

Differences in Balance and Limb Loading Symmetry in Postpartum and Nulliparous Women
During Childcare Related Activities

Theresa L. Libera

Thesis submitted to the faculty of the Virginia Polytechnic Institute and State University in
partial fulfillment of the requirements for the degree of

Master of Science

In

Biomedical Engineering

Robin M. Queen, Chair

Sara L. Arena, Co-Chair

Miguel Perez

September 20, 2024

Blacksburg, Virginia

Keywords: Postpartum health, postural control, lower extremity load symmetry, childcare
activities

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Abstract

Each year approximately 2.5 million women give birth vaginally, yet postpartum (PP) health often receives minimal attention beyond six weeks.^{1,2} About 20% of postpartum women report chronic pain 3 years postpartum, with common complaints in the pelvis, lower back, hips, and legs.^{3,4} This chronic pain not only impairs quality of life but also triples the risk of developing depression.⁴ Postpartum asymmetrical instability and weakness in the lumbopelvic area are significant contributors to pain, differing notably from nulliparous (NP) women.² Lumbopelvic stability and strength are essential for maintaining balance and controlling the trunk while handling external loads in reducing the risk of injury from deleterious loading in the spine and pelvis.^{2,5-7} The first purpose of this study was to investigate the effect of holding a car seat (no holding, symmetrically, asymmetrically) and the effect of group (PP, NP) on balance and limb loading symmetry during quiet standing. The second purpose of this study was to investigate the effect of group (PP, NP) and lifting a car seat (symmetrically, asymmetrically) on center of pressure (COP) movement and limb loading symmetry. Force plates were used to collect vertical ground reaction forces (vGRFs) and COP during the holding and lifting conditions. To assess balance, the COP root-mean-square (RMS) amplitude and velocity in the medial-lateral (ML) and anterior-posterior (AP) directions were calculated. To assess peak vGRF limb loading symmetry, the Symmetry Index (SI) was used. A linear mixed effects model was used to determine main effect and interactions of group and condition on outcome measures. When holding a car seat, the main effect of condition was found in RMS AP velocity ($p < 0.001$) with interactions between group and condition found in RMS ML velocity ($p = 0.005$), RMS ML ($p = 0.032$), and RMS AP ($p = 0.002$) amplitudes. Significant differences between groups during asymmetrical holding ($p = 0.009$) were also found in AP amplitude. Main effect of condition ($p < 0.001$) and group ($p = 0.05$) were found with peak vGRF SI. During lifting, interactions were found in RMS AP velocity ($p < 0.001$) and main effects of conditions in RMS ML velocity ($p < 0.001$), RMS ML ($p < 0.001$) and AP ($p < 0.001$) amplitude, and peak vGRF SI ($p < 0.001$). Our results indicate that PP women may be at higher risk of developing pain and injury due to the observed challenges of postural stability and control during the more strenuous asymmetric car seat holding. This may be related to pelvic asymmetries and musculoskeletal weaknesses that influence how PP respond to holding conditions compared to NP women. Additionally, our results indicate that holding and lifting result in increased challenges related to PP balance. These findings inform advice given when navigating childcare related tasks involving a car seat. Our results indicate the need to continue to understand how PP and NP women differ during childcare related tasks to further understand differences between groups and the risk factors associated with chronic pain in this population.

Differences in Balance and Limb Loading Symmetry in Postpartum and Nulliparous Women During Childcare Related Activities

General Audience Abstract

Every year, over 3.5 million women give birth in the United States, with about 67.9% delivering vaginally.¹ Over 80% of postpartum (PP) women experience chronic pain in the pelvis, lower back, hip, and legs at 24 weeks after birth, and 20% continue to experience these issues 3 years later.²⁻⁴ PP women often face pelvic instability and weakness, which disturb balance and lead to asymmetric loading in the pelvis and legs.⁵ This imbalance makes daily tasks, such as lifting and carrying a car seat during childcare, more difficult, and increase the risk of chronic pain and injury.^{2, 5-7} This study aimed to explore how different groups – PP and nulliparous (NP) women – and different ways of holding a car seat while standing – no holding, symmetrical holding with two hands in front, and asymmetrical holding with one arm by the side – affect balance and limb loading symmetry. Results showed that postpartum women struggled more with balance as the task became more challenging, with asymmetrical holding showing large differences between groups. PP women also exhibited greater asymmetric limb loading compared to NP women with asymmetrical holding creating the greatest level asymmetric limb loading. The study also aimed to explore how the two groups – PP and NP – and the different ways of lifting a car seat – symmetrically and asymmetrically – affect balance and limb loading. Both groups had more asymmetric limb loading and worse balance with asymmetrical lifting, though NP women showed larger movements during asymmetrical lifting, likely reflecting the movement of the body during the condition. These results highlight the importance to further research balance and limb loading in PP compared to NP women. Understanding whether pelvic instability and weakness may contribute to differences in balance and limb loading is crucial as it may help explain how and why postpartum women face higher risk of injury and chronic pain. Ultimately, such work may find ways to improve postpartum health during daily activities.

Acknowledgements

I would like to thank Dr. Robin Queen and Dr. Sara Arena for their help in this process. I appreciate what I have learned from them throughout my time here. I would also like to thank Dr. Miguel Perez for this guidance and support. I have learned a lot throughout this process on how our research can make an impact and I will carry that with me through the rest of my career. I am also very thankful for all the women who have participated in this research, especially to the mothers who had taken the time out of their busy days to contribute. For all the mothers who may engage with this work, I hope you feel both seen and heard.

Thank you to Renee for always making space for me and keeping your door open, to Sara for always going out of her way to be a true friend, to Robyn for always listening and understanding, and to Alison for always supporting me. I would also like to acknowledge my friends and lab mates that have since graduated or are still around. I cherish all the memories we have made in and out of the lab. Thank you for making the good times great.

I am profoundly grateful for my family throughout this process. Thank you to my brothers, Dominic and Jacob, and my sister Hannah for never leaving my side and only ever wanting the best for me. Thank you to Peeps for the endless snuggles. I also want to make a special thank you to my Mom and Dad for always building me up and helping me find the good in everything. Thank you for pushing me to do better and to be better every day and for showing me the type of person that I want to be in this world.

Hit the hill.

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List of Abbreviations

PP	Postpartum
COP	Center of Pressure
NP	Nulliparous
SI	Symmetry Index
GRF	Ground Reaction Force
vGRF	Vertical Ground Reaction Force
PGP	Pelvic Girdle Pain
SIJ	Sacroiliac Joint
RMS	Root-Mean-Square
AP	Anterior-Posterior
ML	Medial-Lateral
N	Newton
NPL	Non-preferred Limb
PL	Preferred Limb
D	Dominant Limb
ND	Non-dominant Limb
kg/m ²	kilogram per meter square
m	meter
kg	kilogram
mm/s	millimeter per second
mm	millimeter

Chapter 1: Introduction

Motivation

Every year, up to 3.6 million women enter the postpartum (PP) stage, believed to last up to 6 months after childbirth.^{6,7} The postpartum period is associated with prolonged musculoskeletal weakness, in and around the lumbopelvic area, and low back pain.⁸ Changes during pregnancy have lasting effects throughout the postpartum period, commonly appearing as musculoskeletal weakness and pelvic asymmetries that contribute to chronic pain in the lumbopelvic area.^{9,10} Musculoskeletal weakness and chronic pain are associated with a decline in balance ability.¹¹ Research in postpartum women has found decreased balance performance during quiet standing, based on changes in various center of pressure (COP) measures.^{12,13} Additionally, research examining dynamic balance while standing on a moving surface has reported a decrease in balance performance that persists up to 6 weeks postpartum.¹⁴ During natural standing, the body relies on the dynamic coordination of the pelvis and the spine to maintain an upright posture.¹⁵ This can be of major concern during both lifting and holding conditions, a daily occurrence for postpartum women.

Repetitive child-care-related lifting of a car seat can cause asymmetrical spinal loading and lead to the development of chronic low back pain.¹⁶ During child-care-related lifting tasks, the trunk extension strength in postpartum women is significantly reduced when compared to nulliparous (NP) controls.^{17,18} In addition, postpartum women had significantly lower paraspinal muscle responsiveness during symmetrical and asymmetrical lifting tasks.^{5,17} These findings also indicate reduced spinal strength, which is necessary when ensuring the pelvis and spine can act as a stabilized and coordinated structure between the upper and lower extremities.¹⁹

In addition to lifting, external symmetrical and asymmetrical infant holding is a common daily task for postpartum women and there is a lack of research relating to the biomechanical response to this exposure.^{9, 18} This study serves as an exploratory pilot study to assess (1) holding a car seat during quiet standing and (2) lifting of a car seat in PP women, compared to NP controls. Specifically, holding and lifting tasks will be evaluated in symmetrical (i.e., holding and lifting with both hands) and asymmetrical (i.e., holding and lifting with one hand) conditions²⁰ as both are common daily tasks within the PP population. Additionally, limb loading symmetry will be examined, as asymmetry is related to mobility impairment and overuse injury.²¹ The central hypothesis is that postpartum women will exhibit reduced postural control and higher limb loading asymmetry. This hypothesis will be assessed through the following aims.

Aim 1: Determine the effects of loading condition (no load, symmetrical, asymmetrical) and group (PP, NP) on postural control and limb loading during quiet standing.

H1a) PP women will experience poorer postural control as demonstrated by an increase in COP RMS amplitude and velocity, in all directions, as the condition becomes more difficult with asymmetric holding.

H1b) PP women will have a higher limb loading asymmetry, as defined by the Symmetry Index (SI) of the vertical ground reaction forces (GRF), compared to controls, with an increase in asymmetry transitioning from no load to asymmetric loading.

Aim 2: Determine the effects of loading condition (symmetrical, asymmetrical) and group (PP, NP) on postural control and limb loading during lifting.

H2a) PP women will experience poorer postural control as demonstrated by an increase in COP RMS amplitude and velocity, in all directions, during symmetrical and asymmetrical lifting compared to controls.

H2b) PP women will have a higher limb loading asymmetry, as defined by the Symmetry Index (SI) of the vertical ground reaction force (GRF), with an increase in asymmetry transitioning from symmetrical to asymmetrical lifting.

Background

Every year, more than 3 million women give birth annually, with the most common form of child birth being a vaginal delivery.²² Despite this large number, postpartum (PP) health is widely neglected, with one general medical assessment confined to 6 weeks after delivery and no set guidelines given to mothers on how to safely navigate their new daily tasks involving infant care.^{5,23} Throughout pregnancy, the musculoskeletal system undergoes significant changes in preparation for birth, which can have lasting effects on women during the postpartum period. Hormonal shifts, including elevated levels of estradiol, progesterone, and relaxin, lead to reduced collagen density and increased ligament laxity throughout the pelvis and the entire body.²⁴⁻²⁶ These hormonal changes soften and widen connective tissue in the pelvis and surrounding musculoskeletal structures.²⁷⁻²⁹ From this wide neglect in PP health, many PP women report a range of issues including rectus abdominis separation, hip and leg pain, pubic symphysis pain, urinary and anal incontinence, and pelvic organ prolapse.³⁰⁻³⁸ Notably, 74% of women report persistent back and pelvic pain within the first year after a vaginal birth, affecting daily activities, sleep, quality of life, and emotional well-being.⁴² Additionally, 67% of postpartum women experience pain at 6 weeks postpartum, with up to 20% suffering from chronic pain 3 years after birth.^{3,39}

Common musculoskeletal disorders include pelvic girdle pain (PGP), low back pain, pelvic pain, pubic symphysis pain, and peripheral nerve injuries.^{5,9} Of these disorders, pelvic girdle pain is the most common in up to 41% of postpartum women and is associated with a threefold increase risk of developing depression.⁴ PGP is characterized by pain between the posterior iliac crests and the gluteal fold, often radiating to the thighs and pubic symphysis and can include pain in the

pelvis, lower back, hips, and legs.^{4, 40-42} This condition is associated with abnormal motor control and malalignment of the pelvis and surrounding joints and ligaments.⁴³ Women with PGP often experience greater disability in daily activities compared to those with lumbar pain alone.³ PGP is also associated with impaired weight transfer and functional limitations in walking, sitting, lifting, lowering, and standing.⁴⁴⁻⁴⁶ PGP has also been associated with abnormal pressure distribution in the lumbopelvic area, resulting from asymmetries and malalignment in the pelvis and lumbar spine that occur due to ligament laxity initially occurring during pregnancy.⁴⁷⁻⁵⁰

Ligament laxity is an increase in the flexibility of ligaments and is caused by hormonal shifts, including elevated levels of estradiol, progesterone, and relaxin. Increased ligamentous laxity can have systemic impacts throughout the body.²⁴⁻²⁶ In pregnant women, however, these hormonal changes tend to soften and widen connective tissue in the pelvis at the sacroiliac joint (SIJ) and pubic symphysis (Figure 1), in preparation for childbirth.^{28, 29, 47, 51} Although hormone levels generally return to pre-pregnancy levels within a few days following birth, decreased collagen integrity persists, increasing ligament laxity and contributing to various musculoskeletal issues that persist into the postpartum period.^{25, 28, 52} For example, past research has found a persistent pubic symphysis diastasis known as a persistent widening of the pubic symphysis. In postpartum women who had this persistent widening, 48.5% of them had widening greater than 2 cm.⁵³ Ligament laxity also contributes to an increase in abnormal pressure distribution in the lumbopelvic area, created from the restructuring of the pelvis and in the lumbar spine.^{47-50, 54}

Throughout pregnancy, the lumbar spine increases in curvature following the anterior pressure of the fetus as it grows. As the curvature increases over the approximate 9 months, the paraspinal muscles exist in a continued state of activation in an attempt to stabilize the spine, which has lasting effects of reduced paraspinal muscle activity that persists in postpartum women.¹⁸ In addition to this, this prolonged change in shape changes how load is transferred through the spine down to the pelvis and lower extremities.⁵⁵ This redistribution in weight as well as the altered structure facilitates asymmetries in the pelvis that are seen to persist during the postpartum period.⁵

The asymmetries in the pelvis that are due to ligament laxity, skeletal restructuring, and the growth of the fetus target the connections in the pelvis that are meant to restrict movement between bones and have weight bearing purposes, as well as organ support.^{29,47} Past research has found persistent bilateral anterior tilting of the pelvis that was significantly present in postpartum women, 1 to 6 months postpartum, compared to nulliparous women.⁵⁴ Past research has also found a persistent asymmetric external rotation that was significantly different in postpartum levels compared to pre-pregnancy levels.⁵⁶

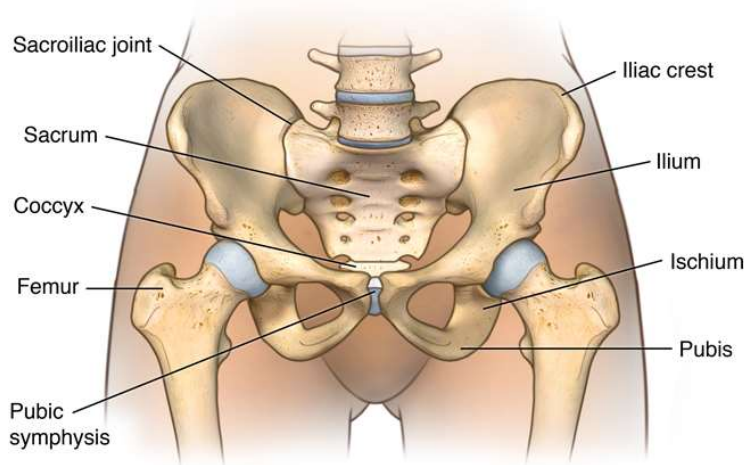


Figure 1: Anterior view of the female pelvis ⁵⁷

In addition to skeletal restructuring, changes that may require healing time following birth also occur at the muscular level. Excessive activation of the paraspinal muscles, as well as excessive stretching of the abdominal and pelvic floor muscles during pregnancy and childbirth can lead to persistent weakness and asymmetry that persist postpartum. ^{36, 37} For example, past research has found a significant reduction in paraspinal muscle activity as well as asymmetric activation in postpartum women when compared to nulliparous women during car seat lifting. ¹⁸ Additionally, postpartum women also exhibit a reduction in trunk extension strength compared to nulliparous women. ¹⁷ This is particularly concerning given the heightened need for muscle activation and skeletal stability in the lumbopelvic area in maintaining balance and load transfer through the pelvis and in the lower extremities. ^{9, 11, 13} Such postural control and limb loading help ensure that daily activities are performed efficiently and safely, reducing the likelihood of movements that can create deleterious loading. ⁶³

While little research has been done on how limb loading or balance changes in postpartum women during childcare related activities, there has been some research related to balance

performance in postpartum women during quiet standing. In particular, examination of overall dynamic postural stability, a metric determined from a moving base of support measured by the Biodex Balance System, found a reduction in overall stability that declined during pregnancy and remained diminished at 6 weeks postpartum.¹⁴ In addition, during quiet standing, center of pressure assessment has found elevated path length and average radial distance in postpartum women at 8 weeks compared to controls¹³; decreases in anterior-posterior (AP) path length and velocity that persisted 6 months in postpartum women¹²; and an increase in medial-lateral (ML) sway that increased in women 6 months postpartum⁵⁸. This past research implies that postpartum postural stability and control is elevated due to pregnancy and does not always return to pre-pregnancy levels. However, there is still little research that has explored balance and limb loading in postpartum women during strenuous daily tasks such as car seat handling, as well as how these levels differ compared to nulliparous women.

Car seat use is the most common form of transportation for an infant under 1 year of age.⁵⁹ A previous study that asked mothers how they generally navigate car seat handling found that women generally do not take into account their own musculoskeletal health and safety during these tasks and tend to focus only on infant safety and convenience.⁵⁹ Car seat handling can be done symmetrically or asymmetrically. Both modes of handling can depend on where the car seat is placed relative to the midline of the body. Symmetrical holding or lifting orients the load relative to the front of the body using both hands to essentially distribute load evenly in the body. Asymmetrical lifting or holding can be accomplished using one hand and orienting the car seat at the side of the body, thereby introducing uneven body loading. Regardless of the load placement, the handling of an external load of this size and weight increases the reliance on paraspinal

muscle activation as well as skeletal stability.⁴² In addition to this, both handling types increase the amount of asymmetrical shear and compressive forces at the lumbar spine and can contribute to injury and chronic pain, especially in individuals exhibiting lumbopelvic weakness or skeletal malalignments.⁶⁰⁻⁶² Past research that has specifically examined car seat lifting has found that this activity increases paraspinal muscle activation significantly more than any other childcare handling activity involving lifting.⁶³ When such research has investigated car seat handling, however, it was done through the perspective of muscle activation and extension strength. No research has examined car seat handling practices specifically in the postpartum population and particularly with respect to how it may impact balance and limb loading through the lens of injury risk and chronic pain when compared to nulliparous women.

