Differences in Load Symmetry of the Lower Extremities in Postpartum Women During Daily Tasks and Childcare Loading Conditions

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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

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May 7, 2024
Blacksburg, Virginia

Keywords: Postpartum health, lower extremity load symmetry, childcare loading

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Abstract

In 2021, over three and a half million women entered the postpartum period in the United States [1]. Despite their prevalence, postpartum health is a largely overlooked area. After delivery, 25% of women within this population experience lumbopelvic or pelvic pain during the typical postpartum period [3], up to 8 weeks post-delivery, and research has found these women may continue to experience pain years after delivery [4]. Persistent pelvic region pain in postpartum women may result in lower limb load asymmetry. Additionally, external loading from carrying a child may alter the degree of asymmetric loading that exists in the lower limbs. Therefore, the first purpose of this study was to investigate the effect of daily tasks on lower extremity load symmetry using metrics that have successfully identified load asymmetry in other populations. Load symmetry was found to differ between task, with the largest asymmetry occurring between limbs during the sit-to-stand task for the peak impact force (PIF = 9.08% symmetry) and during the stair descent task for the average loading rate (ALR = 15.43% symmetry). The increase in asymmetry during these tasks may be attributed to increased muscle activation and force production. The second purpose of this study was to investigate the effect of an external child load on lower extremity load asymmetry during a 14-meter level walking task. A significant increase was found between the no load and both child load conditions for PIF and ALR ($p < 0.001$ for both metrics). No statistically significant differences in symmetry were found between carrying the child centrally in a carrier and carrying on one side of the body without a carrier. The lack of difference in asymmetry during child carrying conditions may indicate mothers naturally compensate for the external child load as both ALR and PIF values increased during these conditions, but asymmetry was not impacted. Our results indicate the need to continue to examine different carrying conditions in postpartum women to better understand risk factors for pain or injury and provide evidence-based recommendations for postpartum activity progression.

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General Audience Abstract

In 2021, over three and a half million women entered the postpartum period in the United States [1]. Despite their prevalence, postpartum health is a largely overlooked area and 25% of women experience low back or pelvic pain past the typical postpartum period of 8 weeks post delivery [3]. Research has found women may continue to experience this pain years after delivery and result from the lower limbs being loaded unequally. The extra weight from carrying a child may also impact the amount of unequal loading placed onto the lower limbs. The first purpose of this study was to investigate the effect of daily tasks on load symmetry in the lower limbs using measures that have successfully identified unequal load distribution in non-pregnant individuals. Load symmetry was found to differ between task, with the largest asymmetry occurring between limbs during the sit-to-stand task for the force applied to lower limbs during initial contact of the feet and during the stair descent task for the rate that force was applied to lower limbs. The second purpose of this study was to investigate the effect of an external child load on lower extremity load asymmetry during a 14-meter level walking task. A significant increase was found between the no load and both baby load conditions for force applied during initial contact of the feet and rate this force was applied. No difference was found between child carrying external loading condition when evaluating asymmetry. Our results indicate the need to continue to investigate the unique loading patterns of postpartum women to better understand the specific risk factors for pain or injury development within this population.

Acknowledgments

I would like to thank Dr. Robin Queen and Dr. Sara Arena for their help and guidance through this process. They have both had a significant positive impact on my time as an undergraduate and graduate student. From mentoring my senior design team, teaching me during COVID, and giving me the opportunity to pursue postpartum biomechanics, I truly appreciate the influence they've had on my time at Virginia Tech. I would like to thank Dr. Cunningham for the time she spent training me in the clinical metrics used in this study. I would like to thank Dr. Johnson for providing clinical expertise in the OBGYN field. I would also like to acknowledge all the mothers who volunteered their time to participate in this study, despite their busy schedules. They helped make this research possible. Lastly, I would like to acknowledge Dr. Christopher Arena, who it has been a pleasure to work with this year as a GTA.

I would also like to acknowledge my lab mates who made this final year at Virginia Tech enjoyable and memorable. Not only was I able to improve my crossword ability, but I became average at pickleball and was even able to beat Theresa once. Sam, thank you for all the miles, job listings, and unwavering positive attitude. Theresa, thank you for always looking out for me, helping me succeed during this process, providing flavor blasted goldfish, and hiding eggs with me. I wish you all the best of luck and will miss coming into the lab every day.

Table of Contents

Abstract…………………………………………………………………………………..1

General Abstract……………………………………………………………………...…...2

Acknowledgements……………………………………………………………………....3

List of Figures……………………..………………………………………………….....5

List of Tables………………………………………..………………………………5

List of Abbreviations……………………………………...………………………6

Chapter 1: Introduction……………………………………………………………......…7

Chapter 2: Manuscript 1…………………………………………………………......….23

Chapter 3: Manuscript 2…………………………………………………………......…….38

Chapter 4: Conclusion……………………………………………………………......……53

References…………………………………………………...…………………..56

List of Figures

Figure 1: Anatomy of female pelvis..12
Figure 2: External rotation of pubic bone from ariel view..12
Figure 3: The loadsol® and sample data..21
Figure 4: Participant performs quiet stand...28
Figure 5: Participant performs sit to stand..29
Figure 6: Participant performs fourteen meter level walk...30
Figure 7: Participant performs stairs ascent, Participant performs stair descent..............31
Figure 8: PIF NSI across task..34
Figure 9: ALR NSI across task...35
Figure 10: Participant with three loading conditions..44
Figure 11: Gait speed across carrying conditions..47
Figure 12: Carrying and Non-Carrying side PIF across loading condition......................48
Figure 13: Carrying and Non-Carrying side ALR across loading condition....................49
Figure 14: PIF NSI across loading conditions...51
Figure 15: ALR NSI across loading conditions..52

List of Tables

Table 1: PIF Values..32
Table 2: ALR Values..32
Table 3: Participant Demographics..45

List of Abbreviations

BW	Body Weight
ACLR	Anterior Cruciate Ligament Reconstruction
SI	Sacroiliac
N	Newtons
yrs	years
kg	kilograms
cm	centimeters
m/s	meters per second
BW/s	body weight per second
N/s	newton per second

Chapter 1: Introduction

Motivation

In 2021, there were 3,664,292 births in the United States with almost 97% of the births being a single baby [1]. In the same year, over three and a half million mothers entered the postpartum period [1]. This period typically lasts six to eight weeks post birth but may last up to 6 months depending on the restoration of physiological and anatomical changes from pregnancy [2]. During pregnancy, 45% of women experience lumbopelvic or pelvic pain and 25% continue to experience this pain into the postpartum period [3]. Additionally, a study examining the long-term prevalence of persistent postpartum pain found that 7.3% of women reported pain and 6.1% reported significant pain in the lower abdomen, pelvis, or lower back related to delivery at an average of 2.3 years postpartum [4]. As most mothers in the United States have a single postpartum appointment with their doctor six weeks after delivery [5], continued pain past this six-week appointment could indicate a need for additional medical evaluation and potential interventions. Potential causes of persistent pain include asymmetric ligament mobility surrounding the sacroiliac joint (SIJ) or asymmetric pelvic alignment [6]. During pregnancy, the hormone relaxin is produced in greater amounts to increase ligamentous laxity, relax pelvic joints, and widen the hips in preparation for birth [2]. Increased ligamentous laxity may be associated with lower limb injury in pregnant and postpartum individuals due to the increased range of joint motion [8]. As such, low back pain and high levels of relaxin during late pregnancy are correlated, suggesting relaxin may play a role in the reorientation of the pelvis during pregnancy [9].

Another potential cause of persistent pain in postpartum women is load asymmetry in the lower limbs. Unequal loading between lower limbs has been linked to self-identified pain in the lower back, pelvis, and hips [10] as well as with muscle imbalance resulting from joint degeneration or injury [11]. Unresolved physiological changes from pregnancy could increase load asymmetry in postpartum women [6]. Furthermore, many of the daily tasks performed by postpartum women include the additional weight of a child which is a significant risk factor for developing musculoskeletal pain or injury [12].

Mothers often carry their child on one side of the body which could exacerbate any asymmetric lower extremity loading present. Additionally, it would increase the risk of developing a musculoskeletal injury as repetitive asymmetrical loading is correlated with overuse and chronic injuries [13].

Load symmetry in the lower limbs can be quantified using force plates, pressure plates, pressure sensing insoles, and force sensing insoles. Pressure sensing insoles often require cabling and participants to wear a belt or backpack that may influence the load distribution in the lower limbs [14]. Force and pressure plates are only able to measure ground reaction forces for certain steps and over limited distances for specific tasks. Force sensing insoles are a good alternative as they don't require extra cabling, allow participants to walk longer distances, and to perform a variety of tasks such as stair ambulation. Additionally, research has demonstrated that these inserts have excellent validity and reliability when compared against force plates [15]. In this study, loadsol® (Novel Electronics, Pittsburg, PA) were used to measure the normal force between the foot and the shoe during 5 different tasks: quiet stand, sit to stand, 14-meter level walk, stair ascent, and stair descent.

The normal force was used to calculate the peak impact force (PIF) and average loading rate (ALR) during each trial. These metrics were selected as they have successfully evaluated symmetry in lower limb loading in anterior cruciate ligament reconstruction (ACLR) patients [16] where the surgical limb is loaded less than the non-surgical limb [17]. Postpartum women may also experience this loading abnormality as asymmetric support of the lower limbs could relate to lower limb dysfunction, joint and muscle pain, or due to the development of poor motor patterns [11].

Therefore, the purpose of this research was to quantify load symmetry in the lower limbs of postpartum women during daily childcare child carrying conditions while performing daily activities. Understanding loading and load asymmetry in common daily tasks and carrying scenarios can provide insight on potential mechanisms of and interventions for persistent pain in postpartum women. Load symmetry was evaluated using the

Normalized Symmetry Index (NSI) for peak impact force and average loading rate during each movement task. The NSI was chosen as it allows for comparison of symmetry across a range of data from multiple trials of different lengths in addition to its ability to account for cases where other symmetry indices have difficulty [19]. Specifically, this work aims to:

Specific Aim 1: Determine if lower extremity load symmetry measured beneath the feet in postpartum women differs between tasks without an additional load.

Hypothesis 1a: A difference in PIF NSI (asymmetry) will exist between sit to stand, level walking, stair ascent, and stair descent with larger asymmetry occurring during stair ascent and descent.

Hypothesis 1b: A difference in ALR NSI will exist between sit to stand, level walking, stair ascent, and stair descent with a larger loading rate asymmetry occurring during stair ascent and descent.

Specific Aim 2: Determine the differences in load symmetry in postpartum women during simulated child carrying tasks during level walking (no load, baby, baby in carrier)

Hypothesis 2a: A significant difference will exist in load symmetry based on the carrying task with a greater asymmetry during the baby load on hip condition when compared to the no load condition during level walking.

Hypothesis 2b: A significant difference will exist in load symmetry based on the carrying task with a greater loading rate asymmetry during the baby load on hip condition compared to the no load walking trials.

Background

Levels of relaxin increase drastically during the first 13 weeks of pregnancy, remain steady until late pregnancy, and begin to decrease after delivery [1]. This hormone allows for relaxation of the pelvic ligaments which is essential for pregnancy and delivery [15]. Increased pelvic laxity results in altered collagen structure in the surrounding area which allows for the separation of the pubic symphysis [15]. Separation of pubic symphysis allows the pelvic bones to widen during delivery and following delivery, around 30% of pregnant women report symptoms of symphysis pubis dysfunction where they experience pain, or their pelvis feels unstable [37]. Additionally, 20% of pregnant women experience pelvic girdle pain (PGP) which is the second most common reason for sick leave, after fatigue and sleep problems [21]. PGP is defined as pain around the pelvic joints, lower back, hips, and thighs [2]. It can occur from a combination of ligament laxity and abnormal motor control, resulting in malalignment and instability of the pelvis or lower limb joints which could be a major factor in pain development [2]. Relaxin levels begin to decrease after birth but may take up to 12 months to reach pre-pregnancy levels [2]. The continued influence of relaxin during the postpartum period could increase the risk of developing a musculoskeletal disorder or experiencing pain due to increased ligamentous laxity [2].

The origin of pain or impairments can be identified through clinical assessments. The assessments can identify unresolved changes or injuries from pregnancy like rectus abdominis muscle separation, limited range of motion within the hips, PGP, lumbopelvic instability, and weakened hip abductor strength. Separated abdominal muscles are indicative of weakened abdominals which may result in PGP, LBP, and UI [50]. It is important to differentiate between LBP and PGP as they result in different pains and musculoskeletal impairments [51]. LBP can be identified through limited range of motion within the hips which may result in altered lumbopelvic mechanics [52]. PGP can be identified through weak hip abductors which may result in a pelvic tilt in the coronal plane and indicate increased joint laxity [53]. Furthermore, weakness in the pelvic girdle can be identified through poor pelvic stability and difficulty with load transfer through the pelvis [5]. The results of these assessments can be used to evaluate a postpartum

women's healing process, if there are unresolved changes from pregnancy, and the origin of any pain they may experience.

In addition to the pain postpartum women may experience from increased levels of relaxin, there are multiple childcare tasks that may increase the risk for increased pain or injury. These high-risk childcare activities are defined as tasks that place a high biomechanical stress on the body and increase the potential for injury from repetition, prolonged duration, or the weight of the child [59]. Such tasks include carrying a child in a car seat, carrying a child on one hip, holding a child while bending down, lifting a child on or off a changing table, and lifting a child up from the floor [2]. Musculoskeletal injury or pain could result from these kinds of motions depending on the frequency or weight of the child and could prevent postpartum women from fully recovering after delivery [59].

Many women develop musculoskeletal disorders during the postpartum period due to the continued influence of relaxin and the ergonomic stresses of childcare tasks [7]. Peripheral nerves are susceptible to injury in pregnant and postpartum women from compression, traction, ischemia, and laceration [7]. Furthermore, pregnancy related swelling increases compressive forces on peripheral nerves during childcare activities [7]. Common disorders include low back pain, pelvic pain, osteitis pubis, pubic symphysis pain, carpal tunnel syndrome, peripheral edema, lateral femoral cutaneous neuropathy, and DeQuervain's tenosynovitis [7]. Of these disorders, back and pelvic pain are the most prevalent [7]. Back pain is described as a dull pain in the lumbar region and is experienced when an individual is in forward flexion and there is restriction of lumbar movement [25]. PGP pain is described as stabbing, shooting, dull, or a burning sensation [25]. During the postpartum period, 30 to 45% of women experience low back pain which can be attributed to forward rotation of the pelvis or hyperlordosis from increased laxity in the sacroiliac ligaments [7]. Additionally, it is estimated that 22% of women experience PGP during pregnancy, labor, or while postpartum and up to 8% experience disability from the pain [3]. PGP is defined as pain in the symphysis pubis, sacroiliac joints, and pain in the gluteal region [25]. This pain may radiate past the gluteal fold and

into the posterior thigh [25]. Additionally, PGP pain is recurring, and symptoms can be aggravated by simple daily activities like walking, sitting, stair climbing, or standing [25]. Unequal weight bearing on the legs is a factor for this type of pain development [25].

