF_New = FFT_SS_1_RRF(1:N/2+1);
FFT_SS_1_RRF_New(2:end-1) = 2*FFT_SS_1_RRF_New(2:end-1);

% Find Max of peaks
[Max_SS1_LGM, Loc_Max_SS1_LGM] = max(FFT_SS_1_LGM_New(2:end));
[Max_SS1_LRF, Loc_Max_SS1_LRF] = max(FFT_SS_1_LRF_New(2:end));
[Max_SS1_RGM, Loc_Max_SS1_RGM] = max(FFT_SS_1_RGM_New(2:end));
[Max_SS1_RRF, Loc_Max_SS1_RRF] = max(FFT_SS_1_RRF_New(2:end));

% Find freq of max peak
DomFreqLGM_1 = f1(Loc_Max_SS1_LGM);
DomFreqLRF_1 = f1(Loc_Max_SS1_LRF);
DomFreqRGM_1 = f1(Loc_Max_SS1_RGM);
DomFreqRRF_1 = f1(Loc_Max_SS1_RRF);

% Compute the FFT of the signal SS 2
fs = 1000; % Sampling frequency in Hz
[rows,cols] = size(SS_2_LGM); % Number of samples in the signal
N = rows;
f2 = fs*(0:N/2)/N; % Define the frequency range

FFT_SS_2_LGM = fft(SS_2_LGM);
FFT_SS_2_LGM = abs(FFT_SS_2_LGM/N);
FFT_SS_2_LGM_New = FFT_SS_2_LGM(1:N/2+1);
FFT_SS_2_LGM_New(2:end-1) = 2*FFT_SS_2_LGM_New(2:end-1);

FFT_SS_2_LRF = fft(SS_2_LRF);
FFT_SS_2_LRF = abs(FFT_SS_2_LRF/N);
FFT_SS_2_LRF_New = FFT_SS_2_LRF(1:N/2+1);
FFT_SS_2_LRF_New(2:end-1) = 2*FFT_SS_2_LRF_New(2:end-1);

FFT_SS_2_RGM = fft(SS_2_RGM);
FFT_SS_2_RGM = abs(FFT_SS_2_RGM/N);
FFT_SS_2_RGM_New = FFT_SS_2_RGM(1:N/2+1);
FFT_SS_2_RGM_New(2:end-1) = 2*FFT_SS_2_RGM_New(2:end-1);

FFT_SS_2_RRF = fft(SS_2_RRF);
FFT_SS_2_RRF = abs(FFT_SS_2_RRF/N);
FFT_SS_2_RRF_New = FFT_SS_2_RRF(1:N/2+1);
FFT_SS_2_RRF_New(2:end-1) = 2*FFT_SS_2_RRF_New(2:end-1);

% Find Max of peaks
[Max_SS2_LGM, Loc_Max_SS2_LGM] = max(FFT_SS_2_LGM_New(2:end));
[Max_SS2_LRF, Loc_Max_SS2_LRF] = max(FFT_SS_2_LRF_New(2:end));
[Max_SS2_RGM, Loc_Max_SS2_RGM] = max(FFT_SS_2_RGM_New(2:end));
[Max_SS2_RRF, Loc_Max_SS2_RRF] = max(FFT_SS_2_RRF_New(2:end));
```

```
% Find freq of max peak
DomFreqLGM_2 = f2(Loc_Max_SS2_LGM);
DomFreqLRF_2 = f2(Loc_Max_SS2_LRF);
DomFreqRGM_2 = f2(Loc_Max_SS2_RGM);
DomFreqRRF_2 = f2(Loc_Max_SS2_RRF);


% Compute the FFT of the signal SS 3
fs = 1000; % Sampling frequency in Hz
[rows,cols] = size(SS_3_LGM); % Number of samples in the signal
N = rows;
f3 = fs*(0:N/2)/N; % Define the frequency range

FFT_SS_3_LGM = fft(SS_3_LGM);
FFT_SS_3_LGM = abs(FFT_SS_3_LGM/N);
FFT_SS_3_LGM_New = FFT_SS_3_LGM(1:N/2+1);
FFT_SS_3_LGM_New(2:end-1) = 2*FFT_SS_3_LGM_New(2:end-1);

FFT_SS_3_LRF = fft(SS_3_LRF);
FFT_SS_3_LRF = abs(FFT_SS_3_LRF/N);
FFT_SS_3_LRF_New = FFT_SS_3_LRF(1:N/2+1);
FFT_SS_3_LRF_New(2:end-1) = 2*FFT_SS_3_LRF_New(2:end-1);