In addition to car seat handling, it is important to note that repetitive strain can disrupt postural balance, leading to uneven lower extremity force distribution and exacerbating pelvic malalignments and overall musculoskeletal damage.^{59, 64} Additionally, asymmetrical loading, seen during gait, has been identified as a risk factor for chronic pain and injury due to the unequal loading imposed along the lower extremities.^{65, 66} For postpartum women, in particular, the frequent and heavy lifting involved in infant care can intensify existing musculoskeletal problems and increase the risk of injury and chronic pain.⁶⁰⁻⁶² Therefore, it is essential to understand how balance and limb loading symmetry differ between postpartum women and nulliparous women during common postpartum daily tasks of lifting and holding of a car seat to further understand how prolonged effects of pregnancy may affect postpartum women and if it may put them at a greater risk of injury and chronic pain.

When evaluating balance, metrics derived from the center of pressure (COP) can provide valuable insights. This research focuses on time-domain distance measures of COP amplitude and velocity, commonly used to assess postural control.^{67, 68} The commonly used metrics of COP amplitude and velocity offer context on specific aspects of balance. The COP amplitude reflects stability by understanding the amount of movement that is made in either the AP or ML axis away from the center of support while the COP velocity reflects the amount of movements made in maintaining control of an upright posture in the AP and ML directions.^{67, 68} These two measures allow for analysis of balance from two different perspectives related to COP control and stability. Using the root-mean-square (RMS) with the COP amplitude and velocity allows for a way to quantify these measures while accounting for magnitude and variance.⁶⁹ The RMS is the quadratic mean of the COP magnitude from the center point. A decrease in RMS amplitude and velocity suggests improvement in postural equilibrium maintenance and an increase indicates a decline.⁶⁷ The RMS is calculated using the standard method, which involves taking the square root of the mean of squared magnitudes, denoted as x (Eq. 1).⁶⁸

$$RMS = \sqrt{\frac{1}{N} \sum_{n=1}^N (x)^2} \quad (\text{Eq. 1})$$

For COP velocity, the instantaneous velocity for the anterior-posterior (AP) and medial-lateral (ML) axes are calculated by the change in position over the change in time (Eq. 2).^{68, 70}

$$COP\ velocity = x = \frac{COP_{AP}[n+1] - COP_{AP}[n]}{t[n+1] - t[n]} \quad (\text{Eq. 2})$$

For COP amplitude, positional values at each instance are used for the AP and ML axes, following a method demonstrated by Quijox et al. (Eq. 3).⁷¹

$$AP\ COP\ amplitude = x = COP_{AP}[n] \quad (\text{Eq. 3})$$

Our second type of outcome measures relating to limb loading symmetry is assessed using vertical ground reaction forces (vGRFs). Common symmetry indices include the Ratio Index (RI)⁷², Limb Symmetry Index (LSI)⁷³, Normalized Symmetry Index (NSI)⁷⁴, the Absolute Symmetry Index (ASI)⁷⁵, and the Symmetry Index (SI)⁷⁶. These indices have been used in surgical populations, denoting metrics associated with the surgical limb as *S* and the non-surgical limb as *NS*.

The RI calculates the ratio of metrics between the non-surgical and surgical limbs, with values exceeding 100% indicating full asymmetry and 0% indicating perfect symmetry (Eq. 4).^{72, 77} The index calculates values that are positive when the value for the X_{NS} is greater than X_S .

$$RI = \left[1 - \frac{X_s}{X_{NS}} \right] \times 100\% \quad (\text{Eq. 4})$$

The LSI, used to assess athletes post-ACL reconstruction, compares the metrics of the dominant and non-dominant limbs, with values outside the 90%-110% indicating asymmetry (Eq. 5).^{78, 79}

This metric has primarily been used for assessing when athletes are ready to return to sport following ACL reconstruction surgery using distance measures.^{78, 79}

$$LSI = \left[\frac{X_s}{X_{NS}} \right] \times 100\% \quad (\text{Eq. 5})$$

The NSI measures the difference between limbs and normalizes it by the range of values between the maximum and minimum measurements, requiring a minimum of 3 trials (Eq. 6).⁷⁴

The NSI has bounded results meaning values range from 0 to +/-100%, indicating full symmetry to full asymmetry, respectively.⁷⁴

$$NSI = \frac{X_{ND,t} - X_{D,t}}{\max_{t=1:n}(\max(0, X_{ND,t}, X_{D,t})) - \min_{t=1:n}(\min(0, X_{ND,t}, X_{D,t}))} \times 100\% \quad (\text{Eq. 6})$$

The ASI calculates the absolute difference between limbs divided by the average of the two values, with a threshold of 10% indicating asymmetry. It uses the left (L) and right I legs as variable references.⁸⁰

$$ASI = \frac{|X_R - X_L|}{0.5(X_R + X_L)} \times 100\% \quad (\text{Eq. 7})$$

The SI, unlike the ASI, indicates direction in terms of sign. Values greater than 10% or less than -10% can suggest levels of asymmetry (Eq. 8).^{76, 80} When the SI produces negative values, the left side is larger than the right, and when positive the right side is larger than the left. The SI is the most commonly used symmetry metric and was chosen due to its proven reliability and consistency in measuring symmetry across different tasks.^{76, 80}

$$SI = \frac{X_R + X_L}{0.5(|X_R| + |X_L|)} \times 100\% \quad (\text{Eq. 8})$$

In this study, we assessed lower extremity symmetry using the SI with vGRFs and evaluated balance performance by measuring the RMS of COP amplitude and velocity in the ML and AP axes. This helps determine postural control and stability, and limb loading during lifting and holding with both symmetrically and asymmetrically positioned loads. Postural control abnormalities and asymmetrical limb loading in postpartum women, compared to controls,

would be identified through these metrics, and they are associated with musculoskeletal disorders and injury that are more prevalent in the postpartum population.^{81, 82} By determining differences in these metrics between postpartum and nulliparous women we can better understand differences that may put postpartum at a higher risk of developing chronic pain and injury during daily tasks involving lifting and holding a car seat. This information can be used to better understand postpartum biomechanics as well as understand ways that we may be able to inform postpartum health and safety during daily activities.

Motivation, Purpose, and Hypothesis

Following birth, 74% of women experience chronic pain, negatively impacting their quality of life, likely resulting from musculoskeletal adaptations developed during pregnancy that did not resolve postpartum.^{39, 83} This pain may arise from malalignment and weakness in the lumbopelvic area.^{5, 9} Investigation of differences in limb loading symmetry and balance between postpartum and nulliparous women may allow us to understand if there are factors related to the PP musculoskeletal system that may contribute to an increased risk of chronic pain and injury in postpartum women during child care related activities.

The purpose of this study was to Investigate postural control and limb loading symmetry differences during different childcare related lifting and holding conditions between postpartum and nulliparous controls. The first hypothesis was that postpartum women will have reduced postural control, with increase in RMS amplitude and velocity (AP and ML) as the condition becomes harder with asymmetrical holding. The second hypothesis was that PP women, compared to NP, would have greater values of peak vGRF SI, with an increase in the SI

changing from the no hold to asymmetric hold. The third hypothesis was that postpartum women would have an increase in the RMS AP and ML amplitude and velocity as the condition becomes more difficult with asymmetrical lifting, compared to NP women. The fourth hypothesis was that PP women would have a higher vGRF SI asymmetry transitioning from symmetric to asymmetric lifting, compared to the NP women. Differences between groups in these metrics during childcare related tasks may indicate possible factors that put postpartum women more at risk of developing chronic pain or injury.

Chapter Two: Differences in Static Balance and Limb Loading Symmetry between Postpartum and Nulliparous Women during Three Car Seat Holding Conditions

Abstract

Understanding the postpartum (PP) response to daily childcare related activities can provide insights into how the PP musculoskeletal system manages everyday challenges. This knowledge can help identify challenges in maintaining balance^{84, 85} and limb loading symmetry that has been associated with musculoskeletal weakness^{84, 85} and malalignment^{84, 85} as well as chronic pain and injury.⁸⁶⁻⁸⁸ Investigating whether PP women experience impairments in postural balance and asymmetrical limb loading compared to nulliparous (NP) women during daily childcare activities may reveal how PP women may be more at risk for developing chronic pain and injury. The purpose of this study was to analyze the effect of group (PP, NP) and the effect of loading conditions (no load, symmetrical, asymmetrical) on balance and limb loading symmetry. PP women were expected to have poorer balance, compared to NP, as it becomes more difficult with asymmetric holding. PP women were also expected to have higher vertical ground reaction force (vGRF) limb loading asymmetry, using the Symmetry Index (SI), with an increase as the conditions become harder from no hold to asymmetric hold. 36 participants were included, with 18 in each group. Each participant did 6 trials of each holding condition. The Center of pressure (COP) was used to calculate the root-mean-square (RMS) of the amplitude and velocity in the anterior-posterior (AP) and medial-lateral (ML) axes as well as the peak vGRF SI using a custom-built code using force plate data. Interaction and main effects were determined using a linear mixed effects model. A significant interaction was found in RMS ML velocity ($p = 0.005$) and amplitude ($p = 0.032$) showing an increase in measures across conditions for both groups. In RMS AP amplitude, an interaction was found ($p = 0.002$) with larger values in the PP group during the asymmetric hold ($p = 0.009$). A main effect of condition was found in AP RMS velocity with values increasing from no hold to asymmetric holding. In peak vGRF SI, main effect of group ($p = 0.05$), showing PP women were significantly greater than NP, and condition ($p < 0.001$), showing a significant increase in metrics from no hold to asymmetric holding, were found. These results show that PP women have differing responses to car seat holding conditions and demonstrate challenges in maintaining balance and higher levels of asymmetrical loading. This research indicates the need to further determine possible factors that may contribute to the interactions found. However, it is possible that effects of pelvic asymmetries and musculoskeletal weakness may be a contributing factor to the differences in balance and load distribution found in this study and may put PP women at a higher risk of developing pain during childcare holding tasks.

Introduction

In the United States, approximately 3.6 million women give birth annually as of 2021.¹ Research indicates that 81% of postpartum (PP) women experience persistent health issues such as perineal pain, backache, and urinary problems at 24 weeks after giving birth.² Moreover, up to 20% of PP women report chronic back and pelvic pain lasting up to 3 years postpartum, with these conditions significantly impairing daily activities.³ Many postpartum women also experience prolonged lower extremity pain and musculoskeletal weakness and asymmetries.^{5, 8, 89} Asymmetric pelvic anterior tilt and external rotation have been seen to persist in postpartum women.^{54, 56} Pelvic malalignments are known to increase the risk of low back⁹⁰ and pelvic pain⁹¹, both conditions that are common in the postpartum population.^{5, 92-94}

Pelvic tilting and rotation also increases the curvature of the lower spine, affecting how weight is distributed through the lumbopelvic region and can alter paraspinal musculature.^{95, 96} Postpartum women have exhibited paraspinal muscle activity reduction and trunk strength weakness when compared to nulliparous women.^{17, 18} Strength and stability in the lumbopelvic region are essential in being able to control the trunk, especially when holding an external load due to the increases in strain on the spine and asymmetrical load distribution in the pelvis and lower extremities.^{56, 97, 98} Managing postural demands, especially while holding an external load, may be challenging for postpartum women when experiencing musculoskeletal dysfunction and balance impairments.⁹⁹ This is especially due to the increase in trunk extensor muscular demand during conditions involving holding an external load.^{100, 101}

Postpartum women commonly use car seats as a mode of transportation for their child and there are currently no guidelines for new mothers on how to safely navigate infant care related daily tasks to avoid loading related injuries and chronic pain.^{18, 102} Transporting infants using car seats introduces asymmetrical loading in the pelvis and lower extremities, especially depending on if the car seat is held symmetrically or asymmetrically.^{18 103, 104} As a child begins to grow and becomes heavier, repetitively holding them in a car seat puts a mother at increased risk of injury and pain.^{5, 59} From past literature, repetitive loading of this type can delay the resolution of post-pregnancy musculoskeletal healing due to the shear and compressive forces imposed at the spine and pelvis, further contributing to chronic pain.⁶⁰⁻⁶² Additionally, holding an external load can also increase asymmetrical limb loading, seen in healthy adults during gait, and has been determined to be significantly related to chronic pain in the lumbopelvic area and lower extremities.^{99, 105} However, holding an external load, specifically a car seat, has not been examined in postpartum women. Nor has their postural response and limb loading response to this type of holding activity.

The aim of this research study was to determine the effects of both postpartum (PP) and nulliparous (NP) women, as well as three distinct car seat holding conditions: no holding (baseline), symmetrical holding, and asymmetrical holding on balance and limb loading symmetry. This study hypothesized that PP women, compared to NP women, would demonstrate worse balance characterized by an increase in root mean square (RMS) amplitude and velocity in the anterior-posterior (AP) and medial-lateral (ML) axes. This effect is expected to be exacerbated under conditions involving asymmetric holding, due to the possible influence of lumbopelvic asymmetries and muscular weakness, impairing the ability to respond effectively to

external loads. The study also hypothesized that PP women would have greater limb loading asymmetry, defined by the Symmetry Index (SI) of the vertical ground reaction forces (vGRF), compared to NP women, with an increase in asymmetry transitioning from no holding to the asymmetric holding condition.

Materials and Methods

Participants

Thirty-six participants were recruited, including 18 postpartum women and 18 nulliparous women for the study approved by Virginia Tech Institutional Review Board (IRB #20-1085). The exclusion criteria for both groups included having a musculoskeletal or neurologic disorder or any other medical condition that affects postural stability, potential pregnancy, history of a lower limb injury that has limited activity for more than 2 days, a prior serious lower limb injury or surgery, and an inability to perform daily tasks requiring holding an external load. For postpartum women specifically, additional exclusion criteria were having had a caesarean delivery¹⁰⁶, having experienced a grade four perineal tear¹⁰⁶. The additional exclusion criteria for the postpartum group were included to reflect current knowledge on safe activities for postpartum women^{106, 107}, and having given birth less than 6 months ago or more than 1 year ago.

Testing Protocol

At the beginning of all data collection sessions, participants signed a Virginia Tech Institutional Review Board approved consent form. Participant demographic data was collected and managed using REDCap (Research Electronic Data Capture) electronic data capture tools hosted at Virginia Tech.^{108, 109} Demographic information included self-reported age, sex assigned at birth,

and which hand they use to write with, to determine their upper limb dominance.¹¹⁰ Additionally, the preferred limb for asymmetrical holding was recorded from asking postpartum women which arm they prefer to use when holding or lifting with one hand, to determine the arm the postpartum participants would naturally carry a car seat on. This preferred limb was subsequently used for asymmetrical holding in postpartum participants, whereas in the nulliparous group, the dominant limb was used. Identifying the dominant limb as the preferred limb in the nulliparous group was done due to the idea that this population does not generally participate in childcare holding tasks involving a car seat. Using the dominant arm for asymmetrical holding helped standardize the condition to provide a consistent basis of comparison against postpartum women. Additional questions were asked of the postpartum participants including the number of children they had given birth to, the weight of their youngest child, and the number of months since they recently gave birth.

Two AMTI force plates (BP600- 600, AMTI, Watertown, MA, USA) were used to collect ground reaction forces and center of pressure, collected at 1190 Hz. Each participant stood in a standardized stance, feet shoulder-width apart, and with each bare foot placed on a single force plate with the two plates located side-by-side. A 10kg loaded car seat was placed on the floor, sitting between two additional force plates in front of the participant. The participant's feet were positioned at 20% of the dominant/preferred limb length away from the load in front of them. The car seat was loaded with 10kgs of ankle weights, to simulate the approximate weight of a 95th percentile nine month old male and female infant.⁸ The total weight of the car seat and added ankle weights was 13.5 kgs. The positions of both feet and the car seat were marked with tape to ensure consistent foot and car seat placement between trials. Participants completed 3

different holding conditions that included a no holding trial, symmetrical holding, and asymmetrical holding. The ordering of symmetrical and asymmetrical conditions was randomized following the no holding condition using the MATLAB random number generator of zeros (that were associated with asymmetrical holding) and ones (associated with symmetrical holding). In both groups, 8 participants performed symmetrical holding before asymmetrical, and 10 participants performed asymmetrical holding before they performed symmetrical holding. Each holding condition trial was 30 seconds long, collected for a total of 6 trials. A rest period of 1 minute was provided between trials and 2 minutes between conditions to decrease the potential impact of fatigue. During the no holding condition, participants stood on the force plates with their eyes open looking at the wall in front of them, approximately 5 meters away, with their hands by their sides, standing as still as possible for 30 seconds (Figure 1A). Participants were not given a target for eyesight maintenance and were instructed on the requirements once before every condition with one study personnel present intended to monitor task performance.

During symmetrical holding, participants held the 13.5kg (car seat plus ankle weights) car seat with both hands placed at the widest parts of the car seat at approximately hip height. Participants were instructed to hold the car seat in this position for 30 seconds while standing as still as possible (Figure 1B). During asymmetrical holding, participants held the car seat handle with the inner elbow of their dominant arm, or preferred limb for postpartum women, at approximately hip height for 30 seconds. Participants were instructed to hold the car seat in this position for 30 seconds while standing as still as possible (Figure 2C). While the shape and weight of the car seat and ankle weights were not considered a true symmetrical load, the

asymmetrical and symmetrical naming conventions were used to differentiate the use of one or two hands, as well as the placement of the car seat, relative to the midline of the body.

