Full length article

Effects of infant transportation on lower extremity joint moments: Baby carrier versus carrying in-arms

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ABSTRACT

Background: The act of babywearing is recognizably a task of load carriage and has gained popularity among millennial caregivers.

Research Question: The implications of babywearing on lower extremity joint moments of the caregiver are still unknown during prolonged transport and a direct comparison of babywearing to carrying an infant in-arms has not been previously conducted.

Methods: Eighteen females participated in this study by performing 3 conditions: a) 3 min walking unloaded (UL), b) 15 min walking while carrying a mannequin infant in-arms (IA), and c) 15 min walking while wearing a mannequin infant in an anteriorly positioned baby carrier (BC). Two separate data analyses were conducted using a repeated measures ANOVA. First, UL compared to the initial minute of walking for IA and BC. Second, UL compared to the final minute of walking for IA and BC.

Results: During initial minute comparisons, both IA and BC conditions increased joint moments in the frontal and sagittal plane at the knee with no change at the ankle and hip. During final minute comparisons, IA maintained the increases in the knee frontal plane joint moments observed during initial minute comparisons but also increased at the hip; however, BC generally showed no statistical difference from UL. Carrying an infant in a baby carrier more closely resembles unloaded walking, while carrying an infant in-arms appears to increase the mechanical load placed on the knee and hip joints in the frontal plane through an increase in joint moments.

Significance: During prolonged transportation, caregivers might choose to employ a baby carrier as opposed to carrying an infant in-arms, as in-arm carriage increases the loading knee abduction moment by 8.7% and the loading knee extension moment by 16.7%.

1. Introduction

The act of babywearing has been common practice for many cultures and has gained popularity among millennial caregivers. This rise in popularity could be attributed to the benefits proposed by baby carrier companies and organizations that promote babywearing. These proposed benefits include facilitation of caregiver-infant bonding, convenience, reduction of infant crying and decreased occurrence of postpartum depression [1,2]. Research has supported some of these claims and showed that infants carried by a walking caregiver exhibited a reduction in crying [3], voluntary movement, and a rapid decline in heart rate compared to those held by a sitting mother [4]. However, with respect to the implications of babywearing on the musculoskeletal system of the caregiver, investigation has been sparse.

Research on the biomechanics of babywearing is limited. One study explored anteriorly loaded babywearing during short-term walking on a 15 m runway. Researchers observed an increase in impact peaks, propulsive and braking impulses, and loading rates when compared to unloaded walking; however, lower extremtiy (LE) joint moments were not reported [5]. A separate study, investigating the effects of various carrier types on the activity of trunk muscles and shoulder tactile pressure, had subjects continuously walk for 20 min [6]. While this study innovatively examined walking while babywearing for a longer duration, LE joint moments were not investigated.

Another task related to infant transportation is that of carrying an infant in-arms, a method that is still common practice among caregivers. Carrying an infant in-arms restricts the natural arm swing patterns that occur during walking. Arm swinging is thought to mitigate the rotation of the trunk and counteract the free vertical moments caused by swinging legs [7–9]. When arm swinging is restricted, other biomechanical adaptations may occur to maintain stability during walking. A study exploring the effects of carrying an infant in-arms on

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the posture of women during walking reported that upper-body posture in the sagittal plane was altered; however, LE gait biomechanics were not investigated [10].

Babywearing is recognizably a task of load carriage. A multitude of studies have investigated the biomechanical adaptations of posterior load carriage during walking and this research suggests that posterior loading significantly alters LE biomechanics, including joint moments [11–16]. Baby carrier companies, however, recommend anterior load carriage for zero to four-month-old infants [17]. Exploration of walking while carrying anterior load has been minimal in literature, especially with reference to LE joint moments as studies have focused on joint kinematics and effects on posture [18]. Two studies investigated LE joint moments while comparing anterior and posterior loads [19,20]. Hall et al. found that load position did not affect the magnitude of frontal plane moments but did not investigate sagittal plane moments [19]. Yali et al. found that anterior load increased ankle, knee, and hip sagittal plane moments greater than a posterior load, but did not compare frontal plane moments [20]. Consequently, further analysis is necessary to fully understand the effects of anterior loading on joint moments as the findings observed during posterior loading may not be directly applicable to the anterior loading experienced during baby-wearing.

