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Sling-based infant carrying affects lumbar and thoracic spine neuromechanics during standing and walking

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ABSTRACT

Background: Regular infant carrying might be a contributing factor for the development and progression of low back and pelvic girdle pain in mothers after childbirth. However, the neuromechanical adaptations of the spine due to different sling-based carrying techniques are not sufficiently well understood in order to provide evidence-based carrying recommendations.
Research question: What are the immediate effects of different sling-based infant carrying techniques on trunk neuromechanics?
Methods: Using a Vicon motion capture and a wireless surface electromyography system, three-dimensional pelvis and spinal kinematics as well as activation patterns of eight trunk muscles were derived from fifteen healthy young women during upright standing and level walking without carrying a load and while carrying a 6 kg-dummy with a sling in front and on either side. Data were analyzed using Statistical Parametric Mapping, allowing group comparisons of discrete parameters (standing) as well as continuous data (walking). To distinguish between clinically relevant and clinically not relevant kinematic findings, statistically significant differences were only considered in case of $\geq 5°$.
Results: Compared to unloaded walking, carrying the dummy in front was mainly associated with increased lumbar lordosis (standing: ($\Delta 8.8°$, $p = 0.006$; walking: ($\Delta \geq 8.2°$, 1–100% of gait cycle [%GC], $p < 0.001$). When carrying the dummy on the preferred side, increased thoracic kyphosis (standing: $\geq 6.4°$, $p \leq 0.003$; walking: $\Delta \geq 5.6°$, 1–100%GC, $p < 0.001$) and axial rotation towards the ipsilateral side (standing: $\Delta 5.3°$, $p = 0.003$; walking: $\Delta \geq 5.0°$, 46–58%GC, $p = 0.002$) were observed. All three conditions entailed increased paraspinal muscle activity during walking, although only unilaterally in side carrying (lumbar, preferred condition: $\Delta \geq 13.2$%maxMVIC, 49–57%GC, $p < 0.001$; thoracic, non-preferred condition: $\Delta \geq 5.3$%maxMVIC, 47–58%GC, $p < 0.001$).
Significance: Carrying an infant alternating on both sides using a sling could be advantageous for preventing musculoskeletal pain resulting from excessive lumbar hyperextension and paraspinal muscle hyperactivation in women after childbirth.

1. Introduction

Low back pain (LBP) and pelvic girdle pain (PGP) are common problems in women after childbirth with an overall prevalence of 25% [1]. During this time, mothers are required to regularly lift up and carry their infants for longer periods. Previous research indicated that carrying a load in front with the arms caused increased lumbar lordosis [2,3], which has been described as a possible contributing factor in the development of LBP in this population [4]. In addition, anterior load carrying was associated with increased trunk muscle activity [3,5,6], which could be another contributing factor, especially when considering that postpartum women were reported to have reduced muscular endurance [7].

Besides anterior carrying, women often carry their infants on the side (antero-laterally) and use sling systems, which were shown to be more energy-efficient than carrying the infant with the arms [8]. While

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many previous investigations were directed to carrying loads on the back, only few studies looked at the effects of anterior load carrying on the spine and none of them included antero-lateral carrying [2,3,5,6,9]. Moreover, apart from general load carrying, only one of these studies investigated the biomechanical effects of carrying and infant [2]. Unfortunately, this study did not include sling-supported carrying techniques and was based on simple angles that were averaged over one gait cycle, allowing no conclusions about the time-dependent characteristics of spinal motion during gait.

For these reasons, more comprehensive knowledge on spine neuromechanics during infant carrying is required. This study therefore aimed at exploring the immediate effects of different sling-based infant carrying techniques on three-dimensional pelvis and spinal kinematics as well as trunk muscle activity during upright standing and level walking in healthy young women. Using advanced statistical methods, this study further aimed at the investigation of continuous data over one full gait cycle rather than pre-defined discrete parameters.

2. Methods

2.1. Participants

Fifteen healthy women (bodymass: 60 ± 9 kg, height: 1.68 ± 0.07 m, age: 27 ± 8 years) were included in the study. Inclusion criteria were no known pregnancy, not having given birth within the last year, being free from acute back pain as well as no ongoing medical treatment or history of spinal surgery. Seven women already gave birth earlier and five of them were experienced in carrying infants using a sling. The study was approved by the ethics committee of ETH Zurich and written informed consent was obtained prior to the laboratory measurements.

2.2. Data collection

Data collection took place in a movement laboratory. An experienced physiotherapist equipped the participants with 75 retro-reflective skin markers according to the IfB full body marker configuration [10] (for current study, only makers on trunk were considered) as well as bipolar surface electrodes bilaterally on the muscles lumbar erector spinae (3 cm lateral of the spinous process of L3), thoracic erector spinae (5 cm lateral of the spinous process of T9), rectus abdominis (approximate center of the lowermost section of the muscle belly) and obliquus externus (15 cm lateral to the umbilicus) [11–13] (Fig. 1A). After an upright standing static trial for reference purposes (reference trial) as well as maximal voluntary isometric contractions (MVIC) for amplitude normalization of the electromyographic signals [13], participants were measured in four different conditions: A) Unloaded (*No Dummy*), B) carrying dummy in front using sling carrier (*Dummy front*), C) carrying dummy on preferred side using sling carrier (*Dummy preferred*) and D) carrying dummy on non-preferred side using sling carrier (*Dummy non-preferred*). The order of the conditions was randomly assigned for each participant. To determine the preferred carrying side, participants were asked prior to the measurement on which side they would prefer to carry an infant. To carry the dummy, two different sling carriers were used (Fig. 1B and C). For the *Dummy front* condition, a 6 m non-elastic cotton towel was used. For the *Dummy preferred* and *Dummy non-preferred* conditions, a 2 m non-elastic cotton towel with two metal rings on one end, known as “ring-sling”, was used. The dummy weighed 6 kg, which corresponds to the average weight of a 10 weeks old infant [14]. The sling carriers were always applied by the same tester using the most common tying techniques provided by an instructor for infant carrying.