To better understand PGP, it is important to know the anatomy of the pelvis. The anterior portion of the pelvis, the pelvic girdle or pubic bone, is comprised of the pubis, ischium, and ilium which connects posteriorly to the spine [68]. There are two pubic bones within the pelvis, one on the left and one on the right, that are connected to the pubic symphysis anteriorly and the sacrum posteriorly [68]. Both pubic bones, the ischial bone, and the iliac bone all joint together through connective tissue [68]. Misalignment of these bones often occurs when tissues are stressed beyond normal levels and result in asymmetric pelvic alignment from tissue adaptation in bone and surrounding muscle mass [67]. Pelvic asymmetry can be defined as asymmetric alignment of the pubic bones in the frontal, sagittal, or transverse plane relative to the vertical axis [67]. Research has found asymmetrical alignment of pubic bones within postpartum women, where either left or right pubic bone was rotated to a greater external angle [31]. This results in one rotational abnormality in the ilium, as seen in Figure 2, and may result in anterior hip pain due to

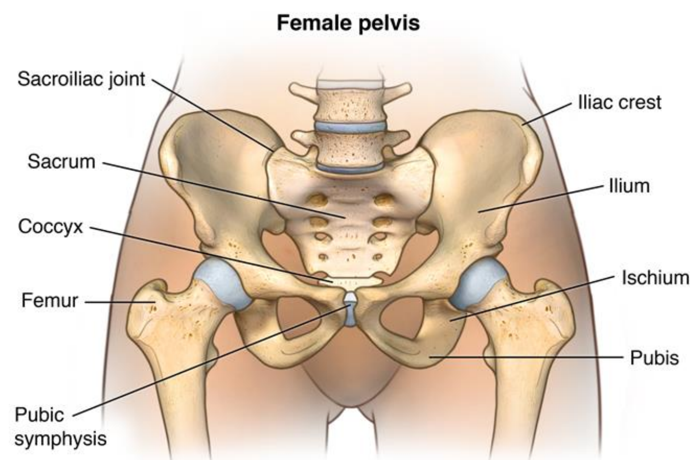

Figure 1: Anatomy of female pelvis [76]

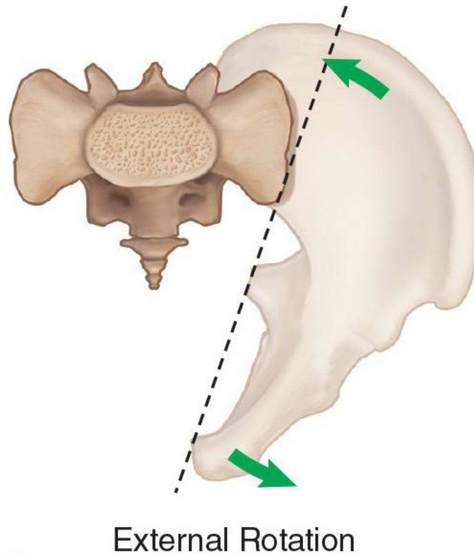

Figure 2: External rotation of pubic bone from ariel view [77]

During pregnancy, relaxin is produced in increased quantities by the corpus luteum and uterine decidua to prepare the body for delivery [17]. This results in greater ligament laxity, particularly in the pelvis, as relaxin alters properties of cartilage and tendons by activating collagenase [17]. Ligament laxity is attributed to greater range of joint motion, which is associated with musculoskeletal injuries due to altered kinematics, especially in the lower extremities [26]. For example, increased pelvic tilt occurs during pregnancy due to increased levels of relaxin and weakened abdominal muscles [27]. Increased levels of relaxin allow the pelvis to tilt forward as the body mass increases and center of mass shifts forward [28]. Pelvic tilt begins to decrease after childbirth and as relaxin levels begin to decline but could lead to asymmetric alignment of the pelvis if not fully resolved [29]. Even if the pelvic tilt resolves, abdominal and pelvic floor musculature may require additional healing time or directed exercise as these muscles have been significantly stretched and potentially torn during vaginal delivery [22]. Pelvic floor muscles consist of two main muscles, the levator ani and coccygeus, that are intertwined [70]. They work to counteract gravitational forces, intra-abdominal pressure, and provide support to pelvic organs [71]. Weakness in the pelvic floor muscles from excessive stretching during pregnancy and delivery may result in musculoskeletal injury from asymmetry in strength and length of these muscles [69]. Both malalignment of the pelvis and increased ligament laxity may be major factors in the development of pelvic pain [2]. Asymmetric pelvic

alignment increases tightness in the surrounding ligaments and muscles of the sacroiliac joint which may result in pelvic pain like PGP or lumbopelvic pain [2]. Furthermore, studies have reported increased levels of relaxin in pregnant women with pelvic joint instability and in those who experience PGP or pelvic floor dysfunction [17].

Similarly, pelvic alignment is different amongst never pregnant, pregnant, and postpartum individuals [3]. Pelvic asymmetry is higher in pregnant and postpartum individuals compared to never pregnant individuals [30]. Even at 3 to 5 months postpartum, pelvic asymmetry may still be prevalent due to increased levels of relaxin [30]. In healthy adults, pelvic asymmetry could be caused by carrying a load on only one shoulder or sitting cross legged for extended periods of time [30]. Postpartum individuals often carry their child on one side of their body for prolonged periods which could further exacerbate any pelvic asymmetry they already experience. This asymmetry within the pelvis could result in low-back pain among pregnant and postpartum individuals [31]. It has been found that asymmetry in joint mobility at the sacroiliac joint (SIJ) is correlated with moderate to severe posterior pelvic pain [31]. Additionally, asymmetric SIJ mobility during pregnancy can predict prolonged pelvic pain during the postpartum period in individuals with moderate to severe posterior pelvic pain [31]. A clinical study of 460 pregnant women found that 9% of participants continued to experience daily pelvic pain 2 years after childbirth [3]. Furthermore, only 5% of the postpartum women who experience lumbopelvic pain visited a physician to seek help [32]. Medical treatment for this pain includes anti-inflammatory drugs, steroid injections into the sacroiliac joints, physical therapy, or surgery [32]. It has been reported that individuals who experience back pain 6 to 7 months postpartum are twice as likely to develop symptoms of depression indicating the importance of managing such pain early in the postpartum period [3].

Several clinical metrics and scales exist to evaluate musculoskeletal pain and/or dysfunction. Metrics specific to pelvic health and strength are beneficial for evaluation of the postpartum population given the common prevalence of PGP and low back pain. In this study, impairments were identified with the Oswestry Disability Index (ODI), urinary

incontinence, a pelvic evaluation, and load symmetry in the lower limbs. The ODI is a self-reported measure that evaluates low back pain (LBP) and its impact on an individual's quality of life (QOL) [19]. Research has found ODI scores to be reliable and valid for measurement of disability amongst individuals with lower back pain [35]. Scores range from 0 to 100 with higher scores indicating a larger negative impact on QOL due to pain [19]. The different categories of interest included in this study were pain intensity, personal care, lifting, walking, sitting, social life, sleeping, and standing [19]. Research has found the average ODI score for asymptomatic individuals to be around 8.7 and the score for individuals with a disability from LBP to be around 12 [36]. ODI scores for postpartum women who seek treatment for persistent PGP are higher than scores for postpartum women who don't experience pain [20]. Women who have greater ODI scores may also experience asymmetrical loading of the lower limbs due to persistent back or pelvic pain.

Another way musculoskeletal impairments have been identified was through the urinary incontinence (UI) questionnaire. This questionnaire identified a participants' history of involuntary loss of urine and potentially weakened pelvic floor muscles [17]. Many women experience urinary incontinence (UI), involuntary loss of urine, or stress urinary incontinence (SUI), involuntary loss of urine from increased intraabdominal pressure, while pregnant or postpartum [17]. UI occurs from either damaged pelvic floor muscles that hold the bladder in place or increased levels of relaxin, both leading to involuntary loss of urine [17]. UI is considered an injury from pregnancy/delivery and may develop after childbirth, especially for vaginal deliveries [18]. It is estimated that 31% of women suffer from UI and 70% from SUI during their third trimester [18]. It is also estimated that 7% of postpartum women experience SUI at three months postpartum [18]. Women who experience UI or SUI during the postpartum period may have weakened pelvic floor muscles or increased levels of relaxin [18].

Loading changes drastically throughout pregnancy and following childbirth. On average, pregnant women gain 15 kg from both the weight of the fetus and overall weight gain [42]. Weight from the fetus is anteriorly centered around the abdomen during this period.

After giving birth, an average of 4.5 to 6 pounds are lost from the baby's weight and amniotic fluid [42]. The weight of the child is no longer centered around the abdomen and may be asymmetrically distributed depending on how the mother chooses to carry the child. Even in nulliparous populations, changes in loading may lead to overuse injuries due to the musculoskeletal system's inability to cope with a mechanical load, either from repetitive loading, increased weight of an applied load, or abrupt changes in load distribution [4]. Injuries are categorized as stress fractures in bones, stress injuries in the musculoskeletal system, and muscle fatigue due to mechanical overload from repetitive or heavy loading [4].

Repetitive exercise or a heavy load placed on the body can result in inadequate time for recovery of the collagen tissues, tendons, and ligaments, from the deformation [13]. Lack of recovery results in a reduction of the cross-sectional area in the affected tissue which increases stress concentration, lowers stress tolerance, and increases injury risk [13]. The short-term effect of heavy or repetitive loading in muscles operating a specific joint fatiguing at different rates due to inconsistent activation [12]. Muscle fatigue is defined as the decrease in maximal force or power generation of the muscle [44]. Fatigue hinders a muscle's ability to reduce dynamic loads placed on the human musculoskeletal system which may result in injury to the area [45]. The long-term effect of heavy or repeated loading may result in joint kinematics that differ from the optimum and natural loading kinematics of the joint [12] due to abnormal strain or bending of the bone [47]. Similarly, repetitive loading from carrying a child may result in abnormal strain on the lumbar spine, pelvis, or lower limbs and result in abnormal function of these regions. Furthermore, postpartum women may be at a greater risk for developing a musculoskeletal injury from increased level of relaxin and ligament laxity present during repetitive or heavy loading [48]. Laxity decreases tension in ligaments which reduces joint stability and increases injury risk factors [48]. Increased laxity results in a longer rest period being required between loading for full recovery [48]. Accumulation of improper recovery time may result in greater injury risk [48]. In this study, participants completed daily tasks with an external baby load in a chest worn baby carrier that symmetrically distributed weight to simulate increased symmetric loading. This

symmetric load combined with repetitive loading of the lower limbs during daily tasks, like walking or stair ambulation, could result in increased risk of injury [48].

In contrast to symmetrical loading, where muscle activation is uniform, asymmetrical loading results in unbalanced muscle activation [18]. The high biomechanical demand from asymmetrical childcare tasks could further exacerbate asymmetries mothers already experience from laxity or muscle impairment [2]. An asymmetrical load causes center of mass shifts which results in spine lateral flexion and asymmetrical trunk muscle activation [18]. As the weight of the asymmetrical load increases, postural instability also increases due to less efficient loading/unloading mechanisms in the hip [18]. Repeatedly asymmetrical loading increases shear and compressive forces in the spine and can result in lumbar pain [18]. It has been hypothesized that repetitive asymmetrical loading during gait could correlate to overuse or chronic injuries [13]. In a kinetic symmetry study done on female runners with and without prior tibial stress fractures, the study suggested that loading asymmetry while running may influence the side that becomes injured [13]. Mothers who carry their child predominantly on one side may be at a greater risk for developing injury or pain due to repetitive asymmetrical loading [13]. This loading combined with reduced joint stability from ligament laxity may further exacerbate asymmetries in muscle activation in postpartum women [48]. In this study, participants completed tasks with a baby carried on the hip to simulate asymmetric external loading. This asymmetric load combined with repetitive loading of the lower limbs during daily tasks could result in unequal muscle activation, pain, or chronic injury [48][13].

Asymmetric loading of the pelvis could make it difficult and painful for postpartum individuals to perform daily tasks such as walking for prolonged periods as well as ascending or descending the stairs [4]. Research has found pregnant women with PGP take shorter steps with less pelvic movement compared to nulliparous women [38]. Taking shorter steps results in a longer double support phase during the gait cycle, decreasing time spent in single limb stance where forces are asymmetrically loaded through pelvic [38]. Shorter steps may suggest impaired weight bearing abilities of the pelvis in individuals with PGP and possible asymmetries in lower limb loading due to

these pelvic impairments [38]. Unfortunately, it is currently unknown what percentage of asymmetry is typical, what is considered too high, and what percentage is dangerous for hip/spine loading [18]. There is still potential for even a low degree of asymmetric loading of the lower limbs to cause low back pain or issues with hip joints [11]. Repetitive loading of one hip combined with increased joint mobility from relaxin could result in a misaligned pelvis and or pelvic pain.

Many of the daily tasks postpartum women perform are completed while carrying a child. Activities that involve carrying a child in a car seat or carrying a child on one hip are considered high risk activities due to the high biomechanical stress they put on the body from repetition, prolonged duration, or the weight of the child [59]. Additionally, the weight of the child may be distributed asymmetrically based on the carrying method chosen by the mother. Carrying a child on the chest or back using a baby carrier will result in load being symmetrically distributed. An added external symmetric load may increase the force applied to lower limbs when completing tasks and make any asymmetric loading between the lower limbs more apparent [55]. Conversely, carrying a child on the hip will result in load being asymmetrically distributed. Research has shown that external asymmetrical loads result in non-uniform muscle activation which may result in unequal loading of the lower limbs or compound any asymmetric loading already present [55]. Evaluation of these loading conditions is important as they may influence the load distribution between the lower limbs during daily activities. Furthermore, external asymmetric loading may result in different load symmetry between the lower limbs when compared to external symmetric loading from the body compensating for the load through lateral spine flexion and asymmetrical trunk muscle activation [18].

There are multiple ways to quantify symmetry between the lower limbs. The most common indexes include the Symmetry Index (SI), Ratio Index (RI), Gait Asymmetry (GA), Symmetry Angle (SA), and Normalized Symmetry Index (NSI) [19]. For subjects who have undergone lower limb surgery, the lower limbs are referred to as surgical (X_S)

and nonsurgical (X_{-NS}). For healthy individuals, limbs are referred to as the non-dominant (X_{-ND}) and dominant limb (X_{-ND}).

The RI uses the ratio of measured values for the nonsurgical and surgical limb as the index of symmetry [19]. Values for this index can range from 0%, full symmetry, to greater than 100%, full asymmetry [19]. Additionally, the value may be negative if $X_{-NS} < X_{-S}$.

Eq. 1

$$RI = \left(1 - \frac{X_{NS}}{X_S}\right) \cdot 100$$

Eq. 2

$$RI = \left(1 - \frac{X_{NS}}{X_S}\right) \cdot 100$$

The SI is the most often used index and a generalization of the values obtained from the RI [19]. Similarly to RI, values can range from 0, full symmetry, to over 100%, full asymmetry and values may be negative if $X_{-NS} < X_{-S}$ [19].

Eq. 3

$$SI = \left(\frac{X_{NS} - X_S}{0.5(|X_S| + |X_{NS}|)}\right) \cdot 100$$

The SA evaluates symmetry within angular data on a scale from 0, full symmetry, to 100%, full asymmetry [19].

Eq. 4

$$SA = \left(\frac{45° - \arctan\left(\frac{X_S}{X_{NS}}\right)}{90°}\right) \cdot 100$$

The GA is a logarithmic transform of the ratio index ranging from 0, full symmetry, to 100%, full asymmetry [19]. GA is difficult to use when the measured variable can result in both negative and positive values as the ratio~~n~~ between the two limbs can only be positive [19].

Eq. 5

$$GA = \ln\left(\frac{X_{NS}}{X_S}\right) \cdot 100 GA = \ln\left(\frac{X_{NS}}{X_S}\right) \cdot 100$$

Eq. 6 $$RI = \left(1 - \frac{X_{NS}}{X_S}\right) \cdot 100$$

Eq. 7 $$RI = \left(1 - \frac{X_{NS}}{X_S}\right) \cdot 100$$

Indexes with no upper bound for asymmetry, like SI or RI, make it difficult to define maximum asymmetry [19]. Additionally, indices tend to behave asymptotically and never reach either fully symmetry or asymmetry (return non-linear results) [19]. The NSI can address the limitations of the SI by returning linear values, normalizing variable magnitude, and bounding the index results from 0 to 100% asymmetry [19]. The maximum range of values within a dataset, seen in the denominator, is used to normalize data and return values between 0 and ±100%, representing full symmetry to full asymmetry respectively [19].

