Research Article

Infant-carrying methods and their biomechanical influence on maternal gait patterns and joint mechanics

Journal of Back and Musculoskeletal Rehabilitation
2025, Vol. 38(5) 1004–1011

DOI: 10.1177/10538127251321771
journals.sagepub.com/home/bmr
Sage | IOS Press

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Abstract

Background: Infant carrying is a common practice among caregivers. Carrying loads such as infant mannequins or bags may alter lower extremity joint angles and induce muscle fatigue in the upper extremities of carriers, including men, women, postpartum women, and women who have not given birth. However, the biomechanical effects of various carrying methods on mothers remain poorly understood.

Objective: This cross-sectional descriptive study compared the effects of unloaded walking with three infant-carrying conditions on gait mechanics.

Methods: Thirty healthy mothers' gait parameters were recorded using a motion capture system under four conditions: unloaded walking (UW), front-facing carrying (FC), back-facing carrying (BC), and in arms carrying (IA).

Results: Across all infant-carrying conditions, notable changes were observed in gait parameters. The front-facing carrying condition elicited the greatest changes in gait mechanics, particularly in pelvis. The in arms carrying condition exhibited minimal changes in gait compared to the back and front-facing carrying conditions. Significant alterations in gait were observed in all infant-carrying conditions compared to unloaded walking ($p < 0.05$). The results indicated that ankle ($M = 41.15 \pm 0.25$; $M = 24.18 \pm 0.29$; $p = 0.0024$), and pelvis ($M = 6.15 \pm 0.35$; $M = 9.25 \pm 0.45$; $p = 0.0036$) movement patterns led to the greatest deviation in gait among four conditions.

Conclusion: Front-facing carrying imposes the greatest biomechanical and physiological strain while back carrier offers more ergonomically efficient alternative. The in arms carrying method introduces dynamic movement that may affect stability. These findings highlight important considerations for ergonomically optimized infant carriers to support maternal musculoskeletal health and minimize strain.

Keywords

gait analysis, women's health, biomechanics, kinematics, musculoskeletal, spine

Received: 4 January 2025; accepted: 2 February 2025

Introduction

The practice of carrying an infant using any form of carrier is referred to as baby-wearing.[1,2] Infant carriers offer multiple benefits, such as keeping the baby close to the mother, providing comfort and security while allowing the mother to perform tasks.[3] They support a infant's physical and emotional development,[4–7] and studies show that mother-infant interactions improve with physical contact, particularly in babywearing contexts, which enhances maternal sensitivity compared to stroller use.[8] However, extended carrying places a musculoskeletal load on mothers, altering their walking biomechanics and potentially exacerbating postpartum issues like lumbopelvic pain, muscle imbalance, and postural changes.[9–12] Even

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in nulliparous women, carrying an infant dummy in various positions elicits distinct neuromechanical responses.[13]

Walking with an infant positioned in front creates an uneven load, shifting weight to one side, increasing lumbar strain, and potentially causing pain and musculoskeletal issues.[14] Front-facing carrying shifts the caregiver's center of gravity forward, similar to pregnancy, leading to increased spine curvature, torso stiffness, and lumbar load, as well as higher caloric expenditure, altered gait, and slower walking speed.[15–17] The back-carrying technique slightly reduces cardiopulmonary strain, metabolic load, and fatigue compared to other methods.[18] Carrying an infant in arms increases knee and hip load in the frontal plane, whereas an anteriorly worn carrier more closely resembles unloaded walking.[19] Biomechanical differences between mothers carrying infants and non-mothers carrying mannequins highlight postpartum health impacts, affecting step timing, forces, and joint mechanics.[20] The aim of this study was to investigate the spatiotemporal and kinematic differences in mothers carrying their own infants under four carrying conditions using a 3D camera-based motion capture system: unloaded (UL), in arms (IA), and two positions using an infant carrier (front-FC and back-BC). The study hypothesizes that front-facing carrying will impose the greatest biomechanical and physiological strain, leading to significant deviations in gait parameters compared to unloaded walking and back-facing carrying will demonstrate better ergonomic efficiency, resulting in fewer gait alterations than front-facing carrying.