To our best knowledge, a direct comparison of babywearing to carrying an infant in-arms has not previously been conducted. Also, investigation of LE joint moments appears to be lacking with regard to infant transportation and minimal within anterior loading literature. A study surveying hip, knee and foot pain during pregnancy and the postpartum period found that pregnancy, either current or recent, was a significant risk factor for LE pain compared to a control group of women [21]. Additionally, a study analyzing the relationship between maternity-related factors and the prevalence of knee osteoarthritis (OA) found that an increasing number of pregnancies was significantly associated with an higher prevalence of knee OA later in life [22]. Therefore, it is important to understand the implications of prolonged infant transportation on the LE of caregivers. These factors make this current study both relevant and significant in improving understanding of the biomechanical implications of babywearing.

The purpose of this study is to explore alterations in LE joint moments during prolonged walking while babywearing, carrying an infant in-arms, and how these conditions compare to each other and to unloaded walking. We hypothesize that both loaded conditions will result in an increase in LE joint moments compared to unloaded walking, but that carrying an infant in-arms will exhibit a larger increase than carrying an infant while babywearing.

2. Methods

2.1. Participants

Eighteen healthy, female participants (age: 22.67 ± 2.08 yrs, height: 1.66 ± 0.06 m, mass: 69.9 ± 24.5 kg) volunteered to take part in this study. Inclusion criteria consisted of no prior experience with babywearing or in-arm carrying, no history of pregnancy, and free from injury at the time of data collection. All participants signed an informed consent approved by the Institutional Review Board at Utah Valley University.

2.2. Experimental protocol

Kinetic data were collected as participants walked on a split-belt instrumented treadmill (1000 Hz, Bertec, Inc., Columbus, OH) in conjunction with a 16-camera motion analysis system (Vicon, Inc., Denver, CO) sampled at 100 Hz. Participants wore a standardized shoe (Launch 2, Brooks, Seattle, WA) for all conditions. A set of reflective markers were secured bilaterally to anatomical landmarks of the foot (first toe, head of the first and fifth metatarsals), ankle (lateral and medial

malleoli), knee (lateral and medial femoral condyles), hip (greater trochanter and iliac crest), and trunk (acromion process). To designate segments, clusters of four reflective markers were placed on the rigid heel of the shoe, lateral shank, lateral thigh, sacrum, and posterior-superior trunk.

After being fitted with the markers previously outlined, participants were asked to complete three walking sessions: a) a baseline of three minutes unloaded (UL), b) 15 min while carrying a mannequin infant (2.73 kg) in-arms (IA), and c) 15 min while wearing a mannequin infant in an anteriorly positioned, structured baby carrier (BC; Ergobaby, Inc., Los Angeles, CA). A mannequin infant was used as carrying an infant is not significantly different from carrying a mannequin during walking [10]. The mannequin infant used for this study had mass lying in the range of mass for infants of age zero to four months [23].

The UL condition was always performed first to obtain a normal, self-selected walking speed (1.11 ± 0.07 m/s). IA and BC conditions were performed at this same speed but with their order randomized. Data were collected every 30 s for the UL condition and every minute for both the IA and BC conditions. Individual trials were collected for the duration of five full gait cycles. For the IA condition, participants were instructed to hold the mannequin with both arms at the front of the trunk positioned to the left so it's head was resting on their shoulder (Fig. 1) and asked to maintain this position without shifting. Investigators aided in securing the carrier to the participants' bodies during the BC condition to ensure the vertical alignment of the carrier complied with the placement suggested in the instruction manual (Fig. 2). Participants were instructed to swing their arms naturally as they walked during this condition. Participants were allowed to rest for 5–10 minutes between conditions as condition parameters were adjusted.