Eq. 8 $$NSI = \frac{X_{ND,t} - X_{D,t}}{\max\limits_{t=1:n}\left(\max\left(0, X_{ND,t}, X_{D,t}\right)\right) - \min\limits_{t=1:n}\left(\min\left(0, X_{ND,t}, X_{D,t}\right)\right)} \cdot 100$$

The numerator represents the difference between the non-dominant and dominant limb for a specific metric during a single trial, indicated by the subscript *t*. The denominator represents the maximum and minimum values for specific metric across *n* trials, where *n* is at least three trials. NSI was chosen to quantify symmetry in this study because it accounts for shortcomings in the other indexes as discussed above. The NSI scales the level of symmetry within a sample to variation within data from multiple trials which can account for cases of high asymmetry and low variable magnitude where the other indices have trouble [3]. The sign of the NSI value, positive or negative, indicates which limb has greater values for a specified metric. A negative NSI value indicates larger values on the dominant limb whereas a positive value would indicate larger values on the non-dominant limb. Additionally, the absolute value of the NSI can be used to investigate the degree of asymmetry between limbs.

Load symmetry in the lower limbs can be quantified using force plates, pressure plates, pressure sensing insoles, and force sensing insoles. Pressure sensing insoles require

cabling from the insoles that the research participant must carry in a backpack and may influence loading in the lower limbs [67]. Force and pressure plates are only able to measure ground reaction forces for specific distances in a laboratory setting. Force sensing insoles are a good alternative to these other options as they don't require extra cabling and capture continuous data in natural environments. For example, participants of this study walked up and down 13 stairs in a stairwell adjacent to the lab instead of performing these tasks on stairs attached to force plates. In this study, loadsol® (Novel Electronics, St. Paul, Minnesota, USA) where the force sensing insoles used. Research has found that data measured at 100 Hz with these insoles have excellent validity and reliability compared to force plates when evaluating walking or running [67].

Figure 3: The loadsol® and sample data (left) [16], loadsol inside shoe (right) [78]

Metrics used to analyze human movement in the lower limbs include both kinematic and kinetic variables. When evaluating lower limb asymmetries, three main approaches include: movement competency, dynamic, isolated muscular assessments, and dynamic force production [5]. Movement competency evaluates the range or quality of movement, but assessment must be performed by a trained observer and there has been debate about the reliability of the scoring system [57]. Isolated muscular assessments measure force output, but only for the selected muscle group that have been isolated [56]. Dynamic force production evaluates force production in lower limbs during discrete tasks [56] where kinetic metrics that can be taken from these force values. Metrics include peak impact force, peak push off force, loading rate, and impulse [15].

In this study, asymmetry in lower limb loading was determined by calculating the NSI for the peak impact force (PIF) and average loading rate (ALR) from the normal forces captured with a force sensing insole. These two metrics have successfully evaluated symmetry in ACLR patients and healthy adults [16]. Loading abnormalities may occur in postpartum women and be identified through ALR and PIF. A lack of side-to-side symmetry in the normal forces between the foot and the shoe has been linked with muscle imbalance in the musculoskeletal system from joint degeneration, injury, or asymmetrical loading of the body from an external weight [18]

Motivation, Purpose, and Hypothesis

Over three million women give birth and enter the postpartum period each year [1]. Despite the size of this population, postpartum health has been largely overlooked with women only receiving one check up with their medical provider at 6 weeks postpartum. One quarter of postpartum women experience lumbopelvic or pelvic pain from the adaptations their bodies went through during pregnancy [3]. This pain may result from asymmetrical pelvic alignment and increased levels of relaxin still present postpartum [6]. Investigation of differences in load symmetry of the lower limbs among postpartum women could highlight unresolved pregnancy changes and improve postpartum health. The purpose of this study was to investigate load symmetry during different child related tasks and carrying conditions amongst postpartum women. The first hypothesis was that a difference in PIF NSI and ALR NSI would exist between tasks with larger values occurring during the stair ambulation tasks. The second hypothesis was that a difference in PIF NSI and ALR NSI would exist between loading conditions with larger values occurring when the participant was carrying a baby. Differences in load symmetry during different tasks or loading conditions may indicate unresolved physiological and anatomical changes from pregnancy and may make women more susceptible to developing a musculoskeletal injury or experiencing prolonged pain.

Chapter 2: The Effect of Task on Loading Symmetry in Postpartum Women

Abstract

Improvements in identification of pain in the lower back and pelvis pain of postpartum women is possible through research into the loading symmetry of the lower limbs in this population during child care related activities. Load symmetry can be evaluated through PIF NSI and ALR NSI from GRFs. It has been proven that asymmetrical loading of the lower limbs is linked to self-identified pain in the lower back, pelvis, or hips [18]. Further understanding if asymmetrical loading is present during the daily activities of postpartum women could indicate unresolved changes from pregnancy and potentially correlate to high levels or pain in the pelvic region. Therefore, the purpose of this study was to analyze if asymmetrical loading of the lower limbs is present during child care activities, what tasks asymmetries were present during, and if it can be linked to pain in the pelvic region. It was hypothesized a difference will exist in PIF NSI and ALR NSI between four daily tasks (sit to stand, level walking, stair ascent, and stair descent) with larger NSI values occurring during stair ascent and descent. 16 participants were recruited for this study and completed three trials of quiet stand, sit to stand, 14 meter level walk, stair descent, and stair ascent. Peak impact force (PIF) and average loading rate (ALR) was calculated using custom MATLAB script, Load Analysis Program (LAP), from normal force values measured by loadsol® shoe inserts. Corresponding normalized symmetry index (NSI) values were calculated for both PIF and ALR and used to determine the effect of task on lower extremity load asymmetry through a linear mixed effects model (LMEM) (RStudio, Boston, Massachusetts). Our results showed that the PIF and ALR metric differed between tasks with concentric muscle contraction, rising from a chair, resulting in the smallest values and stair descent, eccentric muscle contraction, resulting in the largest values. Furthermore, NSI values for both PIF and ALR were found to vary between tasks. The sit to stand task had the largest PIF NSI value (average PIF NIS = 9.08% symmetry) whereas stair descent had the largest ALR NSI value (average ALR NSI = 15.18% symmetry). Our results indicate more resulting tasks result in increased load asymmetry in the lower limbs, which is consistent with current research evaluating lower limb loading asymmetry.

Introduction

In 2021, over three and a half million women entered the postpartum period in the United States [1]. Nearly a quarter of these women experienced lumbopelvic or pelvic pain [3]. Research has found this low back and pelvic pain can persist years after completion of the typical postpartum period [3], defined as 6 to 8 weeks post-delivery [2]. Potential sources for this musculoskeletal pain are increased levels of relaxin, asymmetrical pelvic alignment, and asymmetric loading of the lower limbs. Increased levels of relaxin results in a greater and unnatural range of joint motion which may put pregnant or postpartum women at a higher risk of developing a musculoskeletal injury or pain [8]. Furthermore, relaxin allows for pelvic tilt to occur during pregnancy as body mass increases and center of mass shifts forward [2]. After delivery, pelvic tilt begins to decrease but misalignment may occur if the tilt is not fully resolved [28]. Asymmetric pelvic alignment could further any pelvic girdle pain (PGP) or lumbopelvic pain due to increased tightness in surrounding ligaments and muscles [29]. Research has found greater pelvic asymmetry in nulliparous individuals who experience lower back pain [57]. Given the pelvis's proximity to the lower limbs, asymmetries in the pelvic alignment may be consistent with asymmetries in the lower limbs [5]. Consistently loading this asymmetric misalignment may also result in persistent pain in the lower back, pelvis, and hips [18]. Pain in these regions could cause asymmetrical loading of the lower limbs [10] which may lead to muscle imbalance resulting from joint degeneration or injury [11].

When evaluating lower limb asymmetries, dynamic force production can be used to evaluate force production between limbs and calculate metrics like peak impact force (PIF), peak push off force (PPF), average loading rate (ALR), or impulse (IMP) [15]. ALR and PIF are two metrics that have been found to successfully evaluate symmetry in anterior cruciate ligament reconstruction (ACLR) patients and healthy adults [16]. Asymmetrical loading of the lower limbs is common in individuals who have gone through ACLR where surgical limb is loaded less than non-surgical limb [17]. In this study, ALR and PIF were the metrics chosen to be evaluated in this study as loading abnormalities may also occur in postpartum women. A lack of symmetry in normal forces

between lower limbs has been linked with muscle imbalance in the musculoskeletal system from joint degeneration, injury, or asymmetrical loading of the body from an external weight [18]

Research has found an imbalance in muscle activation in the lumbar region for individuals with chronic lower back pain [59]. Muscle force production may be inhibited due to the presence of lower back pain which is likely limited due to fear of reinjuring the area or experiencing pain [59]. Postpartum women who experience low back pain (LBP) may have lower PIF values as their force production is limited due to pain. Furthermore, PIF normalized symmetry index (NSI) values may be larger in individuals with LBP if pain is not evenly distributed across lower limbs. In addition, research has found pregnant women with PGP have lower walking velocity and a shorter stride compared to pregnant women who don't experience pain [60]. Shorter steps result from longer double support phase during the gait cycle and less time spent in single leg stance where forces are asymmetrically distributed through the pelvis [60]. Shortened steps and slower walking velocity may indicate impaired weight bearing abilities on painful or most painful side [60]. Postpartum women who experience PGP may have larger ALR values due to decreased time between heel strike and toe off. Larger ALR values may also lead to increased NSI values as a greater loading rate could amplify any asymmetries present.

Between tasks, PIF may differ as different levels of muscle activation and movement are required between tasks. For example, stair tasks will result in larger PIF values as increased load is placed on lower limbs from body weight [61]. Larger PIF may also result in larger PIF NSI values during stair tasks. In patients with knee osteoarthritis, stair ambulation is a better indicator of lower limb asymmetries compared to level walking because it is a more demanding activity and results in larger loading values [61].
ALR may differ between tasks as time between heel strike (HS) and toe off (TO) changes with task. For example, time between HS and TO will be longer during the sit to stand task compared to level walking as movements are performed at different cadences. Furthermore, PIF and ALR will differ between loading conditions.

To track the normal forces during each trial, loadsol® (Novel Electronics, St. Paul, Minnesota, USA) were chosen as they can measure forces during tasks where other measure system struggle. Pressure sensing insoles require cabling or participants to carry backpack which influences the load distribution in the lower limbs [14]. Force and pressure plates are only able to measure forces for shorter distances and level tasks. For example, the force plates available in the lab would not have been able to measure the entire 14 meter level walk nor the stair ascent or descent task. Research has found data collected at 100 Hz from loadsol® have excellent validity and reliability compared to force plate data [14].

Weight and load distribution drastically shifts throughout the pregnancy and postpartum period. While pregnant, women gain around 15 kg with the added weight of from the fetus being anteriorly centered around the abdomen and moving the women's center of mass [4]. After delivery, the weight of the child is no longer centered around the abdomen and may be asymmetrically distributed depending on the carrying method a mother chooses. Asymmetrical carrying of a child, like carrying a child on the hip or in an infant care seat, is considered a high risk activity due to the increased biomechanical demand and nonuniform loading [2]. An external asymmetric load results in center of mass shifting, spine lateral flexion, and asymmetrical trunk muscle activation [18]. Lumbar pain may become present from repetitive asymmetric loading due to increased shear and compressive forces placed on the spine [18]. Furthermore, as the weight of this load increases, postural instability increases due to less efficient weight transfer through the hips [10]. Asymmetric loading of the pelvic may make it difficult and painful for postpartum women to complete daily tasks like walking for prolonged periods, ascending, or descending stairs [49].

It is important for postpartum women to maintain symmetric loading of the lower limbs because asymmetric loading can result in musculoskeletal injury or pain [10, 11]. Even in nulliparous individuals, repetitive loading, increased weight of applied load, or abrupt changes in load distribution may result in overuse injuries due to the musculoskeletal system's inability to cope with loading [43]. Heavy or repetitive loading results in joint

kinematics differing from the optimum and natural loading kinematics of a joint [C] which puts surrounding ligaments at a higher risk of injury [46]. Increased loading combined with increased ligament laxity results in a greater chance of injury due to ligament elongation from load combined with greater joint motion [4]. Furthermore, asymmetric loading combined with increased ligament laxity may result in a misaligned pelvis or pelvic pain. Research has found a correlation between ligament laxity, asymmetric mobility of the SI joint, and persisting pelvic pain during the postpartum period [50].

The aim of this study was to determine if lower extremity load symmetry differs between task in postpartum women without an additional load. This study hypothesized that a difference in PIF NSI and ALF NSI will exist between sit to stand, level walking, stair ascent, and stair descent. A difference in values may occur as loading and muscle activation required by the lower limbs may vary between tasks and affect the level of symmetry. Research has found tasks that require greater muscle activation from lower limbs are a better indicator of asymmetries between limbs [61]. Furthermore, the study hypothesized larger PIF NSI and ALR NSI values will occur during stair ascent and descent due to these tasks requiring greater muscle activation from the lower limbs [61].

Methods

Participants:

Sixteen women between six to twelve months postpartum were recruited for this study approved by the university Institutional Review Board (IRB #24-159). All participants signed consent forms prior to the completion of this study. To meet study inclusion criteria, participant's most recent birth had to have been a vaginal delivery, had to wear a women's size 5.5 to 9.5 shoe, and be between the ages of 18 and 40. Postpartum participants were excluded if they had sustained an injury in the last three months that limited their physical activity for more than two days, had a prior serious lower extremity injury or surgery, and if they were currently pregnant.

Testing Procedure:

Participants were each given neutral cushioned running shoes with loadsol® sensors placed inside their respective sizes during the study. The loadsol® sensors are force sensing insoles that were used to record the normal force between the foot and the shoe while data is sampled at 100 Hz. They have been validated with the gold standard force plates for repeatability and reproducibility with data sampled at 100 Hz [67]. The neutral running shoe, Nike Zoom Pegasus (Nike, Inc., Beaverton, OR, USA), was used to standardize footwear between subjects. Limb dominance was then determined by asking participants which hand they prefer to write with [63]. Additionally, preferred carrying side (C) and non carrying side (NC) were determined by which hip the participant naturally carried their own child on. Participants were asked to complete five different activities of daily living which included: quiet stand, 14-meter walk, sit to stand, stair ascent, and stair descent. Participants were instructed to do all activities at a self-selected pace and there was no time limit to completing each task. Additionally, participants were told they could rest between trials if they felt fatigued from any of the tasks. This rest period was not timed, and the length of the rest period was up to the participant's discretion. All tasks were performed unloaded.

Quiet Standing:

Figure 4: Participant performs quiet standing

Participants stood with spine straight, looking forward, legs straight, and with hands at their side for 30 seconds.

Sit to Stand:

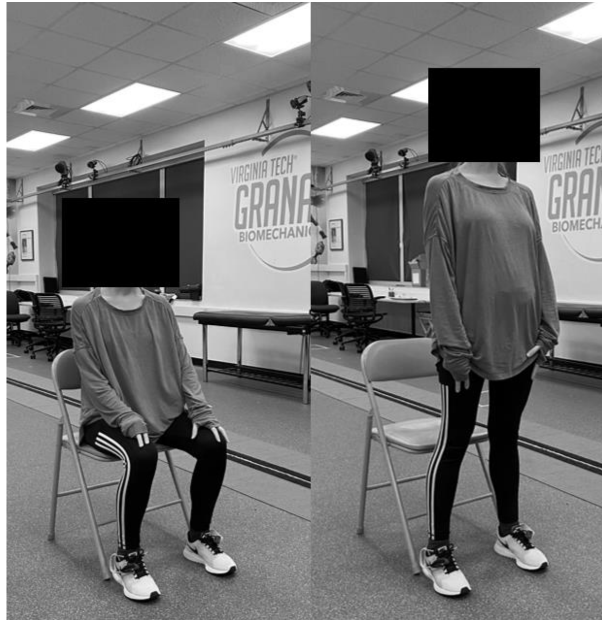

Figure 5: Participant performs sit to stand

Participants started sitting in a chair, rose from the chair until standing, and then sat back down. Participants were instructed to repeat this motion five times consecutively at a natural pace.