Methods

Participants

This study involved 30 infants (mean age of 23.6 ± 1.2 weeks, height of 60.3 ± 4 cm, and weight of 6.3 ± 2.2 kg), and their mothers (mean maternal age of 26 ± 3.91 years, height of 1.68 ± 0.4 m, and weight of 70 ± 10.8 kg), who were followed up at the Child Health and Diseases Child Neurology Polyclinic of Bezmialem Vakıf University Medical Faculty Hospital. This study was conducted in compliance with the principles of the Declaration of Helsinki. All data were processed anonymously to ensure the confidentiality and privacy of participants. Identifiable personal information was excluded from the analysis to protect participant anonymity. Prior to evaluations, written consent was obtained from all participants in compliance with legal requirements. Inclusion criteria required participants to have full-term infants aged 4–10 months, a normal BMI, and willingness to participate. Exclusion criteria included skeletal and neurological disorders. All infants received a general examination by the same pediatrician to confirm the absence of musculoskeletal or neurological issues affecting carrier use.

Experimental protocol

A two-part demographic assessment form was administered for both infants and mothers. The first part collected mothers' sociodemographic and clinical data, including pain and comfort with carrier use. The second part recorded infant demographic information.

Three-dimensional kinematic and kinetic data were collected and analyzed on the dominant side. Participants walked barefoot at a self-selected speed along a 10-m walkway for each carrying condition in a fully equipped gait analysis laboratory (Figure 1). Gait assessments were conducted in the same sequence for all participants, with rest periods provided between each condition. Class Hip Support Kangaroo, Baby Plus Baby-Carrier (The BabyPlus Company, LLC. Indiana, USA) was used during data collection.

Gait analysis was conducted using an eight-camera motion capture system (Vicon Motion Systems Ltd, UK) and an AMTI force plate (AMTI Force and Motion, Watertown, MA). Using this system, the participants' movement patterns, along with the kinematic data of all joints and body segments, were simultaneously captured alongside wireless infrared signals. In this way, the mothers' gait and movements were continuously monitored in real-time through a three-dimensional model on a computer. Each participant was equipped with 34 retroreflective markers, which were strategically positioned on specific anatomical landmarks, including the medial and lateral malleoli, tibial tuberosity, femoral epicondyles, greater

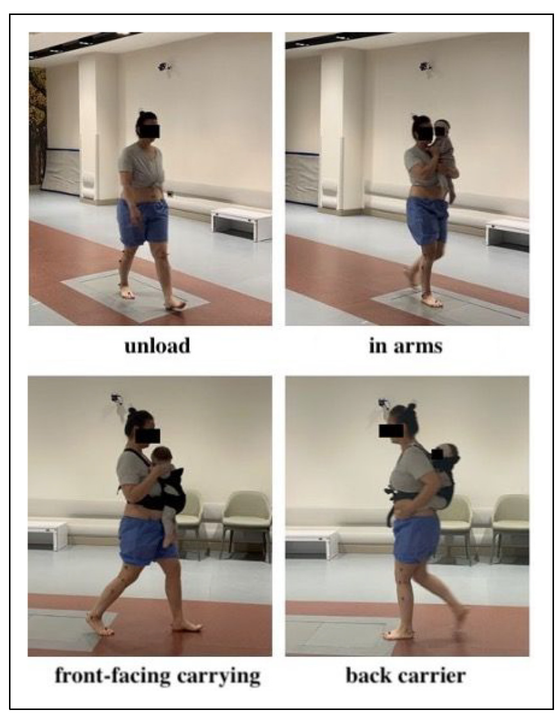

Figure 1. Data collection conditions.

trochanter, acromion process, lateral epicondyle, styloid processes of the radius and ulna, as well as the sacrum, C7 vertebra, and iliac crest, in accordance with a standardized protocol. Five acceptable trials of foot contact with the force plate were collected and averaged for each parameter. Motion capture data were recorded at 100 Hz, while ground reaction forces were captured at 1200 Hz synchronously. Foot contact and ground reaction forces were used to calculate stride percentages normalized to 100%. Lower limb segment lengths, along with participant height, weight, and foot length, were measured manually.