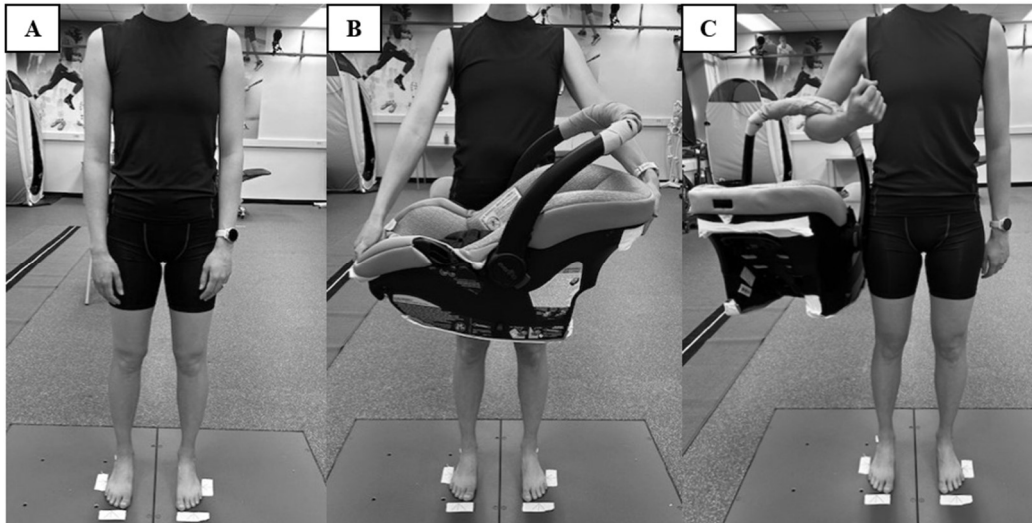


Figure 2: Demonstration of a control participant performing A) No Holding Condition B) Symmetric Holding Condition and C) Asymmetric Holding using their Dominant Limb

Among the 36 total participants, 1 postpartum and 1 nulliparous participant were excluded only from the symmetrical condition. Additionally, one other nulliparous participant had one trial excluded from the symmetrical condition, with all other 5 trials included. Outliers in the data were first identified using box and whiskers plots in JMP and flagging any observations that exceeded 1.5 times the length of the interquartile range in both directions from the 75th and 25th quartiles of the data. COP amplitude and velocity trajectories were then observed for potential outliers to identify areas of the signal that fluctuated. In addition to this, video recordings that occurred alongside the force plate data collection, associated with a different research project, were observed to understand reasoning for fluctuations that occurred in the data. Outliers were excluded if there were significant distractions during the task that included head movements that

were 45 degrees or greater from their original line of sight at the beginning of the trial, including head movement from side to side or up and down. Outliers were also removed if the movement involved adjusting the car seat during the trial, characterized by readjustment of the car seat from its original position at the beginning of the trial. Data was not recollected due to the identification occurring after data collection, ultimately due to improper data collection techniques. While removing conditions from subjects reduces consistencies in the samples included during condition comparisons within groups and during between group comparisons, exclusion of such trials was done so to ensure quality of the data used for analysis.

Data Analysis

Ground reaction forces (GRFs) were filtered using a fourth-order recursive low-pass Butterworth digital filter with a cutoff 10 Hz.¹¹¹ To determine optimal cutoff frequency, a power spectral density was calculated from the ground reaction forces during quiet standing. The quiet standing holding tasks involved little movement and the cutoff frequency was used to reduce the influence of higher frequency noise. GRF measures were normalized to body weight following phase identification for symmetry calculations. Only for the no holding trials, a custom-built MATLAB code extracted data points during the last 25 seconds of a trial to exclude the initial transient oscillatory state that is seen to occur in the COP during bipedal stance within the first 5 seconds of quiet standing trials.¹¹¹ The symmetrical and asymmetrical holding conditions were collected following a lifting phase that was included in a larger study, therefore a custom-built MATLAB code used the following steps to isolate the 25 second holding phase: (1) the end of the lifting phase was identified when, from the start of the lift, the combined vGRFs from the left and right legs remain within +/- 1% of the bodyweight and car seat load for 20 consecutive data samples (body weight for each trial was determined by the stable signal from the participant standing

quietly before the start of the trial); (2) from the end of the lifting trial, the holding trial began 5 seconds later; and (3) from the first point where the holding phase begins, 25 seconds later was identified as the end of the holding phase (Figure 3). The signal included in the holding phase was used to calculate outcomes measures.

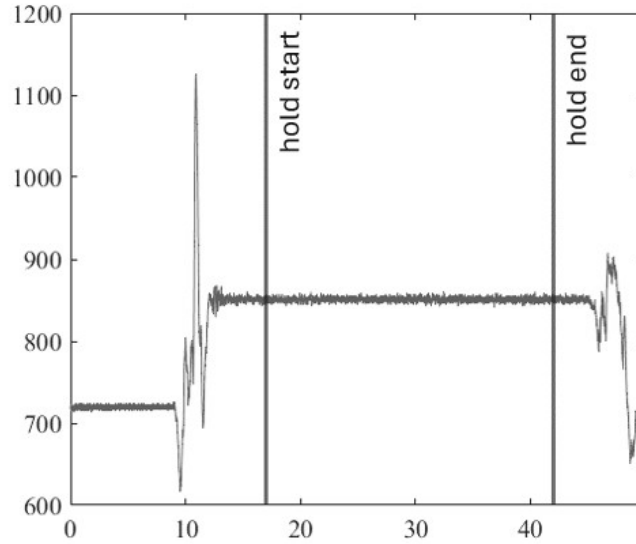


Figure 3: $vGRF$ (N) vs. Time (s) graph with holding phase identification

For the outcome measures, the center of pressure (COP) was calculated by combining the $vGRF$ and COP from the 2 separately loaded force plates where the subscript L indicates the signal taken from the force plate under the left foot and R for the adjacent force plate, under the right foot (Eq. 9).¹¹²

$$COP = \frac{(COP_L \times vGRF_L) + (COP_R \times vGRF_R)}{vGRF_L + vGRF_R} \quad (\text{Eq. 9})$$

The medio-lateral (ML) and anterior-posterior (AP) COP was calculated and then demeaned. The COP instantaneous velocity in the ML and AP axes was calculated (Eq. 10), using every sample of the COP signal identified as n in either direction.⁷⁰

$$COP\ Velocity = x = \frac{COP[n+1] - COP[n]}{t[n+1] - t[n]} \quad (Eq. 10)$$

For the COP amplitude, positional data was used from the demeaned COP signal for the AP and ML axes (Eq. 11), following a similar method demonstrated in past literature.⁷¹ Every sample of the COP signal, in both axes, were then used to calculate the RMS, demonstrated below.⁶⁸

$$COP\ Amplitude = x = COP[n] \quad (Eq. 11)$$

The root-mean-square of the velocity and amplitude is then calculated by taking the square root of the average of the squared values of data in a signal. The RMS calculation is demonstrated below where x represents amplitude and velocity in AP and ML axes used to calculate the RMS COP amplitude and RMS COP velocity for analyses.^{68, 71, 113}

$$RMS = \sqrt{\frac{1}{N} \sum_{n=1}^N [x]^2} \quad (Eq. 12)$$

The SI was used to assess vGRF symmetry.¹¹⁴ The SI was chosen because it has been proven to be a reliable and repeatable symmetry metric between different types of tasks.^{80, 114} An SI value of zero indicates perfect symmetry between the two limbs while the outer bounds are unbounded, with a general threshold of +/- 10% used to determine asymmetry.⁷⁶ The SI equation references the non-preferred limb (*NPL*) and preferred limb (*PL*) for postpartum participants with corresponding metrics for the non-dominant (*ND*) and dominant (*D*) limbs for nulliparous participants. The SI was calculated using the vGRF from both limbs during every sample within a trial. The peak of the absolute values of the SI was used to indicate the peak symmetry experienced during a trial. While a value of 0 indicates perfect symmetry, a greater value in either direction indicates greater asymmetry. A positive value for SI indicates a larger vGRF for

the *NPL* or *ND* while a negative value indicates a larger vGRF for the *PL* or *D* that were present at the time the peak SI occurred. In this study, the absolute value of the SI was used when comparing the degree of symmetry during conditions and between groups.

$$SI = \frac{X_{NPL} - X_{PL}}{0.5 \times (X_{NPL} + X_{PL})} \times 100\% \quad (\text{Eq. 13})$$

The COP RMS velocity and amplitude in the ML and AP directions and the peak vGRF SI were calculated for every trial of each condition for both groups and included in our statistical analysis.

Statistical Analysis

Demographic data (age, height, weight, and BMI) was compared between the NP and PP group using an independent t-test to determine if differences in these measures existed that may impact results (Table 1). Age was included as a covariate in our analysis because it was significantly different between groups and to control for its possible influence on balance between our age groups ($p < 0.001$).¹¹⁵ A linear mixed effects model (LMEM) was selected for its ability to account for both fixed and random effects, while addressing correlations with repeated measures. The outcome measures of ML and AP RMS COP velocity and amplitude, and peak vGRF SI were used in the LMEM, performed in JMP (SAS, Cary, NC), to determine interactions and main effects. In the LMEM participants were included as a random effect, condition and group were included as fixed effects.¹¹⁶ When considering the COP related outcomes measures, age was included as an additional fixed effect to account for its influence on outcome measures. The model was performed using an alpha level of 0.05. If an interaction, or a main effect of condition, was detected the Tukey HSD was used for post-hoc pairwise comparisons. If a main effect of group was detected, an LS Means student t-test was used for post hoc analysis. To

interpret the meaningful relationships between holding conditions, effect sizes were calculated using Cohen’s d. The levels of effect were classified using the following indices: 0.2 for small, 0.5 for medium, and 0.8 for large.¹¹⁷

Results

The nulliparous and postpartum demographics of average age (years), height (m), weight (kg), and BMI (kg/m²) are included in Table 1. Seventeen of the participants in the NP group and PP group had right-hand dominance while only 1 had left-hand dominance.

Table 1: Differences in demographics between groups, mean ± SD

Demographics	Nulliparous (n=18)	Postpartum (n=18)	<i>p-value</i>
Age (years)	26.8 ± 3.10	30.5 ± 3.52	0.001*
Height (m)	1.65 ± 0.07	1.64 ± 0.07	0.319
Weight (kg)	70.86 ± 13.33	71.27 ± 11.21	0.461
BMI (kg/m ²)	26.02 ± 4.18	26.55 ± 4.31	0.365

**p-value < 0.001, difference between nulliparous and postpartum groups*

Of the 18 postpartum women, 14 of them used their dominant arm to hold the car seat asymmetrically, while 4 used their non-dominant arm (Table 2). Postpartum demographics of months post-birth, number of children, and weight of youngest child are included in Table 2. Of all the mothers, 8 of them were primiparous, having given birth once, while the other 10 were multiparous, having given birth multiple times.

Table 2: Postpartum demographics, mean ± SD

	Months Postpartum	Number of children	Weight of youngest child (kg)	Preferred Carrying Side	Dominant Limb
Postpartum (n=18)	8.56 ± 2.23	1.72 ± 0.75	8.83 ± 2.52	Dom: 14 Non-dom: 4	Right: 17 Left: 1

Consolidated results for all outcome measures are shown in Table 3 with the breakdown of results for each measure following.

Table 3: Interaction and Main Effect Result for all Outcome Measures

Measurement Type	Group	Holding Condition	Mean \pm SD	p-value	Effect Size – no hold	Effect Size – symmetric
ML COP RMS Velocity (mm/s)	PP	No Hold	7.14 \pm 1.94	-	-	-
		Symmetric	11.69 \pm 3.92	< 0.001*	1.47	-
		Asymmetric	12.79 \pm 4.64	< 0.001* 0.035**	1.59	0.26
	NP	No Hold	7.12 \pm 2.20	-	-	-
		Symmetric	10.27 \pm 2.51	< 0.001*	1.34	-
		Asymmetric	11.14 \pm 1.14	< 0.001*	2.29	-
AP COP RMS Velocity (mm/s)	-	No Hold	6.06 \pm 1.29	-	-	-
		Symmetric	7.90 \pm 2.67	< 0.001*	-	-
		Asymmetric	13.23 \pm 4.88	< 0.001*,**	-	-
ML COP RMS Amplitude (mm)	PP	No Hold	4.12 \pm 1.70	-	-	-
		Symmetric	5.78 \pm 2.22	< 0.001*	0.84	-
		Asymmetric	5.94 \pm 2.05	< 0.001*	0.96	-
	NP	No Hold	3.97 \pm 1.80	-	-	-
		Symmetric	4.68 \pm 1.47	0.006*	0.43	-
		Asymmetric	4.95 \pm 1.61	< 0.001	0.57	-
AP COP RMS Amplitude (mm)	PP	No Hold	1.28 \pm 0.56	-	-	-
		Symmetric	2.45 \pm 1.52	< 0.001*	1.03	-
		Asymmetric	4.24 \pm 2.32	< 0.001*,** 0.009 #	1.75	0.91
	NP	No Hold	1.15 \pm 0.52	-	-	-
		Symmetric	1.83 \pm 0.82	< 0.001	0.99	-
		Asymmetric	3.07 \pm 1.14	< 0.001*,**	2.17	1.25
Peak vGRF SI (%)	-	No Hold	14.18 \pm 8.27	-	-	-
		Symmetric	24.89 \pm 14.41	< 0.001*	-	-
		Asymmetric	86.33 \pm 28.99	< 0.001*,**	-	-
	PP	-	44.82 \pm 20.11	0.046 #	-	-
	NP	-	39.16 \pm 18.43	-	-	-

*p-value, compared to no holding condition

**p-value, compared to symmetric holding condition

#p-value, compared to NP group

ML COP RMS velocity

An interaction of group and condition was found ($p = 0.005$), with no significance associated with age ($p = 0.61$). For the PP group, significant differences appeared between the asymmetric holding and no holding condition (Asymmetric: 12.79 ± 4.64 mm/s; No holding: 7.14 ± 1.94 mm/s; $p < 0.001$), symmetric and no hold (Symmetric: 11.69 ± 3.92 mm/s; No holding: 7.14 ± 1.94 mm/s; $p < 0.001$), and between asymmetric and symmetric holding ($p = 0.035$). Of these comparisons the metric increases from no holding to the asymmetrical holding condition. In the NP group, significant differences appeared between asymmetric holding and the no holding condition (Asymmetric: 11.14 ± 1.14 mm/s; No holding: 7.12 ± 2.20 mm/s; $p < 0.001$) and between symmetric holding and no holding (Symmetric: 10.27 ± 2.51 mm/s; No holding: 7.12 ± 2.20 mm/s; $p < 0.001$). In both groups, a large effect size is calculated between no hold and symmetrical hold, with NP showing an effect size of 1.34 and PP having 1.47, and between no hold and asymmetrical hold, with NP having an effect size of 2.29 and PP having 1.59.¹¹⁷ The PP group showed a small effect size, 0.26, between symmetrical and asymmetrical holding.¹¹⁷ Though not statistically significant, the postpartum group exhibited large magnitudes of change in this metric transitioning from no load to symmetrical and to asymmetrical, as well as from symmetrical to asymmetrical. Though not significantly different, the PP group also had larger values in comparison to the NP group during symmetric holding, with a medium effect size of 0.43 ($p = 0.34$), and asymmetric holding, with a medium effect size of 0.49 ($p = 0.27$). The two

groups, in comparison to one another, showed similar values during the no holding condition, lacking a significant difference ($p = 0.99$).

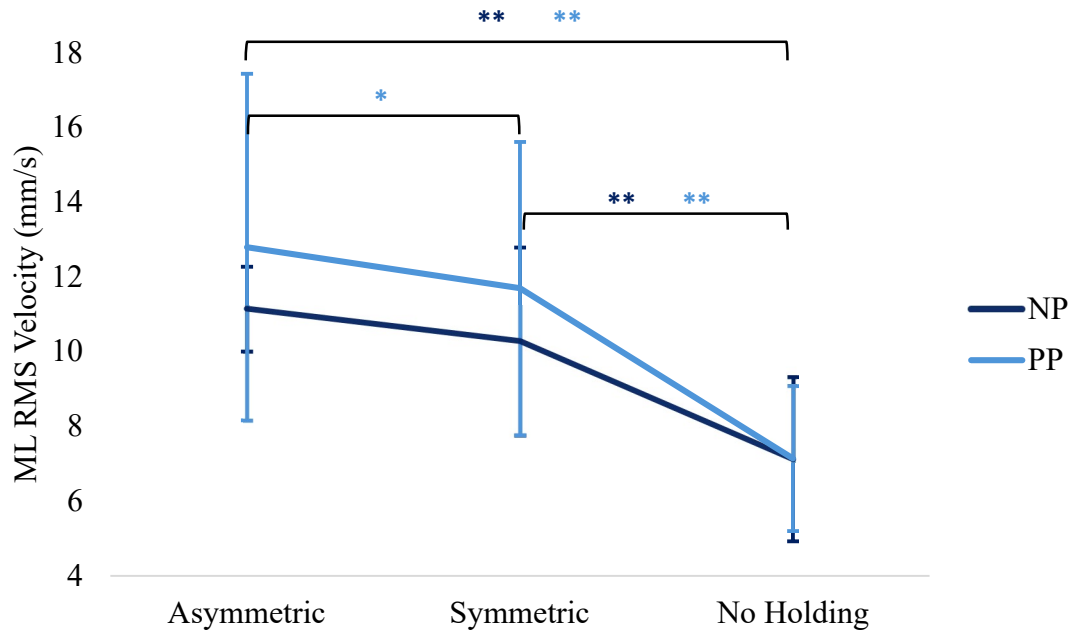


Figure 4: Group*Condition interaction plot for ML RMS velocity; ** p -value < 0.001 , * $p = 0.035$

AP COP RMS velocity

There was no significant interaction ($p = 0.48$), main effect of group ($p = 0.83$), or effect of age ($p = 0.72$). However, a main effect of condition was detected ($p < 0.001$). AP RMS velocity significantly increases from the no hold (6.06 ± 1.29 mm/s) to symmetric hold (7.90 ± 2.67 mm/s, $p < 0.001$), and to asymmetric hold (13.23 ± 4.88 mm/s, $p < 0.001$). There was also a significant increase from no hold to symmetric ($p < 0.001$).