Fourteen Meter Walk:

Figure 6: Participant performs fourteen meter level walk

Participants walked fourteen meters across a level surface at a self-selected pace as if walking through the grocery store.

Stair Ascent:

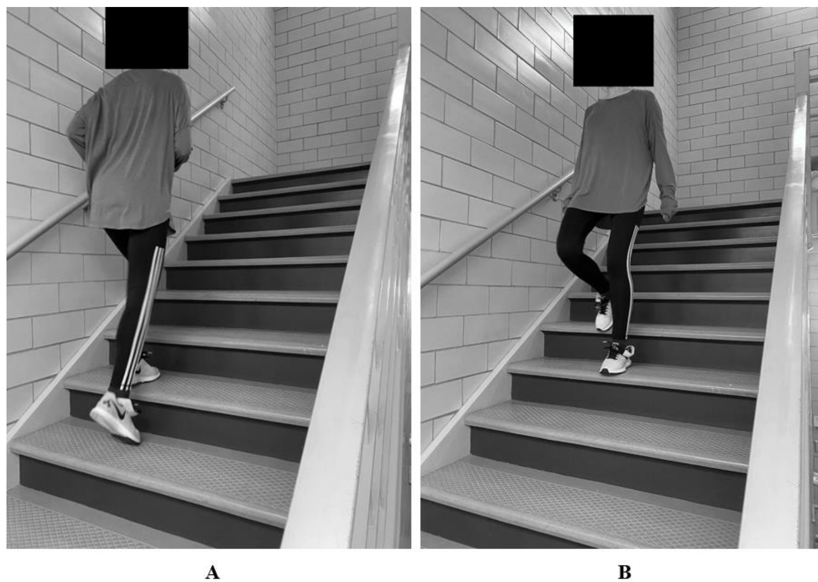

Figure 7: Participant performs stair ascent (A), Participant performs stair descent (B)

Participant started at the bottom 13 stairs and walked to the top of stairs at self-selected pace as if climbing home stairs.

Stair Descent:

Participant started at the top 13 stairs and walked to the bottom of stairs at self-selected pace as if descending home stairs.

Data analysis:

The loadsol® data was then processed in a custom MATLAB script, Load Analysis Program (https://github.com/GranataLab/LAP), to extract PIF and ALR, both normalized to body weight. PIF is the maximum force exerted onto the feet during the first 30% of the ground contact time, the time between heel strike and toe off [6]. ALR is the speed at which the forces impact the body [25]. The loading rate was calculated by dividing the change in force between heel strike to peak impact by the respective time [64]. This study calculated the ALR from 20 to 80 percent of the time between heel strike and the peak impact force [64]. For level walking and stair tasks, initial contact was defined as the point in time the force measured by loadsol® sensors exceeded 60 N. Similarly, toe off was defined as the time point where measured force was less than 60 N. For sit to stand task, initial contact was defined as the period when subject began to rise from chair and toe off when subject sat back down in chair.

NSI was used to assess symmetry [66]. The NSI was chosen because it scales the level of symmetry within a sample to variation within data from multiple trials which can account for cases of high asymmetry and low variable magnitude where other symmetry indices have trouble [66]. An NSI value of zero represents perfect symmetry whereas a value of 100 represents perfect asymmetry [66]. The equation below illustrates how NSI is calculated. This equation was adapted from Queen et al. [6] to reference non preferred carrying side (NC) and preferred carrying (C) side for participants. The sign of the NSI value indicates which side, either NC or C, had greater values for a specific metric. However, in this study we took the absolute value of the NSI values for each participant as we were interested in evaluating the degree of asymmetry during all conditions and not on the direction of the asymmetry.

$$NSI = abs\left(\frac{X_{NC,t} - X_{C,t}}{max_{t=1:n}(\max(0, X_{NC,t}, X_{C,t})) - min_{t=1:n}(\min(0, X_{NC,t}, X_{C,t}))} * 100\right)$$

Statistics:

A linear mixed effects model (LMEM) (RStudio, Boston, Massachusetts) was used in this study to determine the effect of task and loading condition had on the two NSI metrics [67]. This model was chosen because it allows for both random and fixed effects [67]. In this study, the random effect was subjects, and the fixed effects was task. The statistical significance of effects was evaluated using p-value where values lower than 0.05 are considered statistically significant [67]. If LMEM detected a main effect in loading condition, post-hoc pairwise comparison was preformed to identify individual effects between conditions.

Results:

Table 1: PIF Values

	Sit to Stand	Walk	Ascent	Descent	*p*-value
Carrying Side (BW)	0.566 ± 0.058	1.094 ± 0.150	1.091 ± 0.132	1.321 ± 0.193	<0.001
Non Carrying Side (BW)	0.575 ± 0.077	1.096 ± 0.158	1.107 ± 0.132	1.346 ± 0.244	<0.001

Table 2: ALR Values

	Sit to Stand	Walk	Ascent	Descent	*p*-value
Carrying Side (BW/s)	2.224 ± 0.619	6.325 ± 1.827	6.211 ± 2.046	9.276 ± 2.703	<0.001
Non Carrying Side (BW/s)	2.154 ± 0.605	6.658 ± 2.313	5.893 ± 1.580	9.141 ± 2.898	<0.001

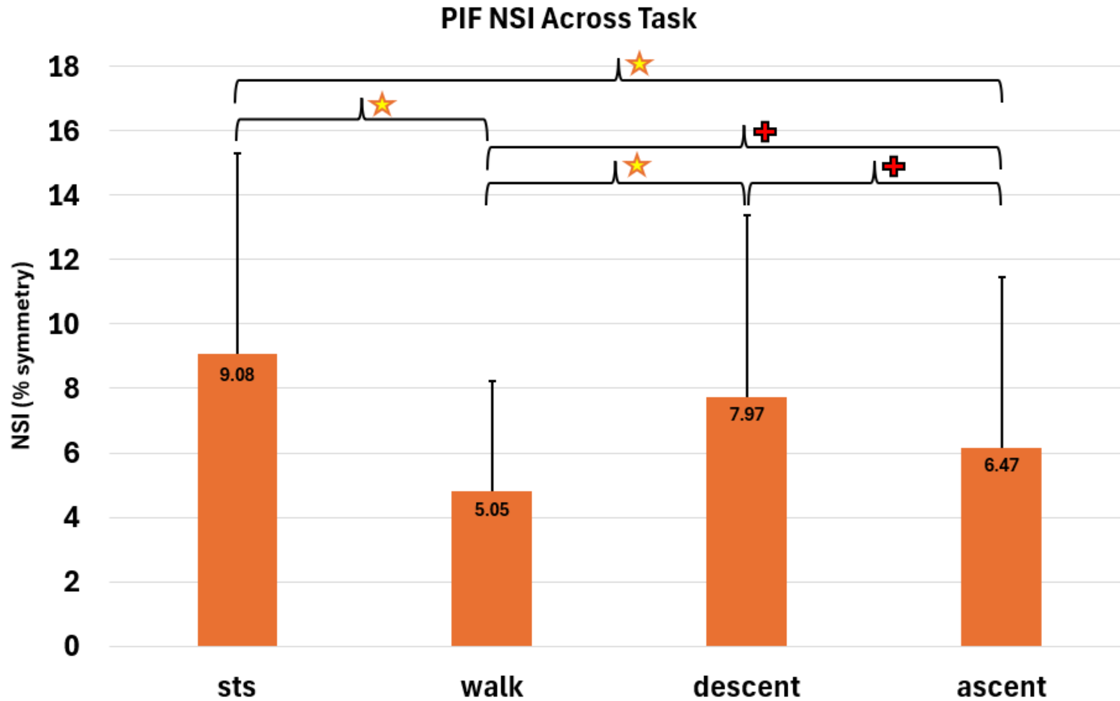

Figure 8: PIF NSI across task, star ( ) indicates p <0.001 and plus ( ) indicates p <0.050

<u>PIF NSI Values</u>

PIF NSI was found to differ between task (p <0.001). A statistically significant difference was comparing the sit to stand task PIF NSI values with the level walk task (p <0.001) and the ascent task (p <0.001) NSI values. Similarly, a statistically significant difference was found when comparing the level walk task NSI values with the descent (p <0.001) and ascent (p = 0.037) task values. Finally, a statistically significant difference was found between the stair descent and stair ascent values (p = 0.042). The largest PIF NSI values, largest degree of asymmetry, were present during the sit to stand task (average PIF NSI = 9.08%) and smallest during the level walk task (average PIF NSI = 5.05%).

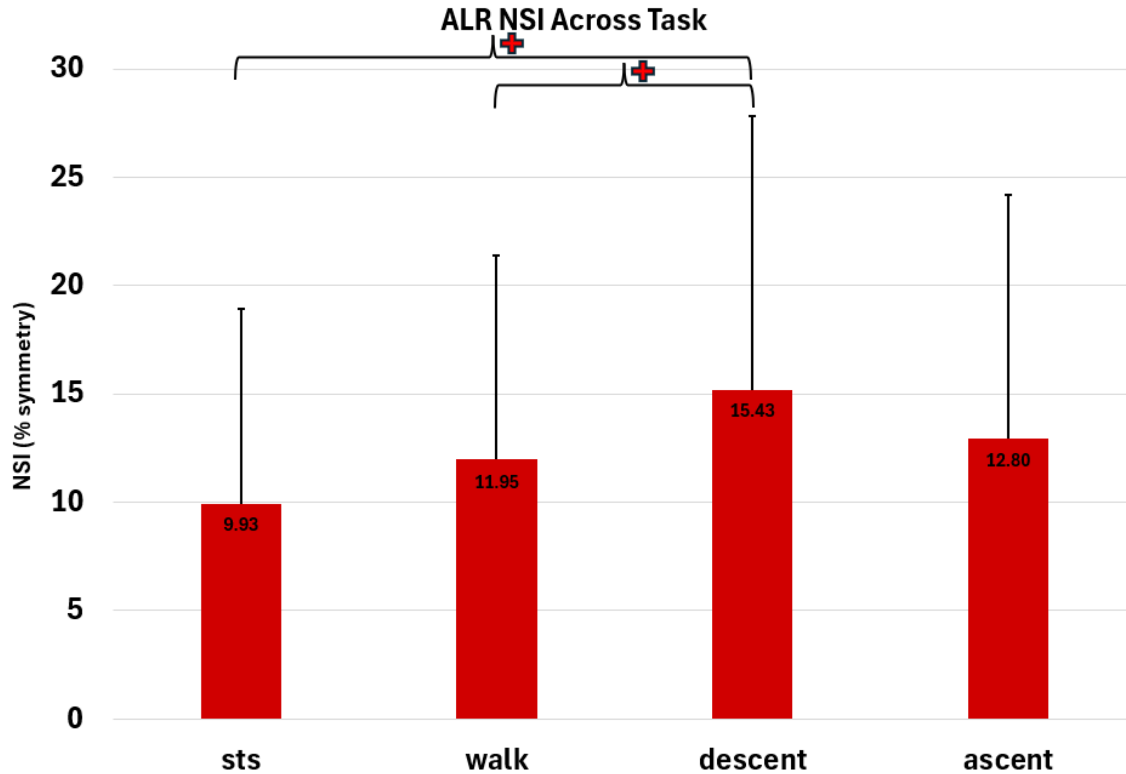

Figure 9: ALR NSI across task, plus (✚) indicates p <0.050

<u>ALR NSI Values</u>

ALR NSI was found to differ between tasks (p = 0.015). A statistically significant difference was found during when comparing the sit to stand task NSI values with the stair descent (p = 0.018) task values. Additionally, a statistically significant difference was found between the walk task and stair descent (p = 0.021) task values. The largest ALR NSI values were present during stair descent task (average ALR NSI = 15.43% symmetry) and smallest during the sit to stand task (average ALR NSI = 9.93% symmetry).

Discussion

The purpose of this study was to determine if differences in load symmetry existed between different daily tasks in postpartum women. Many statistically significant differences were found between tasks for NSI or both the PIF and ALR values. For PIF NSI, the sit to stand task was found to have the greatest level of asymmetry in PIF values

and have significantly different values from the level walk task and stair ascent task. For ALR NSI, the stair descent task was found to have the highest level of asymmetry in ALR values and found to be statistically different compared to the walk and sit to stand task. These results support our original hypothesis that a difference will exist in lower extremity load symmetry between tasks with no additional load. Additionally, the stair descent task resulted in the greatest ALR NSI values, supporting our original hypothesis, but the sit to stand task resulted in the greatest PIF NSI values, contradicting our original hypothesis. All the results from this study support the notion that different tasks postpartum women perform result in different levels of lower extremity loading and asymmetry, implying increased effort, or muscle activation, necessary to complete a specific task may result in higher levels of asymmetry in loading of the lower limbs.

For the PIF values, the sit to stand task resulted in the smallest values (average PIF = 0.566 BW) and were statistically different compared to the other three tasks. During the beginning of the sit to stand task, concentric muscle contraction is required by the lower limbs as participants rise from a chair to a standing position, where the peak impact force is identified [73]. During concentric contraction muscle fibers shorten to increase muscle tension and combat gravitational forces [73]. PIF values were largest during the stair descent (average PIF = 1.321 BW) and were statistically different compared to the other three tasks. Stair descent requires eccentric muscle contraction where the muscle-tendon complex lengthens to decelerate the body from gravitational forces [73]. Even though perceived effort is smaller during eccentric contraction [73], research has found this contraction generates greater force compared to concentric contraction. Our PIF findings support this notion as the PIF are smallest during the sit to stand task, concentric contraction, and greatest during the stair descent task, eccentric contraction.

The ALR values followed the same trend as the PIF values with the sit to stand task having the smallest ALR values (average ALR = 2.224 BW/s) and stair descent having the greatest values (average ALR = 9.276 BW/s). ALR is determined by dividing 20-80% of forces between the beginning of the stand to the peak impact with the corresponding time interval. It is understandable that the ALR values followed the same trend as the PIF

values as the force values leading up to the PIF impact the calculation of ALR. For example, the task deemed more demanding in the previous paragraph, stair descent, resulted in both the greatest PIF and ALR values across all tasks. Speed, or time between initial contact to PIF, for each task differed given the nature of each unique movement. Based on the results in Table 1 and Table 2, it seems both the rate of loading, speed, and amount of loading increased for the more demanding tasks.

The PIF NSI values showed multiple statistically significant differences in asymmetry between tasks. The largest NSI value for PIF, highest level of asymmetry, was found during the sit to stand task (average PIF NSI = 9.08% symmetry) and smallest during the level walk task (average PIF NSI = 5.05% symmetry). This result contradicts our original hypothesis that the greatest asymmetry would be identified during the stair ascent and descent task. However, the second largest NSI PIF values were during the stair descent task (average PIF NSI = 7.97% symmetry). Research suggests that tasks with larger PIF, such as stair ambulation tasks, result in larger PIF NSI values as they are considered more demanding tasks [61]. Stair ascent and descent showed a statistically significant difference when compared to the level walking task but were still smaller than the PIF NSI values during the sit to stand task. Compared to literature involving a healthy cohort, ages 18 to 30, the magnitude of asymmetry in postpartum women during the sit to stand task was found to be comparable [80]. Additionally, literature has found the sit to stand task to result in the greatest magnitude of asymmetry across walking, stair ascent, stair descent, and sit to stand [80]. The literature found asymmetry in healthy adults to be 10.07% [80] whereas this study found asymmetry to be 9.08% symmetry for PIF during the sit to stand task. However, the literature used the absolute symmetry index (ASI) which has no upper bound for asymmetry and makes it difficult to define maximum asymmetry [19]. This difference in symmetry indices used may account for the difference in asymmetry values found between our study and literature results [80].