Data analysis

Kinetic and kinematic data during walking under various conditions were processed using the Vicon plug-in gait model, with MATLAB (MathWorks, Natick, MA, USA) utilized for data analysis. Following marker placement on mothers, participants were instructed to complete four walking sessions: (a) unloaded (UL), (b) in arms (IA), (c) walking while carrying their babies in a front-facing infant-carrier (FC), and (d) walking while carrying their babies in a back infant-carrier (BC). At the end of each data collection session, mothers were given a 5-min rest period.

- During unloaded walking conditions, mothers were given sufficient time to acclimate to the study protocol and testing environment while walking on the walkway without their infants.
- During IA condition, participants were instructed to hold their infants in front of their bodies, with the baby's pelvis resting against their abdomen, and walked without changing this position.
- During FC and BC conditions, participants walked at a self-selected speed on the walkway using the infant carrier.

For each condition, lower extremity joint range of motion values were reported as means (SD) and assessed for normality using the Kolmogorov-Smirnov test. All tests were two-tailed, with statistical significance set at $p < 0.05$. Statistical analysis was performed using SPSS (version 21, Chicago, IL). Sample size calculation with G-Power (version 3.2.1, G*Power-Universität Düsseldorf) indicated that 30 participants provided a power of 0.80 and an effect size of 0.8, based on a 10% standard deviation and a 95% confidence interval ($z = 1.96$).

Results

The study included 30 participants with a mean maternal age of 26 ± 3.91 years, height of 1.68 ± 0.4 m, and weight of 70 ± 10.8 kg. Infants had a mean age of 23.6 ± 1.2 weeks, height of 60.3 ± 4 cm, and weight of 6.3 ± 2.2 kg. Among the mothers participating in our study, 5 had completed a master's or doctoral degree, 4 held a bachelor's degree, 5 were high school graduates but unemployed, and 16 were homemakers. Of these participants, 7 (23.3%) received caregiver support, while 23 (76.7%) did not. A total of 24 mothers (80%) reported a habit of using a infant-carrier, whereas 6 (30%) had never used one before. None of the mothers reported pain, and all found the carrier to be comfortable.

Biomechanical and gait parameters were analyzed to evaluate different walking conditions, with mean cadence values shown in Table 1. In the Front-facing infant carrier (FC) condition, the highest cadence was observed, with an average of 113.52 ± 2.62 steps per minute. In contrast, the Unloaded Walking (UL) condition showed a cadence of 110.69 ± 1.79 steps per minute, slightly lower than FC, which is expected as walking without load allows for a more natural gait. The Back infant carrier (BC) condition had a cadence of 102.99 ± 4.64 steps per minute. The In arms (IA) condition demonstrated the lowest cadence of 102.18 ± 4.34 steps per minute, suggesting that carrying the infant in the arms imposes greater biomechanical constraints and reduces walking efficiency. The data highlights the impact of different infant-carrying positions on walking dynamics. The front-facing infant carrier appears to provide the most efficient gait pattern, with the highest cadence and speed, which could be attributed to better load distribution and enhanced comfort. In contrast, carrying the infant in the arms or in the back carrier tends to reduce walking speed and cadence, likely due to increased energy expenditure and changes in biomechanics.

The lower extremity joint moments, range of motions, and pelvis kinematics were compared for test conditions (Figure 2). Increased varus/valgus moments at the knee joint were observed in the IA and FC conditions compared to UL, likely due to restricted arm swing for postural balance. Additionally, hip flexion was greater in FC compared to UL, and knee flexion-extension moments were lower in FC than in UL and BC. Vertical ground reaction moments were 6.36% higher with the infant carrier and 14.8% higher when carrying the baby IA, compared to unloaded walking.

Table 1. Average cadence and walking speed during tested conditions.