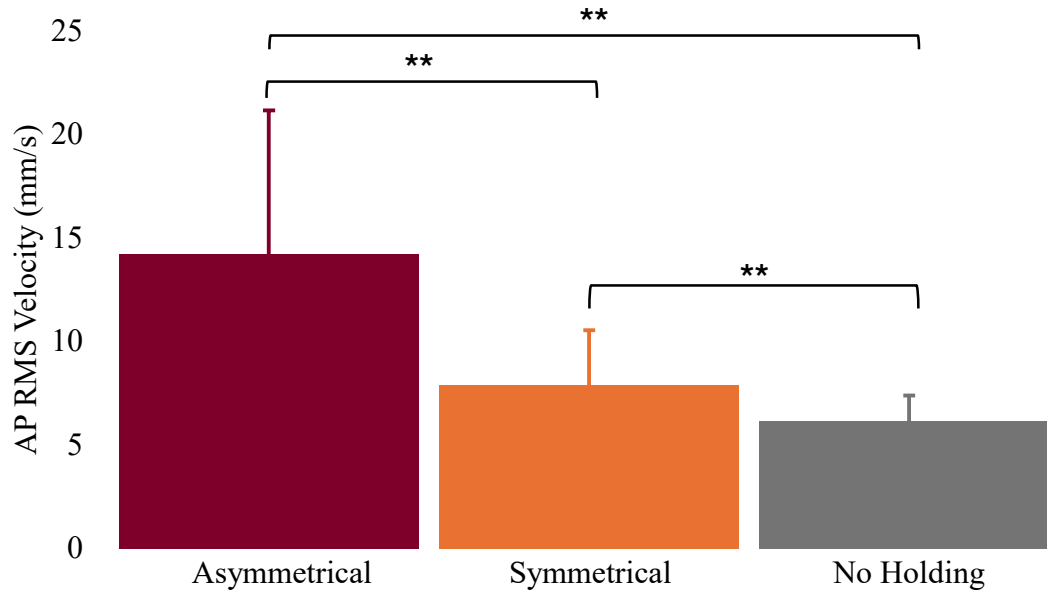


Figure 5: Main Effect of condition for AP RMS velocity; ** p -value < 0.001

ML COP RMS amplitude

An interaction of group and condition was found ($p = 0.032$) with no significance associated with age ($p = 0.5687$). For the PP group significant differences appeared between no hold (4.12 ± 1.70 mm) and symmetric hold (5.78 ± 2.22 mm, $p < 0.001$) and asymmetric hold (5.94 ± 2.05 mm, $p < 0.001$). For the NP group, significant increases appeared from no load (3.97 ± 1.80 mm) to symmetric (4.68 ± 1.47 mm, $p = 0.006$) and to asymmetric (4.95 ± 1.61 mm, $p < 0.001$). For the PP group, a large effect size is shown for the differences between no hold and symmetrical hold, with PP showing 0.84, and between no hold and asymmetrical hold, with PP showing 0.96.¹¹⁷ For the NP group, medium effect sizes were calculated for condition differences with 0.43 for no hold to symmetric, and 0.57 for no hold to asymmetric.¹¹⁷ Though not statistically significant, the postpartum group exhibited greater magnitudes of change in this metric transitioning from no hold to symmetrical and to asymmetrical. The PP group also had larger values in comparison to the NP group during symmetric ($p = 0.09$), with a medium effect size of 0.58, and asymmetrical

holding ($p = 0.11$), with a medium effect size of 0.53, although they were not significantly different. The two groups also showed very similar values during the no holding, also not showing a significant difference ($p = 0.93$).

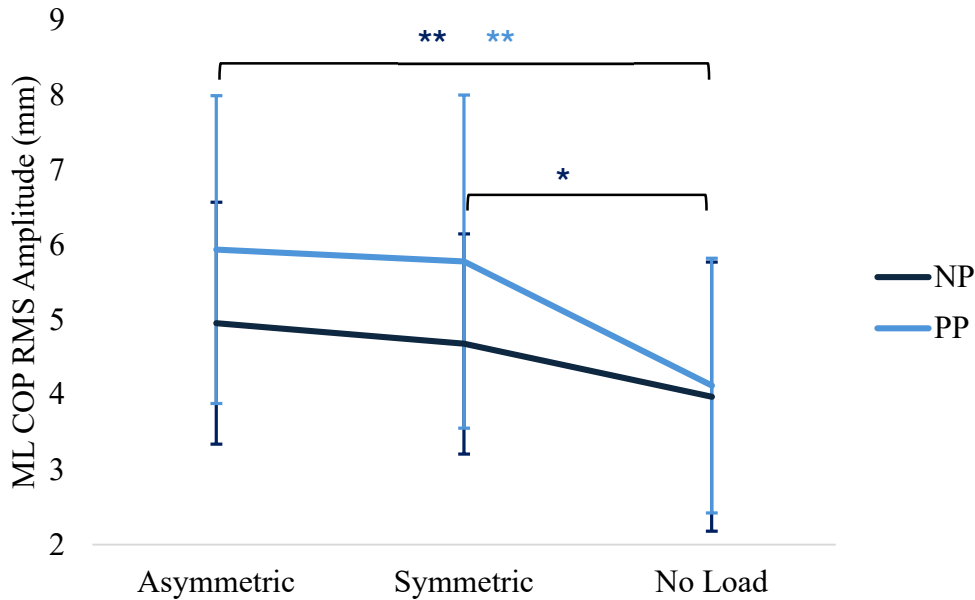


Figure 6: Group*Condition interaction for ML RMS amplitude; $**p < 0.001$, $*p = 0.006$

AP COP RMS amplitude

An interaction of group and condition was found ($p = 0.002$) with no significant effect of age ($p = 0.89$). For the PP group significant increases appeared from no hold (1.28 ± 0.56 mm/s) to symmetric (2.45 ± 1.52 mm, $p < 0.001$) and to asymmetric (4.24 ± 2.32 mm, $p < 0.001$), as well as from symmetric to asymmetric ($p < 0.001$). The largest values occurred during asymmetric holding and the smallest during the no holding condition. In the NP group, significant increases occurred from no hold (1.15 ± 0.52 mm) to symmetric (1.83 ± 0.82 mm, $p < 0.001$) and to asymmetric (3.07 ± 1.14 mm, $p < 0.001$) and from symmetric to asymmetric holding ($p < 0.001$). For both groups, a large effect size was found in three comparisons. First, between no hold and symmetrical, NP had an effect size of 0.99 and PP had an effect size of 1.03.¹¹⁷ Second, between

no hold and asymmetrical hold, NP had an effect size of 2.17 while PP had 1.75.¹¹⁷ Third, between symmetric and asymmetric, NP had an effect size of 1.25 and PP had an effect size of 0.91.¹¹⁷ A significant larger value ($p = 0.009$) was found in the PP compared to the NP group during asymmetric holding. While not significantly different, the PP group showed larger magnitudes of change in this metric transitioning across conditions from no hold to asymmetric holding. Additionally, while not significantly different, the PP group showed greater values compared to the NP group during symmetric ($p = 0.23$), with a medium effect size of 0.51, with a slightly larger value during the no holding condition ($p = 0.93$).

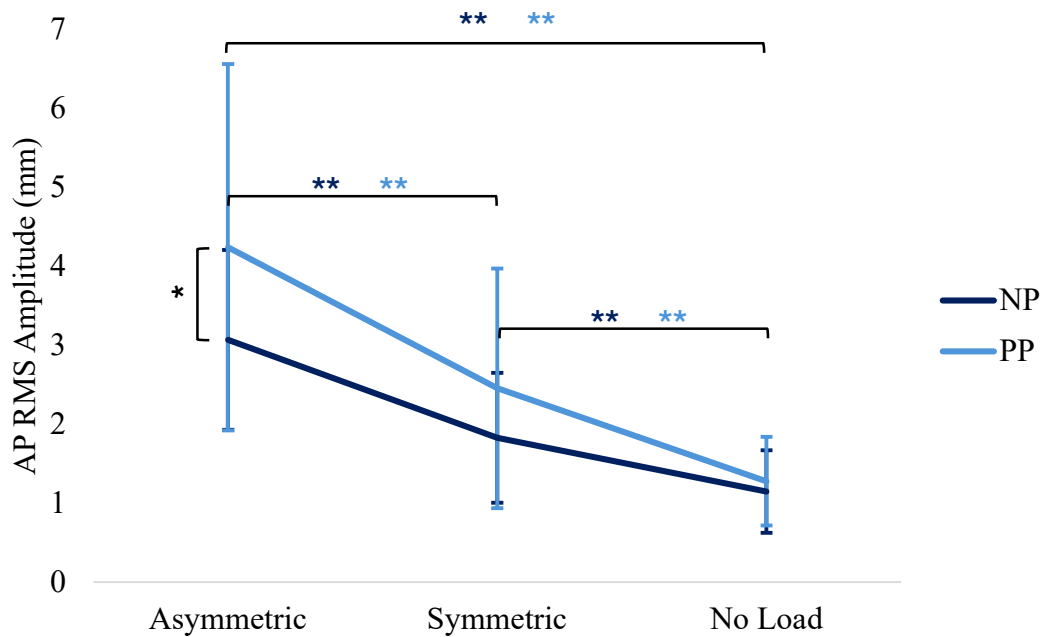


Figure 7: Group*Condition interaction plot for AP RMS amplitude; $**p < 0.001$, $*p = 0.009$

Peak vGRF SI

No interaction was detected ($p = 0.32$), although the main effects of group ($p = 0.05$) and condition ($p < 0.001$) were found to be significant. Main effect of group shows significantly larger values ($p = 0.046$) in the PP group ($44.82 \pm 20.11\%$) compared to the NP group ($39.16 \pm$

18.43 %). Main effect of condition shows a significant comparison between all conditions ($p < 0.001$) with the smallest peak vGRF SI during no holding (14.18 ± 8.27 %), increasing with symmetric holding (24.89 ± 14.41 %) and the largest values during asymmetric holding (86.33 ± 28.99 %).

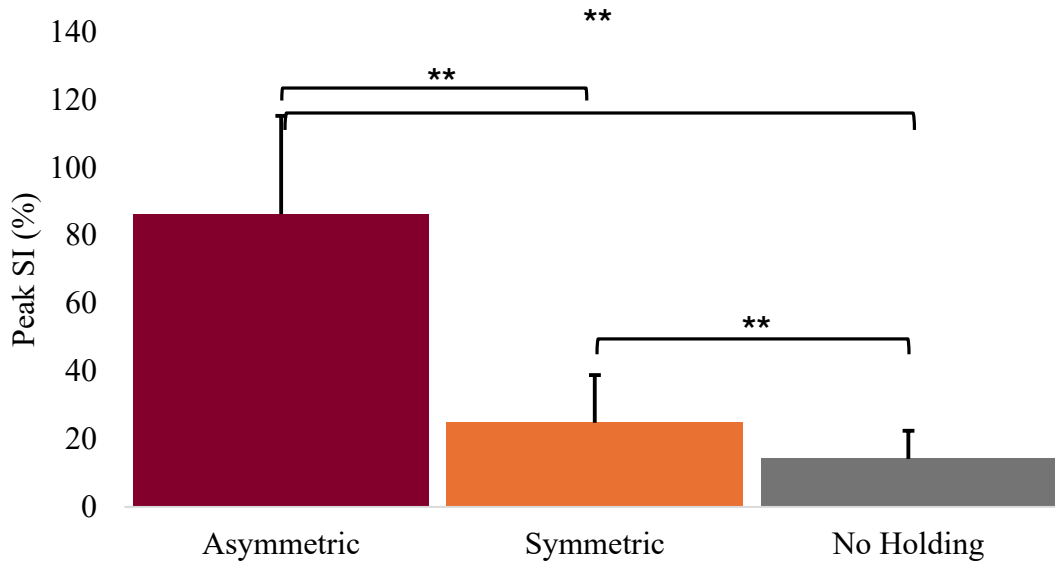


Figure 8: Main effect of condition for Peak vGRF SI; $**p < 0.001$

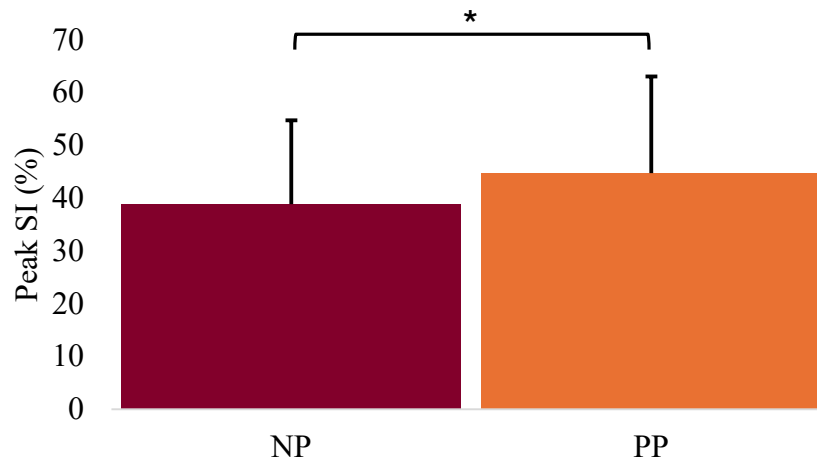


Figure 9: Main effect of group for Peak vGRF SI; $*p = 0.046$

Discussion

The purpose of this study was to determine the effect of group (NP, PP) and condition (no load, asymmetric, symmetric) on balance and load symmetry. All but one of our balance related COP metric results support our first hypothesis stating that PP women will exhibit poorer postural control, compared to NP women, as demonstrated through a decrease in COP RMS amplitude and velocity in the AP and ML axes, as the condition becomes more difficult with asymmetric holding.

There was a significant interaction in the RMS velocity and amplitude, showing that PP and NP women responded differently to the holding conditions with greatest values present in asymmetric holding. The increase across holding conditions for both groups are consistent with existing literature that shows conditions of holding symmetrical and asymmetrical loads cause an increase in COP measures in the ML direction.^{110, 118} Specifically, in ML RMS velocity, both groups showed large effects between no holding and holding conditions. For the PP and NP groups, the transition between no holding to asymmetrical had magnitude changes that were greater than the minimally important difference (MID) of 4.3 mm/s in COP velocity, determined from a balance impaired population.¹¹⁹ From this, the change in RMS velocity between conditions might be interpreted as meaningful, though further evaluation is needed to confirm its relevance from a clinical perspective. Between no holding and symmetric holding, only the PP group had a change greater than the MID. Additionally, the small effect between symmetric and asymmetric holding in PP women were below the MID. In the ML amplitude, while the PP group had large effect sizes between no holding and holding conditions, none of the differences between conditions surpassed the MID of 2.3 mm.¹¹⁹ The interactions in ML RMS velocity and

amplitude suggest that PP women respond differently under holding conditions with the largest values appearing in asymmetrical holding.

In the AP amplitude, a significant interaction between group and condition was observed. The increase in measures across holding condition in both groups, align with previous literature that found an increase in COP metrics in the AP direction with symmetric and asymmetric holding positions.^{110, 118} The significant difference between the PP and NP women during asymmetrical holding has a small effect with magnitude differences between groups that do not surpass the MID associated with RMS amplitude.¹¹⁹ The only increase that surpassed the MID occurred between no holding and asymmetrical holding in PP women.¹¹⁹ Past research has found a relationship between pelvic asymmetries and chronic pain with a reduction in COP control and stability during quiet standing, which may indicate a possible factor associated with the observed differences between groups in response to holding positions in postpartum women.^{56, 95-97}

Our study was adequately powered to detect the MID between groups using the effect size of 0.4 for COP velocity when accounting for group variance from the data collected in this study.¹¹⁹ The minimal number of significant differences between the PP and NP groups in all COP measures suggests that the anticipated differences in COP metrics were not as large as expected. However, due to our abundance of significant interactions, indicating differences in holding responses between groups, the MID threshold in the context of PP and NP comparisons during holding conditions may need to be reevaluated to determine if there may be more appropriate levels of change in COP measures between groups that may be considered clinically meaningful.

Additionally, during the no holding condition, there were no significant differences in COP measures between PP and NP groups, which contrasts with past literature finding reduced COP metrics in postpartum women compared to nulliparous women.^{12, 13} This discrepancy may be due to our study including women with an average 8.5 months postpartum, whereas past studies included women up to 6 months postpartum, suggesting a possible return to baseline balance levels in postpartum women after 6 months.^{12, 13} Additionally, variables related to history of pain, number of births, weight of the youngest child, and physical activity, may be related to the minimal differences between groups that were initially expected to appear both during the no holding and symmetric and asymmetric holding conditions.

In addition to this observation, while not significantly different, the PP group did exhibit larger values in outcome measures, compared to the NP group, during symmetric and asymmetric holding conditions. With the inclusion of additional participants we may find that an element of the postpartum group contributes to the decrease in COP control and stability specifically during car seat holding. Possible factors that may contribute to the larger values in the PP group during holding conditions may be related to the skeletal instability and muscular weakness associated with the postpartum population. While our study was adequately powered when anticipating the MID levels of difference in outcome measures, a larger sample size may reveal more pronounced differences between groups given possible large levels of variance that may be present in either group.

When interpreting COP measures, an increase in either the RMS COP velocity or RMS COP amplitude indicate a decrease in balance.^{67, 120} More specifically, COP amplitude reflects the

ability to maintain a stable posture, an increase amplitude suggests instability because the COP travels a greater distance from the center of support, approaching the edge of the base of support.^{60, 62, 121} The COP velocity measures the control of these movements, while an increase in this metric can indicate difficulty in maintaining control of movements during quiet standing.^{61, 62, 121, 122} While holding a load, shear forces and asymmetrical loading along the spine increase, demanding greater muscle activation, and significantly heightens postural demands as well as increasing asymmetrical loading to the lower extremities. Asymmetrical lumbopelvic alignment, paraspinal responsiveness, and weakened trunk strength, and chronic pain seen to persist postpartum, may possibly be related to the differences in COP responses during holding conditions, and the group differences in vGRF symmetry we see in our study.^{56, 95-97} Our results indicate that the PP group responds differently to holding conditions compared to the NP group. The PP group experienced greater decreases in COP control and stability in the ML direction, with the most pronounced reductions occurring during asymmetric holding. Additionally, PP women showed different responses in COP stability in the AP direction compared to the NP group with significant reductions in the asymmetric holding condition.

We found significant main effects of both condition and group on peak vGRF SI. The main effect of condition is consistent with past literature showing that limb loading asymmetry increases in response to holding conditions including symmetrical and asymmetrical holding, seen in healthy adults.^{99, 123, 124} The main effect of group indicates that postpartum women experience greater asymmetry. This partially aligns with our second hypothesis that postpartum group would show significantly larger peak vGRF SI compared to NP women, with the greatest asymmetry in asymmetric holding. Past literature has determined a relationship between

asymmetrical limb loading, pelvic asymmetries, and chronic pain, which may be related to the increase asymmetry observed in postpartum women.^{99, 123} Additionally, the main effect of condition highlights the risk of increased limb loading asymmetry, potentially related to chronic pain associated with childcare related activities.⁸⁶⁻⁸⁸ The levels of the SI can also give context into how to interpret possible risks associated with conditions or differences between groups. Our average vGRF SI values are non-zero in both groups during the no holding condition, agreeing with past literature finding a high percentage of non-zero SI values in healthy adult women.⁹⁹ However, our results surpass the 10% threshold used to define SI asymmetry, previously used when assessing asymmetry during walking, suggesting a possible need to revise the baseline threshold in the context of postpartum and nulliparous comparisons while holding a car seat.