The ALR NSI values showed statistical differences between stair ascent, level walk, and sit to stand task. ALR NSI values were largest during stair descent (average ALR NSI = 15.43% symmetry), second largest during stair ascent (average ALR NSI = 12.80%

symmetry), and smallest during sit to stand (average ALR NSI = 9.93% symmetry). These results support our original hypothesis that the stair ascent and descent tasks will result in the largest ALR NSI values. For the sit to stand task, NSI values for both PIF and ALR were fairly consistent, but the other tasks had increased NSI values for the ALR metric. Compared to literature evaluating ALR asymmetry of healthy individuals, ages 18 to 30, the sit to stand task was found to have the greatest magnitude (25.42%), followed by stair descent (13.89%) [80]. This differs from our results as sit to stand was found to have an average asymmetry much smaller, but the stair descent task resulted in a symmetry value similar to what literature has found [80]. The difference in magnitude of symmetry during the sit to stand task compared to literature may be attributed to postpartum women having smaller magnitudes for both PIF and ALR values compared to the four tasks. Furthermore, NSI values may have increased for ALR as the metric values were larger and had greater variation compared to the PIF metric. Increased ALR NSI values could indicate which postpartum women are more susceptible to injury or pain and during what tasks.

Although this study was able to identify numerous statistical differences between tasks, limitations exist that future work could address and improve upon. For example, this was a pilot study and had a relatively small sample size of 16 participants. A larger sample size may better represent the postpartum population and detect differences in loading patterns between tasks. Furthermore, a nulliparous cohort could provide direct comparison of loading patterns and level of asymmetry during each task between groups as this study is only able to compare between tasks amongst postpartum women. In this study, a neutral running shoe, Nike Zoom Pegasus, was used to standardize footwear across participants. However, participants may not have been familiar with this shoe and altered their natural movement.

The effect of daily task on load symmetry in the lower limbs of postpartum women had not been yet investigated. Quantifying load symmetry in the lower limbs identified asymmetries in loading and indicate which women have not returned to their pre pregnancy state or have an increased risk of developing pain in the pelvic region. It is

evident both the PIF and ALR metrics differ between tasks in addition to their corresponding NSI values. Overall, postpartum women showed to have the increased NSI PIF values during the sit to stand task and increase NSI ALR values during the stair ambulation tasks. This information can be used in future work to compare lower limb load symmetry in a postpartum and nulliparous cohort to potentially identify altered load mechanics between groups. It would be beneficial to compare groups as altered load mechanics in postpartum women may indicate malalignment of the pelvis or lower limb joints and be a major factor in pain development [22].

Chapter 3: The Effect of Child Carrying Conditions on Loading Symmetry in Postpartum Women During Level Walking Task

Abstract

Understanding how child carrying positions during level walking effect load symmetry in the lower limbs of postpartum women is important for identifying unnatural loading patterns and potential unresolved changes from pregnancy. External loading from a child may influence lower extremity loading as carrying position impacts center of mass, spine lateral flexion, and trunk muscle activation [18]. The purpose of this study was to investigate the differences in lower extremity load asymmetry during simulated child carrying while level walking. Three simulated child carrying conditions no load, child carrying on the preferred hip, child carrying in a frontal baby carrier) were used during a series of walking trials. It was hypothesized that carrying a child on the hip would result in the greatest asymmetry in both peak impact force (PIF) and average loading rate (ALR). For this study, 16 postpartum participants were recruited and completed three 14 meter level walking trials, one trial for each carrying condition. PIF and ALR were calculated using the normal forces under each foot measure with the loadsol® (Novel Electronics, Pittsburg, PA) shoe inserts. Additionally, normalized symmetry index (NSI) values were calculated for both metrics and a linear mixed effects model (LMEM) (RStudio, Boston, Massachusetts) was used to determine the effect of loading condition on level walking asymmetry. Gait speed was not found to differ between loading conditions ($p = 0.936$), so it was not factored into the LMEM as a covariant. The difference in the PIF and ALR values across both child load conditions were statistically significant compared to the no load condition ($p < 0.001$ for both metrics) with values for both metrics being higher during the child load conditions. While there were differences in the ALR and PIF between carrying conditions, side-to-side symmetry was not different based on the carrying condition

Introduction

Of the three and a half million mothers who entered the postpartum period in 2021 [1], around 25% continued to experience lumbopelvic pain from pregnancy [3]. Research has shown this pain persists, with 7.3% of postpartum women continuing to experience lumbopelvic pain from pregnancy up to 2.3 years postpartum [4]. Potential sources for this musculoskeletal pain are asymmetrical pelvic alignment from increased levels of relaxin, weakness in pelvic floor musculature, and asymmetric loading of the lower limbs.

Increased ligamentous laxity, due to greater levels of relaxin, may be associated with lower limb injury in pregnant and postpartum individuals due to increased joint mobility [8]. Increased ligamentous laxity allows for essential relaxation of the pelvic ligaments in preparation for delivery. Relaxation of pelvic ligaments may influence pelvic position during pregnancy as low back pain and high levels of relaxin during late pregnancy are correlated [9]. During pregnancy, relaxin allows for pelvic tilt as the fetus grows and center of mass changes [2]. Pelvic tilt begins to decrease post-delivery, but misalignment may occur if tilt is not fully resolved [28] and asymmetric alignment of the pelvis could increase any pain or tightness in the pelvis, lumbopelvic, or surrounding regions [29]. Additionally, abdominal and pelvic floor musculature may involve prolonged healing time or require directed exercises even if pelvic tilt resolves postpartum [22]. Weakness in these muscles may occur from excessive stretching during pregnancy and increase risk for injury in postpartum women from asymmetry strength and length of these muscles [60]. Pelvic alignment, muscle weakness, and increased ligament laxity are all major factors in the development of pelvic pain in this population [2]. Research has found repetitive loading of asymmetric pelvic floor musculature results in persistent pain [18] and influence asymmetrical loading of lower limbs [10] combined with increased external loading from a child may increase risk of musculoskeletal injury or experiencing pain [15]

When carrying a child, women may use a frontal baby carrier, where external weight is symmetrically loaded through pelvis, or on a hip, where weight is asymmetrically loaded

through pelvis. When carrying a child on the hip, the center of mass shifts and results in lateral spine flexion and asymmetric trunk muscle activation [18]. Repetitive asymmetric loading of the pelvis increases the shear and compressive forces applied to the spine and could result in lumbar pain [18] or chronic injury [13]. Additionally, asymmetries in muscle activation may be further exacerbated from increased ligament laxity and reduced joint stability during repetitive loading [48]. Carrying a child on the hip may result in chronic pain or difficulty for postpartum women to complete daily tasks such as walking for prolonged periods, ascending, or descending stairs [4]. Postpartum women who experience pelvic girdle pain (PGP) have shown to take shorter steps and spend less time in single support phase during the gait cycle where forces are asymmetrically loaded through pelvis [38]. Shorter steps suggest impaired weight bearing abilities of the pelvis for postpartum women with PGP due to presence of pain [38] which may lead to asymmetric of the lower limbs. Research has found individuals with chronic low back pain have a similar gait pattern where they take shorter steps and have higher weight bearing asymmetry compared to healthy individuals [75]. Furthermore, carrying a child may influence weight distribution in the pelvis and load asymmetry in the lower limbs. Added weight from a symmetric load, baby in a frontal carrier, may result in more apparent asymmetries between limbs due to increase forces applied [55]. Conversely, carrying a child on the hip will result in an asymmetrically distributed external weight between lower limbs and potentially compound on any asymmetric load already present [55]. External asymmetric loading may result in different load symmetry compared to external symmetric loading due to compensation for load through lateral spine flexion and asymmetrical trunk muscle activation [18]. Evaluation of both external symmetric and asymmetric loading is important as they may influence load distribution between lower limbs during daily activities.

The aim of this study was to determine if lower extremity load symmetry differs between different carrying conditions in postpartum women during a 14-meter level walking task. This study hypothesized that load asymmetry will exist between the three carrying conditions (no load, baby on preferred hip, and baby frontal in carrier) with greater larger load asymmetry during the baby on preferred hip condition due to the asymmetric trunk

activation and lateral spine flexion that may occur to compensate for the external asymmetric load [18].

Methods:

Nineteen women between six to twelve months postpartum were recruited for this Virginia Tech Institutional Review Board (IRB#24-159) approved study and signed informed consent prior to completion of the study. For participants to meet the study inclusion criteria, their most recent birth had to have been a vaginal delivery, had to wear a women's size 5.5 to 9.5 shoe, and be between the ages of 18 and 40. Participants were excluded if they had sustained an injury in the last three months that limited their physical activity for more than two days, had a prior serious lower extremity injury or surgery, and were currently pregnant. For the study, participants were given neutral running shoes, Nike Zoom Pegasus (Nike, Inc., Beaverton, OR, USA), with loadsol® sensors of their respective size placed inside. Participant's limb dominance was determined by which hand they stated they preferred to write with [63]. Participants completed a 14-meter level walking task with three carrying conditions while loadsol® sensors measured the normal force between the food and ground. Participants were instructed to walk naturally, as if walking through a grocery store. The conditions included no external load, baby on the preferred hip, and baby in a frontal carrier. A pediatric mannequin was used to simulate the weight and size of a nine month old infant (8.55 kg which represents the 50th percentile weight for a nine month old infants). Participants initially walked with no additional load and then randomly selected between the other two carrying conditions (baby on the preferred hip or baby in a frontal carrier) for the second trial followed by the completion of the third condition. During the task, the time to complete the 14 meter distance was recorded with a stopwatch and used to calculate gait speed for each participant.

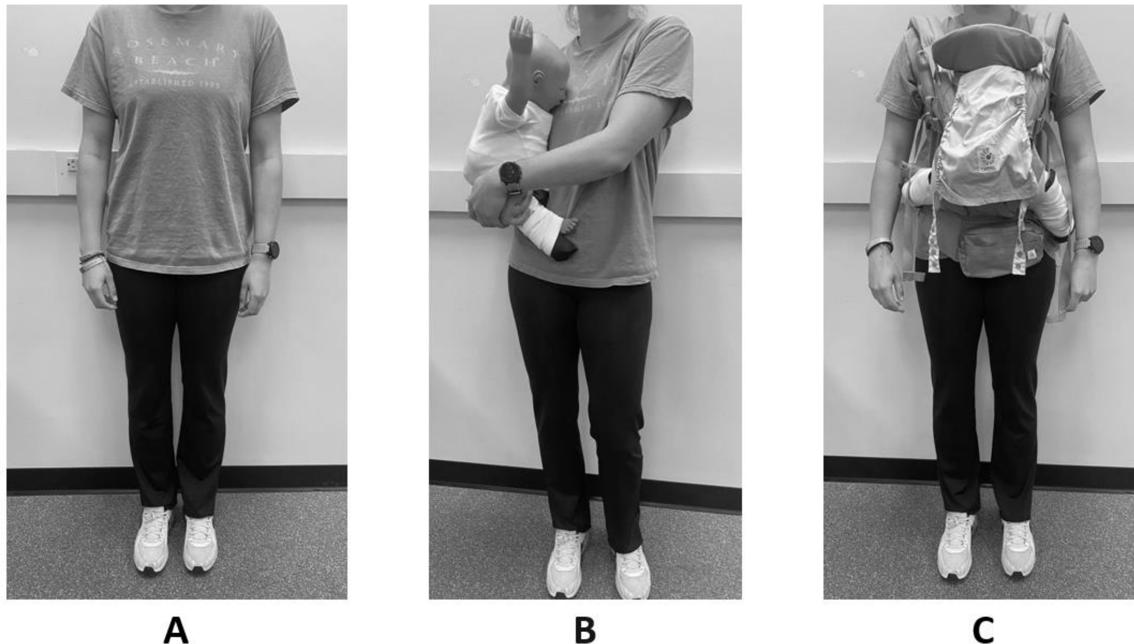

Figure 10: Participant with no additional load (A), baby on preferred hip loading condition (B), and baby in frontal carrier loading condition (C)

Data analysis:

The loadsol® sensors were used to record the normal force between the foot and the shoe while data was sampled at 100 Hz and have been validated with the gold standard force plates for reproducibility with data sampled at 100 Hz [67]. A custom MATLAB script, Load Analysis Program (https://github.com/GranataLab/LAP), was used to calculate the peak impact force (PIF) and average loading rate (ALR) normalized to body weight from the loadsol® data [67]. PIF was defined as the maximum force exerted within the first 30% of ground contact, the period between heel strike and toe off [67]. ALR was defined as the speed at which the forces impact the body [25] and was calculated as the slope of the line between 20% and 80% of the time between ground contact and the peak impact force [64]. Initial contact with the ground was defined as the point where the force measured by the sensor exceeded 60 N and toe-off was defined as point where these forces dropped lower than 60 N. For the level walk, stair scent, and stair descent task, the first and last step was removed from the trial as cadence was either increasing or slowing during these two phases and participants were not moving at a steady state. The

remaining middle steps were used to calculate PIF, ALR, and symmetry of the two metrics. The number of steps differed during the 14 meter level walk depending on cadence of participant, but average step count was 9. The number of steps during stair ascent and descent remained fairly consistent as all participants walked up and down the same 13 steps. Average step count for stair ascent and descent was and for stair descent was 6. For the sit to stand task, all repetitions were kept as cadence was kept consistent throughout the length of the task.

The Normalized Symmetry Index (NSI) was used to evaluate PIF and ALR symmetry between the carrying and non-carrying side [6]. The NSI is a universal index for assessing asymmetry and risk for injury in humans [66]. This index was chosen as it accounts for variation between subjects by scaling symmetry within a sample with multiple repetitions [66]. In the 14-meter level walking task, the NSI is able to account for variation between each step. This is useful in steps where high asymmetry exists between limbs, but the corresponding normal force magnitudes are low, a scenario where other symmetry indices have trouble [66]. An NSI value of zero indicates perfect symmetry between lower limbs whereas a value of 100 indicates perfect asymmetry [6]. The equation below, adapted from Queen et al. [6], demonstrates how NSI is calculated in reference to participant's preferred carrying side (NP) and preferred carrying side (P). The sign of the NSI value represents which side an asymmetry exists on, either the NP side if positive or the P side if negative. The absolute value was taken for the NSI values as this study evaluated the degree of asymmetry in the lower limbs, not which side asymmetry existed on.

$$NSI = abs\left(\frac{X_{NC,t} - X_{C,t}}{max_{t=1:n}(\max(0,X_{NC,t},X_{C,t})) - min_{t=1:n}(\min(0,X_{NC,t},X_{C,t}))} * 100\right)$$

Statistics analysis:

A custom linear mixed effects model (LMEM) (RStudio,Boston, Massachusetts) was used to compare the effect of carrying condition during a level walking task on PIF, ALR, and their corresponding NSI values. A LMEM was chosen as it allows for

comparison of both random and fixed effects [67]. In this study, the fixed effects were carrying condition and gait speed, and random effect was subject. *p*-values were used to determine the statistical significance of each effect with values lower than 0.05 representing statistical significance [67]. If LMEM detected a main effect in loading condition, post-hoc pairwise comparison was preformed to identify individual effects between conditions.

Results:

Participants of this study were an average age of 31 ± 3.0 years old, weight of 68.4 ± 12.2 kg, and height of 164.5 ± 5.0 cm. Participants had between 1 to 3 children, with an average number of 1.7 ± 0.8 children. Participants ranged from 6.5 to 12 months postpartum, at an average of 8.91 ± 1.7 months postpartum. Participant's youngest child had an average weight of 8.45 kg, which differs by 0.1 kg compared to the weighted baby mannequin. Participants had an average Oswestry Disability Index (ODI) score of 3.86 ± 6.63 and scores ranged from 0 to 20. ODI scores indicate the impact low back pain has on the quality of one's life with scores 20 and above indicating moderate disability [79]. The difference in leg length was minimal across participants at an average of 0.95 ± 0.7 centimeters difference. Lastly, 75% of participants preferred to carry their child on the hip opposite of their dominant upper extremity.