In each condition, participants conducted two practice walking trials to get familiar with the respective carrying technique. Subsequently, upright standing was measured two times for the duration of 30 s and participants were asked to walk along an 8 m-walkway at a self-selected normal speed until at least five trials were recorded. The position of the arms was thereby not standardized. Data were collected using a 22-camera optoelectronic motion capture system (Vicon UK, Oxford, UK; sampled at 100 Hz), five consecutively arranged force plates (Kistler, Winterthur, Switzerland; sampled at 2 kHz) and a 16-channel wireless surface electromyography system (Trigno™, Delsys, Natick, MA, USA; sampled at 2 kHz). However, force plate data were only used for gait event detection.

2.3. Data reduction and parameters of interest

The software Vicon Nexus 2.6 (Vicon UK, Oxford, UK) was used for data pre-processing, which included the reconstruction and filtering of the marker trajectories and setting of the gait events (based on force plate data). Post-processing of the kinematic and muscle activity data was then carried out using custom-built MATLAB-routines (version R2017a, MathWorks Inc., Natick, MA, USA) [15–17]. The parameters of interest were three-dimensional pelvis angles, sagittal and frontal curvature and inclination angles of the lumbar and thoracic spines, transverse rotation angles of the lumbar and thoracic spines as well as electromyographic activity of the selected trunk muscles and spatio-temporal gait parameters.

To quantify pelvis motion, position and orientation of a rigid pelvis segment defined by the markers RTAS, LTAS, RTPS, LTPS and SACR (Fig. 1A) was determined relative to the reference trial using a least-squares fit of the corresponding marker point cloud and expressed as absolute angles (segment versus global coordinate system) [10]. Spinal curvature angles were calculated based on the circles that were fitted into the markers SPL1-5 and SACR (lumbar) and SPT1-5 (thoracic). More details on the spinal curvature calculation as well as accuracy and soft tissue artifacts can be found elsewhere [18,19]. Furthermore, absolute (i.e. versus global coordinate system) sagittal and frontal plane spinal inclination angles were calculated based on the lines connecting the markers SPT1 and SACR (total spine), SPL1 and SACR (lumbar) and SPT1 and SPT5 (thoracic). For spinal rotation, angles between the intersecting lines formed by the markers STER-SPC3/LTPS-RTPS (total spine), LTBH-RTBH/LTPS-RTPS (lumbar) and STER-SPC3/LTBH-RTBH (thoracic) in the transverse plane were calculated. Pelvis as well as spinal curvature and rotation angles were then low-pass filtered at a cutoff frequency of 6 Hz (Butterworth, fourth order, zero-phase).

The electromyographic raw signals were corrected for baseline offset, bandpass-filtered with cutoff frequencies of 10 and 500 Hz (Butterworth, fourth order, zero-phase) and full-wave rectified. In order to have a smooth signal for group comparisons of continuous data, linear envelopes were created using a low-pass filter with a cutoff frequency of 6 Hz (Butterworth, fourth order, zero-phase) [20].

For the upright standing trials, data of the first 10 s in each condition were averaged over time. Kinematic and muscle activity data of the level walking trials were time-normalized to a full gait cycle consisting of 101 points on the preferred side in the conditions A, B and C and non-preferred side in the condition D. In addition, spatio-temporal gait parameters (walking speed, cadence, stride length, stride time, step length, step time, stance phase and swing phase) were calculated and expressed as dimensionless numbers (using leg length as individual characteristic length, where applicable) [21]. For statistical purposes, continuous kinematic and muscle activity data as well as spatio-temporal gait parameters were finally averaged over five trials.

To substantiate the evaluation of the different carrying techniques, the dummy’s sagittal plane net moments as well as the height of the lever arms with reference to the SACR marker were geometrically approximated during upright standing using lateral view digital photographs and the software ImageJ (version 1.52a, U. S. National Institutes of Health, Bethesda, MD, USA).