Test Condition	Cadence (step/min)	Speed (distance/min)
Unloaded Walking (UL)	110.69 ± 1.79	3.68 ± 0.05
In arms (IA)	102.18 ± 4.34	3.40 ± 0.14
Front-facing infant carrier (FC)	113.52 ± 2.62	3.78 ± 0.08
Back infant carrier (BC)	102.99 ± 4.64	3.43 ± 0.15

UL: Unloaded Walking; IA: In arms; FC: Front-facing infant carrier; BC: Back infant carrier.

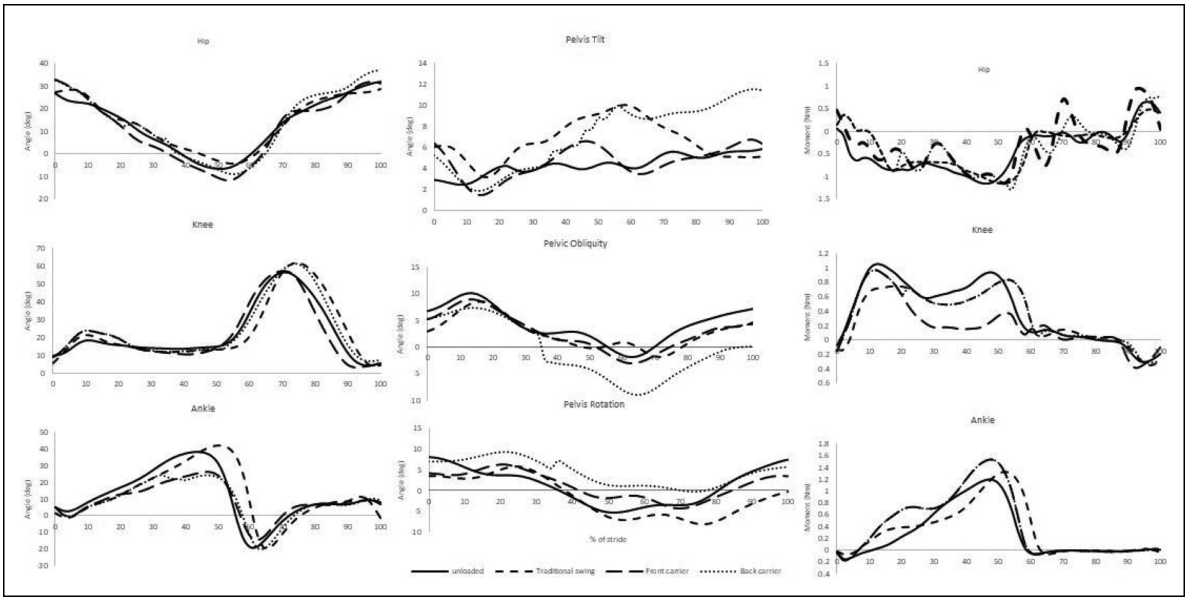

Figure 2. Lower extremity sagittal plane moments and kinematics during (1) unloaded walking (2) in arms (3) front-facing infant carrier (4) back infant carrier conditions.

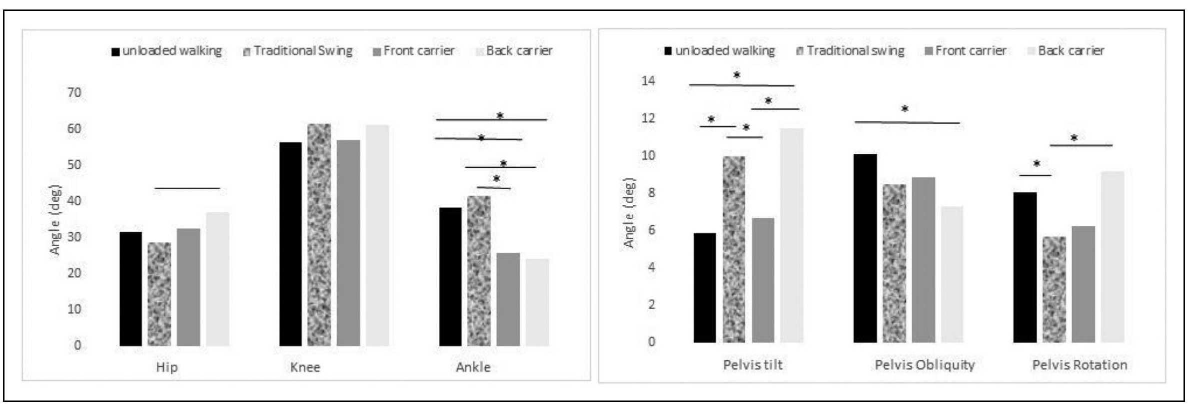

Figure 3. Range of motion of lower extremity joints in the sagittal plane under different conditions * indicate statistical significance at $p < 0.05$.