2.3. Data analysis

To compute internal moments in the sagittal and frontal planes in the right LE, custom programming in Visual 3D (C-Motion, Inc. Germantown, MD) was used. Each collected trial consisted of five full gait cycles. The average for variables of interest (ankle: peak dorsiflexion, peak plantarflexion, loading eversion, and push-off eversion moments; knee: loading extension, push-off extension, loading abduction, and push-off abduction moments; hip: peak flexion, peak extension, loading abduction, and push-off abduction moments) were generated from the five gait cycle values and used for statistical analyses. Data were filtered using a 4th order Butterworth filter with cutoff frequencies of 50 Hz for analog data and 10 Hz for kinematic data. Individual conditions were normalized to their respective mass (UL:

Fig. 1. In-arm condition (IA). Participants were instructed to hold the mannequin with both arms at the front of the trunk, positioned to the left, and to maintain this position without shifting for 15 min of treadmill walking.

Fig. 2. Baby carrier condition (BC). Investigators aided in securing the carrier to the participants' bodies to ensure vertical alignment of the carrier complied with the placement suggested by the instruction manual: the carrier should be high enough on the caregiver's chest so they can kiss the infant on the head.

body mass, IA: body mass + mannequin mass, BC: body mass + mannequin mass + carrier mass).

2.4. Statistical analysis

Two repeated measures ANOVA tests were used to compare condition differences (SPSS, IBM, New York, NY). First, to compare the three conditions for the first minute of walking for IA and BC to the UL baseline condition. Second, to compare the conditions for the last minute of walking for IA and BC to UL. When the ANOVA revealed a main effect ($p < 0.05$), post hoc comparisons with bonferroni adjustments were utilized to compare the means between the three conditions. When a variable was found to have a significant difference between conditions, a percent change for the variable was calculated for each subject. These individual subject percent changes were then averaged for each comparison so we could report an overall percent change for each variable.

3. Results

3.1. UL vs. initial minute

All initial minute values are presented in Table 1.

During initial minute comparisons, we found no statistically significant changes in sagittal or frontal plane ankle (Figs. 33.1 and 4 4.1)

or hip moments (Figs. 33.5 and 4 4.5).

At the knee, the loading extension and abduction moments both increased for IA and BC (Figs. 33.3 and 4 4.3). The difference in loading extension moment was greatest for the IA condition, with IA having a 19.2% increase from UL, compared to BC having a 10.5% increase. The loading abduction moment for IA increased by 5.9% from UL, while BC increased by 3.4% from UL and there was no statistically significant difference between IA and BC. The push-off extension and abduction moments both increased for IA compared to UL (Figs. 33.3 and 4 4.3). Specifically, the push-off extension moment increased by 10.7% from UL, with no difference between UL and BC. The push-off abduction moment increased for both IA and BC from UL with no difference between IA and BC (IA had a percent increase of 5.6% and BC 6.6%).