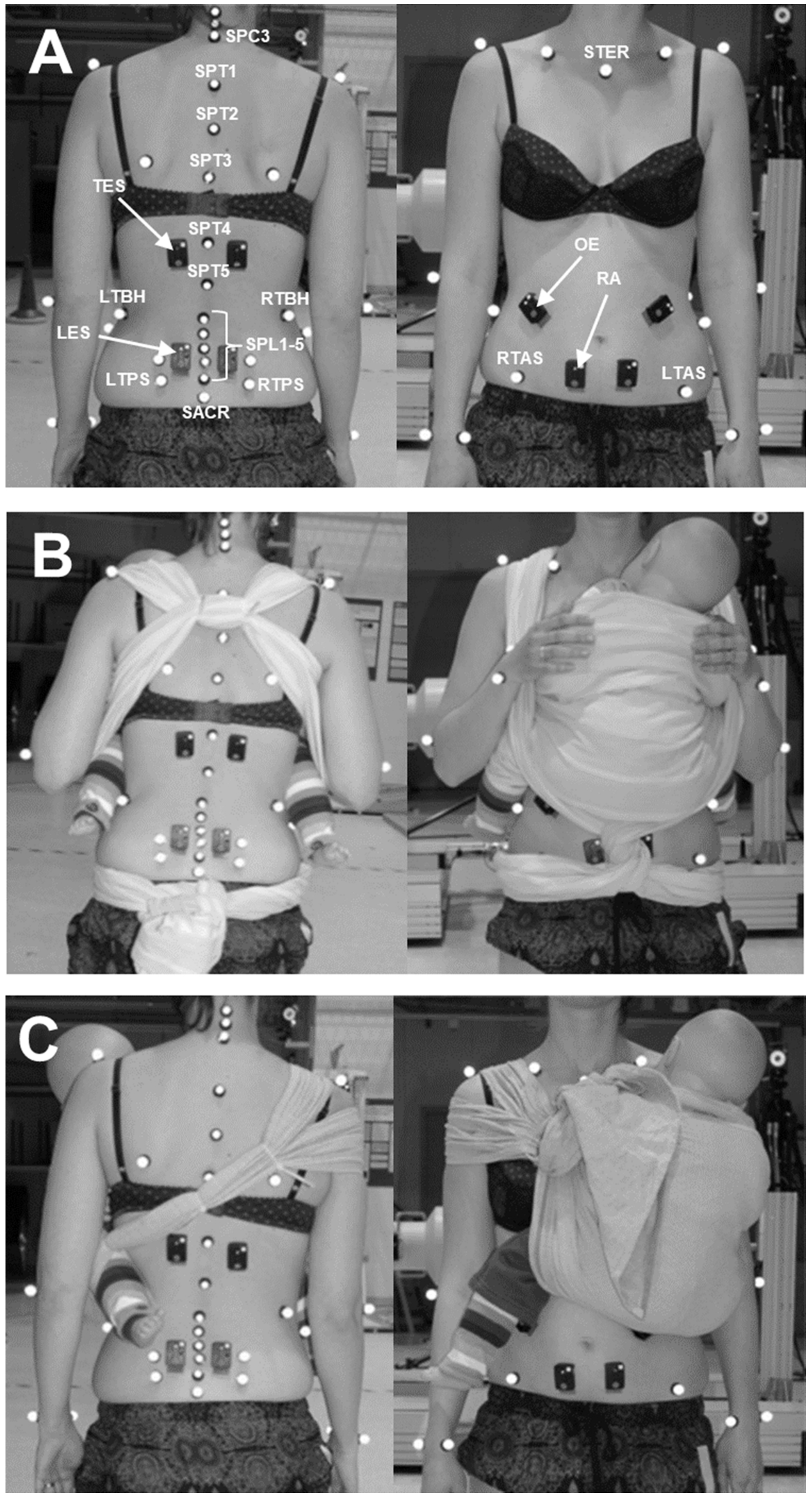

Fig. 1. Placement of the markers on the trunk according to the IfB full body model for the assessment of spinal curvature and rotation angles as well as electrodes for the bilateral electromyographic assessment of the muscles lumbar and thoracic erector spinae (LES and TES, respectively), rectus abdominis (RA) and obliquus externus (OE) in the conditions A) *No Dummy* (including relevant marker names), B) *Dummy front* and C) *Dummy preferred/non-preferred*.

2.4. Statistical analyses

Statistical analyses were carried out using the MATLAB-based spm1d-package for n-dimensional Statistical Parametric Mapping (http://www.spm1d.org/index.html). Prior to any inferential procedures, normal distribution of the kinematic and muscle activity data during most parts of upright standing and level walking as well as the spatio-temporal gait parameters was confirmed using the function "spm1d.stats.normality.anova1rm". Group comparisons of continuous as well as discrete data were then carried out using one-way repeated measures analyses of variance (ANOVA) with post hoc paired t-tests (functions: "spm1d.stats.anova1rm" and "spm1d.stats. ttest_paired"). The alpha-level was thereby set at 0.05 for the ANOVAs and at a Bonferroni-corrected 0.008 for the post hoc comparisons. To identify clinically relevant statistically significant differences for the kinematic parameters, minimal clinical important differences (MCID) of 5° were

Table 1
Reported are mean and standard deviation (SD) for the kinematics, kinetics and muscle activity parameters during standing in the conditions *No Dummy*, *Dummy front*, *Dummy preferred* and *Dummy non-preferred*. In addition, results for the group comparisons (one-way repeated measures analyses of variance (ANOVA) and post hoc pairwise comparisons (paired t-tests), two-tailed) are presented. Statistical significance was accepted at alpha-levels of 0.05 and 0.008 for ANOVA and post hoc pairwise comparisons, respectively.