FFT_SS_3_RGM = fft(SS_3_RGM);
FFT_SS_3_RGM = abs(FFT_SS_3_RGM/N);
FFT_SS_3_RGM_New = FFT_SS_3_RGM(1:N/2+1);
FFT_SS_3_RGM_New(2:end-1) = 2*FFT_SS_3_RGM_New(2:end-1);

FFT_SS_3_RRF = fft(SS_3_RRF);
FFT_SS_3_RRF = abs(FFT_SS_3_RRF/N);
FFT_SS_3_RRF_New = FFT_SS_3_RRF(1:N/2+1);
FFT_SS_3_RRF_New(2:end-1) = 2*FFT_SS_3_RRF_New(2:end-1);

% Find Max of peaks
[Max_SS3_LGM, Loc_Max_SS3_LGM] = max(FFT_SS_3_LGM_New(2:end));
[Max_SS3_LRF, Loc_Max_SS3_LRF] = max(FFT_SS_3_LRF_New(2:end));
[Max_SS3_RGM, Loc_Max_SS3_RGM] = max(FFT_SS_3_RGM_New(2:end));
[Max_SS3_RRF, Loc_Max_SS3_RRF] = max(FFT_SS_3_RRF_New(2:end));

% Find freq of max peak
DomFreqLGM_3 = f3(Loc_Max_SS3_LGM);
DomFreqLRF_3 = f3(Loc_Max_SS3_LRF);
DomFreqRGM_3 = f3(Loc_Max_SS3_RGM);
DomFreqRRF_3 = f3(Loc_Max_SS3_RRF);

%% 3. Average the Dominant Frequency

% LGM Avg
DOMFreq_LGM = [DomFreqLGM_1 DomFreqLGM_2 DomFreqLGM_3];
DOMFreq_Avg_LGM = mean(DOMFreq_LGM);

% LRF Avg
DOMFreq_LRF = [DomFreqLRF_1 DomFreqLRF_2 DomFreqLRF_3];
DOMFreq_Avg_LRF = mean(DOMFreq_LRF);
```

```
% RGM Avg
DOMFreq_RGM = [DomFreqRGM_1 DomFreqRGM_2 DomFreqRGM_3];
DOMFreq_Avg_RGM = mean(DOMFreq_RGM);