3.2. UL vs. final minute

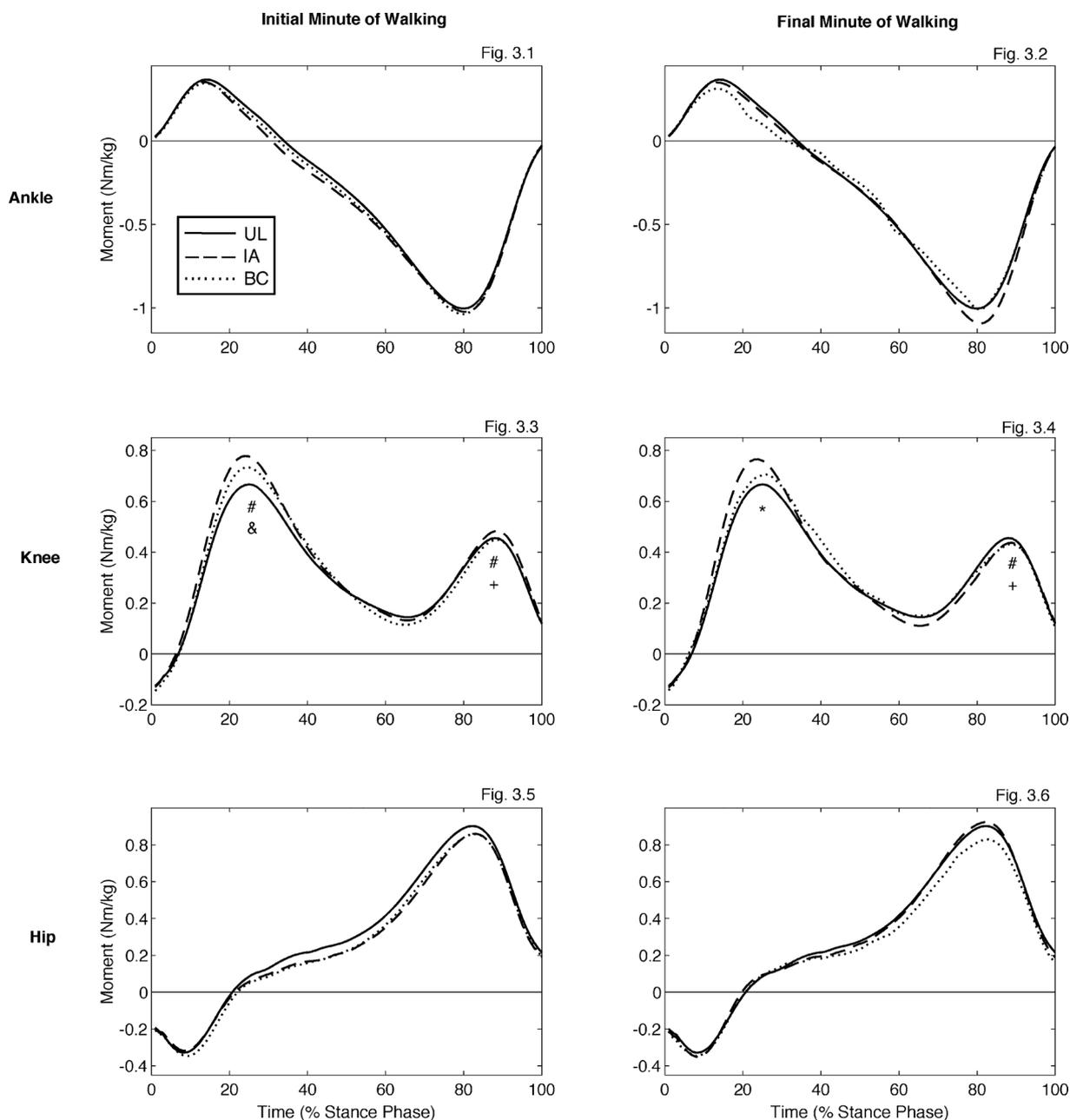All final minute values are presented in Table 2.

During final minute comparisons, we found no changes in ankle moments (Figs. 33.2 and 4 4.2).

At the knee, the loading and push-off extension moments showed the same trend as with the initial comparison (Fig. 33.4); the greatest increase for the loading extension moment was observed during the IA conditions with a 16.7% increase while BC had a percent increase of 11.0%. The push-off extension moment showed an increase of 8.1% in IA, with no difference between UL and BC. Interestingly, the loading knee abduction moment comparisons during the final minute were different than initial minute comparisons. The final minute showed a 8.7% increase for only the IA and not for the BC condition with no significant difference between UL and BC (Fig. 44.4), whereas during initial minute this moment increased for both IA and BC. The push-off knee abduction moment showed similar results as the initial comparisons with a 10.0% increase for IA and 7.6% increase fo BC compared to UL and no statistical difference between IA and BC.