Despite these findings, the study has limitations. The removal of the symmetrical condition for two subjects (one PP and one NP) and one symmetrical trial from one other NP subject introduces inconsistencies in sample sizes included for the holding conditions. This reduction in data may affect the accuracy of condition comparisons by decreasing the amount of data used to calculate the means for each group. The current research study also did not account for factors such as the number of births or weight of youngest child, which might influence musculoskeletal health associated through cumulative degradation of stability that could be associated with multiple births or the increased level of experience with infants that are the approximate weight of the weight used in our study. and ultimately the outcome measure differences between groups. The included sample sizes for both PP and NP groups may not fully represent the general population due to small sample size and lack of diversity, as well as varying levels of

physiological health, physical activity, or sleep not accounted for in this study. Given that this was a pilot study with significant interactions, further research with larger and more diverse samples is needed to clarify these findings and better understand the impact of these factors on outcomes measures. In addition, physiological health encompasses several aspects that are crucial for balance, including muscle activity and pelvic stability. In the postpartum period, many women experience changes in muscle tone and stability that are variable from person to person and can result in altered movement patterns and decreased postural control and stability. Physical activity levels are also crucial; regular exercise enhances muscle tone, improves coordination, and increases body awareness, all of which contribute to better balance. Sleep also plays a vital role in cognitive and motor functions. Insufficient or poor-quality sleep can impair reaction times and coordination, which are essential for maintaining balance.^{125, 126} Additionally, there may be other factors related to kinematic compensations taking place during the holding conditions that could explain changes in the COP that were not addressed in this study. For example, during quiet standing, the body primarily relies on the ankle for small movements, while the hips manage larger adjustments related to the body's center of mass. In asymmetric car seat holding, individuals can compensate through lateral trunk flexion when holding the car seat at their side. This position may limit hip movement in the AP direction, relying more on the smaller ankle muscles to control AP movements. As a result, the differences observed between the PP and NP groups during the asymmetric holding condition may stem from this reliance on the smaller muscle group around the ankle, compared to the hips, in the AP direction.¹⁶

Despite these limitations, our results indicate that postpartum and nulliparous women respond differently to car seat holding conditions, with a decrease in COP control and stability as holding

condition becomes most difficult with asymmetrical holding. Our results indicate that there is an additional factor causing these different responses that may be linked to musculoskeletal health in postpartum women as well as possibly putting them at an increased risk of developing chronic pain and injury during these tasks. Additionally, our results indicate that postpartum women exhibit greater levels of asymmetrical limb loading during all holding conditions. Asymmetrical holding diminished postural control and stability in both groups, while symmetric holding resulted in a moderate decline. Asymmetric holding also induced the highest peak vGRF SI, whereas symmetric holding showed moderate values, with postpartum women exhibiting greater asymmetry compared to controls indicating possibly deleterious asymmetrical loading in the PP population and tasks that may be linked to chronic pain.⁵ Further research is required to better evaluate these risks in the postpartum population during holding a car seat. Additionally, it is important to understand the differences between PP and NP women that may contribute to their varying responses to different holding conditions, contributing factors related to group demographics, and underlying movement mechanics during the holding conditions. Gaining insight into these differences could help identify factors that put the PP population at a greater risk for developing chronic pain, ultimately aiding in the improvement of postpartum healing and health.

Chapter Three: Differences in Center of Pressure Movement and Limb Loading Symmetry between Postpartum and Nulliparous Women during Car Seat Lifting

Abstract

Each year, over 3 million women give birth, yet postpartum (PP) health often receives minimal attention beyond the first 6 weeks. Immediately following childbirth, PP women engage in frequent childcare related lifting tasks, such as lifting a car seat, which can impede post-pregnancy healing.⁵ Studies show that PP women often experience reduced paraspinal muscle activity¹⁸ and trunk extension strength¹⁷ compared to nulliparous (NP) women, which is associated with decreased postural control and stability.^{84, 85, 127} Additionally, asymmetrical pelvic tilting can contribute to chronic pain and increase shear forces in the pelvis and lower extremities during lifting tasks.⁸⁶⁻⁸⁸ Understanding PP responses, compared to NP, to daily childcare activities involving lifting a car seat may be able to reveal differences in postural challenges and limb loading that may be related to chronic pain in the PP population. The purpose of this study was to analyze the effect of group (PP and NP) and the effect of lifting condition (symmetric and asymmetric) on center of pressure (COP) movement and limb loading symmetry. It was hypothesized that PP women would experience poorer postural control, compared to NP, with the more difficult asymmetrical lift. It was also hypothesized that PP women, compared to NP, will have a higher vertical ground reaction force (vGRF) limb loading asymmetry, using the Symmetry Index (SI), with the larger values seen during asymmetric lifting. Eighteen participants were collected for each group, with a total of 36 participants. A total of 6 trials per symmetric and asymmetric lifting was collected from each participant. Using 4 force plates, a custom-built code was used to calculate the root-mean-square (RMS) COP amplitude and velocity in the medial-lateral (ML) and anterior-posterior (AP) axes, as well as the peak vGRF SI. A linear mixed effects model was used to determine interactions and effects. Our results show an interaction in AP RMS velocity ($p < 0.001$) showing a significant increase from symmetric to asymmetric and a significantly larger metric in NP compared to PP during asymmetric lifting, likely reflecting lifting technique in NP women. Our results also show main effects of condition in ML RMS amplitude ($p < 0.001$), ML ($p < 0.001$) and AP RMS amplitude ($p < 0.001$), and peak vGRF SI ($p < 0.001$). Overall, our results indicate that the more challenging condition of asymmetrical lifting increases COP movement and asymmetrical loading and may contribute to chronic pain and injury. However, further research is needed to investigate differences between PP and NP women during car seat lifting conditions.

Introduction

Each year, more than 3 million women give birth in the United States, with vaginal delivery being the most common method as of 2022.²² However, postpartum (PP) health often receives minimal attention, usually confined to a single medical assessment 6 weeks after delivery.^{5, 23} Approximately 81% of PP women experience chronic perineal pain, backaches, and urinary incontinence at 24 months postpartum.^{1, 2} Postpartum women frequently report musculoskeletal complaints such as lumbopelvic pain and lower extremity pain.^{5, 8, 89, 128} Furthermore, 20% of women continue to suffer from chronic back and pelvic pain 3 years after childbirth.³

Pelvic asymmetries are closely associated with low back and pelvic pain. Persistent asymmetrical anterior pelvic tilt and external rotation have been identified in postpartum women and can contribute to reduced postural control and stability and increase abnormal limb loading.^{5, 54, 56} Asymmetries in the pelvis can lead to asymmetrical loading of the pelvis and lower extremities, which can result in a challenges when maintaining postural stability and control and can increase the risk of chronic pain and spinal injury during lifting tasks.^{12, 13, 105} During lifting, monitoring COP is crucial for understanding how effectively an individual is adjusting their body to manage the load. Excessive or irregular COP movement during lifting can indicate suboptimal lifting techniques or difficulties in controlling the load. Postpartum women may be particularly vulnerable to these issues due to changes in pelvic alignment and muscle strength.¹²⁹ Compared to nulliparous women, postpartum women exhibit trunk extension weakness and reduced paraspinal muscle responsiveness during childcare related tasks, such as lifting a car seat.^{17, 18} Paraspinal muscles and trunk extension strength are crucial for maintaining spinal

stability during lifting tasks.^{100, 130} Weakness in these muscles can lead to increased lumbopelvic pain and a greater risk of injury.^{18, 131}

Immediately following childbirth, postpartum women engage in lifting tasks, such as handling a car seat, without adequate guidance on safe techniques.^{18, 59, 102} Many mothers prioritize their children's needs over their own health, especially when it comes to convenience and safety during childcare related lifting.⁵⁹ As their child grows, the increasing weight and frequency of lifting elevate the risk of developing spinal injuries and chronic pain.¹³² Lifting of a car seat can include twisting or bending of the back, which increases shear strain and injury, contributing to the development of chronic pain.¹³³ The repetitive nature of these lifting tasks delays post-pregnancy musculoskeletal healing and can contribute to deficits in postpartum musculoskeletal function.⁶⁰⁻⁶² Postpartum women may face greater challenges and risks due to delayed healing and decreased support of the spine and pelvis during lifting tasks of a car seat.^{104, 134, 135} However, there is limited research that investigates childcare related car seat lifting methods in postpartum women that includes understanding COP movement and limb loading symmetry. Examining these in postpartum women, compared to nulliparous women, can identify specific biomechanical challenges in this population during daily tasks involving car seat lifting.

The aim of this research was to determine the effect of two different lifting conditions (symmetrical and asymmetrical) and group (postpartum and nulliparous) on balance and limb loading symmetry. This study hypothesized that PP women would experience poorer postural control, demonstrated by an increase in center of pressure (COP) root-mean-square (RMS)

amplitude and velocity in the anterior-posterior (AP) and medial-lateral (ML) axes, with the greatest difficulty occurring during asymmetrical lifting due to challenges in responding to asymmetrical loads and the possible influence of pelvic and spinal instability. Additionally, this study hypothesized that PP women, compared to NP women, would experience a greater limb loading asymmetry, as measured by the Symmetry Index (SI) from vertical ground reaction forces (vGRFs).

Materials and Methods

Participants

A total of 36 participants consisting of 18 postpartum women and 18 nulliparous controls were recruited and consented through the Virginia Tech Institutional Review Board approved research study (IRB #20-1085). Participants were included if they did not have any musculoskeletal, neurological disorders, or medical conditions that affect balance, were not currently pregnant, had never sustained an injury in the leg that limited their physical activity for more than 48 hours, had no history of a serious injury or surgery in one or more lower extremities, and were able to perform daily tasks involving lifting of an external weight. Additional inclusion criteria included for postpartum participants involved having a vaginal delivery¹⁰⁶, having never had grade 4 perineal tearing¹⁰⁶, and having given birth in the last 6 to 12 months. The inclusion criteria related to vaginal delivery and perineal tearing were included to reflect safe child-care-related activity guidelines for women having experience a caesarean delivery and high grade tearing.^{106, 107}

Testing Protocol

Prior to any testing, all participants signed a consent form approved by the Virginia Tech Institutional Review Board. Participant demographic information was collected and stored using REDCap (Research Electronic Data Capture) electronic data capture tools hosted by Virginia Tech.^{108, 109} Demographic information included self-reported age, sex assigned at birth, upper limb dominance determined by the hand used to write with¹¹⁰, as well as the preferred limb used for asymmetrical lifting and holding. For the NP group, the dominant arm was used as the preferred limb. This was selected because NP women typically do not engage in car seat lifting tasks. Utilizing the dominant arm ensured standardization and consistencies in comparisons with natural lifting patterns in PP women. Additional demographic information recorded from postpartum participants included number of months postpartum, number of children they had given birth too, and their youngest child's weight.

Four in-ground AMTI force plates (BP600- 600, AMTI, Watertown, MA, USA) collected ground reaction forces and center of pressure at 1190 Hz. Participants stood barefoot on two in-ground force plates. They stood feet shoulder-width apart at a distance equal to 20% of their dominant limb or preferred limb away from a car seat on the floor in front of them, sitting on top of two additional in-ground force plates. The car seat was loaded with 10kg of additional weight to simulate the average weight of a nine month old infant (approximately 10kg represents the 95th percentile weight for a nine month old male and female infant).⁸ With the added ankle weights, the total weight of the car seat was 13.5 kgs. Tape was used to ensure consistent foot placement placed at the forefoot, hindfoot, and lateral sides of the feet. Tape was also used to ensure consistent placement of the external weight during every trial for each participant. Participants completed 6 trials of 2 lifting conditions each: symmetrical and asymmetrical.

Lifting condition ordering was randomized per participant using the random number generator in MATLAB. In the NP and PP groups, 8 women performed the symmetrical lifting first with 10 participants performed the asymmetrical lift first. To minimize the potential influence of fatigue, a 1-minute rest period was provided between trials with a 2 minute rest period provided between conditions. During symmetrical lifting, participants lifted the car seat with both hands, placed at the widest parts of the car seat (Figure 10). From floor level, participants lifted to approximately hip height.

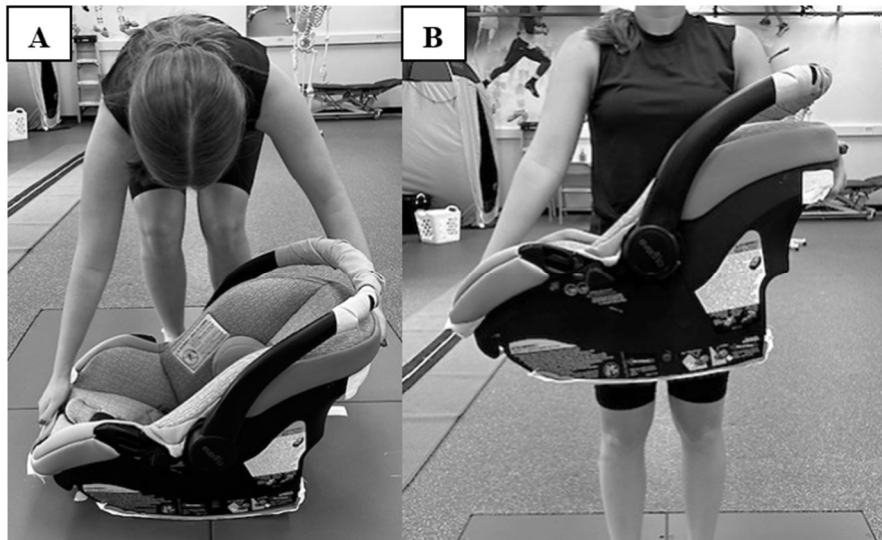


Figure 10: Demonstration of a symmetrical lift (A) From the floor, (B) To hip height

During asymmetrical lifting, participants lifted the car seat with their preferred limb in postpartum women, dominant limb in nulliparous women, using their inner elbow in a scooping like motion lifting from floor level to approximately hip height (Figure 11). Participants were asked to keep their feet in place during each lifting condition. Due to the fact that the shape and weight distribution of the ankle weights and the car seat do not create a truly symmetrical load, the naming conventions of symmetrical (using two hands) and asymmetrical (using one arm)

were used to differentiate between the position of the car seat relative to the middle of the body during the lifting conditions.

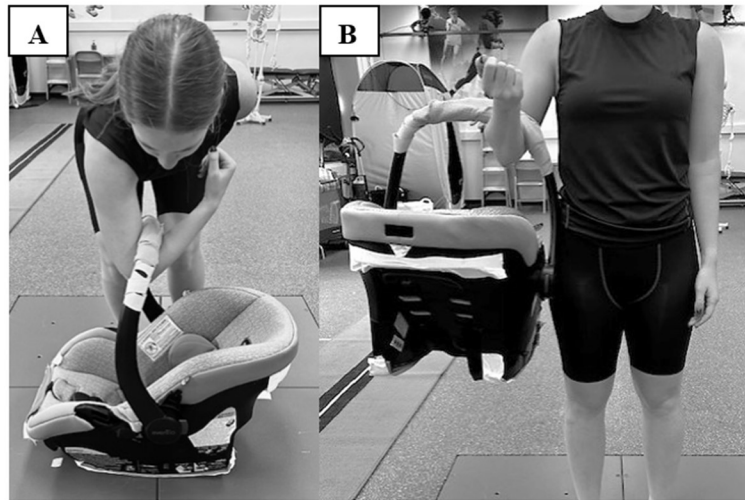


Figure 11: Demonstration of an asymmetric lift (A) From the floor, (B) To hip height

Data Analysis

Filtering of GRF data used a cutoff frequency of 20 Hz using a fourth-order recursive low-pass Butterworth filter.¹¹¹ This cutoff frequency was determined using a power spectral density graph from the GRF data during a lifting condition. The 20 Hz cutoff was selected to include higher frequency signals produced by rapid movements during lifting trials while reducing the influence of higher frequency noise.¹¹¹ A custom MATLAB script was used to first detect when the combined force readings from the two force plates, where the car seat was sitting on initially, dropped below 10% of the total weight of the loaded car seat. At this instance, using the 4 time-synched force plates, all connected through Qualisys during data collection, the beginning of the lifting trial was identified (Figure 12).

During the lifting motion, the ground reaction forces measured by the two force plates the participants stood on increased rapidly, reaching a peak approximately 1.25 times the total weight of the body plus car seat. After this peak, the rate at which the force changed decreased, and the forces began to stabilize around the combined weight of the body plus the car seat. This stabilization began to occur as the participant neared full hip extension and slowed down to achieve a stable upright posture. To analyze this, the total vGRF was examined in groups of 20 data points at a time. The end of the lifting phase was identified when all 20 data points fell within +/- 1% range of the combined body weight and car seat. The first data point within this stable range was used to mark the end of the lifting phase. After reaching the upright posture, participants often adjusted the car seat for comfort, which caused additional fluctuations in the vGRFs. These post lifting adjustments were not considered part of the lifting phase analysis since the participant was already upright. By analyzing data in 20-point segments, we could clearly differentiate between the lift phase and subsequent slower adjustments, as faster movements caused a wider range of point values within each 20-point segment compared to the slower movements of weight adjustment (Figure 12).