		Subjects with valid data	1) No Dummy	2) Dummy front	3) Dummy preferred	4) Dummy non-preferred	p-values	
							ANOVA	Post hoc pairwise comparisons
Kinematics [°]								
Pelvis	Sagittal	15	0.00 SD 1.40	−2.10 SD 1.67	−0.83 SD 1.18	−0.95 SD 1.83	0.003*	1 vs. 2: 0.007* 2 vs. 3: 0.003*
	Frontal	15	0.03 SD 0.45	−0.07 SD 0.88	−0.83 SD 1.08	−0.76 SD 1.46	0.036*	1 vs. 3: 0.005*
	Transverse	15	−0.04 SD 1.56	−0.93 SD 2.55	−0.84 SD 2.30	−0.24 SD 2.42	0.641	–
Lumbar curvature	Sagittal	15	−34.72 SD 10.59	−43.55 SD 15.16	−38.14 SD 13.20	−37.08 SD 11.98	0.002*	1 vs. 2: 0.006**
	Frontal	15	2.80 SD 11.13	3.56 SD 10.56	6.55 SD 10.18	1.20 SD 11.78	0.619	–
Thoracic curvature	Sagittal	13	41.65 SD 7.24	46.55 SD 8.72	48.09 SD 6.47	46.95 SD 6.78	< 0.001*	1 vs. 2: 0.007* 1 vs. 3: < 0.001** 1 vs. 4: 0.003**
	Frontal	13	1.36 SD 3.92	1.41 SD 4.82	−3.20 SD 8.52	−4.08 SD 6.69	0.038*	–
Lumbar inclination	Sagittal	15	11.17 SD 6.17	8.16 SD 7.44	7.56 SD 6.27	8.37 SD 5.54	< 0.001*	1 vs. 2: 0.003* 1 vs. 3: < 0.001* 1 vs. 4: 0.001*
	Frontal	15	−0.64 SD 2.77	−0.32 SD 2.09	2.90 SD 2.44	3.79 SD 2.22	< 0.001*	1 vs. 3: < 0.001* 1 vs. 4: 0.003* 2 vs. 3: < 0.001* 2 vs. 4: 0.001*
Thoracic inclination	Sagittal	13	0.11 SD 4.23	−2.31 SD 3.69	−1.26 SD 4.20	−2.00 SD 4.30	0.003*	1 vs. 2: 0.002* 1 vs. 3: 0.002* 1 vs. 4: 0.004*
	Frontal	13	0.20 SD 2.01	0.24 SD 2.34	2.85 SD 2.09	3.00 SD 3.05	0.004*	1 vs. 3: < 0.001* 2 vs. 3: 0.001*
Total inclination	Sagittal	13	0.70 SD 2.14	−2.03 SD 2.90	−1.58 SD 1.72	−1.24 SD 1.57	< 0.001*	1 vs. 2: < 0.001* 1 vs. 3: < 0.001* 1 vs. 4: < 0.001*
	Frontal	13	0.30 SD 1.44	0.60 SD 1.45	3.29 SD 2.02	3.24 SD 2.18	< 0.001*	1 vs. 3: < 0.001* 1 vs. 4: 0.006* 2 vs. 3: < 0.001* 2 vs. 4: 0.009*
Lumbar rotation	Transverse	2	–	–	–	–	–	–
Thoracic rotation	Transverse	2	–	–	–	–	–	–
Total rotation	Transverse	8	−0.18 SD 3.38	−0.22 SD 2.05	−5.47 SD 4.85	−4.00 SD 4.89	0.011*	1 vs. 3: 0.003**
Kinetics								
Dummy's net moment [Nm]	Sagittal	12	–	12.82 SD 2.09	10.81 SD 1.36	10.25 SD 2.29	< 0.001*	1 vs. 2: < 0.001* 1 vs. 3: 0.001*

(*continued on next page*)

Table 1 (*continued*)

		Subjects with valid data	1) No Dummy	2) Dummy front	3) Dummy preferred	4) Dummy non-preferred	p-values	
							ANOVA	Post hoc pairwise comparisons
Height of lever arm [m]	Sagittal	12	–	0.23 SD 0.02	0.23 SD 0.02	0.22 SD 0.02	0.059	–
Muscle activity [%meanMVIC]								
Lumbar erector spinae	Ipsilateral	12	5.20 SD 3.09	7.22 SD 4.42	4.90 SD 2.72	5.19 SD 2.76	0.007*	–
	Contralateral	12	5.50 SD 3.12	7.60 SD 3.68	8.64 SD 6.02	8.57 SD 4.83	0.036*	–
Thoracic erector spinae	Ipsilateral	15	5.42 SD 3.10	7.72 SD 4.59	5.93 SD 4.77	6.31 SD 3.39	0.120	–
	Contralateral	15	4.93 SD 1.93	9.60 SD 4.23	9.28 SD 5.15	7.15 SD 3.68	< 0.001*	1 vs. 2: < 0.001* 1 vs. 3: 0.002*
Rectus abdominis	Ipsilateral	13	4.96 SD 2.29	4.27 SD 3.04	5.96 SD 4.79	5.38 SD 6.33	0.702	–
	Contralateral	13	4.57 SD 3.23	4.47 SD 3.17	4.30 SD 3.07	5.98 SD 7.13	0.591	–
Obliquus externus	Ipsilateral	14	12.82 SD 7.34	8.15 SD 5.94	8.90 SD 6.56	7.18 SD 3.60	< 0.001*	1 vs. 2: 0.004* 1 vs. 3: 0.003*
	Contralateral	15	10.02 SD 3.32	6.63 SD 3.68	9.73 SD 4.84	10.01 SD 6.82	0.037*	1 vs. 2: < 0.003*

* Statistically significant difference.
** Statistically significant and clinically relevant difference (only kinematics).

considered [15–17,22]. Due to a lack of appropriate reference values, no MCID's were considered for the other parameters.