During initial minute comparisons, there were no changes at the hip. This same result was not found during final minute comparisons. We found no significant difference between UL and BC (Fig. 44.6) for the loading and push-off hip abduction moments but observed an increase for IA (4.1% and 7.7%, respectively).

4. Discussion

In this study, it was hypothesized that both IA and BC would increase LE joint moments compared to unloaded walking, but IA would exhibit larger increases than BC. The results for the loading knee extension moment during both initial and final minute comparisons

Table 1
Initial minute: mean ± standard error.

Joint	Moments (Nm/kg)	Initial minute			p-value		
		UL	IA	BC	UL vs IA	UL vs BC	IA vs BC
Ankle	Peak Dorsiflexion	0.404 ± 0.039	0.429 ± 0.037	0.416 ± 0.045	0.313	0.672	0.502
	Peak Plantarflexion	−0.952 ± 0.062	−0.947 ± 0.067	−0.952 ± 0.063	0.708	0.936	0.538
	Loading Eversion	−0.572 ± 0.029	−0.582 ± 0.027	−0.565 ± 0.028	0.630	0.777	0.147
	Push-off Eversion	−0.197 ± 0.022	−0.200 ± 0.024	−0.216 ± 0.026	0.641	0.176	0.216
Knee	Loading Extension #&	0.724 ± 0.057	0.838 ± 0.055	0.801 ± 0.072	0.000	0.017	0.242
	Push off Extension#+	0.482 ± 0.036	0.532 ± 0.038	0.499 ± 0.039	0.003	0.201	0.007
	Loading Abduction#&	−1.023 ± 0.031	−1.079 ± 0.032	−1.056 ± 0.033	0.005	0.045	0.146
	Push off Abduction #&	−0.812 ± 0.033	−0.852 ± 0.036	−0.862 ± 0.036	0.003	0.000	0.586
Hip	Peak Flexion	0.916 ± 0.066	0.911 ± 0.074	0.916 ± 0.062	0.826	0.984	0.811
	Peak Extension	−0.346 ± 0.032	−0.314 ± 0.033	−0.344 ± 0.033	0.227	0.940	0.013
	Loading Abduction	−1.528 ± 0.037	−1.561 ± 0.031	−1.541 ± 0.038	0.053	0.435	0.389
	Push off Abduction	−1.366 ± 0.045	−1.411 ± 0.047	−1.389 ± 0.046	0.068	0.217	0.359

Note: * - Significant difference between all conditions. # - Significant difference between UL and IA. & - Significant difference between UL and BC. + - Significant difference between IA and BC. Ankle dorsiflexion and inversion, knee extension and adduction, and hip flexion and adduction moments are positive based on the right hand rule.