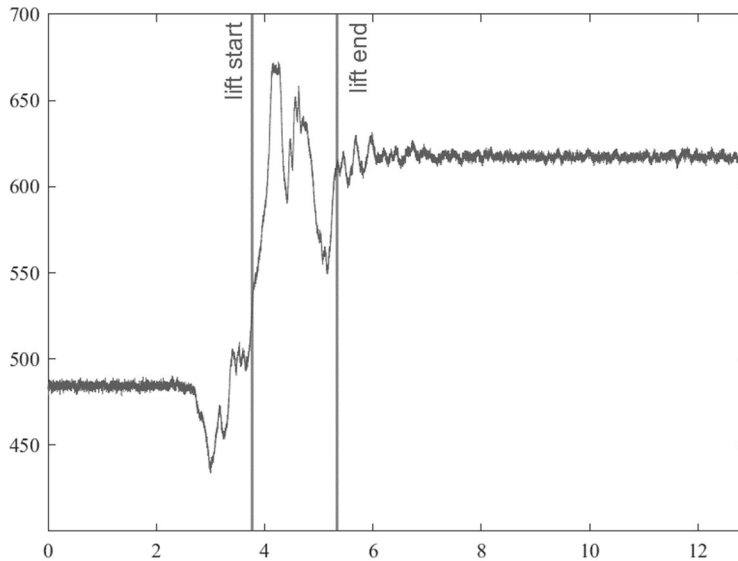


Figure 12: vGRF (N) vs Time (s) graph with lifting phase identification

The center of pressure was calculated between the two force plates that the participants stood on. Using the methods adopted from Winter¹¹², the net COP was calculated by combining the vGRF and COP from the force plates. This calculation followed the same methods demonstrated chapter 2 equation 1.¹¹² The COP was calculated in the medio-lateral (ML) and anterior-posterior (AP) directions and demeaned. The instantaneous velocity in the ML and AP directions was calculated following the method demonstrated in chapter 2 equation 2.⁷⁰ Every sample of the COP amplitude signal was used when calculating the RMS amplitude demonstrated in chapter 2 equation 3.⁷¹ The RMS COP velocity and amplitude were calculated using the methods of demonstrated in chapter 2 equation 4.^{68, 71, 113}

To assess vertical ground reaction force (vGRF) symmetry, the Symmetry Index (SI) was used.¹¹⁴ The SI, adopted by Robinson et al.¹¹⁴, has proven to be a dependable and consistent measure of symmetry across different tasks.^{80, 114} The SI was calculated using similar methods to Robinson et al., demonstrated with chapter 2 equation 5. The *NPL* refers to the non-preferred

limb, or the non-dominant limb in controls, while the *PL* refers to the preferred limb, or the dominant limb in controls. The SI is unbounded meaning there is no limit to the maximum value that can be obtained from the calculation. A calculation of 0 indicates perfect symmetry with a threshold of +/- 10% that is generally used to determine when values can be determined as asymmetric.⁷⁶ Using the vGRFs from both limbs, the SI was calculated from every sample during a lifting trial. The peak SI was determined by taking the maximum of the absolute values of the SI, during a trial. While a value of 0 indicates perfect symmetry, a greater value in either direction indicates greater asymmetry. Positive values mean that the non-preferred limb or non-dominant limb experienced a higher vGRF at the instance of peak symmetry, while negative values mean the preferred or dominant limb experienced a larger vGRF. For statistical analysis, the absolute value of the SI was used. The outcome measures of COP RMS velocity and amplitude in the ML and AP directions and the peak vGRF SI were calculated for all conditions and all trials and were included in our statistical analyses.

Statistical Analysis

The NP and PP demographics of age, height, weight, and BMI were compared using an independent t-test, included in Table 3. The outcome measures of COP RMS velocity and amplitude in the ML and AP axes were included in a linear mixed effects (LMEM) model that identified the fixed effects as group and condition and random effects as participants. The LMEM was performed in JMP (SAS, Cary, NC), with an alpha level of 0.05, to determine interactions and main effects.¹¹⁶ Upon detecting an interaction, the Tukey HSD was used to interpret pairwise post-hoc pairwise comparisons. When a main effect of lifting condition or group was detected, an LS Means student t-test post-hoc testing was performed. Effect size

levels were used to interpret magnitudes of difference between conditions using the standard indices of 0.2 identified as a small effect, 0.5 as medium, and 0.8 as large.¹¹⁷

Results

Demographic comparisons between groups are included in Table 1. A total of 17 NP women (94.4%) were right-hand dominant while only one participant (5.6%) was left-hand dominant. Averages of postpartum specific demographics including the number of children, weight of youngest child, and months postpartum are included in Table 5.

Table 4: Group demographics, mean ± SD

	Age (years)	Height (m)	Weight (kg)	BMI (kg/m ²)
Nulliparous (n=18)	26.8 ± 3.10	1.65 ± 0.07	70.86 ± 13.33	26.02 ± 4.18
Postpartum (n=18)	30.5 ± 3.52	1.64 ± 0.07	71.27 ± 11.21	26.55 ± 4.31
<i>p-value</i>	<0.001*	0.319	0.461	0.365

**p-value < 0.001, NP and PP group differences*

Four PP participants (22.22%) used their non-dominant as their preferred limb during asymmetrical lifting while 14 participants (77.77%) used their dominant limb. Eight of the PP women had only given birth once (primiparous) while 10 of them had given birth multiple times (multiparous).

Table 5: Demographics of postpartum group, mean \pm SD

	Postpartum (n=18)
Months Postpartum	8.56 \pm 2.23
Number of children	1.72 \pm 0.75
Weight of youngest child (kg)	8.83 \pm 2.52
Preferred Carrying Side	Dom: 14 Non-dom: 4
Dominant Limb	Right: 17 Left: 1

The results for all outcomes measures are consolidated in Table 6.

Table 6: Lifting Condition Results

Measurement Type	Group	Condition	Mean \pm SD	p-value	Effect Size – symmetric
ML COP RMS Velocity (mm/s)	-	Symmetric	133.04 \pm 30.25		
		Asymmetric	143.39 \pm 32.45	< 0.001*	
AP COP RMS Velocity (mm/s)	PP	Symmetric	81.18 \pm 25.48		
		Asymmetric	109.75 \pm 36.55	< 0.001*	1.41
	NP	Symmetric	80.26 \pm 19.01		
		Asymmetric	130.62 \pm 34.37	< 0.001* 0.002**	1.61
ML COP RMS Amplitude (mm)	-	Symmetric	34.16 \pm 9.59		
		Asymmetric	38.51 \pm 8.74	< 0.001*	
AP COP RMS Amplitude (mm)	-	Symmetric	10.04 \pm 3.99		
		Asymmetric	16.52 \pm 5.64	< 0.001*	
Peak vGRF SI (%)	-	Symmetric	40.24 \pm 15.79		
		Asymmetric	72.89 \pm 26.09	< 0.001*	

* $p < 0.001$, difference between symmetric lifting condition

** $p = 0.002$, significant increase compared to PP group

ML COP RMS velocity

There was no interaction ($p = 0.55$), main effect of group ($p = 0.97$) with a small effect size of 0.07, or effect of age ($p = 0.55$). A main effect of condition, however, was found ($p < 0.001$).

The ML RMS velocity was significantly larger ($p < 0.001$) with asymmetric lifting (143.39 ± 32.45 mm/s) compared to symmetric lifting (133.04 ± 30.25 mm/s).

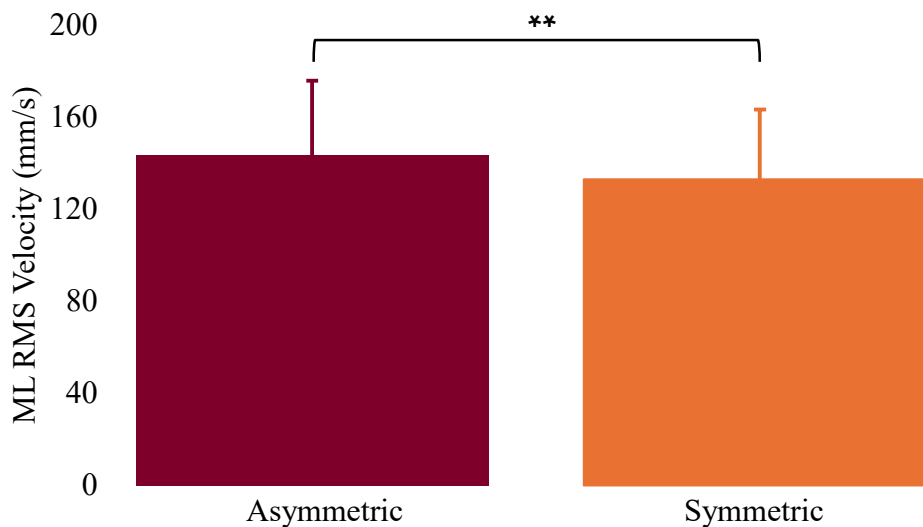


Figure 13: Main effect of task for ML RMS velocity; ** p -value < 0.001

AP COP RMS velocity

An interaction was found between group and condition ($p < 0.001$). The AP RMS velocity for asymmetric lifting (NP: 130.62 ± 34.37 mm/s; PP: 109.75 ± 36.55 mm/s) was significantly larger (NP: $p < 0.001$; PP: $p < 0.001$) than symmetric lifting (NP: 80.26 ± 19.01 mm/s; PP: 81.18 ± 25.48 mm/s) in both groups. Both groups showed large effects between conditions with NP showing an effect of 1.61 and PP showing an effect of 1.41.¹¹⁷ Additionally, the NP group was significantly larger than the PP group in the asymmetric lifting condition ($p = 0.002$).

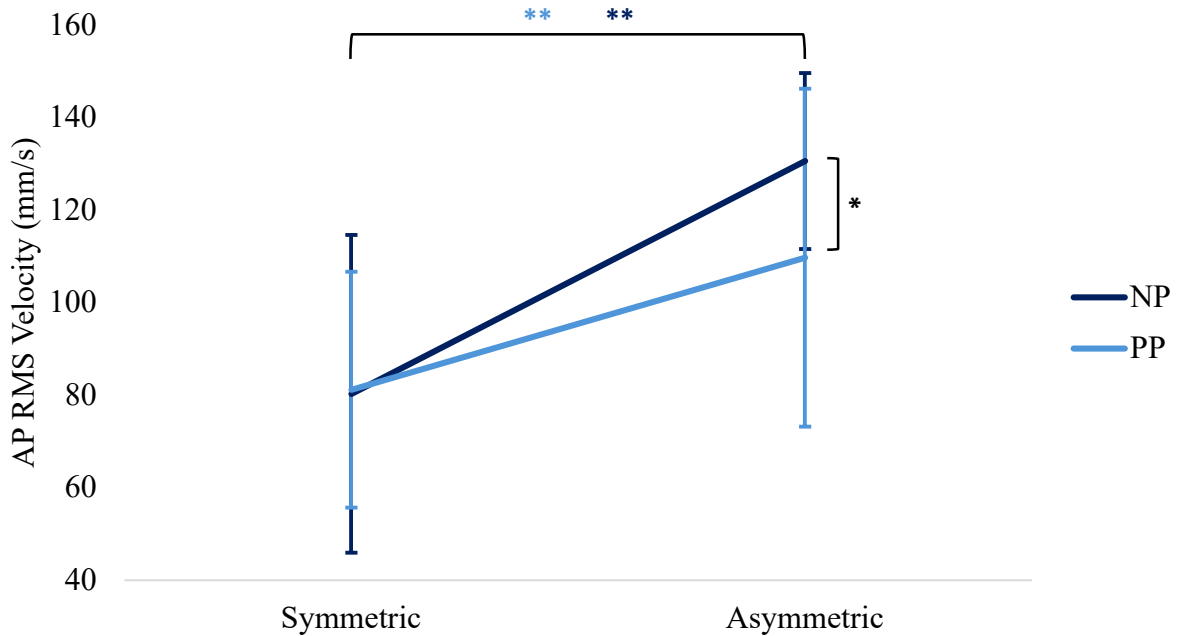


Figure 14: Interaction plot for AP RMS velocity; ** p -value < 0.001, * p -value = 0.002

ML COP RMS amplitude

There was no significance found in the interaction ($p = 0.51$), effect of group ($p = 0.34$) showing a small effect size of 0.1, or in the effect of age ($p = 0.49$). However, there was a main effect of condition ($p < 0.001$). The amplitude was significantly larger for asymmetric lifting compared to symmetric lifting (Asymmetric: 38.51 ± 8.74 mm; Symmetric lifting: 34.16 ± 9.59 mm; $p < 0.001$).

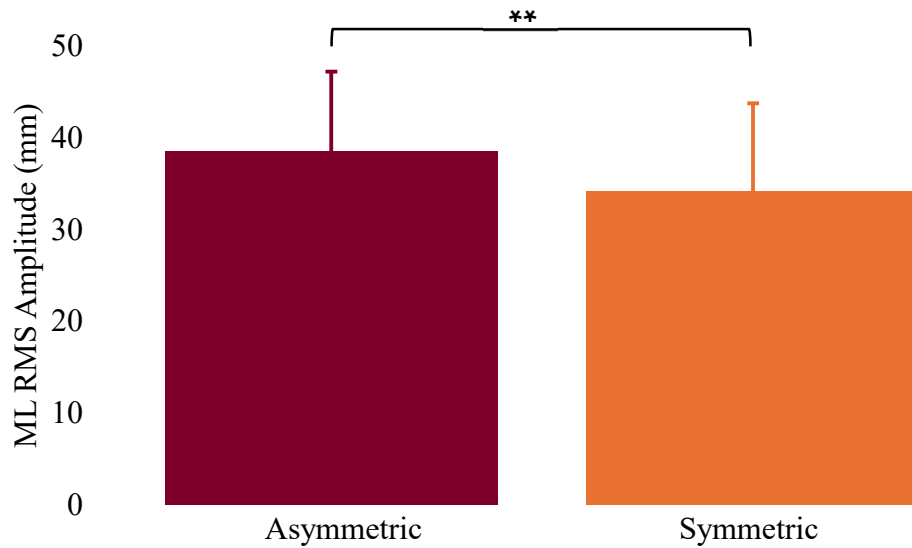


Figure 15: Main effect of task for ML RMS amplitude; $**p < 0.001$

AP COP RMS amplitude

There was no significance found in the interaction ($p = 0.18$), effect of group ($p = 0.76$) with a small effect of 0.1, or effect of age ($p = 0.53$). A main effect of task was found ($p < 0.001$). The AP RMS amplitude was significantly larger for asymmetric lifting compared to symmetric lifting (Asymmetric: 16.52 ± 5.64 mm; Symmetric lifting: 10.04 ± 3.99 mm; $p < 0.001$).

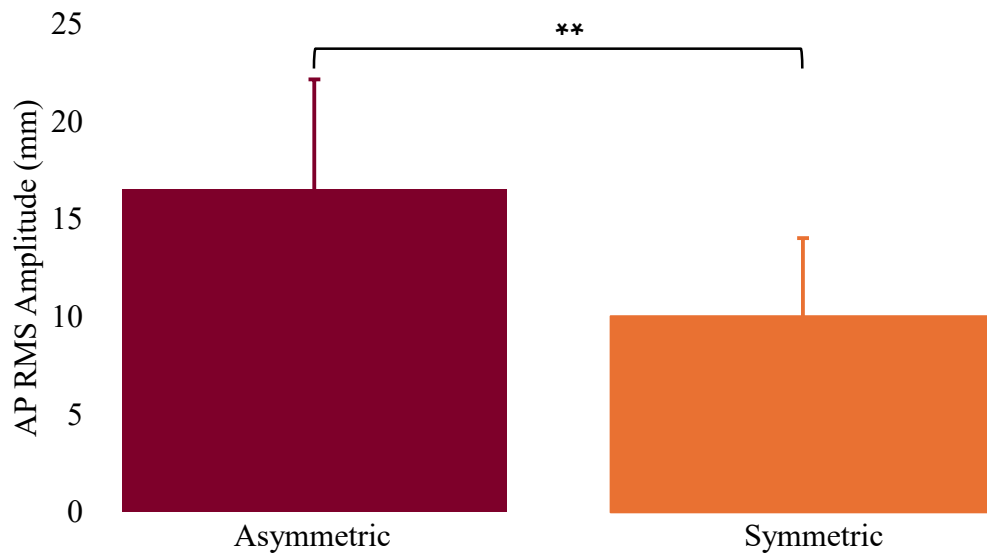


Figure 16: Main effect of task for AP RMS amplitude; $**p\text{-value} < 0.001$

Peak vGRF SI

There was no significance found in the interaction ($p = 0.11$) or in effect of group ($p = 0.52$) with a small effect size of 0.1. Main effect of task ($p < 0.001$) was detected. The peak SI was larger for asymmetric compared to symmetric lifting (Asymmetric: 72.89 ± 26.09 %; Symmetric: 40.24 ± 15.79 %; $p < 0.001$).

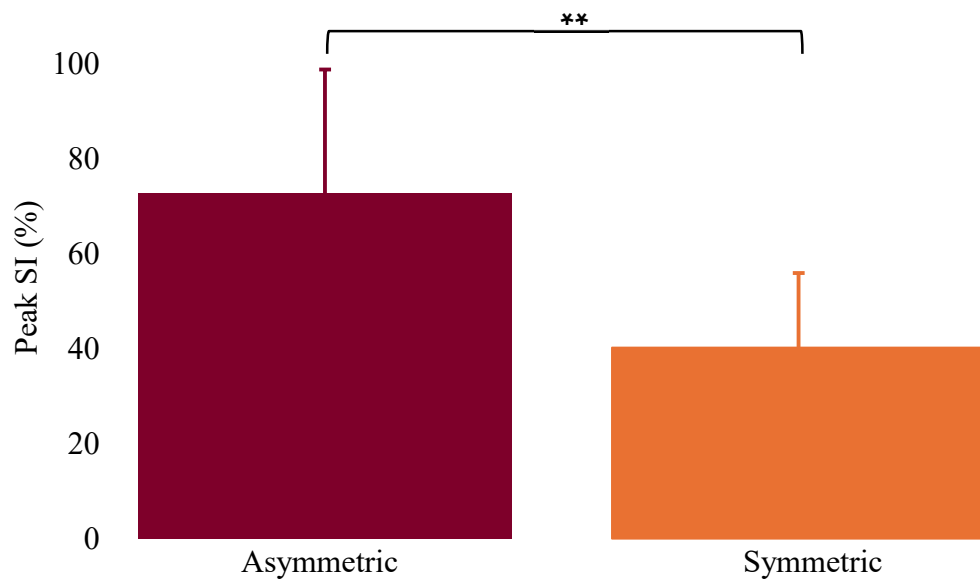


Figure 17: Main effect of task for Peak SI; ** $p < 0.001$

Discussion

The purpose of this study was to determine the effect of group (NP, PP) and lifting condition (asymmetric, symmetric) on COP movement and peak vGRF symmetry. Our results do not support our first hypothesis that PP women would have poorer COP movement, seen through an increase in COP RMS amplitude and velocity in both AP and ML directions, as the lifting condition becomes more challenging with asymmetrical lifting. However, our data demonstrates meaningful results.

