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Elena Kokkoni
University of Delaware

Joshua Haworth
University of Nebraska at Omaha, jlhaworth@unomaha.edu

Regina T. Harbourne
University of Nebraska Medical Center

Nicholas Stergiou
University of Nebraska at Omaha, nstergiou@unomaha.edu

Anastasia Kyvelidou
Creighton University, anastasiakyvelidou@creighton.edu

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Infant sitting postural control appears robust across changes in surface context

Elena Kokkoni[a], Joshua L. Haworth[b], Regina T. Harbourne[c], Nicholas Stergiou[d,e] and Anastasia Kyvelidou[f]

a Biomechanics and Movement Science Program, University of Delaware, Newark, DE, USA;

b Department of Kinesiology, Whittier College, Whittier, CA, USA;

c Rangos School of Health Sciences, Physical Therapy, Duquesne University, Pittsburgh, PA, USA;

d Department of Biomechanics, University of Nebraska at Omaha, Omaha, NE, USA;

e Department of Environmental Agricultural and Occupational Health, College of Public Health, University of Nebraska Medical Center, Omaha, NE, USA;

f Department of Physical Therapy, Creighton University, Omaha, NE, USA

ABSTRACT

Aim of the study: Independent sitting requires the control of the involved body segments over the base of support using information obtained from the three sensory systems (visual, vestibular, and somatosensory). The contribution of somatosensory information in infant sitting has not been explored. To address this gap, we altered the context of the sitting support surface and examined the infants' immediate postural responses.

Materials and methods: Ten 7-month-old typically developing infants sat on compliant and firm surfaces in one session. Spatial, frequency, and temporal measures of postural control were obtained using center of pressure data.

Results Our results suggest that infants' postural sway is not immediately affected by the different types of foam surface while sitting.

Conclusions: It seems that mature sitter infants are able to adapt to different environmental constraints by disregarding the distorted somatosensory information from the support surface and relying more on their remaining senses (visual and vestibular) to control their sitting posture.

KEYWORDS

Development; posture; somatosensory

Introduction

The emergence of self-sitting ability is an early developmental milestone known to inevitably impact later perceptual, cognitive, and social skills. Mastering the control of both head and trunk in independent sitting renders the arms available for other functional activities such as reaching and exploration of the nearest environment whereas the vertical postural orientation experienced in the sitting position may constitute the foundation for other consequent more complex motor skills such as standing and walking (Assaiante and Amblard 1995; Rochat and Goubet 1995). Hence, a time delay in sitting acquisition or poor postural control while sitting may hinder the progression of critical functional skills in development highlighting the demand for designing early interventions for pediatric populations in need.

Although the achievement of independent sitting appears to be an innate part of the normal maturation process, on the contrary, it requires the infant to learn how to control the body's degrees of freedom and to adapt to environmental and growth changes (Harbourne and Stergiou 2003). In order to overcome the different constraints present (environmental, biomechanical, and task), the infant utilizes sensory information obtained from the three sensory systems (visual, vestibular, and somatosensory). The contribution of the visual system on sitting postural control has been well documented as it was originally thought to be the dominant modality responsible for controlling upright posture (Bertenthal et al. 1997; Barela et al. 2000). However, studies on infant standing postural control showing age- and ability-related trends under somatosensory input alteration emphasized also the presence of a dynamic relationship between the somatosensory system and upright posture in development (Barela et al. 1999; Metcalfe and Clark 2000; Metcalfe et al. 2005). Along this line of examination, a few studies have documented changes in body sway of seated infants while providing a touch stimulus or have examined muscle activation patterns during postural responses to discrete unexpected perturbations on the support surface (Hadders-Algra et al. 1996; Chen et al. 2007). However, there is no study that examined body sway in the "natural" sitting position under continuous alteration of the somatosensory stimulus induced by the different contexts of the support surface. The information obtained from the latter paradigm could potentially give an insight on infants' dynamic adaptive strategies as the environmental constraints continuously change, and therefore sitting postural control is challenged.