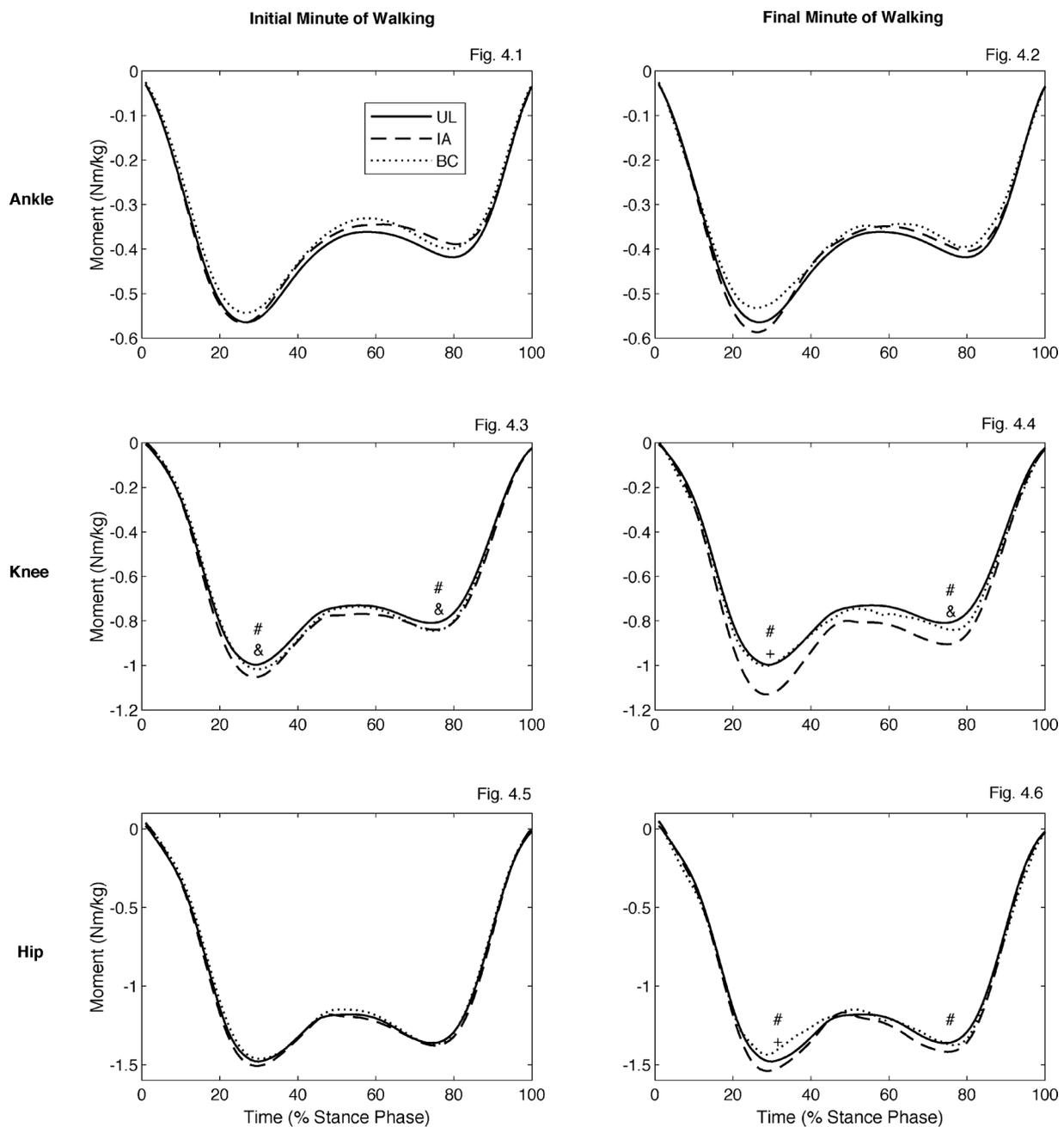**Initial Minute of Walking**   **Final Minute of Walking**

Fig. 3. Sagittal plane internal moments at the ankle, knee, and hip during initial and final minutes of walking. Data are presented as group means for all conditions and normalized to one full gait cycle. Ankle dorsiflexion and inversion, knee extension and adduction, and hip flexion and adduction moments are positive based on the right hand rule. *indicates significant difference between all conditions. # indicates significant difference between UL and IA. & indicates significant difference between UL and BC. + indicates significant difference between IA and BC (p < 0.05).

support our hypothesis, however, the results of the ankle and hip moments do not.

Our results showed an increase in the loading knee extension moment during IA and BC in both initial and final minute comparisons. This finding is in agreement with other research where investigators found that anterior loading exhibited an increase in external loading knee flexion moment [20]. This external flexion moment and the internal extension moment of the current study are both representative of knee extensor involvement. The quadriceps contract eccentrically to assist with shock attenuation during weight acceptance of walking [24,25], and it is likely that the observed increase in this moment was a mechanism employed to assist with dissipating the increased load of IA and BC condition. The greater demand on the knee extensors may lead to fatigue of these muscles during prolonged walking when transporting

a baby.