Figure 3 represents the lower extremity joints range of motions in the sagittal plane and pelvis movement in the sagittal, coronal, and transverse planes. The results indicated that hip joint range of motions during IA–BC conditions was statistically different ($M = 38.69 \pm 0.73$; $M = 29.88 \pm 1.20$; $p = 0.039$). Similarly, ankle range of motions showed different patterns during different infant-carrying conditions. The ankle joint range of motion was statistically different for IA–FC ($M = 41.15 \pm 0.25$; $M = 24.18 \pm 0.29$; $p = 0.0024$), IA–BC ($M = 41.15 \pm 0.25$; $M = 22.16 \pm 1.09$; $p = 0.0018$), UL–BC ($M = 40.04 \pm 0.58$; $M = 22.16 \pm 1.09$; $p = 0.0044$), and UL-FC ($M = 40.04 \pm 0.58$; $M = 24.18 \pm 0.29$; $p = 0.0048$) conditions.

Pelvis tilt trajectories were statistically different for UL–IA ($M = 6.15 \pm 0.35$; $M = 9.25 \pm 0.45$; $p = 0.0036$), IA–FC ($M = 9.25 \pm 0.45$; $M = 6.78 \pm 0.79$; $p = 0.004$), FC–BC ($M = 6.78 \pm 0.79$; $M = 11.58 \pm 0.1$; $p = 0.0045$), and UL–BC ($M = 6.15 \pm 0.35$; $M = 11.58 \pm 0.1$; $p = 0.0042$) conditions. Similarly, pelvis obliquity was statistically different when UL–BC ($M = 9.26 \pm 0.3$; $M = 6.22 \pm 0.58$; $p = 0.0036$) conditions were compared. The pelvis rotation was statistically different for UL–IA ($M = 8.02 \pm 0.75$; $M = 5.34 \pm 0.29$; $p = 0.003$) and IA–BC ($M = 5.34 \pm 0.29$; $M = 9.44 \pm 0.2$; $p = 0.0033$) conditions.

Discussion

This study compared the biomechanics and physiological demands of unloaded walking with three infant-carrying methods: in arms, front-facing, and back carrier. Key findings show that infant-carrying significantly impacts gait patterns and joint mechanics compared to unloaded walking, with important implications for caregiver health.

Infants over 12 months generally prefer to walk independently, while 6-month-olds rely on being carried, which can strain caregivers musculoskeletally.[21] Infant carriers are commonly used for children aged 5–12 months.[22] To reduce suffocation risk, as noted by Bergounioux et al.,[23] for infants under 3 months, we included only infants over 4 months.

Our results showed varying cadence rates across carrying conditions, with reduced step counts in participants who slowed their pace while carrying an infant. Previous studies indicate that mannequin carrying reduces step length and gait speed.[14,24–26] Another study reported lower cadence in FC and BC compared to UL.[27] In contrast, our participants had higher cadence in UL and FC, possibly compensating for shorter steps, which may have increased postural sway to maintain balance. In contrast, our participants had the highest cadence was observed in the Front-facing infant carrier (FC) condition. This increased cadence compared to other conditions suggests that carrying the infant in a front-facing position promotes a more efficient and natural walking pattern. The enhanced comfort and stability offered by the front-facing carrier likely facilitate a more consistent and fluid step frequency. In contrast, the Unloaded Walking (UL) condition, while showing the second-highest cadence, still demonstrated a lower step frequency than FC. This is not unexpected as walking without load enables a more natural gait without the compensatory strategies required when carrying a load. The In arms (IA) condition showed the lowest cadence, indicating that carrying the infant in the arms imposes greater biomechanical constraints. The reduced cadence likely results from the additional load, which requires more energy and alters gait mechanics. Similarly, the Back infant carrier (BC) condition, is slightly higher than IA but still lower than both UL and FC. This suggests that while the back carrier may provide some degree of comfort, it still impedes gait efficiency to a greater extent than the front-facing carrier. Bouterse and Wall-Scheffler[28] highlighted that cultural and environmental factors affect walking speed and energy expenditure in infant carrying, influencing biomechanical outcomes. These factors are crucial for understanding caregivers' neuromechanical responses and energy demands.