Assessing infants' adaptive responses under challenging surface conditions may also add critical information to the existing body of postural evaluation and training techniques used as part of early rehabilitation, especially for populations whose motor performance might be modulated by sensory impairments. For example, designing a sensorimotor sitting postural intervention could potentially benefit children with hemiplegia, the majority of which (70%) present sensory deficits (Tixard et al. 1954; Twitchell 1966), or children with spastic quadriplegic or cerebral palsy (CP) whose damage in the sensory cortex is related to motor area deficit (Hoon et al. 2002). Another population could be children with spastic diplegic CP, whose sensory deficits are consistent with dorsal column sensory modalities including position sense of the legs (McLaughlin et al. 2005). As the development of motor ability of children with CP seems to involve poor postural control in combination with sensory deficits, a few studies have examined standing postural responses under sensory alteration conditions. It was found that children's standing body sway was more affected from the distortion coming from the support surface compared to visual distortion, and this effect was more evident in children with CP rather than typically developing children (Cherng et al. 1999; Saxena et al. 2014). In these studies, foam on the support surface was used as a method of distortion of somatosensory information in order to investigate motor responses. The information obtained supports the critical role of the somatosensory system in controlling standing posture under various environmental constraints, and the motive behind using altered support surface contexts as part of the sensorimotor training for pathological populations. However, there are no studies that examined sitting postural responses under altered support surface contexts that could give an insight into the role of the somatosensory system for controlling sitting, and the potential application of this paradigm in the early rehabilitation setting.

In the present study, we aimed to fill this gap by using posturography to detect changes in sitting postural control, while typically developing infants were sitting under conditions that would challenge the somatosensory input. To achieve this goal and in line with previous studies, we used foam as a method for somatosensory alteration (i.e., to provide inaccurate somatosensory information to detect body orientation). We also found sitting on a foam cushion to be the most appropriate and well tolerated way of manipulating somatosensation in infants based on our preliminary testing. Choosing the foam properties was challenging since previous studies on children provided little or no information about the foam properties used in their paradigms. Therefore, instead of comparing a single compliant surface to a noncompliant surface, we examined a range of foam properties in an effort to better understand how the different levels of distortion may challenge sitting posture. A similar paradigm has also been used in adult standing postural control demonstrating that the different properties of foam induced different postural responses (Patel et al. 2008a, 2008b). Our hypothesis was that all foam surfaces would induce an increase in infants' postural sway while quiet sitting, as captured by measures of center of pressure (COP) at the base of support. Since sitting postural performance also depends on how the infants overcome their biomechanical constraints, we also wished to explore how growth measures (height and weight) would contribute to their response to the sensory alteration.

Materials and methods

Participants

Ten 7-month full-term typically developing infants (230.5 ± 9.1 days, 4 males, 6 females) with the ability to independently sit with no health problems participated in the present study (Table 1). Inclusion criteria for entry into the study for the infants were: (a) a score on the Gross Motor Quotient of the Peabody Developmental Motor Scale-2 of greater than 0.5 SD below the mean; (b) age between 6 and 8 months at the time of data collection; and (c) mature sitting. The last item required the infant to be able to sit for 5 min or more without falling, to reach for toys in independent sitting with both hands without disrupting balance, and for the parent to be confident to leave the infant alone in a sitting position without protection and the concern of falling. Furthermore, it was preferred if the infant was not yet able to crawl, and not yet able to move in and out of the sitting position independently. The exclusion criteria were: (a) a score on the Peabody Gross Motor Scale of greater than 0.5 SD below the mean; and (b) immature sitting which means inability to sit for 5 min or more without falling. Before their infant's participation, the parents signed an informed consent document.

Table 1. Descriptive characteristics of the infants.

					Gross motor scale percentile ranking				
ID	Gender	Age (days)	Mass (kg)	Seated height (m)	Stationary	Locomotion	Reflexes	Stage of sitting	Crawling experience
s1	F	247	9.232	0.508	84	63	63	3	Yes
s2	M	240	8.888	0.481	63	37	63	3	No
s3	M	222	9.437	0.516	75	50	75	3	No
s4	F	225	7.704	0.429	84	50	75	3	No
s5	F	228	7.739	0.463	75	50	50	3	No
s6	F	234	7.703	0.444	75	50	50	3	No
s7	F	236	6.741	0.483	50	50	58	3	No
s8	M	224	8.933	0.459	75	50	50	3	No
s9	M	217	8.630	0.503	75	50	50	3	No
s10	F	232	6.852	0.440	75	50	50	3	No
Mean		230.5	8.186	0.473	73.1	50	58.4		
SD		9.1	0.968	0.03	9.97	6.13	10.25		