Through review of research investigating frontal plane hip moments during anterior loaded walking, the only studies found were those analyzing pregnancy load. Foti et al. looked at the gait of women during pregnancy and one year postpartum; they reported a significant increase in the loading hip abduction moment during pregnancy [26]. We also observed an increase in this moment during final minute comparisons, but for the IA condition only. Our BC condition more closely resembles pregnancy load than the IA condition does. It is interesting, then, that there was no significant changes in hip moments during the BC condition. One possible explanation for this discrepancy between our BC condition and pregnancy load is that the hormone relaxin is found in higher concentration in the blood of pregnant women and has been associated with an increase in the range of motion of the pelvis

Initial Minute of Walking   **Final Minute of Walking**

Fig. 4. Frontal plane internal moments at the ankle, knee, and hip during initial and final minutes of walking. Data are presented as group means for all conditions and normalized to one full gait cycle. Ankle dorsiflexion and inversion, knee extension and adduction, and hip flexion and adduction moments are positive based on the right hand rule. *indicates significant difference between all conditions. # indicates significant difference between UL and IA. & indicates significant difference between UL and BC. + indicates significant difference between IA and BC (p < 0.05).

and surrounding joints [27]. Therefore, the hormonal changes that a woman experiences during pregnancy may cause an exaggeration in the biomechanical changes observed and may not be directly applicable to the results of the current study.

While both IA and BC conditions can be classified as walking while carrying an anterior load, IA restricts the arm swing patterns employed during normal walking. It is thought that arm swings mitigate trunk rotation and counteract the free vertical moments caused by swinging legs [7–9]. Li et al. found that these moments produced in the LE during stance phase increased when arm movements were restricted [9]. Perhaps carrying an infant in-arms increases LE joint moments to maintain stability as arm restriction causes destabilization while caregivers transfer weight from one foot to the other. These factors may have contributed to the greater differences observed within the IA condition

compared to BC at both the knee and hip joints. Similar to the IA condition of the current study, Hall et al. had participants walk while carrying a load with both hands at the front of the body, thereby restricting the arm swing patterns employed during normal walking [19]. Researchers reported an increase in external knee adduction moment during the loading phase of walking. This increase in the external adduction moment and the internal abduction moment observed during the IA condition in the current study are both indicative of medial loading at the knee. A previous study found that a history of pregnancy is associated with greater development of knee OA in later life [22], while another study concluded that a 1% increase in the external knee adduction moment (i.e. internal knee abduction moment) can increase the risk for progression of knee OA 6.46 times for individuals diagnosed with knee OA [28]. Therefore, employing a baby carrier may be a

Table 2
Final minute: mean ± standard error.

Joint	Moments (Nm/kg)	UL	Final minute IA	BC	p-value UL vs IA	UL vs BC	IA vs BC
Ankle	Peak Dorsiflexion	0.404 ± 0.039	0.421 ± 0.042	0.473 ± 0.057	0.417	0.217	0.400
	Peak Plantarflexion	−0.952 ± 0.062	−0.982 ± 0.053	−0.986 ± 0.084	0.384	0.512	0.934
	Loading Eversion	−0.572 ± 0.029	−0.576 ± 0.028	−0.551 ± 0.030	0.864	0.160	0.085
	Push-off Eversion	−0.197 ± 0.022	−0.198 ± 0.023	−0.217 ± 0.031	0.894	0.261	0.362
Knee	Loading Extension*	0.724 ± 0.057	0.842 ± 0.070	0.794 ± 0.061	0.001	0.004	0.049
	Push off Extension#+	0.482 ± 0.036	0.522 ± 0.040	0.496 ± 0.041	0.011	0.399	0.042
	Loading Abduction#+	−1.023 ± 0.031	−1.111 ± 0.036	−1.047 ± 0.038	0.000	0.197	0.000
	Push off Abduction#&	−0.812 ± 0.033	−0.893 ± 0.037	−0.869 ± 0.036	0.000	0.000	0.087
Hip	Peak Flexion	0.916 ± 0.066	0.968 ± 0.067	0.928 ± 0.070	0.038	0.642	0.036
	Peak Extension	−0.346 ± 0.032	−0.332 ± 0.034	−0.341 ± 0.036	0.594	0.888	0.475
	Loading Abduction#+	−1.528 ± 0.037	−1.591 ± 0.037	−1.514 ± 0.042	0.000	0.369	0.000
	Push off Abduction#	−1.366 ± 0.045	−1.466 ± 0.046	−1.406 ± 0.056	0.000	0.185	0.054
Joint	Angles (Deg)	UL	IA	BC	UL vs BC	UL vs BC	IA vs BC
Knee	Loading Flexion#&	−16.76 ± 1.128	−18.51 ± 1.218	−18.196 ± 1.129	0.000	0.017	0.242