% RRF Avg
DOMFreq_RRF = [DomFreqRRF_1 DomFreqRRF_2 DomFreqRRF_3];
DOMFreq_Avg_RRF = mean(DOMFreq_RRF);
```

BIBLIOGRAPHY

1. Pavličev M, Romero R, Mitteroecker P. Evolution of the human pelvis and obstructed labor: new explanations of an old obstetrical dilemma. *American Journal of Obstetrics and Gynecology*. 2020;222(1):3–16.

2. Stålberg K, Bodestedt Å, Lyrenås S, Axelsson O. A narrow pelvic outlet increases the risk for emergency cesarean section. *Acta Obstet Gynecol Scand*. 2006;85(7):821–4.

3. Samuel C, Coghlan J, Bateman J. Effects of relaxin, pregnancy and parturition on collagen metabolism in the rat pubic symphysis. *Journal of Endocrinology*. 1998;159(1):117–25.

4. Kilpatrick SK, Ecker JL. Severe maternal morbidity: screening and review. *American Journal of Obstetrics and Gynecology*. 2016;215(3):B17–22.

5. Nour NM. An introduction to maternal mortality. *Rev Obstet Gynecol*. 2008;1(2):77–81.

6. Hoyert DL. Maternal Mortality Rates in the United States, 2021. 2023;

7. Osterman J. K. M. *Changes in primary and repeat cesarean delivery: United States 2016-2021*. National Center for Health Statistics (U.S.); 2022. [cited 2024 Feb 2] Available from: https://stacks.cdc.gov/view/cdc/117432.

8. Kaunitz AM, Hughes JM, Grimes DA, Smith JC, Rochat RW, Kafrissen ME. Causes of maternal mortality in the United States. *Obstet Gynecol*. 1985;65(5):605–12.

9. Kiapour A, Joukar A, Elgafy H, Erbulut DU, Agarwal AK, Goel VK. Biomechanics of the Sacroiliac Joint: Anatomy, Function, Biomechanics, Sexual Dimorphism, and Causes of Pain. *Int J Spine Surg*. 2020;14(s1):S3–13.

10. Dumas GA, Reid JG. Laxity of Knee Cruciate Ligaments During Pregnancy. *J Orthop Sports Phys Ther*. 1997;26(1):2–6.

11. Conder R, Zamani R, Akrami M. The Biomechanics of Pregnancy: A Systematic Review. *JFMK*. 2019;4(4):72.

12. Branco M, Santos-Rocha R, Vieira F, Aguiar L, Veloso AP. Three-Dimensional Kinetic Adaptations of Gait throughout Pregnancy and Postpartum. *Scientifica*. 2015;2015:1–14.

13. Mei Q, Gu Y, Fernandez J. Alterations of Pregnant Gait during Pregnancy and Post-Partum. *Sci Rep*. 2018;8(1):2217.

14. Branco M, Santos-Rocha R, Aguiar L, Vieira F, Veloso A. Kinematic Analysis of Gait in the Second and Third Trimesters of Pregnancy. *Journal of Pregnancy*. 2013;2013:1–9.

15. Branco M, Santos-Rocha R, Vieira F. Biomechanics of Gait during Pregnancy. *The Scientific World Journal*. 2014;2014:1–5.

16. Gilleard W, Crosbie J, Smith R. A longitudinal study of the effect of pregnancy on rising to stand from a chair. *Journal of Biomechanics*. 2008;41(4):779–87.

17. Forczek W, Masłoń A, Frączek B, Curyło M, Salamaga M, Suder A. Does the first trimester of pregnancy induce alterations in the walking pattern? *PLoS ONE*. 2019;14(1):e0209766.

18. Hagan L, Wong CK. Gait in Pregnant Women: Spinal and Lower Extremity Changes From Pre- to Postpartum. *Journal of Women's Health Physical Therapy*. 2010;34(2):46–56.

19. Persaud-Sharma V. Rethinking maternal healthcare for the 21st century in the United States. [date unknown];

20. Agrawal P. Maternal mortality and morbidity in the United States of America. *Bull World Health Organ*. 2015;93(3):135–135.

21. Main EK, Menard MK. Maternal Mortality: Time for National Action. *Obstetrics & Gynecology*. 2013;122(4):735–6.

22. Shahin Z, Shah GH, Mase WA, Apenteng B. Hospital Characteristics and Other Factors Associated with the Risk of Postpartum Hemorrhage in the United States. *Journal of Women's Health*. 2023;32(2):187–91.

23. Leeman L, Fontaine P. Hypertensive disorders of pregnancy. *Am Fam Physician*. 2008;78(1):93–100.

24. Grimm MJ. Forces Involved with Labor and Delivery—A Biomechanical Perspective. *Ann Biomed Eng*. 2021;49(8):1819–35.

25. Stansfield E, Kumar K, Mitteroecker P, Grunstra NDS. Biomechanical trade-offs in the pelvic floor constrain the evolution of the human birth canal. *Proc Natl Acad Sci USA*. 2021;118(16):e2022159118.

26. Branco MAC, Santos-Rocha R, Vieira F, Aguiar L, Veloso AP. Three-dimensional kinematic adaptations of gait throughout pregnancy and post-partum. *Acta Bioeng Biomech*. 2016;18(2):153–62.

27. Creanga AA, Berg CJ, Ko JY, et al. Maternal Mortality and Morbidity in the United States: Where Are We Now? *Journal of Women's Health*. 2014;23(1):3–9.