A study evaluating three infant-carrying techniques using a 10 kg teddy bear found that mothers walked faster in the BC condition compared to UL.[18] Conversely, our research demonstrated that mothers walked faster in the FC condition compared to UL, likely due to increased comfort and safety when carrying real infants in the FC position. Based on these findings, we hypothesize that carrying an infant in the FC position is more comfortable and safer compared to the BC condition.

Williams et al.[29] reported higher knee abduction and extension moments in nulliparous women carrying a mannequin, indicating reduced joint loading compared to an infant carrier. In contrast, we observed increased knee flexion and extension moments in the UL and BC conditions, along with greater hip flexion in the FC compared to UL, suggesting that infant carriers result in lower joint loading at the hip and knee. Notably, our study focuses on joint loading effects in mothers carrying real infants, the primary demographic using infant carriers in daily life. This indicates that the FC condition offers greater health advantages compared to the BC condition. Moreover, our study specifically focuses on the joint loading effects in mothers, the primary demographic group using baby carriers in daily life, and their real infants. This underscores the significance and unique contribution of our findings and highlights the necessity of our study.

Arm swing reduces trunk rotation and neutralizes vertical moments generated by leg swings.[30] Hall et al.[31] observed restricted arm swing patterns in participants carrying loads in front while walking. Similarly, our study found reduced arm swing in the IA and FC conditions compared to UL, likely to improve postural balance. Additionally, vertical ground reaction moments were 6.36% higher with the infant carrier and 14.8% higher when carrying the infant IA compared to unloaded walking.

Majumdar et al.[32] reported a tendency for increased hip flexion when carrying a backpack, while Yali et al.[33] found that front-loading elevated sagittal plane moments at the ankle, knee, and hip joints compared to back-carrying. Another study also indicated increased hip and knee flexion during front-carrying, suggesting compensatory lower limb mechanics for balancing anterior loads.[27] Our findings corroborate this literature, showing a significant increase in hip flexion during the FC condition compared to unloaded walking. Our findings suggest that carrying techniques, such as infant-carrying in the IA (in arms) and BC (back-carrying) positions, significantly alter the hip joint ROM, which could be attributed to changes in posture and muscle activation patterns. The reduction in hip joint flexion during the IA-BC comparison implies a more stable but restricted movement pattern in the back-carrying position, potentially to ensure better control over the infant's position.

A study reported increased knee and hip moments in the IA condition after a 15-min walk, with further increases in knee extension during loading and knee abduction during push-off in BC condition compared to IA.[29] Similarly, Havens et al.[34] found comparable lower extremity joint positions between UL and infant carrier conditions during a walking and retrieval task, indicating minimal biomechanical differences between holding and carrying a mannequin. In our study, the increased hip flexion during FC compared to UL, alongside smaller knee flexion-extension moments during FC, aligns with the existing literature. These findings suggest that using an infant carrier may promote mechanics similar to those of unloaded walking.