3. Results

Due to frequent sling carrier-dependent covering of markers required for the calculation of lumbar and thoracic spinal rotation angles, these two parameters were not considered in the statistical analysis.

3.1. Upright standing

3.1.1. Kinematics, kinetics and muscle activity

Participants showed a clinically relevant increased lumbar lordosis angle in the *Dummy front* (Δ8.8°, p = 0.006) as well as thoracic kyphosis angle in the *Dummy preferred* and *Dummy non-preferred* (Δ6.4°, p < 0.001 and Δ5.3°, p = 0.003, respectively) compared to the *No Dummy* condition (Table 1). The total spinal rotation angle was increased towards the ipsilateral side in the *Dummy preferred* (Δ5.3°, p = 0.003) compared to the *No Dummy* condition. The dummy's sagittal plane net moments were significantly decreased in *Dummy preferred* (Δ2.0Nm, p < 0.001) and *Dummy non-preferred* (Δ2.6Nm, p = 0.001) compared to the *Dummy front* condition, whereas the height of the lever arms remained unchanged. The contralateral thoracic erector spinae muscle showed increased (Δ4.7%maxMVIC, p < 0.001 and Δ4.4% maxMVIC, p = 0.002, respectively) and the ipsilateral obliquus externus muscle decreased activity (Δ4.7%maxMVIC, p = 0.004 and Δ3.9%maxMVIC, p = 0.003, respectively) in the *Dummy front* and *Dummy preferred* compared to the *No Dummy* condition. In addition, the activity of the contralateral obliquus externus muscle was lower in the *Dummy front* (Δ3.4%maxMVIC, p = 0.003) than the *No Dummy* condition.

3.2. Level walking

3.2.1. Kinematics and muscle activity

Overall group comparisons (ANOVA) revealed for the majority of parameters at least one supra-threshold cluster (Table 2). The respective post hoc pairwise comparisons indicated thereby clinically relevant larger lumbar lordosis angles in the *Dummy front* compared to the *No Dummy* (Δ≥8.2°, 1–100% of gait cycle [%GC], p < 0.001), *Dummy preferred* (Δ≥5.0°, 59–78%GC, p < 0.001) and *Dummy non-preferred* conditions (Δ≥5.6°, 29–70%GC, p < 0.001) (Fig. 2). In addition, lumbar lordosis angles were larger in the *Dummy preferred* than the *No Dummy* condition (Δ≥5.8°, 39–44%GC, p = 0.008; Δ≥5.3°, 98–100%GC, p = 0.008). Thoracic kyphosis angles were larger in the *Dummy preferred* than the *No Dummy* condition (Δ≥5.6°, 1–100%GC, p < 0.001). The total spinal rotation angle was increased towards the ipsilateral side in the *Dummy preferred* compared to the *No Dummy* (Δ≥5.0°, 46–58%GC, p = 0.002) and *Dummy front* conditions (Δ≥5.3°, 1–7%GC, p = 0.008).

The lumbar erector spinae muscles in the *Dummy non-preferred* condition showed decreased activity on the ipsilateral side (Δ≥16.3% maxMVIC, 2–5%GC, p = 0.001) compared to the *Dummy front* and increased activity on the contralateral side (Δ≥13.2%maxMVIC, 49–57%GC, p < 0.001) compared to the *No Dummy* condition (Fig. 3). Furthermore, activity of the thoracic erector spinae muscles was bilaterally higher in the *Dummy front* vs. the *No Dummy* condition (ipsilateral: Δ≥9.5%maxMVIC, 2–5%GC, p = 0.003; contralateral: Δ≥9.5%maxMVIC, 54–63%GC, p < 0.001). In addition, higher activity for the thoracic erector spinae muscle was found in the *Dummy preferred* vs. *No Dummy* condition (Δ≥5.3%maxMVIC, 47–58%GC, p < 0.001). No differences were identified for the abdominal muscles. A complete set of F- and t-curves for the ANOVA and post hoc pairwise comparisons, respectively, can be foundin Figures A1-A8 and B1-B16 in the electronic supplementary material.

Table 2
Reported are results for the group comparisons (one-way repeated measures analyses of variance (ANOVA), two-tailed) of the kinematic and muscle activity parameters during walking using one-dimensional Statistical Parametric Mapping. Statistical significance was accepted at an alpha-level of 0.05.