28. Centers for Disease Control and Prevention. Pregnancy Mortality Surveillance System. 2023; Available from: https://www.cdc.gov/reproductivehealth/maternal-mortality/pregnancy-mortality-surveillance-system.htm.

29. Collier AY, Molina RL. Maternal Mortality in the United States: Updates on Trends, Causes, and Solutions. *NeoReviews*. 2019;20(10):e561–74.

30. Fantu S, Segni H, Alemseged F. Incidence, Causes and Outcome of Obstructed Labor in Jimma University Specialized Hospital. *Ethiop J Health Sci* [Internet]. 2011 [cited 2024

Feb 7];20(3) Available from: http://www.ajol.info/index.php/ejhs/article/view/69443. doi:10.4314/ejhs.v20i3.69443.

31. Ayenew AA. Incidence, causes, and maternofetal outcomes of obstructed labor in Ethiopia: systematic review and meta-analysis. *Reprod Health*. 2021;18(1):61.

32. Rane A, Iyer J, Ananthram H, Currie T. Can We Deliver Better? *J Obstet Gynecol India*. 2017;67(3):157–61.

33. Washburn SL. Tools and human evolution. *Sci Am*. 1960;203:63–75.

34. Trevathan W. Primate pelvic anatomy and implications for birth. *Phil Trans R Soc B*. 2015;370(1663):20140065.

35. Feltovich H. Labour and delivery: a clinician's perspective on a biomechanics problem. *Interface Focus*. 2019;9(5):20190032.

36. World Health Organization. Maternal Health and Safe Motherhood Programme. Education material for teachers of midwifery : midwifery education modules. *Midwifery education modules*. 2008;6.

37. Fine EA, Bracken M, Berkowitz RL. An evaluation of the usefulness of x-ray pelvimetry: Comparison of the Thoms and modified Ball methods with manual pelvimetry. *American Journal of Obstetrics and Gynecology*. 1980;137(1):15–20.

38. Wells JCK, DeSilva JM, Stock JT. The obstetric dilemma: An ancient game of Russian roulette, or a variable dilemma sensitive to ecology? *American J Phys Anthropol*. 2012;149(S55):40–71.

39. Wells JCK. The New "Obstetrical Dilemma": Stunting, Obesity and the Risk of Obstructed Labour. *The Anatomical Record*. 2017;300(4):716–31.

40. Bagwell JJ, Reynolds N, Smith JA, et al. An exploratory analysis of gait biomechanics and muscle activation in pregnant females with high and low scores for low back or pelvic girdle pain during and after pregnancy. *Clinical Biomechanics*. 2022;97:105705.

41. Bagwell JJ, Reynolds N, Walaszek M, et al. Lower extremity kinetics and muscle activation during gait are significantly different during and after pregnancy compared to nulliparous females. *Gait & Posture*. 2020;81:33–40.

42. Aldabe D, Milosavljevic S, Bussey MD. Is pregnancy related pelvic girdle pain associated with altered kinematic, kinetic and motor control of the pelvis? A systematic review. *Eur Spine J*. 2012;21(9):1777–87.

43. Foti T, Davids JR, Bagley A. A Biomechanical Analysis of Gait During Pregnancy*: *The Journal of Bone and Joint Surgery-American Volume*. 2000;82(5):625–32.

44. Young J. Relaxation of the Pelvic Joints in Pregnancy: Pelvic Arthropathy of Pregnancy. *BJOG*. 1940;47(5):493–524.

45. Daneau C, Abboud J, Marchand A-A, et al. Mechanisms Underlying Lumbopelvic Pain During Pregnancy: A Proposed Model. *Front Pain Res*. 2021;2:773988.

46. Paisley TS, Joy EA, Price RJ. Exercise During Pregnancy: A Practical Approach. *Current Sports Medicine Reports*. 2003;2(6):325–30.

47. Ribeiro AP, João SMA, Sacco ICN. Static and Dynamic Biomechanical Adaptations of the Lower Limbs and Gait Pattern Changes during Pregnancy. *Womens Health (Lond Engl)*. 2013;9(1):99–108.

48. De Groot M, Pool-Goudzwaard AL, Spoor CW, Snijders CJ. The active straight leg raising test (ASLR) in pregnant women: Differences in muscle activity and force between patients and healthy subjects. *Manual Therapy*. 2008;13(1):68–74.

49. Kilpatrick S, Garrison E. Normal Labor and Delivery. *Obstetrics: Normal and Problem Pregnancies*. Elsevier; 2017. p. 246–70. [cited 2024 Apr 6] Available from: https://linkinghub.elsevier.com/retrieve/pii/B9780323321082000123.

50. McKinney JR, Allshouse AA, Heyborne KD. Duration of labor and maternal and neonatal morbidity. *American Journal of Obstetrics & Gynecology MFM*. 2019;1(3):100032.