Procedures

Data were collected on a single day for each infant at a specifically designed laboratory space that simulates a common living room to provide a soothing environment. All infants were tested for about 15 min with the Peabody Gross Motor Scale by a physical therapist prior to the data collection session that took approximately 45 min. During the data collection, infants were sitting on a force plate (Advanced Mechanical Technology, Watertown, MA, USA) under five different conditions: four foam conditions and a no-foam condition. The order of conditions was randomized. For the different foam conditions, a set of four incrementally compliant foam (FXI Foamex Innovations, Media, PA, USA) support surfaces (Table 2) was used in order to challenge somatosensory input (Figure 1). The range selected was appropriate for the expected mass of a 7-month-old infant based on our preliminary testing. The small mass of an infant would induce adequate foam indentation but no more than 25% of the total thickness of the foam, thus minimizing the potential effect of mechanical postural support that would lead to misleading results. Each data collection was videotaped using two Panasonic video cameras (Model 5100 HS) interfaced with a Panasonic Digital AV Mixer (Model WJ MX30) positioned to record both sagittal and frontal views of the infant. A qualitative record of the infant's performance and emotional state during the procedure was obtained, required for the selection of segments of data to be analyzed later. Before the data collection session started, infants were allowed time to become familiar with the new environment, whereas the investigator and the parent remained close to the infants during the whole procedure to assure their safety and keep them in a calm state.

Table 2. Foam type properties.

Foam material	Dimensions (m)	Density (kg/m^3)	Indentation force deflection (kg/m^2)
Hard	$0.5 \times 0.5 \times 0.1$	28.8	1335
Medium hard	$0.5 \times 0.5 \times 0.1$	24	915
Medium soft	$0.5 \times 0.5 \times 0.1$	24	703
Soft	$0.5 \times 0.5 \times 0.1$	19.2	450

Note: The range was selected based on the expected mass of the infants (based on target age) that would induce adequate indentation but no more than 25% of the total thickness of the foam (10 cm), in an effort to minimize mechanical support that could potentially affect our results. For example, s7 (the lightest infant) would induce an indentation of between 0.5 and 1.5 cm and s3 (the heaviest infant) between 0.7 and 2.1 cm.

Figure 1. Infant sitting on the foam placed on the forceplate during data collection.

Data processing

Force data acquisition and processing were controlled through the AMTINetForce software (Advanced Mechanical Technology Inc., Watertown, MA, USA). Component forces (Fx, Fy, Fz) and moments (Mx, My, Mz) were sampled at 200 Hz for the purpose of collecting a total of 2000 points; the required number for later analysis of our variables as shown from previous work (Yentes et al. 2013). COP displacements in both the anterior–posterior (AP) and medial–lateral (ML) sway directions were calculated from the forces and moments through the software. Data were then exported in ASCII format for further analysis.

Video records were used to identify three segments for each condition when the infant's performance met specific behavioral criteria and then the COP data were selected during this time. The segments of the COP data were selected when the infant exhibited at least 10 s of quiet sitting behavior. The specific behavioral criteria were: (i) not moving the arms (not reaching, holding an object, or flapping); (ii) not vocalizing or crying; (iii) not in the process of falling; (iv) not leaning their trunk more than 45 to either side. Initially, we tried to select longer segments since each condition trial lasted 1 min, however, the experienced infants moved too frequently (including arm or leg movement) to obtain longer than 10 s segments across all trials.