		Subjects with valid data	F-threshold	Supra-threshold clusters		
				No.	Localization	p-values
Kinematics						
Pelvis	Sagittal	15	4.291	Cluster 1	3-92%	< 0.001
	Frontal	15	5.093	–	–	–
	Transverse	15	4.711	Cluster 1	0-2%	0.049
				Cluster 2	37-59%	0.007
Lumbar curvature	Sagittal	15	3.617	Cluster 1	0-100%	< 0.001
	Frontal	15	4.220	–	–	–
Thoracic curvature	Sagittal	13	3.478	Cluster 1	0-100%	< 0.001
	Frontal	13	4.046	–	–	–
Lumbar inclination	Sagittal	15	3.605	Cluster 1	0-100%	0.001
	Frontal	15	4.684	Cluster 1	0-100%	< 0.001
Thoracic inclination	Sagittal	13	3.614	Cluster 1	0-100%	< 0.001
	Frontal	13	4.084	Cluster 1	0-57%	0.007
Total inclination	Sagittal	13	3.860	Cluster 1	0-100%	< 0.001
	Frontal	13	4.359	Cluster 1	0-100%	< 0.001
Lumbar rotation	Transverse	2	–	–	–	–
Thoracic rotation	Transverse	2	–	–	–	–
Total rotation	Transverse	9	4.893	Cluster 1	0-6%	0.046
				Cluster 2	45-58%	0.037
Muscle activity						
Lumbar erector spinae	Ipsilateral	12	5.927	Cluster 1	0-9%	0.004
				Cluster 2	74-77%	0.040
				Cluster 3	96-100%	0.030
	Contralateral	12	5.923	Cluster 1	5-8%	0.036
				Cluster 2	46-62%	< 0.001
Thoracic erector spinae	Ipsilateral	15	5.683	Cluster 1	79-91%	< 0.001
	Contralateral	15	5.724	Cluster 1	26-31%	0.019
				Cluster 2	45-61%	< 0.001
				Cluster 3	65-67%	0.045
Rectus abdominis	Ipsilateral	13	5.032	–	–	–
	Contralateral	13	5.057	–	–	–
Obliquus externus	Ipsilateral	14	5.225	Cluster 1	32-44%	0.009
				Cluster 2	75-84%	0.021
	Contralateral	15	5.097	–	–	–

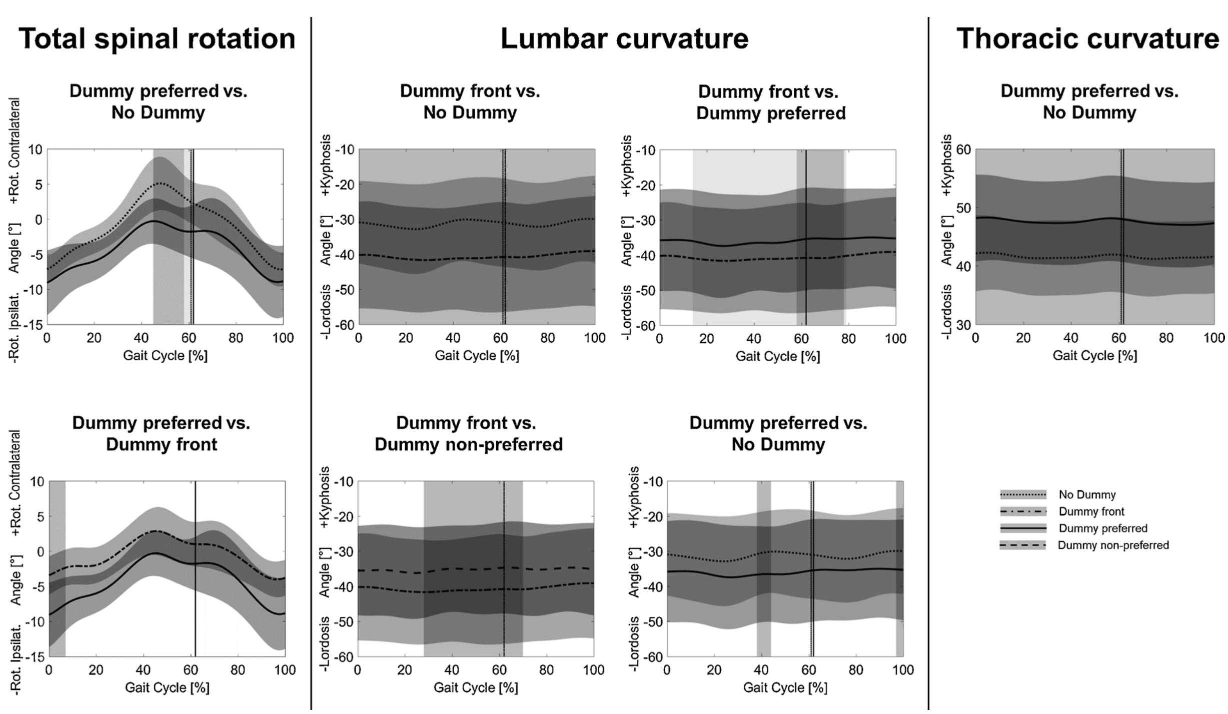

Fig. 2. Post hoc pairwise comparisons for the total spine rotation as well as sagittal lumbar and thoracic curvature angles. Illustrated are mean and standard deviation (SD) of the conditions that showed statistically significant (p ≤ 0.008, light gray shaded) and clinically relevant (> 5°, dark gray shaded) mean differences. The vertical lines separate the stance and swing phases in the respective conditions.