In the AP RMS velocity, an interaction shows an increase in values with asymmetrical lifting in both groups as well as a significant increase in NP, compared to PP, during asymmetrical lifting. It is possible that differences in kinematics during the lift may have resulted in the differences in the magnitude of AP RMS velocity.¹³⁶ In our research study, lifting the carrier from the floor with your elbow requires a larger range of motion, compared to having to lift with just the hand.^{67, 137, 138} Due to this greater motion, and potential unfamiliarity with lifting a car seat in this manner, the control group may have performed drastically different lifting techniques compared to PP women who are believed to perform this task more regularly. Past research has found that variations in levels of squatting, or bending at the knees, can create changes in the COP trajectory in the AP axis.¹³⁶ In addition to this, past literature has also demonstrated that when incorporating a forward lean into a squat, COP measures increase in the same direction as the lean and may explain a motion that is leading the group differences we see during asymmetrical lifting in our study.¹³⁶

Our findings indicate that lifting conditions influence COP measures. Our findings align with past literature indicating lateral increases in COP metrics in response to asymmetric lifting due to the lateral position of the load.¹³⁸ When interpreting COP metrics in the context of a lifting task, COP amplitude reflects how the body shifts during the demands of the lift and the changing posture, while the COP velocity provides context into how quickly these movements are occurring during the lift.^{67, 120} Our results show that asymmetrical lifting increases challenges to stability in both axes of movement (AP and ML). Our results also show that asymmetrical lifting increases challenges to control resulting in faster movements in response to controlling the load

and movement, which may indicate differences in lifting techniques or postures adopted by NP women compared to PP women, seen in the significantly larger COP RMS velocity in the AP direction.

The minimal group differences can indicate that postpartum women are not as different from nulliparous women to the level we initially anticipated. When considering our small differences in peak vGRF from the data collected, our study is not adequately powered to determine group differences. Post hoc testing in determining the sample size needed to consider a difference of about 5% SI in group differences when considering group variance from our data, in generating a conservative effect size with adequate power, a sample size of approximately 106 would be required.¹³⁹ This metric was chosen for sample size determination because vGRF symmetry significantly affects spinal loading and injury risk during lifting tasks.^{66, 140, 141} In our study, it is possible that group variance may have obscured potential group differences. Additionally, possible factors may have a contribution to outcome measures like lifting technique, strength, or postpartum demographics relating to the number of children they have given birth too, months postpartum, or weight of their youngest child.

In peak vGRF SI, statistical analyses revealed a main effect of condition, with asymmetric lifting producing the highest level of asymmetry. This finding does not align with our hypothesis that PP women would exhibit greater vGRF asymmetry with the transition from symmetric to asymmetric lifting. The main effect of condition on peak vGRF SI indicates that asymmetrical lifting elicits greater asymmetrical limb loading which may increase loading imbalances in the pelvis and spine that contribute to chronic pain.^{99, 123} This information can be used to inform the

potential risks associated with childcare related lifting of a car seat. Additionally, past literature has determined a general threshold of determining asymmetry as when greater than 10%.^{76, 80} Our results exhibit symmetry levels above 10% for both lifting conditions. This may indicate the need for changes in interpretation of asymmetry level thresholds, when in the context of car seat lifting tasks in PP and NP women.

This study has identified an interaction and significant effects of condition, though several limitations should be addressed. This study did not account for possible influences of postpartum demographics including number of children, weight of their youngest child, or number of months postpartum. The sample sizes in both groups limit the possibility of the samples representing the general population due to a lack of racial diversity present in the surrounding area as well as other factors related to physical activity, sleep, and physiological health differences between groups that were not considered. Additionally, the controls were instructed to only use their dominant hand during the lift while postpartum women used their preferred arm. Not allowing for the use of the preferred arm in controls may introduce an influence of weakness or unfamiliarity with using the dominant arm for this type of task in controls. The current research study also did not account for group differences in movement variability during lifting¹⁴² as well as the type of lift performed by each participant. Different lifting types include stoop, squat, or a combination of both and may influence results. Additionally, the lab environment where the data was captured may not represent the natural environments and postures encountered by postpartum participants, particularly considering the potential for distractions and multitasking. Additionally, the nature of the lifting tasks should be considered. Symmetrical lifting involved placing two straight arms on either end of the car seat, while asymmetrical lift required a more

exaggerated motion with one arm under the car seat handle. This difference in lifting technique may have influenced condition related outcome measures and should be considered for future studies.

Overall, asymmetric lifting introduced less stability, exhibited by greater distances traveled by the COP from the center of support, and control of these movements, compared to symmetrical lifting. Asymmetrical lifting also induced the highest peak vGRF SI, compared to symmetrical lifting.

These findings suggest that asymmetrically lifting a car seat increases asymmetrical loading on the body and elevates postural demands, which can contribute to chronic pain and injury.^{5, 66}

Additionally, such lifting types might be particularly problematic for individuals with compromised balance and musculoskeletal asymmetries due to the increased loading imbalances and postural challenges. Further research is needed to understand how these risk factors may vary between postpartum and nulliparous women, and to identify the specific factors that contribute to these differences during lifting conditions.

Chapter 4: Conclusion

Pregnancy induces profound changes in the pelvis, lumbar spine, and lower extremities, which continue to affect postpartum women, often leading to chronic pain that persists up to 3 years after birth.^{3, 31, 34, 37} Research shows that women with chronic pain frequently experience differences in postural control^{11, 143, 144}, compared to controls, and changes in asymmetrical pelvic and limb loading¹⁰⁵. Altered postural balance reflects the ability to maintain an upright posture, highlighting potential weaknesses in terms of control and stability of the body during upright stance.^{67, 120} Additionally, changes in asymmetrical limb loading can increase the risk of joint degradation or injury in the lumbopelvic area and lower extremities.^{99, 123} Changes in postural control and limb loading in postpartum women may indicate musculoskeletal challenges following pregnancy, potentially increasing the risk of injury and chronic pain compared to women who have never been pregnant during strenuous daily activities including childcare holding and lifting.^{5, 90, 91, 96, 105}

The first purpose of this study was to examine the effect of group (PP, NP) and holding condition (no load, symmetrical, asymmetrical) on balance and limb loading. The no holding condition consists of standing with no load while the symmetrical holding included the use of two hands in holding the car seat in front of the body while asymmetrical holding required the use of one hand to hold the car seat at the side of the body. Our results indicate that the PP and NP groups show different strengths and magnitudes of change in COP metrics across the holding conditions. The two groups differed in AP RMS amplitude during asymmetrical loading with group differences in peak vGRF SI overall. Our results also demonstrate that asymmetric holding resulted in the largest COP values and peak vGRF SI values. Our results indicate the need to continue to

examine differences in postpartum and nulliparous women during holding conditions to better understand potential risk factors for musculoskeletal pain and injury. Prolonged ligament laxity, pelvic misalignment, and muscle weakness may increase the risk of pain and injury in postpartum women during car seat holding activities.^{25, 28, 51, 52} Impaired resolution of musculoskeletal changes and pelvic asymmetries, that have been seen to be present in postpartum women, may be possible contributors to the differences in responses to holding conditions in the PP women.^{5, 54, 56} There are, however, factors relating to kinematics that may have influenced results during car seat holding. These factors should be examined in future research to understand how or if these measures may be explained through lower extremity joint-specific compensations that may be occurring during a holding task.

The second purpose of this study was to examine the effect of lifting condition (symmetrical, asymmetrical) and group (PP, NP) on postural control and limb loading symmetry. The lifting conditions included lifting a weighted car seat from the floor to hip height symmetrically, using both hands in front of the body, and asymmetrically, using one arm by the side. Our results indicate that the ML COP velocity, AP and ML amplitude, and peak SI all have a main effect of condition with asymmetrical lifting having the largest values. Our results also exhibited an interaction between group and condition for AP COP velocity with asymmetrical lifting exhibiting greater values, and the NP group exhibiting a greater value during asymmetrical lifting that may be more representative of the lifting technique used during asymmetrical lifting. Our results demonstrate that asymmetrical lifting increases COP movement as well as limb load asymmetry. This is likely due to the increase in postural demands and difficulty during asymmetrical lifting due to the increase in shear forces and difficulty in the required motion for

the lift.⁶⁰⁻⁶² The limited group specific differences within conditions may emphasize the possibility that postpartum women do not differ to the magnitude as initially anticipated as well as the fact that a larger sample size is needed to reliably group differences within conditions (preliminarily determined using the vGRF SI effect size). In addition, our data exhibits large standard deviations in all measures for both groups, which further indicates the need to increase the sample size to better estimate an average for each measure during all conditions and explore group-specific differences within holding and lifting conditions that may give insight into biomechanical responses during specific conditions. Regardless of this, these results highlight the altered balance and limb symmetry patterns associated with lifting conditions with asymmetrical lifting exhibiting the greatest values.

In the future, it would be beneficial to develop a study that may consider a wider range of group demographics to provide a more reliable interpretation of how balance and limb loading differ between postpartum women and nulliparous women and the influence of certain factors, possibly including postpartum related demographics such as number of children or weight of their youngest child, as well as physical activity and sleep in the 24 hours. Additional limitations of this study include the inability to compare the included sample to the general population of controls and postpartum women due to the small sample included. This lack in diversity is present in races and in demographics relating to overall health, including both physical and psychological health. Additional limitations of this study include the lack of control for the use of a preferred lifting arm in controls during asymmetrical lifting and holding, introducing an aspect of weakness and unfamiliarity of using this arm for this type of task. Additionally,

individuals can perform different techniques for lifting depending on how they bend and extend their body and can influence our results.

Despite limitations, these findings indicate that postpartum women have different levels of postural challenges and limb loading symmetry responses when it comes to maintaining an upright posture during car seat holding as well as a changes in these metrics associated with lifting conditions. The discrepancies in interactions detected for holding and lifting conditions is likely due to the great influence of the lifting motion on COP movement. During car seat holding, postpartum related factors of pelvic instability or muscular weakness may contribute to the differences in balance and limb loading we see during holding positions. This research indicates the need to continue to examine holding and lifting mechanics in the postpartum population, compared to nulliparous women, to better identify how the postural challenges and limb loading asymmetry responses to holding a car seat may be possible risk factors for pain as well factors that may contribute to these differences. In identifying risk factors, recommendations for safe techniques and daily task guidelines can be determined and implemented to improve postpartum health and safety during car seat loading and lifting conditions of daily life.

References

1. Elflein J. Births in the U.S.: Statista 2024.
2. Thompson JF, Roberts CL, Currie M, et al. Prevalence and persistence of health problems after childbirth: associations with parity and method of birth. *Birth*. 2002;29(2):83-94.
3. Norén L, Östgaard S, Johansson G, et al. Lumbar back and posterior pelvic pain during pregnancy: a 3-year follow-up. *European spine journal*. 2002;11:267-271.
4. Gutke A, Josefsson A, Öberg B. Pelvic girdle pain and lumbar pain in relation to postpartum depressive symptoms. *Spine*. 2007;32(13):1430-1436.
5. Fitzgerald CM, Segal N. *Musculoskeletal health in pregnancy and postpartum*. Switz Springer. 2015.
6. Osterman MJ, Hamilton BE, Martin JA, et al. Births: Final data for 2020. 2022.
7. Romano M, Cacciatore A, Giordano R, et al. Postpartum period: three distinct but continuous phases. *Journal of prenatal medicine*. 2010;4(2):22.
8. Division of Nutrition PA, and Obesity. Using the WHO growth charts. Centers for Disease Control and Prevention. 2015.
9. Borg-Stein J, Dugan SA. Musculoskeletal disorders of pregnancy, delivery and postpartum. *Phys Med Rehabil Clin N Am*. 2007;18(3):459-476, ix.
10. Öztürk G, Geler Külçü D, Aydoğ E, et al. Effects of lower back pain on postural equilibrium and fall risk during the third trimester of pregnancy. *The Journal of Maternal-Fetal & Neonatal Medicine*. 2016;29(8):1358-1362.
11. Caffaro RR, França FJR, Burke TN, et al. Postural control in individuals with and without non-specific chronic low back pain: a preliminary case-control study. *European spine journal*. 2014;23:807-813.
12. Opala-Berdzik A, Błaszczuk JW, Bacik B, et al. Static Postural Stability in Women during and after Pregnancy: A Prospective Longitudinal Study. *PLoS One*. 2015;10(6):e0124207.
13. Butler EE, Colón I, Druzin ML, et al. Postural equilibrium during pregnancy: decreased stability with an increased reliance on visual cues. *American journal of obstetrics and gynecology*. 2006;195(4):1104-1108.
14. Inanir A, Cakmak B, Hisim Y, et al. Evaluation of postural equilibrium and fall risk during pregnancy. *Gait & posture*. 2014;39(4):1122-1125.
15. McGregor A, Hukins D. Lower limb involvement in spinal function and low back pain. *Journal of back and musculoskeletal rehabilitation*. 2009;22(4):219-222.
16. Runge C, Shupert C, Horak F, et al. Ankle and hip postural strategies defined by joint torques. *Gait & posture*. 1999;10(2):161-170.
17. Adele Stewart B. Women, ergonomics and back disorder: how home based childcare work may augment the risk of lower back disorder in pregnant and postpartum women. 2020.
18. Brown H, Paul L, Hislop J, et al. Erector spinae activity during three methods of lifting a baby car seat in postnatal women and matched controls. *Physiotherapy*. 2004;90(4):204-209.
19. Granacher U, Gollhofer A, Hortobágyi T, et al. The importance of trunk muscle strength for balance, functional performance, and fall prevention in seniors: a systematic review. *Sports medicine*. 2013;43(7):627-641.
20. Simonds AH, Abraham K, Spitznagle T. Clinical Practice Guidelines for Pelvic Girdle Pain in the Postpartum Population. *Journal of Women's Health Physical Therapy*. 2022;46(1):E1-E38.

21. Lomaglio MJ, Eng JJ. Muscle strength and weight-bearing symmetry relate to sit-to-stand performance in individuals with stroke. *Gait & posture*. 2005;22(2):126-131.
22. Michelle J.K. Osterman MHS, Brady E. Hamilton, Ph.D., Joyce A. Martin, M.P.H., Anne K. Driscoll, Ph.D., and Claudia P. Valenzuela, M.P.H. Births: Final Data for 2022. *National Vital Statistics Reports*. 2024;73(2).
23. Borders N. After the afterbirth: a critical review of postpartum health relative to method of delivery. *Journal of midwifery & women's health*. 2006;51(4):242-248.
24. Maclennan A, Green R, Nicolson R, et al. Serum relaxin and pelvic pain of pregnancy. *The Lancet*. 1986;328(8501):243-245.
25. Reese ME, Casey E. Hormonal influence on the neuromusculoskeletal system in pregnancy. *Musculoskeletal health in pregnancy and postpartum: an evidence-based guide for clinicians*. 2015:19-39.
26. Albert HB, Godskesen M, Westergaard JG. Incidence of four syndromes of pregnancy-related pelvic joint pain. *Spine*. 2002;27(24):2831-2834.
27. Schauburger CW, Rooney BL, Goldsmith L, et al. Peripheral joint laxity increases in pregnancy but does not correlate with serum relaxin levels. *American journal of obstetrics and gynecology*. 1996;174(2):667-671.
28. Ireland ML, Ott SM. The effects of pregnancy on the musculoskeletal system. *Clinical Orthopaedics and Related Research®*. 2000;372:169-179.
29. Arnold C, Van Bell C, Rogers V, et al. The relationship between serum relaxin and knee joint laxity in female athletes. *SLACK Incorporated Thorofare, NJ* 2002:669-673.
30. To W, Wong M. Factors associated with back pain symptoms in pregnancy and the persistence of pain 2 years after pregnancy. *Acta obstetricia et gynecologica Scandinavica*. 2003;82(12):1086-1091.
31. Lou S-Z, Chou Y-L, Chou P-H, et al. Sit-to-stand at different periods of pregnancy. *Clinical Biomechanics*. 2001;16(3):194-198.
32. Dumas G, Reid J. Laxity of knee cruciate ligaments during pregnancy. *Journal of Orthopaedic & Sports Physical Therapy*. 1997;26(1):2-6.
33. Hewat RJ, Ellis DJ. A comparison of the effectiveness of two methods of nipple care. *Birth*. 1987;14(1):41-45.
34. Heckman JD, Sassard R. Musculoskeletal considerations in pregnancy. *JBJS*. 1994;76(11):1720-1730.
35. Bird AR, Menz HB, Hyde CC. The effect of pregnancy on footprint parameters. A prospective investigation. *Journal of the American Podiatric Medical Association*. 1999;89(8):405-409.
36. Vela SA, Lavery LA, Armstrong DG, et al. The effect of increased weight on peak pressures: implications for obesity and diabetic foot pathology. *The Journal of foot and ankle surgery*. 1998;37(5):416-420.
37. Ponnappula P, Boberg JS. Lower extremity changes experienced during pregnancy. *The Journal of foot and ankle surgery*. 2010;49(5):452-458.
38. Östgaard HC, Zetherström G, Roos-Hansson E. Back pain in relation to pregnancy: a 6-year follow-up. *Spine*. 1997;22(24):2945-2950.
39. Fiani B, Sekhon M, Doan T, et al. Sacroiliac joint and pelvic dysfunction due to symphysiolysis in postpartum women. *Cureus*. 2021;13(10).
40. Robinson HS, Eskild A, Heiberg E, et al. Pelvic girdle pain in pregnancy: the impact on function. *Acta obstetricia et gynecologica Scandinavica*. 2006;85(2):160-164.