Multiple variables were selected for inclusion in the analysis based on time, frequency, and distance measures of the COP path that have been commonly used in COP analysis in sitting and standing. Root mean square (RMS), range of the COP path in both the AP and ML directions, sway path (total length of the COP trajectory), and the areas of the 95% confidence circle and 95% confidence ellipse were calculated. In addition, the frequency-domain parameters of the median frequency and frequency dispersion were included. These measures provided information about the amount of variability in postural sway (Stergiou et al. 2006). In order to identify the structure of variability in postural sway, the largest Lyapunov exponent (LyE) and the approximate entropy (ApEn) were also calculated. LyE measures the rate at which nearby trajectories in state space diverge (Abarbanel 1996). Simply put, the LyE quantifies the exponential separation of trajectories in the signal's state space. As nearby points separate, they diverge rapidly and produce instability. The exponent estimates this instability, which is largely affected by the initial conditions of the system, which are the constraints that underlie its function (Dingwell et al. 2000). The LyE for sinusoidal data results in a LyE value of zero because the trajectories mapped in the state space will completely overlap, thus showing no divergence and result in a periodic pattern. Positive LyE values less than 0.5 may indicate the presence of determinism within a time series whereas larger values depict completely random data because of the greater degree of divergence of trajectories. ApEn measures regularity, thus the logarithmic likelihood that runs of patterns that are in close proximity remain close on the next incremental comparisons. The ApEn values range between 0 and 2. A value of 0 indicates perfect periodic control of postural sway and a value of 2 depicts completely random sway. In general, small ApEn values show greater tendency to remain close and therefore determinism in our data. The ApEn measure was calculated using the algorithm developed in previous work (Pincus and Goldberger 1994). All measures were implemented in MATLAB (Mathworks, Natick, MA, USA).

The COP data were analyzed unfiltered in order to examine the variability in postural sway over time. Because the same instrumentation was used for all subjects, it can be assumed that a consistent level of measurement noise was the same for all infants and any difference observed would be from changes of postural control itself. If the data were filtered, important information about these changes of postural control would be lost.

Statistical analyses

Initially, values from all dependent variables were averaged within and between subjects. Subsequently, group means were subjected to one-way repeated measures ANOVA comparing the conditions of the support surface (five levels: soft foam, medium soft foam, medium hard foam, hard foam, control). Furthermore, regression analysis was performed to identify the potential influence of mass and height in the postural responses. Data were analyzed using PASW Statistics (SPSS Inc. Released 2009. PASW Statistics for Windows, Version 18.0. Chicago, IL: SPSS Inc.).

Results

No significant differences ($p < .05$) were found for any of the dependent variables (Table 3). As a post hoc analysis and in an attempt to reduce the large standard deviations found, we considered excluding the one infant that had crawling experience at the time of data collection. Again, the results remained the same showing no significant differences among conditions.

One surprising finding that came up from plotting our data was the identification of distinct groups for two of our measures. For Sway Path and Range of sway in the ML direction, groups of trajectories were observed in the plot confirming the presence of different postural strategies among our subjects (Figures 2 and 3). Three group means (Table 4) were compared to identify these groups and it was found that they were statistically different ($p < .05$, F2 ¼ 12.211, F2 ¼ 5.487).

Regression analysis revealed a relationship between Sway Path and the anthropometric features of the infants possibly explaining the formation of these groups. Firstly, this analysis was applied to the control condition (Figure 4) and afterwards all conditions were considered (Figure 5). Results showed that there is a strong negative relationship between Sway Path and mass but not height (R2 ¼ 0.9099, R2 ¼ 0.2456) for the control condition. Similarly, considering all conditions seems to have a strong negative relationship between Sway Path and mass (R2 ¼ 0.9001, Soft foam; R2 ¼ 0.9523, Medium soft foam; R2 ¼ 0.9488, Medium hard foam; R2 ¼ 0.9561, Hard foam).

Discussion

The achievement of independent sitting posture requires the infant to overcome the different environmental, biomechanical, and task constraints (Harbourne and Stergiou 2003) by utilizing sensory information obtained from the environment. There is limited information regarding infants' control of body sway in the "natural" quiet sitting position under continuous alteration of the somatosensory information. In the present study, we used posturography to detect changes in sitting postural control, while typically developing infants were "naturally" sitting under altered contexts of the support surface that would challenge their somatosensory information. We also aimed to explore how different biomechanical constraints as opposed to growth changes would affect their response to the sensory alteration. Somatosensory information was altered at the base of support of sitting using different densities (soft, medium soft, medium hard, hard) of foam along with a no-foam control condition. We hypothesized that the foam surfaces would induce an increase on infants' postural sway while sitting independently. The information obtained could potentially give an insight on infants' dynamic adaptive strategies as the environmental constraints continuously change, and therefore sitting postural control is challenged.

Table 3. Means and standard deviations used for the statistical analysis.