Table 3: Participant Demographics

Age (yrs)	31.25 ± 2.96
Weight (kg)	68.43 ± 12.22
Height (cm)	164.56 ± 5.06
Number of Children	1.69 ± 0.79
Months Postpartum	8.91 ± 1.71
Weight of youngest child (kg)	8.45 ± 1.77
ODI Score (%)	3.86 ± 6.63
Leg length difference (cm)	0.95 ± 0.73
Preferred Carrying Side (Upper Extremity)	Dominant: 4, Non-Dominant:12

Gait Speed

Gait speed was not found to differ between carrying conditions (p = 0.936). Gait speed was found to be the fastest during the no load condition (average speed = 0.968 m/s ± 0.11) and slowest during the baby on preferred hip load condition (average speed = 0.953 m/s ± 0.10).

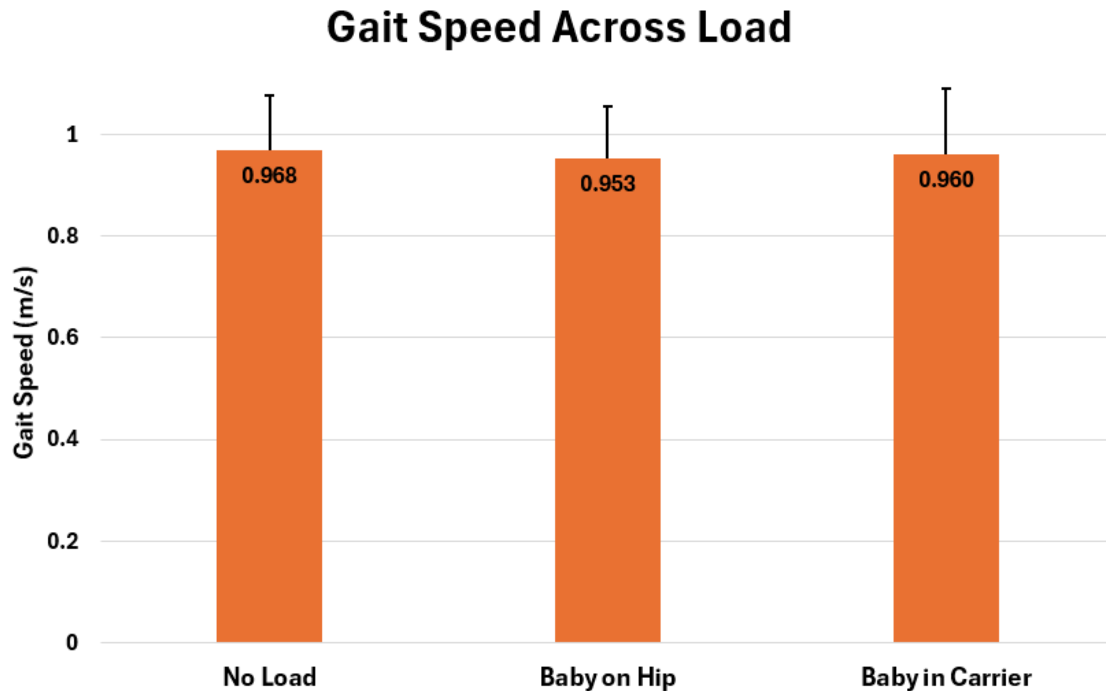

Figure 11: Gait speed across carrying conditions

PIF Values

PIF was found to differ between loading conditions for both the preferred carrying side and the non carrying side (p <0.001 for both sides). On the preferred carrying side, the difference between the no load and baby on hip condition was found to be significantly different (p <0.001). Additionally, the difference between the no load and the baby in carrier conditions was found to be significantly different (p <0.001). The non carrying side followed this same trend with a statistical difference between the no load and baby on hip condition (p <0.001) as well as the no load and baby in carrier condition (p <0.001). The difference between PIF values for the baby on hip and baby in carrier

condition where not found to be significantly different for either side (p = 0.725 for carrying side, p = 0.675 for non carrying side). PIF was found to be the greatest during the baby in frontal carrier load (average PIF = 1.25 BW ± 0.18) and the smallest during the no load condition (average PIF = 1.08 BWW ± 0.13) on the carrying side. On the non carrying side, PIF was the same for both the baby on hip and baby in carrier loading conditions (average PIF = 1.25 BW ± 0.18).

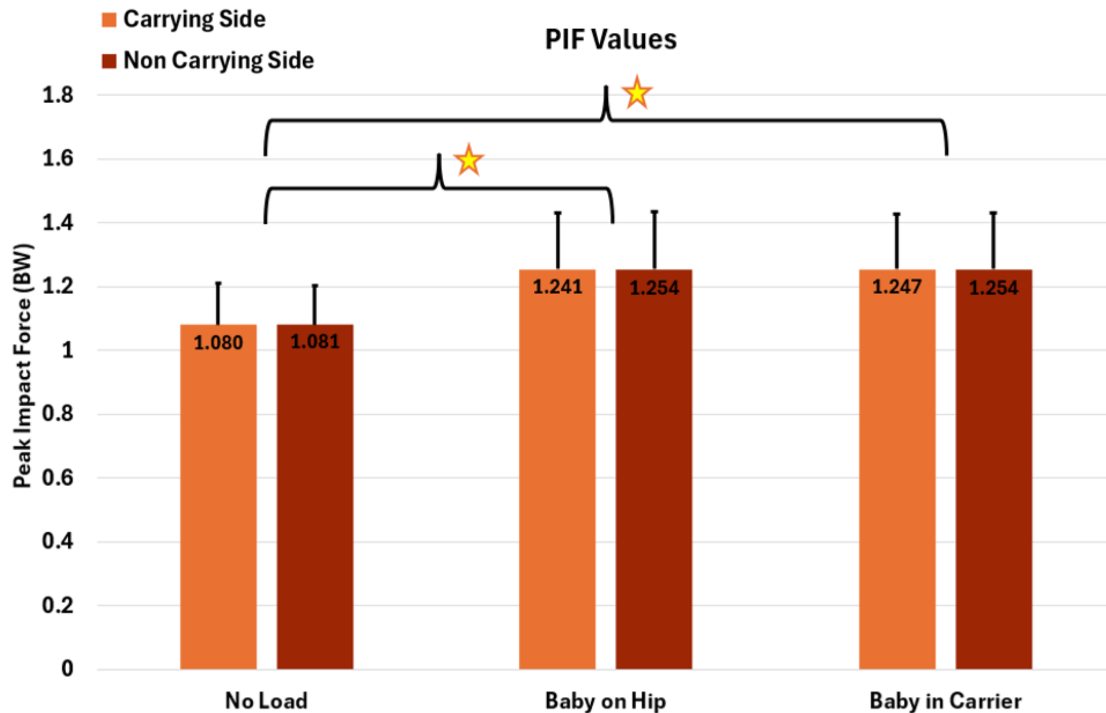

Figure 12: Carrying and Non-Carrying side PIF across loading condition, star (★) indicates p <0.001

<u>ALR Values</u>

ALR was found to differ between loading conditions for both the carrying and non carrying side (p <0.001). On the carrying side, the difference in ALR values between the no load and baby on hip condition was found to be significantly different (p <0.001). The difference between no load and baby in carrier condition was also found to be significant on this side (p <0.001). On the non carrying side, a significant difference was found between the no load and baby on hip condition (p <0.001) as well as the no load and baby in carrier condition (p <0.001). The difference between ALR values for the baby on hip

and baby in carrier condition were not found to be significantly different for either side (p = 0.881 for carrying side, p = 0.424 for non carrying side). On the carrying side, ALR was found to be the greatest during the baby in carrier condition (average ALR = 7.28 ± 2.73 BW/s) and the smallest during the no load condition (average ALR = 6.32 ± 2.33 BW/s). On the non carrying side, ALR was also found to be the greatest during the baby in carrier condition (average ALR = 7.90 ± 2.56 BW/s) and the smallest during the no load condition (average ALR = 7.04 ± 2.15).

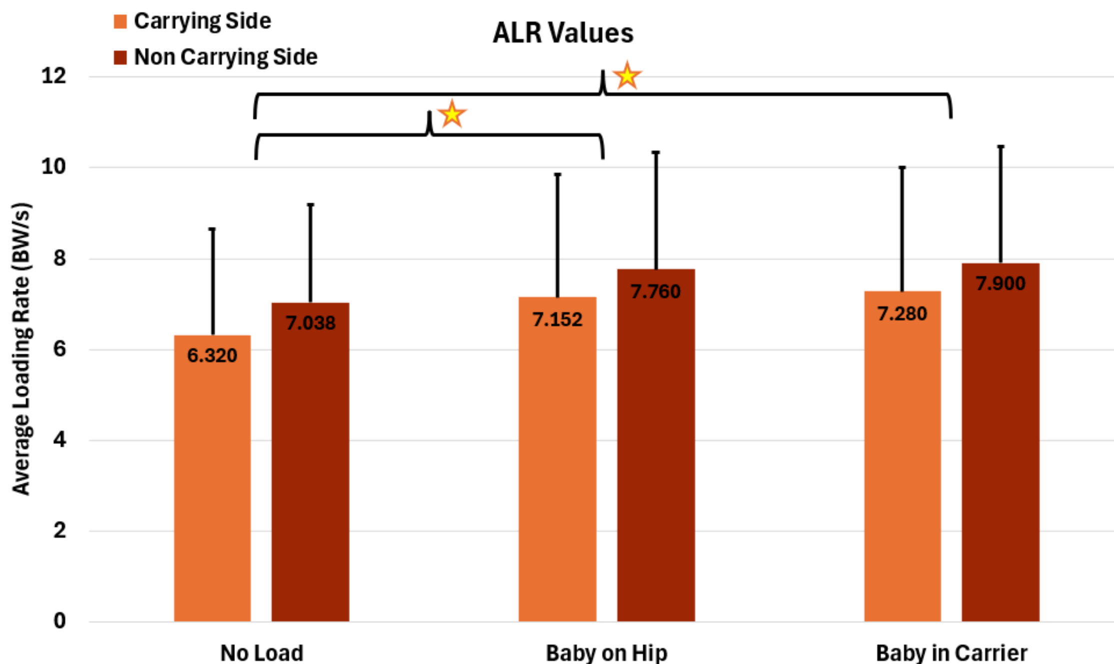

Figure 13: Carrying and Non-Carrying side ALR across loading condition, star (★) indicates p <0.001

PIF NSI

PIF NSI was not different between loading conditions for both the carrying and non carrying side (p = 0.200). PIF NSI was found to be the greatest during the baby in carrier load (average PIF NSI = 4.88 ± 3.38 N) and the smallest during the baby on hip load condition (average PIF NSI = 4.54 ± 3.33 N).

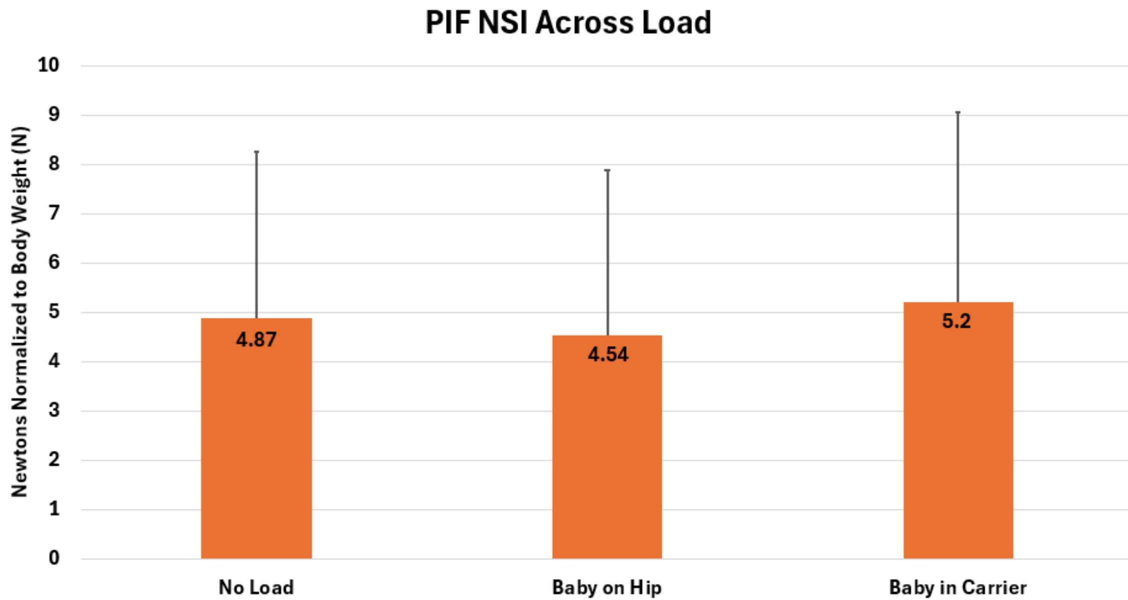

Figure 14: PIF NSI across loading conditions

<u>ALR NSI</u>

The difference between loading conditions was not found to be statistically significant ($p = 0.459$). ALR NSI was found to be the greatest during the baby in carrier condition (average ALR NSI = 5.20 N/s) and the smallest during the baby on hip load condition (average ALR NSI = 4.87 N/s).

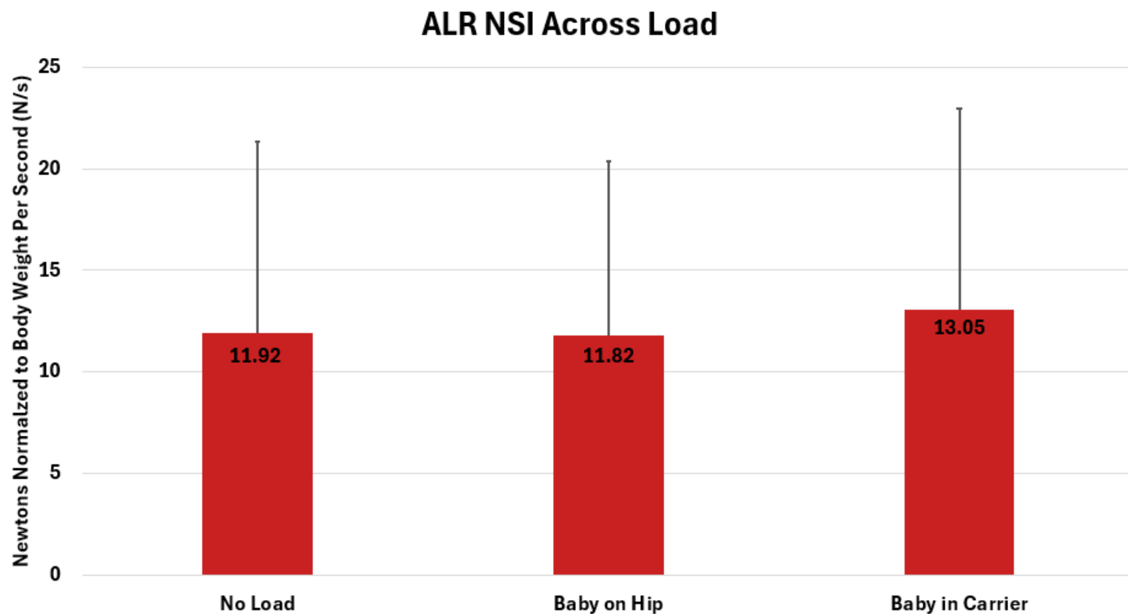

Figure 19: ALR NSI across loading conditions

Discussion

The purpose of this study was to determine load asymmetry between simulated child carrying tasks during the 14-meter level walking task. Identifying asymmetries in limb load with child carrying tasks could help to establish if postpartum women are at a higher risk for developing chronic pain or experiencing a musculoskeletal injury due to unnatural loading of the lower limbs [11]. Although PIF did not differ between baby on hip and baby in carrier condition, PIF asymmetry was improved when holding the baby on hip compared to centrally loaded in the carrier. This differs from our original hypothesis that PIF asymmetry would increase during both loading conditions. Similarly, ALR asymmetry was also improved with the baby on hip condition compared to the centrally loaded carrier condition even though ALR did not differ between these two conditions. This too differs from our original hypothesis that ALR asymmetry would increase during both loading conditions.