Note: * - Significant difference between all conditions. # - Significant difference between UL and IA. & - Significant difference between UL and BC. + - Significant difference between IA and BC. Ankle dorsiflexion and inversion, knee extension and adduction, and hip flexion and adduction are positive based on the right hand rule.

preventative strategy for postpartum mothers when carrying an infant for longer than 15 min as our results show a 8.7% increase in the knee abduction moment for IA, and no difference between BC and UL.

Previous researchers have investigated methods of reducing joint moments. Specifically, Barrios et al. developed a gait retraining protocol to reduce external knee adduction moments [29]. They found that by providing real-time feedback of a subject's frontal plane knee angle along with verbal promptings resulted in significant reductions of the external knee adduction moment. While these results were found in subjects walking unloaded, it would be interesting to see if similar results would be found while carrying an anterior infant load.

Some limitations of this study include the position and size of the baby. We realize caregivers hold infants in locations other than the one we chose; caregivers may be inclined to shift the infant to the side, especially as the infant grows. The mannequin infant used for this study had a mass of 2.73 kg, which falls in the lower quarter of weight-for-age growth chart percentiles for zero month old males and females [23]. Future researchers could explore how heavier infant load carriage and different load positions for both IA and BC, affect the biomechanics of the caregiver. Another limitation is that only females with no history of pregnancy were chosen to take part in this study. Previous research has found that men and women [14] as well as biological mothers and non-mother caregivers [10] adopt similar walking mechanics and adaptations during load carriage. Based on these findings, it is possible that the results of the current study are applicable to other caregiver populations, including postpartum mothers. Lastly, it is unknown when the observed changes occurred during the 15 min. A minute-by-minute comparison could provide insight regarding this matter.

5. Conclusion

Our hypothesis that both loaded conditions would increase LE joint moments was not entirely supported, as not all moments showed this trend for both IA and BC. Our secondary hypothesis (IA condition would show greater increase in joint moments than BC condition) was only supported by the loading knee extension moment during both initial and final minute comparisons. After 15 min of walking, increased moments were observed at the knee and hip for the IA condition. In general, the final minute analysis showed no difference between UL and BC conditions, with the exception of the loading knee extension and push-off knee abduction moments, where an increase in joint moments was observed for the BC condition in addition to IA. In conclusion, caregivers might experience less joint loading if they were to employ a

baby carrier rather than carry an infant in-arms when walking for longer durations, as evidenced by the 8.7% increase in the loading knee abduction moment and 16.7% increase in the loading knee extension moment for the IA condition following 15 min of walking.

Credit author statement

Tyler Standifird: Conceptualization, Methodology, Software, Validation, Formal Analysis, Investigation, Resources, Data Curation, Writing- Review and Editing, Supervision, Project Administration, Funding Acquisition. **Lauran Williams:** Software, Investigation, Writing- original draft, Project Administration, Funding acquisition. **Megan Madsen:** Investigation, Writing- Review and Editing, Project Administration, Visualization.

Conflict of interest

None.

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