The pelvic tilt increase with front-facing infant carriers and decrease with back-carrying.[35] In contrast, our research found the most significant changes in pelvic tilt with back-carrying, while front-carrying remained closest to the unloaded position. This discrepancy likely reflects the active biomechanical adaptations during walking in our study, contrasting with the static conditions of prior research. Pelvic movement, including tilt, obliquity, and rotation, was significantly influenced by different infant-carrying conditions. The pelvic tilt increased when shifting from UL to IA, indicating a change from a more neutral pelvis to accommodate the infant's forward position. This tilt also increased in the IA–FC and FC–BC conditions, suggesting compensatory movements that may affect overall posture and load distribution. Pelvic obliquity showed a notable difference in the UL–BC condition, where back-carrying led to an asymmetrical pelvic position, potentially causing imbalances in muscle activity and contributing to musculoskeletal strain over time. Lastly, our research showed the most significant changes in pelvic tilt with back-carrying, while front-carrying remained closest to the unloaded position. This discrepancy likely reflects the active biomechanical adaptations during walking in our study, contrasting with the static conditions of prior research.

A study found that mothers and nulliparous women exhibited greater ankle dorsiflexion in IA and infant carrier conditions compared to the unloaded condition when examining infant and mannequin carrying using UL, IA, and infant carrier methods.[20] Similarly, our study revealed differences in ankle joint range of motion between the UL–BC and UL–FC conditions.

Musculoskeletal pain is a common health issue among women, particularly during pregnancy and the postpartum period. Factors such as breastfeeding posture, hormonal fluctuations, sleep deprivation, and fatigue contribute to the development of musculoskeletal pain.[36] The methods chosen by a mother to provide physical care for her young children can lead to back strain or injury, depending on the techniques used. Approximately 49% of reported back injuries are attributed to child lifting, with the majority of these childcare-related injuries localized to the lower back.[37] Musculoskeletal strain (MSS) has been linked to the lifting techniques employed by parents.[38] MSS has the potential to cause severe long-term pain and physical disability in affected individuals. Therefore, it is recommended for mothers to engage in physical activities such as aerobic exercises, pelvic floor exercises, stretching, and walking postpartum.[36,39] Studies have shown that individuals with low back pain (LBP) exhibit changes in breathing patterns and diaphragm mechanics. Core stabilization exercises help reduce back pain, while also improving pain, fatigue, anxiety, and sleep quality. Diaphragmatic and pursed-lip breathing exercises have been shown to be as effective as traditional physiotherapy for LBP patients, offering advantages in reducing anxiety and feelings of panic.[40]

This study identifies significant biomechanical changes between unloaded walking and various infant-carrying methods, providing an objective and accurate representation of these differences as they occur in mothers and their infants, much like in their everyday life. This distinction emphasizes the novelty, necessity, and uniqueness of our study compared to existing literature. Our research highlights the mechanical advantages and disadvantages associated with different carrying positions in mothers, offering a comprehensive analysis of their impact on gait dynamics and joint loading. The originality and relevance of this study underscore its contribution to the field, offering critical insights into the biomechanical considerations of maternal health and infant-carrying practices.

A limitation of this study is the variation in infant and maternal weights, despite the lack of statistically significant differences. Furthermore, only the acute effects of various carrying positions were evaluated. Future studies should explore the long-term effects of carrying methods on musculoskeletal health. This study concentrated on caregiver gait biomechanics, the effects on posture and cervical health also require further exploration. Another limitation of our study was the absence of pressure parameters, as they were not the primary focus of the investigation. It is anticipated that the inclusion of pressure parameters related to weight distribution while standing would be beneficial in future studies.

Conclusions

In conclusion, this study identifies significant biomechanical changes between unloaded walking and various infant-carrying methods, particularly in gait dynamics, joint loading, and posture. Increased hip flexion during front-facing carrying indicates compensatory mechanisms affecting locomotion and load distribution. These findings highlight the physiological strain associated with different carrying positions and the necessity for further research on long-term musculoskeletal impacts. Developing ergonomically optimized infant carriers is essential to minimize biomechanical strain, support maternal musculoskeletal health, and enhance caregiver comfort and infant safety.

Acknowledgements

The authors have no acknowledgments.

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Statements and declarations

Ethics approval and consent to participate

The study was approved by Bezmialem Vakıf University Institutional Review Board on May 24, 2022, with approval number 2022/127 and Ethics Committee Decision number: E-54022451-050.05.04-63129.

Funding
The authors received no financial support for the research, authorship, and/or publication of this article.

Declaration of conflicting interests
The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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