In this study, gait speed was calculated by dividing the distance, 14 meters, by the time it took each participant to complete the distance. The gait speed values ranged from 0.763 to 1.227 m/s. Research has found healthy women between the ages of 30 and 39 years have an average gait speed of 1.38 m/s with a range between 1.28 and 1.63 m/s [73]. In healthy women 18 to 29, the average gait speed is also 1.38 m/s. But the range is larger from 1.08 to 1.58 m/s [73]. The average age of participants in this study was 31.25 years old, and the average gait speed for the no load condition fell under what research has found for this age range by 0.412 m/s. Research comparing the gait speed of pregnant (average of 32.25 weeks pregnant and 29 years old) compared to non pregnant individuals found walking speed to decrease by 0.34 m/s [74]. Our results show a similar decrease in gait speed and may also indicate alterations in other gait characteristics such as shorter steps or longer double support time [74]. This decrease in gait speed when the pelvis is asymmetrically loaded may relate to altered pelvic or hip mechanics due to unequal forces being transferred through this area. This is consistent with research as decreased walking speed results in decreased hip flexion [72]. Additionally, even though no significant difference was found between gait speed, this metric was factored into the LMEM as it may impact ALR, PIF, and their corresponding NSI values.

Both PIF and ALR on the participant's preferred carrying side had significant difference between no load and both child loading conditions. This finding is consistent with research as increased external loading results in increased muscle activation and increased ground reaction forces [12]. Similarly, the baby on hip load resulted in values on a magnitude comparable to the baby in carrier load. Research has not investigated the effects on external symmetric and asymmetric load carrying on lower limb loading, but it has been found that an external asymmetric load results in altered coordination during gait compared to an external asymmetric load [74]. Coordination of gait is related to the function of the lower extremities and proximal muscles. Our results differ as both loading conditions resulted in a similar magnitude of PIF and ALR. This may be attributed to the weight of the mannequin remaining constant, even though placement differed. Overall, these results demonstrate both child loads impact the PIF and ALR of postpartum women and may increase risk for injury as repetitive loading combine with increased ligament laxity requires longer rest period between loading to recover from deformation [48].

No significant difference was found between loading conditions for both PIF and ALR NSI values. This differs from our original hypothesis that frontal carrier load condition and baby on preferred hip load condition would result in greater asymmetry values compared to the no load condition. The lack of difference between loading condition suggests the two child loading conditions do not impact the symmetry between lower limbs during level walking. Also, it may indicate mothers can naturally compensate for the external child load conditions as both ALR and PIF values increased during these conditions, but asymmetry was not impacted. As discussed above, research has found that different external loading conditions, an asymmetric or symmetric load, resulted in a difference in interlimb coordination during level walking in healthy college students [74]. Our results differ and may be attributed to the difference in focus populations as research has shown postpartum women experience altered musculoskeletal mechanics during gait and influenced by infant carrying method [75]. Furthermore, repetitive carrying has been shown to increase risk for chronic and overuse injuries [13] due to the musculoskeletal system's inability to cope [43], regardless of asymmetry in loading of lower limbs.

Several limitations warrant discussion. The project was a pilot study and had a relatively small sample size, and it is likely some comparisons are under powered. (can include some power estimates here to back up). Additionally, a never pregnant cohort could provide comparison in loading patterns between either group. Future work could assess altered loading symmetry or patterns between these two groups during the different child carrying loads. Weight of the mannequin also may have impacted the results as it may have differed from the weight of the participant's real baby. The average weight of the participant's real baby was 8.452 kg whereas the mannequin baby was weighted to 8.55 kg. Asymmetric loading of the lower limbs was only evaluated during the level walking task, where PIF and ALR values were the smallest. It would be beneficial to continue this evaluation during the other tasks where increased values were present, such as the stair descent or sit to stand task. This may highlight any significant differences present in loading asymmetry during the different child carrying conditions for the tasks requiring more muscle activation to complete. Finally, the frontal child carrier chosen for this study may have differed from the carrier participants used in their daily life. This may have influenced their natural loading as they adjusted to the frontal carrier.

Overall, postpartum women showed to have increased ALR, and increased PIF values with the child load conditions (in the frontal carrier and on preferred hip) during level walking. Furthermore, it is evident that external loading from a child, whether it is on the hip or in a frontal carrier, has an impact on the mother's movement. These altered loading patterns may increase the risk for postpartum mothers to develop musculoskeletal injury or chronic pain due to repetitive loading. Despite no significant difference being found in lower limb loading asymmetry during child load conditions, repetitive loading from a child still puts postpartum mothers at an increased risk for developing chronic or overuse injuries [13]. Research has not defined a percentage of asymmetric loading between lower limbs to result in injury or chronic pain [18], so there is a potential for even a low degree to impact injury or pain [11].

Chapter 4: Conclusion

Research has found individuals who experience lower back pain also have greater pelvic asymmetry compared to pain free individuals [57]. Given the articulation of the pelvis to the lower limbs, asymmetries in pelvic alignment may be associated with asymmetries in lower limb loading [5]. Furthermore, pain in the lower back, pelvis or hips may result in asymmetrical lower limb loading [10] which may lead to muscle imbalance from joint degeneration and injury [18]. Additionally, force production may be inhibited due to the presence of pain [59] and may indicate impaired weight bearing abilities [60]. Depending on the amount of asymmetry during daily task, postpartum women may have an increased risk for developing musculoskeletal injury or pain [10,11].

The first purpose of this study was to examine the effect of task with no additional external load on load symmetry in the lower limbs of postpartum women. The daily tasks consisted of a sit to stand, 14-meter level walk, stair ascent, and stair descent. Our results indicated that load symmetry differed across tasks, with the sit to stand task having the greatest PIF asymmetry and the stair descent task having the greatest ALR asymmetry. Additionally, both the PIF and ALR metrics differed between tasks, with stair descent resulting in the largest ALR and PIF values. Overall, postpartum women had greater NSI PIF values during the sit to stand task and increase NSI ALR values during the stair ambulation tasks. Our results indicate the need to continue to examine different carrying conditions in postpartum women to better understand potential risk factors for musculoskeletal pain and injury and to provide evidence-based recommendations for postpartum activity progression.

Repetitive loading with the weight of a child may influence risk of injury or pain in postpartum women as increased ligament laxity requires longer rest periods between loading for tissues to recover from deformation [48]. Weight distribution of the child may also influence pain or injury as carrying a child on the hip results in lateral spine flexion and asymmetric trunk muscle activation [18]. Carrying a child on one hip is considered a high-risk activity due to the increased biomechanical stress to the musculoskeletal system

[59]. Repetitive loading combined with asymmetric load distribution of the child may further exacerbate any unequal muscle activation present due to increase ligament laxity and decreased joint stability [48].

The second purpose of this study was to examine the effect of carrying an external child load on lower extremity load symmetry in postpartum women. Our results indicate that postpartum women had lower gait speed compared to non pregnant individuals within the same age range found in published literature [73]. Furthermore, both child carrying conditions, carrying on the hip or in a frontal carrier, resulted in increased ALR and PIF values compared to no load during level walking. Contrary to our original hypothesis, a significant difference in asymmetry between loading conditions was not apparent. This suggests postpartum mothers may have become habituated to baby carrying on the hip and in the frontal carrier condition. However, given this is a preliminary study with a sample size of 16, a post-hoc power analysis indicates the need to collect 66 participants for the study to be powered to detect a difference between carrying conditions. Regardless of load asymmetry, repetitive loading from either child carrying condition exposes mothers to an increased risk of chronic or overuse injury [13]. These results highlight the altered loading patterns of postpartum women when carrying a child on the hip or in a frontal carrier.

In the future, it would be beneficial to develop a study that includes both a nulliparous and postpartum cohort to determine differences in loading mechanics. This would aid in understanding the effect of both task and external child load condition on load symmetry of the lower limbs in postpartum women. Additionally, a larger sample size may more accurately represent the postpartum population as it would better detect differences in loading symmetry across task and carrying conditions. Limitations of this study include the absence of a nulliparous cohort, discrepancy between the participant's own child and the weighted mannequin used, and unfamiliarity with the frontal carrier. However, findings from this study do indicate the need to continue to examine altered loading mechanics of postpartum women during different carrying conditions and tasks to better identify risk factors for pain or injury development. Identified risk factors could be used

to influence recommendations for postpartum activity progression and child carrying techniques.

References

[2] “FastStats - Births and Natality.” *Centers for Disease Control and Prevention*, Centers for Disease Control and Prevention, 16 Dec. 2023, www.cdc.gov/nchs/fastats/births.htm.

[3] Chauhan, Gaurav. “Physiology, Postpartum Changes.” *StatPearls [Internet].*, U.S. National Library of Medicine, 14 Nov. 2022, www.ncbi.nlm.nih.gov/books/NBK555904/.

[4] Wu WH;Meijer OG;Uegaki K;Mens JM;van Dieën JH;Wuisman PI;Ostgaard HC; “Pregnancy-Related Pelvic Girdle Pain (PPP), I: Terminology, Clinical Presentation, and Prevalence.” *European Spine Journal : Official Publication of the European Spine Society, the European Spinal Deformity Society, and the European Section of the Cervical Spine Research Society*, U.S. National Library of Medicine, pubmed.ncbi.nlm.nih.gov/15338362/. Accessed 17 Apr. 2024.

[5] Bijl, Rianne C, et al. “A Retrospective Study on Persistent Pain after Childbirth in the Netherlands.” *Journal of Pain Research*, U.S. National Library of Medicine, 12 Jan. 2016, www.ncbi.nlm.nih.gov/pmc/articles/PMC4716743/#:~:text=At%20a%20mean%20time%20of,0.63%2C%20P%3C0.05).

[6] Kim, Ji-Won, et al. “Analysis of Maximum Joint Moment during Infant Lifting-up Motion.” *Technology and Health Care : Official Journal of the European Society for Engineering and Medicine*, U.S. National Library of Medicine, 2022, www.ncbi.nlm.nih.gov/pmc/articles/PMC9028669/.

[7] Sakamoto, Asuka, et al. “Changes in Pelvic Alignment in a Woman before and after Childbirth, Using Three-Dimensional Pelvic Models Based on Magnetic Resonance Imaging: A Longitudinal Observation Case Report.” *Radiology Case Reports*, U.S. National Library of Medicine, 19 Oct. 2021, www.ncbi.nlm.nih.gov/pmc/articles/PMC8531460/.

[8] Author links open overlay panelJoanne Borg-Stein MD a b c, et al. “Musculoskeletal Disorders of Pregnancy, Delivery and Postpartum.” *Physical Medicine and Rehabilitation Clinics of North America*, Elsevier, 1 Aug. 2007, www.sciencedirect.com/science/article/abs/pii/S1047965107000496?via%3Dihub.

[9] Chu, Stacey R, et al. “Pregnancy Results in Lasting Changes in Knee Joint Laxity.” *PM & R : The Journal of Injury, Function, and Rehabilitation*, U.S. National Library of Medicine, Feb. 2019, www.ncbi.nlm.nih.gov/pmc/articles/PMC6320712/.

[10] B;, Kristiansson P;Svärdsudd K;von Schoultz. “Serum Relaxin, Symphyseal Pain, and Back Pain during Pregnancy.” *American Journal of Obstetrics and Gynecology*, U.S. National Library of Medicine,

pubmed.ncbi.nlm.nih.gov/8942512/#:~:text=There%20was%20a%20significant%20correlation,history%20or%20pain%2Dprovoking%20test. Accessed 17 Apr. 2024.

[11] Sciences, National Academies of, et al. “Musculoskeletal Disorders.” *Selected Health Conditions and Likelihood of Improvement with Treatment.*, U.S. National Library of Medicine, 21 Apr. 2020, www.ncbi.nlm.nih.gov/books/NBK559512/.

[12] Zagrodny, Bartłomiej, et al. “The Influence of External Additional Loading on the Muscle Activity and Ground Reaction Forces during Gait.” *Applied Bionics and Biomechanics*, U.S. National Library of Medicine, 29 July 2021, www.ncbi.nlm.nih.gov/pmc/articles/PMC8342170/#:~:text=The%20muscular%20system%20of%20a,lower%20limb%20should%20be%20similar.

[13] Kumar, Shrawan. “Theories of musculoskeletal injury causation.” *Ergonomics*, vol. 44, no. 1, Jan. 2001, pp. 17–47, https://doi.org/10.1080/00140130120716.

[14] Author links open overlay panelRebecca Avrin Zifchock a, et al. “Kinetic Asymmetry in Female Runners with and without Retrospective Tibial Stress Fractures.” *Journal of Biomechanics*, Elsevier, 14 Nov. 2005, www.sciencedirect.com/science/article/pii/S0021929005004471.

[16] Renner, Kristen E., et al. “The Reliability and Validity of the Loadsol® under Various Walking and Running Conditions.” *MDPI*, Multidisciplinary Digital Publishing Institute, 11 Jan. 2019, www.mdpi.com/1424-8220/19/2/265.

[17] Peebles AT;Renner KE;Miller TK;Moskal JT;Queen RM; “Associations between Distance and Loading Symmetry during Return to Sport Hop Testing.” *Medicine and Science in Sports and Exercise*, U.S. National Library of Medicine, pubmed.ncbi.nlm.nih.gov/30376512/.

[18] Dehghan, F, et al. “The Effect of Relaxin on the Musculoskeletal System.” *Scandinavian Journal of Medicine & Science in Sports*, U.S. National Library of Medicine, Aug. 2014, www.ncbi.nlm.nih.gov/pmc/articles/PMC4282454/.

[19] M;, Stodółka J;Sobera. “Symmetry of Lower Limb Loading in Healthy Adults during Normal and Abnormal Stance.” *Acta of Bioengineering and Biomechanics*, U.S. National Library of Medicine, pubmed.ncbi.nlm.nih.gov/29205215/.

[20] Queen, Robin, et al. “A Novel Method for Measuring Asymmetry in Kinematic and Kinetic Variables: The Normalized Symmetry Index.” *Journal of Biomechanics*, U.S. National Library of Medicine, 23 Jan. 2020, www.ncbi.nlm.nih.gov/pmc/articles/PMC6960348/.

[21] GA;, Harvey MA;Johnston SL;Davies. “Mid-Trimester Serum Relaxin Concentrations and Post-Partum Pelvic Floor Dysfunction.” *Acta Obstetricia et Gynecologica Scandinavica*, U.S. National Library of Medicine, pubmed.ncbi.nlm.nih.gov/18951211/#:~:text=Relaxin%20was%20slightly%20higher%20(not,for%20baseline%20and%20obstetrical%20factors.

[22] “Musculoskeletal Health in Pregnancy and Postpartum.” *SpringerLink*, Springer International Publishing, link.springer.com/book/10.1007/978-3-319-14319-4.

[24] professional, Cleveland Clinic medical. “Relaxin: Hormone, Production in Pregnancy & Function.” *Cleveland Clinic*, my.clevelandclinic.org/health/body/24305-relaxin. Accessed 17 Apr. 2024.

[25] T;, Sanders MJ;Morse. “The Ergonomics of Caring for Children: An Exploratory Study.” *The American Journal of Occupational Therapy : Official Publication of the American Occupational Therapy Association*, U.S. National Library of Medicine, pubmed.ncbi.nlm.nih.gov/15969276/.

[26] Puddle, Damien L, and Peter S Maulder. “Ground Reaction Forces and Loading Rates Associated with Parkour and Traditional Drop Landing Techniques.” *Journal of Sports Science & Medicine*, U.S. National Library of Medicine, 1 Mar. 2013, www.ncbi.nlm.nih.gov/pmc/articles/PMC3761764/#:~:text=Loading%20rate%20%2D%20the%20speed%20at,et%20al.%2C%201999.