41. Stomp-van den Berg SG, Hendriksen IJ, Bruinvels DJ, et al. Predictors for postpartum pelvic girdle pain in working women: the Mom@ Work cohort study. *PAIN®*. 2012;153(12):2370-2379.
42. Brynhildsen J, Hansson Å, Persson A, et al. Follow-up of patients with low back pain during pregnancy. *Obstetrics & Gynecology*. 1998;91(2):182-186.
43. Bastiaanssen JM, de Bie RA, Bastiaenen CH, et al. A historical perspective on pregnancy-related low back and/or pelvic girdle pain. *European Journal of Obstetrics & Gynecology and Reproductive Biology*. 2005;120(1):3-14.
44. Franke Jr BA. Formative dynamics: the pelvic girdle. *Journal of Manual & Manipulative Therapy*. 2003;11(1):12-40.
45. Wuytack F, Curtis E, Begley C. Experiences of first-time mothers with persistent pelvic girdle pain after childbirth: descriptive qualitative study. *Physical therapy*. 2015;95(10):1354-1364.
46. Elden H, Gutke A, Kjellby-Wendt G, et al. Predictors and consequences of long-term pregnancy-related pelvic girdle pain: a longitudinal follow-up study. *BMC musculoskeletal disorders*. 2016;17:1-13.
47. Corton MM. Anatomy of the pelvis: how the pelvis is built for support. *Clinical obstetrics and gynecology*. 2005;48(3):611-626.
48. Buyruk HM, Stam HJ, Snijders CJ, et al. Measurement of sacroiliac joint stiffness in peripartum pelvic pain patients with Doppler imaging of vibrations (DIV). *European Journal of Obstetrics & Gynecology and Reproductive Biology*. 1999;83(2):159-163.
49. Agten CA, Zubler V, Zanetti M, et al. Postpartum bone marrow edema at the sacroiliac joints may mimic sacroiliitis of axial spondyloarthritis on MRI. *American Journal of Roentgenology*. 2018;211(6):1306-1312.
50. Vleeming A, Vries HJd, Mens JM, et al. Possible role of the long dorsal sacroiliac ligament in women with peripartum pelvic pain. *Acta obstetrica et gynecologica Scandinavica*. 2002;81(5):430-436.
51. Dragoo JL, Lee RS, Benhaim P, et al. Relaxin receptors in the human female anterior cruciate ligament. *The American journal of sports medicine*. 2003;31(4):577-584.
52. Dehghan F, Haerian B, Muniandy S, et al. The effect of relaxin on the musculoskeletal system. *Scandinavian journal of medicine & science in sports*. 2014;24(4):e220-e229.
53. Sung J-H, Kang M, Lim S-J, et al. A case–control study of clinical characteristics and risk factors of symptomatic postpartum pubic symphysis diastasis. *Scientific Reports*. 2021;11(1):3289.
54. Yamaguchi M, Morino S, Nishiguchi S, et al. Comparison of pelvic alignment among never-pregnant women, pregnant women, and postpartum women (pelvic alignment and pregnancy). *J Women's Health Care*. 2016;5(01):2167-0420.1000294.
55. Müller A, Rockenfeller R, Damm N, et al. Load distribution in the lumbar spine during modeled compression depends on lordosis. *Frontiers in Bioengineering and Biotechnology*. 2021;9:661258.
56. Sakamoto A, Gamada K. Altered musculoskeletal mechanics as risk factors for postpartum pelvic girdle pain: a literature review. *Journal of Physical Therapy Science*. 2019;31(10):831-838.
57. Center. UoRM. Anatomy of the Male and Female Pelvis Available: <https://www.urmc.rochester.edu/encyclopedia/content.aspx?contenttypeid=85&contentid=P0738>

58. Jang J, Hsiao KT, Hsiao-Wecksler ET. Balance (perceived and actual) and preferred stance width during pregnancy. *Clinical biomechanics*. 2008;23(4):468-476.
59. Griffin SD, Price VJ. Living with lifting: mothers' perceptions of lifting and back strain in childcare. *Occupational Therapy International*. 2000;7(1):1-20.
60. Coenen P, Kingma I, Boot CR, et al. Cumulative mechanical low-back load at work is a determinant of low-back pain. *Occupational and Environmental Medicine*. 2014;71(5):332-337.
61. Kumar S. Theories of musculoskeletal injury causation. *Ergonomics*. 2001;44(1):17-47.
62. Ben-Masaud A, Solomonow D, Davidson B, et al. Motor control of lumbar instability following exposure to various cyclic load magnitudes. *European Spine Journal*. 2009;18:1022-1034.
63. Safer F Siddicky YC, Yunsheng Zou, Kathryn L Havens. Characterizing the muscle activity of postpartum mothers during three infant lifting tasks *American Society of Biomechanics* 2023.
64. Owen BD. Intervention for musculoskeletal disorders among child-care workers. *Pediatrics*. 1994;94(6):1077-1079.
65. Zhang XA, Ye M, Wang CT. Effect of unilateral load carriage on postures and gait symmetry in ground reaction force during walking. *Computer methods in biomechanics and biomedical engineering*. 2010;13(3):339-344.
66. Maines JM, Reiser RF. Ground reaction force bilateral asymmetries during submaximal sagittal plane lifting from the floor. *International Journal of Industrial Ergonomics*. 2006;36(2):109-117.
67. Palmieri RM, Ingersoll CD, Stone MB, et al. Center-of-pressure parameters used in the assessment of postural control. *Journal of sport rehabilitation*. 2002;11(1):51-66.
68. Prieto TE, Myklebust JB, Hoffmann RG, et al. Measures of postural steadiness: differences between healthy young and elderly adults. *IEEE Transactions on biomedical engineering*. 1996;43(9):956-966.
69. Podolski G. Standard deviation: Root mean square versus range conversion. *Quality Engineering*. 1989;2(2):155-161.
70. Hsue B-J, Miller F, Su F-C. The dynamic balance of the children with cerebral palsy and typical developing during gait: Part II: Instantaneous velocity and acceleration of COM and COP and their relationship. *Gait & posture*. 2009;29(3):471-476.
71. Quijoux F, Nicolai A, Chairi I, et al. A review of center of pressure (COP) variables to quantify standing balance in elderly people: Algorithms and open-access code. *Physiological reports*. 2021;9(22):e15067.
72. Ganguli S, Mukherji P, Bose K. Gait evaluation of unilateral below-knee amputees fitted with patellar-tendon-bearing prostheses. *Journal of the Indian Medical Association*. 1974;63(8):256-259.
73. Barber SD, Noyes FR, Mangine RE, et al. Quantitative assessment of functional limitations in normal and anterior cruciate ligament-deficient knees. *Clinical Orthopaedics and Related Research (1976-2007)*. 1990;255:204-214.
74. Queen R, Dickerson L, Ranganathan S, et al. A novel method for measuring asymmetry in kinematic and kinetic variables: the normalized symmetry index. *Journal of biomechanics*. 2020;99:109531.
75. Karamanidis K, Arampatzis A, Brüggemann G-P. Symmetry and reproducibility of kinematic parameters during various running techniques. *ISBS-Conference Proceedings Archive* 2002.

76. Robinson R, Herzog W, Nigg BM. Use of force platform variables to quantify the effects of chiropractic manipulation on gait symmetry. *Journal of manipulative and physiological therapeutics*. 1987;10(4):172-176.
77. Struzik A, Winiarski S, Zawadzki J. Inter-limb asymmetry of leg stiffness in national second-league basketball players during countermovement jumps. *Symmetry*. 2022;14(3):440.
78. Rohman E, Steubs JT, Tompkins M. Changes in involved and uninvolved limb function during rehabilitation after anterior cruciate ligament reconstruction: implications for Limb Symmetry Index measures. *The American journal of sports medicine*. 2015;43(6):1391-1398.
79. Wellsandt E, Failla MJ, Snyder-Mackler L. Limb symmetry indexes can overestimate knee function after anterior cruciate ligament injury. *Journal of Orthopaedic & Sports Physical Therapy*. 2017;47(5):334-338.
80. Herzog W, Nigg BM, Read LJ, et al. Asymmetries in ground reaction force patterns in normal human gait. *Med Sci Sports Exerc*. 1989;21(1):110-114.
81. Heil J. Load-induced changes of inter-limb asymmetries in dynamic postural control in healthy subjects. *Frontiers in human neuroscience*. 2022;16:824730.
82. Ruhe A, Fejer R, Walker B. Center of pressure excursion as a measure of balance performance in patients with non-specific low back pain compared to healthy controls: a systematic review of the literature. *European Spine Journal*. 2011;20:358-368.
83. Holdcroft A. Postpartum lower abdominal pain. *Current Review of Pain*. 1999;3(2):137-143.
84. Hodges PW. Changes in motor planning of feedforward postural responses of the trunk muscles in low back pain. *Experimental brain research*. 2001;141:261-266.
85. Hodges PW, Richardson CA. Inefficient muscular stabilization of the lumbar spine associated with low back pain: a motor control evaluation of transversus abdominis. *Spine*. 1996;21(22):2640-2650.
86. Burnett DR, Campbell-Kyureghyan NH, Cerrito PB, et al. Symmetry of ground reaction forces and muscle activity in asymptomatic subjects during walking, sit-to-stand, and stand-to-sit tasks. *Journal of Electromyography and Kinesiology*. 2011;21(4):610-615.
87. Zahraee MH, Karimi MT, Mostamand J, et al. Analysis of asymmetry of the forces applied on the lower limb in subjects with nonspecific chronic low back pain. *BioMed research international*. 2014;2014.
88. Duffell LD, Gulati V, Southgate DF, et al. Measuring body weight distribution during sit-to-stand in patients with early knee osteoarthritis. *Gait & posture*. 2013;38(4):745-750.
89. Vullo VJ, Richardson JK, Hurvitz EA. Hip, knee, and foot pain during pregnancy and the postpartum period. *Journal of family practice*. 1996;43(1):63-69.
90. Yu Q, Huang H, Zhang Z, et al. The association between pelvic asymmetry and non-specific chronic low back pain as assessed by the global postural system. *BMC Musculoskeletal Disorders*. 2020;21:1-10.
91. Sedighimehr N, Manshadi FD, Shokouhi N, et al. Pelvic musculoskeletal dysfunctions in women with and without chronic pelvic pain. *Journal of bodywork and movement therapies*. 2018;22(1):92-96.
92. Boissonnault JS, Blaschak MJ. Incidence of diastasis recti abdominis during the childbearing year. *Physical therapy*. 1988;68(7):1082-1086.
93. Hills NF, Graham RB, McLean L. Comparison of trunk muscle function between women with and without diastasis recti abdominis at 1 year postpartum. *Physical therapy*. 2018;98(10):891-901.

94. Oddsson LI, De Luca CJ. Activation imbalances in lumbar spine muscles in the presence of chronic low back pain. *Journal of applied physiology*. 2003;94(4):1410-1420.
95. Çiçek H, Keskin HL, Tuhanioğlu Ü, et al. Simultaneous disruption of the pubic symphysis and sacroiliac joint during vaginal birth. *Case Reports in Orthopedics*. 2015;2015.
96. Stolarczyk A, Stępiński P, Sasinowski Ł, et al. Peripartum Pubic Symphysis Diastasis—Practical Guidelines. *Journal of clinical medicine*. 2021;10(11):2443.
97. Ritchie JR. Orthopedic considerations during pregnancy. *Clinical obstetrics and gynecology*. 2003;46(2):456-466.
98. Segal NA, Boyer ER, Teran-Yengle P, et al. Pregnancy leads to lasting changes in foot structure. *American journal of physical medicine & rehabilitation*. 2013;92(3):232-240.
99. Stodółka J, Sobera M. Symmetry of lower limb loading in healthy adults during normal and abnormal stance. *Acta of bioengineering and biomechanics*. 2017;19(3):93-100.
100. Granata KP, Marras W. The influence of trunk muscle coactivity on dynamic spinal loads. *Spine*. 1995;20(8):913-919.
101. Golubić A, Šarabon N, Marković G. Association between trunk muscle strength and static balance in older women. *Journal of women & aging*. 2021;33(3):288-297.
102. Cholewicki J, Simons AP, Radebold A. Effects of external trunk loads on lumbar spine stability. *Journal of biomechanics*. 2000;33(11):1377-1385.
103. Marras WS, Granata K. Spine loading during trunk lateral bending motions. *Journal of biomechanics*. 1997;30(7):697-703.
104. Huang Q-M, Andersson E, Thorstensson A. Intramuscular myoelectric activity and selective coactivation of trunk muscles during lateral flexion with and without load. *Spine*. 2001;26(13):1465-1472.
105. Sadeghisani M, Sobhani V, Kabir MM, et al. Investigation of weight-bearing symmetry in a group of athletes with low back pain and healthy people during gait. *Journal of Mechanics in Medicine and Biology*. 2017;17(05):1750086.
106. Minig L, Trimble EL, Sarsotti C, et al. Building the evidence base for postoperative and postpartum advice. *Obstetrics & Gynecology*. 2009;114(4):892-900.
107. Clinic C. Types of delivery for pregnancy Available: <https://my.clevelandclinic.org/health/articles/9675-pregnancy-types-of-delivery>.
108. Harris PA, Taylor R, Minor BL, et al. The REDCap consortium: building an international community of software platform partners. *Journal of biomedical informatics*. 2019;95:103208.
109. Harris PA, Taylor R, Thielke R, et al. Research electronic data capture (REDCap)—a metadata-driven methodology and workflow process for providing translational research informatics support. *Journal of biomedical informatics*. 2009;42(2):377-381.
110. Haddad JM, Rietdyk S, Ryu JH, et al. Postural asymmetries in response to holding evenly and unevenly distributed loads during self-selected stance. *Journal of Motor Behavior*. 2011;43(4):345-355.
111. Koltermann JJ, Gerber M, Beck H, et al. Validation of different filters for center of pressure measurements by a cross-section study. *Technologies*. 2019;7(4):68.
112. Winter DA. Human balance and posture control during standing and walking. *Gait & posture*. 1995;3(4):193-214.
113. Cornilleau-Pérès V, Shabana N, Droulez J, et al. Measurement of the visual contribution to postural steadiness from the COP movement: methodology and reliability. *Gait & Posture*. 2005;22(2):96-106.

114. Nigg S, Vienneau J, Maurer C, et al. Development of a symmetry index using discrete variables. *Gait & posture*. 2013;38(1):115-119.
115. Balogun J, Akindede K, Nihinlola J, et al. Age-related changes in balance performance. *Disability and rehabilitation*. 1994;16(2):58-62.
116. Pinheiro JC, Bates DM. Linear mixed-effects models: basic concepts and examples. *Mixed-effects models in S and S-Plus*. 2000:3-56.
117. Sullivan GM, Feinn R. Using effect size—or why the P value is not enough. *Journal of graduate medical education*. 2012;4(3):279-282.
118. Hill M, Duncan M, Oxford S, et al. Effects of external loads on postural sway during quiet stance in adults aged 20–80 years. *Applied ergonomics*. 2018;66:64-69.
119. Fujimoto C, Kawahara T, Kinoshita M, et al. Minimally important differences for subjective improvement in postural stability in patients with bilateral vestibulopathy. *Neuroscience Letters*. 2021;747:135706.
120. Geurts AC, Nienhuis B, Mulder TW. Intrasubject variability of selected force-platform parameters in the quantification of postural control. *Archives of physical medicine and rehabilitation*. 1993;74(11):1144-1150.
121. Shigaki L, Vieira ER, de Oliveira Gil AW, et al. Effects of holding an external load on the standing balance of older and younger adults with and without chronic low back pain. *Journal of Manipulative and Physiological Therapeutics*. 2017;40(4):284-292.
122. Wu G, MacLeod M. The control of body orientation and center of mass location under asymmetrical loading. *Gait & posture*. 2001;13(2):95-101.
123. Zagrodny B, Ludwicki M, Wojnicz W. The Influence of External Additional Loading on the Muscle Activity and Ground Reaction Forces during Gait. *Applied Bionics and Biomechanics*. 2021;2021(1):5532012.
124. McMullin D, Stobbe T, Bang S, et al. Asymmetric loading on the body during symmetric lifts. *Advances in Industrial Ergonomics and Safety VII Taylor & Francis, London*. 1995:719-725.
125. Killgore WD. Effects of sleep deprivation on cognition. *Progress in brain research*. 2010;185:105-129.
126. Umemura GS, Furtado F, Santos FCd, et al. Is balance control affected by sleep deprivation? A systematic review of the impact of sleep on the control of balance. *Frontiers in neuroscience*. 2022;16:779086.
127. Brumagne S, Cordo P, Lysens R, et al. The role of paraspinal muscle spindles in lumbosacral position sense in individuals with and without low back pain. *Spine*. 2000;25(8):989-994.
128. Fiat F, Merghes PE, Scurtu AD, et al. The main changes in pregnancy—therapeutic approach to musculoskeletal pain. *Medicina*. 2022;58(8):1115.
129. Rodrigues-de-Souza DP, Beleza ACS, García-Luque L, et al. Asymmetries of the muscle mechanical properties of the pelvic floor in nulliparous and multiparous women, and men: a cross-sectional study. *Symmetry*. 2022;14(10):2124.
130. Granata K, Wilson S. Trunk posture and spinal stability. *Clinical biomechanics*. 2001;16(8):650-659.
131. Noonan AM, Brown SH. Paraspinal muscle pathophysiology associated with low back pain and spine degenerative disorders. *JOR spine*. 2021;4(3):e1171.
132. Sbriccoli P, Yousuf K, Kupershtein I, et al. Static load repetition is a risk factor in the development of lumbar cumulative musculoskeletal disorder. *Spine*. 2004;29(23):2643-2653.

133. King PM, Gratz R, Scheuer G, et al. The ergonomics of child care: conducting worksite analyses. *Work*. 1996;6(1):25-32.
134. Bazrgari B, Shirazi-Adl A. Spinal stability and role of passive stiffness in dynamic squat and stoop lifts. *Computer methods in biomechanics and biomedical engineering*. 2007;10(5):351-360.
135. Taube W, Gruber M, Gollhofer A. Spinal and supraspinal adaptations associated with balance training and their functional relevance. *Acta physiologica*. 2008;193(2):101-116.
136. Kitamura T, Kido A, Ishida Y, et al. Muscle activity pattern with a shifted center of pressure during the squat exercise. *Journal of sports science & medicine*. 2019;18(2):248.
137. Dutta T, Holliday PJ, Gorski SM, et al. The effects of caregiver experience on low back loads during floor and overhead lift maneuvering activities. *International Journal of Industrial Ergonomics*. 2011;41(6):653-660.
138. Jeong H, Yamada K, Kido M, et al. Analysis of difference in center-of-pressure positions between experts and novices during asymmetric lifting. *IEEE journal of translational engineering in health and medicine*. 2016;4:1-11.
139. Ottinger CR. Changes in Ground Reaction Force and Muscle Activation during Offset Loading in Barbell Squats. Concordia University Chicago 2022.
140. Leskinen T, Stålhammar H, Kuorinka I, et al. A dynamic analysis of spinal compression with different lifting techniques. *Ergonomics*. 1983;26(6):595-604.
141. Freivalds A, Chaffin DB, Garg A, et al. A dynamic biomechanical evaluation of lifting maximum acceptable loads. *Journal of biomechanics*. 1984;17(4):251-262.
142. Sedighi A, Nussbaum MA. Exploration of different classes of metrics to characterize motor variability during repetitive symmetric and asymmetric lifting tasks. *Scientific Reports*. 2019;9(1):9821.
143. Lafond D, Champagne A, Descarreaux M, et al. Postural control during prolonged standing in persons with chronic low back pain. *Gait & posture*. 2009;29(3):421-427.
144. Della Volpe R, Popa T, Ginanneschi F, et al. Changes in coordination of postural control during dynamic stance in chronic low back pain patients. *Gait & posture*. 2006;24(3):349-355.