51. Terranova Paul. Abnormal Labor ☆. *Reference Module in Biomedical Sciences*. Elsevier; 2017. p. B9780128012383048169. [cited 2024 Apr 6] Available from: https://linkinghub.elsevier.com/retrieve/pii/B9780128012383048169.

52. Fraser WD, Kramer MS. Labor and Delivery. *Women and Health*. Elsevier; 2000. p. 182–95. [cited 2024 Apr 6] Available from: https://linkinghub.elsevier.com/retrieve/pii/B9780122881459500188.

53. Caughey AB, Cahill AG, Guise J-M, Rouse DJ. Safe prevention of the primary cesarean delivery. *American Journal of Obstetrics and Gynecology*. 2014;210(3):179–93.

54. Grobman WA, Bailit J, Lai Y, et al. Association of the Duration of Active Pushing With Obstetric Outcomes. *Obstetrics & Gynecology*. 2016;127(4):667–73.

55. Rouse DJ, Weiner SJ, Bloom SL, et al. Second-stage labor duration in nulliparous women: relationship to maternal and perinatal outcomes. *American Journal of Obstetrics and Gynecology*. 2009;201(4):357.e1-357.e7.

56. Gogoi MP. MATERNAL MORTALITY FROM CAESAREAN SECTION IN INFECTED CASES*. *BJOG*. 1971;78(4):373–6.

57. Hollins Martin CJ, Snowden A, Martin CR. Concurrent analysis: validation of the domains within the Birth Satisfaction Scale. *Journal of Reproductive and Infant Psychology*. 2012;30(3):247–60.

58. Clement S. Psychological aspects of caesarean section. *Best Practice & Research Clinical Obstetrics & Gynaecology*. 2001;15(1):109–26.

59. Baas CI, Wiegers TA, De Cock TP, et al. Client-Related Factors Associated with a "Less than Good" Experience of Midwifery Care during Childbirth in the Netherlands. *Birth*. 2017;44(1):58–67.

60. Zanardo V, Giliberti L, Giliberti E, Volpe F, Straface G, Greco P. The role of elective and emergency cesarean delivery in maternal postpartum anhedonia, anxiety, and depression. *Intl J Gynecology & Obste*. 2018;143(3):374–8.

61. Zanardo V, Soldera G, Volpe F, et al. Influence of elective and emergency cesarean delivery on mother emotions and bonding. *Early Human Development*. 2016;99:17–20.

62. Roux SL, Van Rensburg E. South African Mothers' Perceptions and Experiences of an Unplanned Caesarean Section. *Journal of Psychology in Africa*. 2011;21(3):429–38.

63. Barbosa-Leiker C, Fleming S, Hollins Martin CJ, Martin CR. Psychometric properties of the Birth Satisfaction Scale-Revised (BSS-R) for US mothers. *Journal of Reproductive and Infant Psychology*. 2015;33(5):504–11.

64. Hollins Martin C, Martin C. A survey of women's birth experiences in Scotland using the Birth Satisfaction Scale (BSS). *EJPCH*. 2015;3(4):478.

65. Hollins Martin CJ, Martin CR. Development and psychometric properties of the Birth Satisfaction Scale-Revised (BSS-R). *Midwifery*. 2014;30(6):610–9.

66. Brockington IF, Fraser C, Wilson D. The Postpartum Bonding Questionnaire: a validation. *Arch Womens Ment Health*. 2006;9(5):233–42.

67. Levis B, Negeri Z, Sun Y, Benedetti A, Thombs BD. Accuracy of the Edinburgh Postnatal Depression Scale (EPDS) for screening to detect major depression among pregnant and postpartum women: systematic review and meta-analysis of individual participant data. *BMJ*. 2020;m4022.

68. Cox JL, Holden JM, Sagovsky R. Detection of Postnatal Depression: Development of the 10-item Edinburgh Postnatal Depression Scale. *Br J Psychiatry*. 1987;150(6):782–6.

69. Murray L, Carothers AD. The Validation of the Edinburgh Post-natal Depression Scale on a Community Sample. *Br J Psychiatry*. 1990;157(2):288–90.

70. Bateman BT, Berman MF, Riley LE, Leffert LR. The Epidemiology of Postpartum Hemorrhage in a Large, Nationwide Sample of Deliveries. *Anesthesia & Analgesia*. 2010;110(5):1368–73.

71. Leardini A, Cappozzo A, Catani F, et al. Validation of a functional method for the estimation of hip joint centre location. *Journal of Biomechanics*. 1999;32(1):99–103.

72. Wu G, Siegler S, Allard P, et al. ISB recommendation on definitions of joint coordinate system of various joints for the reporting of human joint motion—part I: ankle, hip, and spine. *Journal of Biomechanics*. 2002;35(4):543–8.

73. Kempe P, Vikström-Bolin M. Women's satisfaction with the birthing experience in relation to duration of labour, obstetric interventions and mode of birth. *European Journal of Obstetrics & Gynecology and Reproductive Biology*. 2020;246:156–9.