[27] Hall, Heather. “Diastasis Recti Rehabilitation.” *StatPearls [Internet].*, U.S. National Library of Medicine, 8 Aug. 2023, www.ncbi.nlm.nih.gov/books/NBK573063/#:~:text=Patients%20may%20notice%20an%20overall,stress%20incontinence%20and%20back%20pain.

[28] Conder, Rebecca, et al. “The Biomechanics of Pregnancy: A Systematic Review.” *Journal of Functional Morphology and Kinesiology*, U.S. National Library of Medicine, 2 Dec. 2019, www.ncbi.nlm.nih.gov/pmc/articles/PMC7739277/#:~:text=Weakened%20abdominal%20muscles%20during%20pregnancy,anterior%20pelvic%20tilt%20%5B30%5D.

[29] A;, Foti T;Davids JR;Bagley. “A Biomechanical Analysis of Gait during Pregnancy.” *The Journal of Bone and Joint Surgery. American Volume*, U.S. National Library of Medicine, pubmed.ncbi.nlm.nih.gov/10819273/. Accessed 18 Apr. 2024.

[30] Sakamoto, Asuka, and Kazuyoshi Gamada. “Altered Musculoskeletal Mechanics as Risk Factors for Postpartum Pelvic Girdle Pain: A Literature Review.” *Journal of Physical Therapy Science*, The Society of Physical Therapy Science, 19 Oct. 2019, www.jstage.jst.go.jp/article/jpts/31/10/31_jpts-2019-098/_article.

[31] *(PDF) Comparison of Pelvic Alignment among Never-Pregnant Women, Pregnant Women, and Postpartum Women*, www.researchgate.net/publication/292148470_Comparison_of_pelvic_alignment_among_never-pregnant_women_pregnant_women_and_postpartum_women. Accessed 18 Apr. 2024.

[32] Heidari, Pedram, et al. “The Role of Ultrasound in Diagnosis of the Causes of Low Back Pain: A Review of the Literature.” *Asian Journal of Sports Medicine*, U.S. National Library of Medicine, Mar. 2015, www.ncbi.nlm.nih.gov/pmc/articles/PMC4393543/.

[33] Stuge, Britt. "Diagnostikk Og Behandling AV Bekkenleddsplager." *Tidsskrift for Den Norske Legeforening*, 4 Nov. 2010, tidsskriftet.no/2010/11/oversiktsartikkel/diagnostikk-og-behandling-av-bekkenleddsplager.

[35] PB;, Fairbank JC;Pynsent. "The Oswestry Disability Index." *Spine*, U.S. National Library of Medicine, pubmed.ncbi.nlm.nih.gov/11074683/. Accessed 18 Apr. 2024.

[36] Research, From the Department of. "Validity and Reliability of English and Marathi Oswestry... : Spine." *LWW*, journals.lww.com/spinejournal/abstract/2013/05150/validity_and_reliability_of_english_and_marathi.16.aspx. Accessed 22 Apr. 2024.

[37] Tonosu, Juichi, et al. "The Normative Score and the Cut-off Value of the Oswestry Disability Index (ODI)." *European Spine Journal : Official Publication of the European Spine Society, the European Spinal Deformity Society, and the European Section of the Cervical Spine Research Society*, U.S. National Library of Medicine, Aug. 2012, www.ncbi.nlm.nih.gov/pmc/articles/PMC3535252/%C2%A0.

[38] B;, Gutke A;Lundberg M;Östgaard HC;Öberg. "Impact of Postpartum Lumbopelvic Pain on Disability, Pain Intensity, Health-Related Quality of Life, Activity Level, Kinesiophobia, and Depressive Symptoms." *European Spine Journal : Official Publication of the European Spine Society, the European Spinal Deformity Society, and the European Section of the Cervical Spine Research Society*, U.S. National Library of Medicine, pubmed.ncbi.nlm.nih.gov/20593205/#:~:text=The%20impacts%20were%20similar%20among,in%20lumbar%20or%20pelvic%20areas. Accessed 18 Apr. 2024.

[39] Christensen L;Vøllestad NK;Veierød MB;Jakobsen VE;Stuge B;Bakke ES;Cabri J;Robinson HS; "Trunk, Pelvic and Hip Kinematics during the Stork Test in Pregnant Women with Pelvic Girdle Pain, Asymptomatic Pregnant and Non-Pregnant Women." *Clinical Biomechanics (Bristol, Avon)*, U.S. National Library of Medicine, pubmed.ncbi.nlm.nih.gov/32920251/. Accessed 18 Apr. 2024.

[42] Bagwell, Jennifer J, et al. "The Reliability of Faber Test Hip Range of Motion Measurements." *International Journal of Sports Physical Therapy*, U.S. National Library of Medicine, Dec. 2016, www.ncbi.nlm.nih.gov/pmc/articles/PMC5159634/.

[43] Gutke, Annelie, et al. "Posterior Pelvic Pain Provocation Test Is Negative in Patients with Lumbar Herniated Discs." *European Spine Journal : Official Publication of the European Spine Society, the European Spinal Deformity Society, and the European Section of the Cervical Spine Research Society*, U.S. National Library of Medicine, July 2009, www.ncbi.nlm.nih.gov/pmc/articles/PMC2899577/.

[44] Orejel Bustos, Amaranta, et al. "Overuse-Related Injuries of the Musculoskeletal System: Systematic Review and Quantitative Synthesis of Injuries, Locations, Risk Factors and Assessment Techniques." *Sensors (Basel, Switzerland)*, U.S. National Library of Medicine, 1 Apr. 2021, www.ncbi.nlm.nih.gov/pmc/articles/PMC8037357/.

[45] Enoka, Roger M, and Jacques Duchateau. "Muscle Fatigue: What, Why and How It Influences Muscle Function." *The Journal of Physiology*, U.S. National Library of Medicine, 1 Jan. 2008, www.ncbi.nlm.nih.gov/pmc/articles/PMC2375565/.

[46] E;, Voloshin AS;Mizrahi J;Verbitsky O;Isakov. "Dynamic Loading on the Human Musculoskeletal System -- Effect of Fatigue." *Clinical Biomechanics (Bristol, Avon)*, U.S. National Library of Medicine, pubmed.ncbi.nlm.nih.gov/11415829/#:~:text=BACKGROUND%3A%20Muscles%20act%20to%20lower,attenuate%20loading%20on%20the%20system. Accessed 18 Apr. 2024.

[47] Orejel Bustos A;Belluscio V;Camomilla V;Lucangeli L;Rizzo F;Sciarra T;Martelli F;Giacomozzi C; "Overuse-Related Injuries of the Musculoskeletal System: Systematic Review and Quantitative Synthesis of Injuries, Locations, Risk Factors and Assessment Techniques." *Sensors (Basel, Switzerland)*, U.S. National Library of Medicine, pubmed.ncbi.nlm.nih.gov/33916269/. Accessed 18 Apr. 2024.

[48] Galbraith, R Michael, and Mark E Lavallee. "Medial Tibial Stress Syndrome: Conservative Treatment Options." *Current Reviews in Musculoskeletal Medicine*, U.S. National Library of Medicine, 7 Oct. 2009, www.ncbi.nlm.nih.gov/pmc/articles/PMC2848339/ or https://www.sciencedirect.com/science/article/abs/pii/S1360859208000107.

[49] Author links open overlay panelMoshe Solomonow B.Sc., et al. "Ligaments: A Source of Musculoskeletal Disorders." *Journal of Bodywork and Movement Therapies*, Churchill Livingstone, 14 Apr. 2008, www.sciencedirect.com/science/article/abs/pii/S1360859208000107.

[50] "Musculoskeletal Health Program." *Centers for Disease Control and Prevention*, Centers for Disease Control and Prevention, 21 Mar. 2022, www.cdc.gov/niosh/programs/msd/default.html#:~:text=Description,limbs%2C%20neck%20and%20lower%20back.

[51] Flynn T;Fritz J;Whitman J;Wainner R;Magel J;Rendeiro D;Butler B;Garber M;Allison S; "A Clinical Prediction Rule for Classifying Patients with Low Back Pain Who Demonstrate Short-Term Improvement with Spinal Manipulation." *Spine*, U.S. National Library of Medicine, pubmed.ncbi.nlm.nih.gov/12486357/.

[52] Bozorgmehr, Ali, et al. "Relationships between Muscular Impairments, Pain, and Disability in Patients with Chronic Nonspecific Low Back Pain: A Cross Sectional Study." *Journal of Exercise Rehabilitation*, U.S. National Library of Medicine, 27 Dec. 2018, www.ncbi.nlm.nih.gov/pmc/articles/PMC6323331/.

[53] *Effect of Correcting Limited Hip Internal Rotation on Postpartum ...*, scholar.cu.edu.eg/sites/default/files/mahyyosri/files/correcting_limited_hip_ir_on_lbp.pdf.

[54] Mani, Mohanieshwari, and Jincy Samuel. "Evaluation of lumbar lordosis and hip extensor strength in postpartum woman with pelvic girdle pain - a case control study."

Journal of Ecophysiology and Occupational Health, 18 Apr. 2023, pp. 8–13, https://doi.org/10.18311/jeoh/2023/32074.

[55] Author links open overlay panelCraig Liebenson DC a, et al. "The Active Straight Leg Raise Test and Lumbar Spine Stability." *PM&R*, No longer published by Elsevier, 11 June 2009, www.sciencedirect.com/science/article/abs/pii/S1934148209003372.

[56] *Sex and Mechanism of Injury Influence Knee Joint Loading Symmetry During Gait 6 Months After ACLR,* onlinelibrary.wiley.com/doi/full/10.1002/jor.24822. Accessed 19 Apr. 2024.

[57] Heil, Jessica. "Load-Induced Changes of Inter-Limb Asymmetries in Dynamic Postural Control in Healthy Subjects." *Frontiers in Human Neuroscience*, U.S. National Library of Medicine, 11 Mar. 2022, www.ncbi.nlm.nih.gov/pmc/articles/PMC8963187/.

[58] Author links open overlay panelEinas Al-Eisa, et al. "Fluctuating Asymmetry and Low Back Pain." *Evolution and Human Behavior*, Elsevier, 28 Jan. 2004, www.sciencedirect.com/science/article/abs/pii/S1090513803000813.

[59] Kurki, Helen K. "Bilateral asymmetry in the human pelvis." *The Anatomical Record*, vol. 300, no. 4, 15 Mar. 2017, pp. 653–665, https://doi.org/10.1002/ar.23546.

[60] CJ;, Oddsson LI;De Luca. "Activation Imbalances in Lumbar Spine Muscles in the Presence of Chronic Low Back Pain." *Journal of Applied Physiology (Bethesda, Md. : 1985)*, U.S. National Library of Medicine, pubmed.ncbi.nlm.nih.gov/12482760/.

[61] Author links open overlay panelLene Christensen a, et al. "Kinematic and Spatiotemporal Gait Characteristics in Pregnant Women with Pelvic Girdle Pain, Asymptomatic Pregnant and Non-Pregnant Women." *Clinical Biomechanics*, Elsevier, 23 May 2019, www.sciencedirect.com/science/article/pii/S0268003319300750.

[62] Author links open overlay panelV.L. Talis a, et al. "Asymmetric Leg Loading during Sit-to-Stand, Walking and Quiet Standing in Patients after Unilateral Total Hip Replacement Surgery." *Clinical Biomechanics*, Elsevier, 31 Dec. 2007, www.sciencedirect.com/science/article/abs/pii/S0268003307002641.

[63] Kamonseki, Danilo Harudy, et al. "Reliability, validity, and minimal detectable change of side hop test in Male Children and Adolescents." *Physical Therapy in Sport*, vol. 34, Nov. 2018, pp. 141–147, https://doi.org/10.1016/j.ptsp.2018.09.009.

[64] Pollard CD;Norcross MF;Johnson ST;Stone AE;Chang E;Hoffman MA; "A Biomechanical Comparison of Dominant and Non-Dominant Limbs during a Side-Step Cutting Task." *Sports Biomechanics*, U.S. National Library of Medicine, pubmed.ncbi.nlm.nih.gov/29671697/. Accessed 19 Apr. 2024.

[65] RM;, Peebles AT;Maguire LA;Renner KE;Queen. "Validity and Repeatability of Single-Sensor Loadsol Insoles during Landing." *Sensors (Basel, Switzerland)*, U.S.

National Library of Medicine, pubmed.ncbi.nlm.nih.gov/30469462/. Accessed 19 Apr. 2024.

[67] Renner, Kristen E, et al. "The Reliability and Validity of the Loadsol® under Various Walking and Running Conditions." *Sensors (Basel, Switzerland)*, U.S. National Library of Medicine, 11 Jan. 2019, www.ncbi.nlm.nih.gov/pmc/articles/PMC6359506/.

[68] Yu, Qiuhua, et al. "The Association between Pelvic Asymmetry and Non-Specific Chronic Low Back Pain as Assessed by the Global Postural System." *BMC Musculoskeletal Disorders*, U.S. National Library of Medicine, 5 Sept. 2020, www.ncbi.nlm.nih.gov/pmc/articles/PMC7487478/#:~:text=Pelvic%20asymmetry%20refers%20to%20the,relative%20to%20the%20vertical%20axis.

[69] Chaudhry, Shazia R. "Anatomy, Abdomen and Pelvis, Pelvis." *StatPearls [Internet].*, U.S. National Library of Medicine, 25 July 2023, www.ncbi.nlm.nih.gov/books/NBK482258/.

[70] Oleksy, Łukasz, et al. "The Influence of Pelvis Reposition Exercises on Pelvic Floor Muscles Asymmetry: A Randomized Prospective Study." *Medicine*, U.S. National Library of Medicine, Jan. 2019, www.ncbi.nlm.nih.gov/pmc/articles/PMC6336649/%C2%A0.

[71] professional, Cleveland Clinic medical. "Pelvic Floor Muscles: Anatomy, Function & Conditions." *Cleveland Clinic*, my.clevelandclinic.org/health/body/22729-pelvic-floor-muscles. Accessed 19 Apr. 2024.

[72] Easley, Deanna C, et al. "Female Pelvic Floor Biomechanics: Bridging The Gap." *Current Opinion in Urology*, U.S. National Library of Medicine, May 2017, www.ncbi.nlm.nih.gov/pmc/articles/PMC5639926/.

[73] Easley, Deanna C, et al. "Female Pelvic Floor Biomechanics: Bridging The Gap." *Current Opinion in Urology*, U.S. National Library of Medicine, May 2017, www.ncbi.nlm.nih.gov/pmc/articles/PMC5639926/.

[74] Havens, Kathryn L., et al. "The Combined Influence of Infant Carrying Method and Motherhood on Gait Mechanics." *Human Kinetics*, Human Kinetics, 20 Nov. 2023, journals.humankinetics.com/view/journals/jab/40/2/article-p105.xml.

[76] Ortho, Comp. "Anatomy of the Male and Female Pelvis." *Comprehensive Orthopaedics*, 13 Feb. 2017, comportho.com/anatomy/anatomy-of-the-male-and-female-pelvis/.

[77] Muscolino, Joe. "Motions of the Joints of the Pelvis (Sacroiliac Joints)." *Learn Muscles*, 30 Aug. 2017, learnmuscles.com/blog/2017/08/30/motions-of-the-joints-of-the-pelvis/.

[78] "Loadsol®." *Novel USA*, www.novelusa.com/loadsol.

[79] *(PDF) the Oswestry Disability Index*, www.researchgate.net/publication/315906466_The_Oswestry_Disability_Index.

[80] Streamer, Jill, et al. "Exploration of Movement Variability and Limb Loading Asymmetry During Simulated Daily Functional Tasks." *Vtechworks.Lib.vt.Edu*, 27 Apr. 2022.