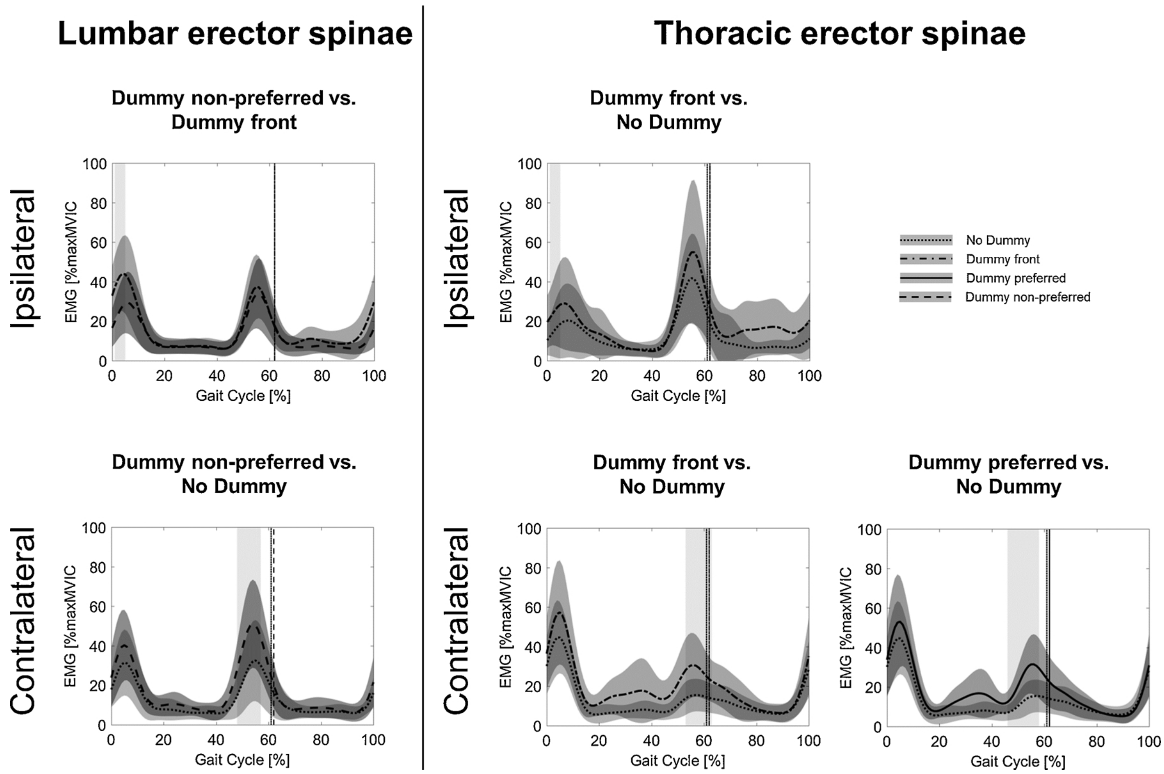

Fig. 3. Post hoc pairwise comparisons for ipsilateral and contralateral thoracic and lumbar erector spinae muscle activity. Illustrated are mean and standard deviation (SD) of the conditions that showed statistically significant (p ≤ 0.008, light gray shaded) mean differences. The vertical lines separate the stance and swing phases in the respective conditions.

Table 3
Reported are mean and standard deviation (SD) for the spatio-temporal gait parameters in the conditions *No Dummy*, *Dummy front*, *Dummy preferred* and *Dummy non-preferred*. In addition, results for the group comparisons (one-way repeated measures analyses of variance (ANOVA) and post hoc pairwise comparisons (paired t-tests), two-tailed) are presented. Statistical significance was accepted at alpha-levels of 0.05 and 0.008 for ANOVA and post hoc pairwise comparisons, respectively.

		Subjects with valid data	1) No Dummy	2) Dummy front	3) Dummy preferred	4) Dummy non-preferred	p-values	
							ANOVA	Post hoc pairwise comparisons
Walking speed[a]		15	0.43 SD 0.05	0.42 SD 0.04	0.43 SD 0.05	0.42 SD 0.05	0.199	–
Cadence[a]		15	0.58 SD 0.04	0.58 SD 0.04	0.59 SD 0.05	0.58 SD 0.05	0.314	–
Stride length[a]		15	1.49 SD 0.12	1.45 SD 0.07	1.46 SD 0.08	1.45 SD 0.09	0.058	–
Stride time[a]		15	3.49 SD 0.26	3.46 SD 0.26	3.43 SD 0.27	3.48 SD 0.28	0.375	–
Step length[a]	Ipsilateral	15	0.78 SD 0.63	0.78 SD 0.66	0.76 SD 0.61	0.67 SD 0.48	0.935	–
	Contralateral	15	0.76 SD 0.06	0.72 SD 0.04	0.73 SD 0.05	0.72 SD 0.05	0.001*	1 vs. 2: 0.001* 1 vs. 4: 0.002*
Step time[a]	Ipsilateral	15	1.75 SD 0.13	1.72 SD 0.12	1.73 SD 0.14	1.75 SD 0.15	0.538	–
	Contralateral	15	1.75 SD 0.13	1.74 SD 0.14	1.72 SD 0.14	1.74 SD 0.15	0.430	–
Stance phase [%]	Ipsilateral	15	61.00 SD 1.89	61.87 SD 1.25	62.07 SD 1.39	62.20 SD 1.66	0.019*	1 vs. 3: 0.001*
	Contralateral	15	61.47 SD 1.55	61.80 SD 1.15	62.20 SD 1.47	62.07 SD 1.58	0.165	–
Swing phase [%]	Ipsilateral	15	39.00 SD 1.89	38.13 SD 1.25	37.93 SD 1.39	37.80 SD 1.66	0.019*	1 vs. 3: 0.001*
	Contralateral	15	38.53 SD 1.55	38.20 SD 1.15	37.80 SD 1.47	37.93 SD 1.58	0.165	–

[a] Expressed as dimensionless numbers according to Hof [21].
* Statistically significant difference.

3.2.2. Spatio-temporal gait parameters

Contralateral step length as well as ipsilateral stance and swing phases showed differences in the loaded compared to the *No Dummy* condition (Table 3). However, although statistically significant, these differences were very small and should therefore only be considered tendencies rather than of clinical relevance.

4. Discussion

This study investigated the immediate effects of carrying a 6 kg-dummy with a sling in front and on the sides on trunk neuromechanics during upright standing and level walking in a group of healthy young women. Compared to unloaded walking, carrying the dummy in front resulted in increased lumbar lordosis and bilaterally increased paraspinal muscle activity. Carrying the dummy on the preferred side caused increased thoracic kyphosis, reduced axial rotation of the spine away from the dummy and increased contralateral thoracic paraspinal muscle activity. Carrying the dummy on the non-preferred side also led to increased thoracic kyphosis, but only during standing. Furthermore, antero-lateral carrying indicated increased contralateral lumbar paraspinal muscle activity (only non-preferred side) and tendencies for a slight increase in lumbar lordosis.

Since no relevant differences could be found for the spatio-temporal gait parameters, none of these neuromechanical deviations seems to be due to altered walking speeds. In contrast, Junqueira et al. [2] reported slower walking when carrying a dummy in front. However, they did not use normalized gait parameters and when adopting the previously suggested MCID of 0.10-0.20 m/s [23], their reported differences of 0.05–0.06 m/s would not be considered of clinical importance. This also applies to their observed deviations in pelvis kinematics during standing and walking (< 2.4°) [2], which would be considered clinically not relevant with the currently adopted MCID of 5°.

Regarding sagittal spinal curvature angles, the current findings are in line with Junqueira et al. [2] for lumbar lordosis but not thoracic kyphosis, which could be explained by the different carrying techniques. Carrying a dummy in front with the arms might require the thoracic spine to bend forward to properly embrace the dummy. When using a sling, no arms are needed and most of the dummy's weight is passively transferred to the shoulders. To effectively position the body's center of mass posteriorly to a more balanced location by increasing lumbar lordosis, thoracic erector spinae muscle activity increases to counteract the weight-dependent external flexion moment of the thoracic spine and to keep its posture unchanged thereby. This mechanism was also observed in occupational anterior load carrying [3,5,6].

This is the first study providing data on trunk neuromechanics related antero-lateral infant carrying. The fact that lumbar lordosis was less pronounced compared to the front carrying condition can be attributed to the reduced dummy's sagittal plane net moment. Furthermore, although no differences were found between the two sides, it appears that carrying a dummy on the preferred side evoked slightly more pronounced neuromechanical responses than the non-preferred side. A possible explanation for this could be that humans generally tend to shift their weight to the non-dominant side during standing, which corresponds to the side that is preferred to cradle a baby [24].

The question now arises, what role these neuromechanical adaptations might play in the development or progression of LBP/PGP after childbirth. Firstly, it has to be considered that women have some unique morphologic features (i.e. less kyphotic vertebral body wedging, greater interspinous space and larger interfacet width in thoracolumbar vertebrae), which were suggested to compensate for the bipedal obstetric load during pregnancy by enabling them to increase lordosis with less inter-vertebral rotation [4,25]. When assuming a lumbar extension posture, however, these features result in a size reduction of the intervertebral foramen and could therefore cause irritation of the neural structures [4].

Another important factor is the ten-fold increase of the hormone relaxin during pregnancy, resulting in laxity of the ligamentous structures [26]. Even though the relaxin-levels return to normal within a couple of days after childbirth [27], the increased ligament laxity was observed until 12 weeks postpartum [28], weakening the ability to withstand the increased shear and compression forces in the lumbar spine reported during anterior load carrying [9,29].

Considering now that already a hyperlordotic posture alone was shown to be associated with facet joint pathology [30], increased shear and compression forces together with increased joint laxity could result in additional overloading of the respective structures, placing women in a particularly vulnerable position when carrying their infants in front after childbirth.

Moreover, it was reported that LBP/PGP during pregnancy and in the postpartum phase is related to reduced muscular endurance of the back extensors [7]. And since increased paraspinal muscle activity was observed in all three carrying conditions, it can be assumed that postpartum women are more susceptible to fatigue-related pain when carrying their infants, especially for longer periods.

Limiting factors of the current study included the fact that the application of the sling frequently led to covering of markers required to calculate axial rotations of the spine. As a result, total spinal rotation was calculated by using data from only 9 participants, whereas isolated lumbar and thoracic spinal rotation had to be excluded. The fact that the measurements were conducted solely on healthy participants that were carrying a dummy only for short periods further limited the interpretation of the findings in the context of LBP. Future investigations should therefore be conducted on women immediately after childbirth with and without LBP and include longer carrying periods to shed more light into the mechanisms associated with this complaint.

In conclusion, carrying a 6 kg-dummy in front and on the preferred and non-preferred sides during upright standing and level walking resulted in different neuromechanical responses for each of the three conditions. Carrying the dummy in front was mainly associated with increased lumbar lordosis, whereas increased thoracic kyphosis and less axial rotation away from the dummy were observed when carrying on the preferred side. All three conditions entailed increased paraspinal muscle activity, although only unilaterally in side carrying. Carrying an infant alternating on the preferred and non-preferred sides using a sling could therefore be advantageous to prevent musculoskeletal pain resulting from excessive lumbar hyperextension and paraspinal muscle hyperactivation. Prospective trials including postpartum women with and without LBP/PGP should be conducted to confirm this assumption and to establish evidence-based recommendations.

Conflict of interest statement

The authors declare no conflicts of interest.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.gaitpost.2018.10.013.

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