	Soft	Medium soft	Medium hard	Hard	Control	*F*-ratio	*p*-value
Amount of variation of sway							
RMS AP (mm)	5.489 ± 2.212	4.527 ± 1.665	5.034 ± 1.935	4.986 ± 2.371	5.187 ± 3.304	**0.342**	**.847**
RMS ML (mm)	3.928 ± 1.174	3.013 ± 0.824	3.616 ± 1.107	3.670 ± 1.047	3.594 ± 1.758	**1.657**	**.181**
Range AP (mm)	28.385 ± 10.551	23.294 ± 6.096	28.907 ± 15.218	31.115 ± 17.946	30.321 ± 20.902	**0.952**	**.445**
Range ML (mm)	22.025 ± 7.511	17.969 ± 4.453	20.799 ± 6.371	22.325 ± 7.353	23.389 ± 15.68	**1.657**	**.181**
Sway Path (mm)	1843.74 ± 237.329	1825.493 ± 211.81	1841.263 ± 234.914	1850.063 ± 247.657	1889.377 ± 284.34	**2.607**	**.052**
Circle area (mm^2)	23 045 ± 12 786	16 695 ± 10 067	19 944 ± 16 653	21 150 ± 13 831	19 743 ± 133 227	**0.575**	**.682**
Ellipse area (mm^2)	380.433 ± 208.571	249.698 ± 109.981	342.135 ± 227.291	331.696 ± 188.221	405.894 ± 558.915	**0.716**	**.484**
Frequency of sway							
Med freq (Hz)	1.023 ± 0.864	0.773 ± 0.706	0.857 ± 0.553	1.110 ± 0.762	0.723 ± 0.531	**0.925**	**.460**
Freq disp	0.692 ± 0.093	0.732 ± 0.087	0.727 ± 0.077	0.707 ± 0.098	0.757 ± 0.073	**1.394**	**.266**
Structure of variation of sway							
ApEn AP	0.816 ± 0.249	0.951 ± 0.276	0.846 ± 0.239	0.886 ± 0.240	0.909 ± 0.252	**0.586**	**.675**
ApEn ML	0.980 ± 0.174	1.172 ± 0.203	1.049 ± 0.209	1.031 ± 0.239	1.105 ± 0.231	**1.967**	**.120**
LyE AP	0.126 ± 0.02	0.135 ± 0.04	0.128 ± 0.02	0.136 ± 0.02	0.128 ± 0.02	**0.524**	**.718**
LyE ML	0.128 ± 0.02	0.138 ± 0.01	0.130 ± 0.02	0.128 ± 0.02	0.138 ± 0.02	**1.556**	**.222**

Control of infants' sitting posture may not be affected by changes in surface support context

Our analysis, using all subjects as one group and comparing it across the different foam conditions, did not show any significant differences in any of our spatial, temporal, and frequency measures (Table 3). Our results are in contrast to adult studies that showed differences when standing on a variety of foam surfaces (Patel et al. 2008a, 2008b). However, the case appears to be different in development, where infants are used to shifting stages within very short periods of time. The fact that infants' body sway was not affected by the alteration of somatosensory information suggests two alternative hypotheses about mature sitters: either (i) they do not rely on the somatosensory system to control their sitting posture, and they possibly rely on their remaining senses; or (ii) they are able to disregard distortion of the somatosensory information and quickly adapt to the different environmental conditions.

Infants' adaptability suggested by our alternative hypotheses is supported by our post hoc analysis and by findings of a very recent study on sitting ability. For our post hoc analysis, locomotor experience was investigated as a potential confounder based on the crawling status of one of the participating infants. Previous research has shown that the acquisition of more advanced developmental milestones can have an effect on previously acquired skills. For example, a study found that the onset of independent walking influences infants' postural responses during standing while getting somatosensory information from a light touch on a surface (Metcalfe et al. 2005). They showed that the relationship between their postural sway and the somatosensory stimulus became more stable with walking experience. Based on this information, we excluded the infant with crawling experience from our data and performed the same data and statistical analyses with the remaining nine subjects. Again, no significant differences were identified. Along these lines, and looking into other people's work, we found a recent study by Rachwani et al. (2017) that examined sitting ability under different environmental constraints. They tested infants while they sat on forward and backward slopes and they were surprised to find that experienced sitters were able to keep their sitting balance on very steep slopes. Thus, this study, along with our findings, demonstrate the great behavioral flexibility that infants show in the natural sitting position when they are challenged by the environment.

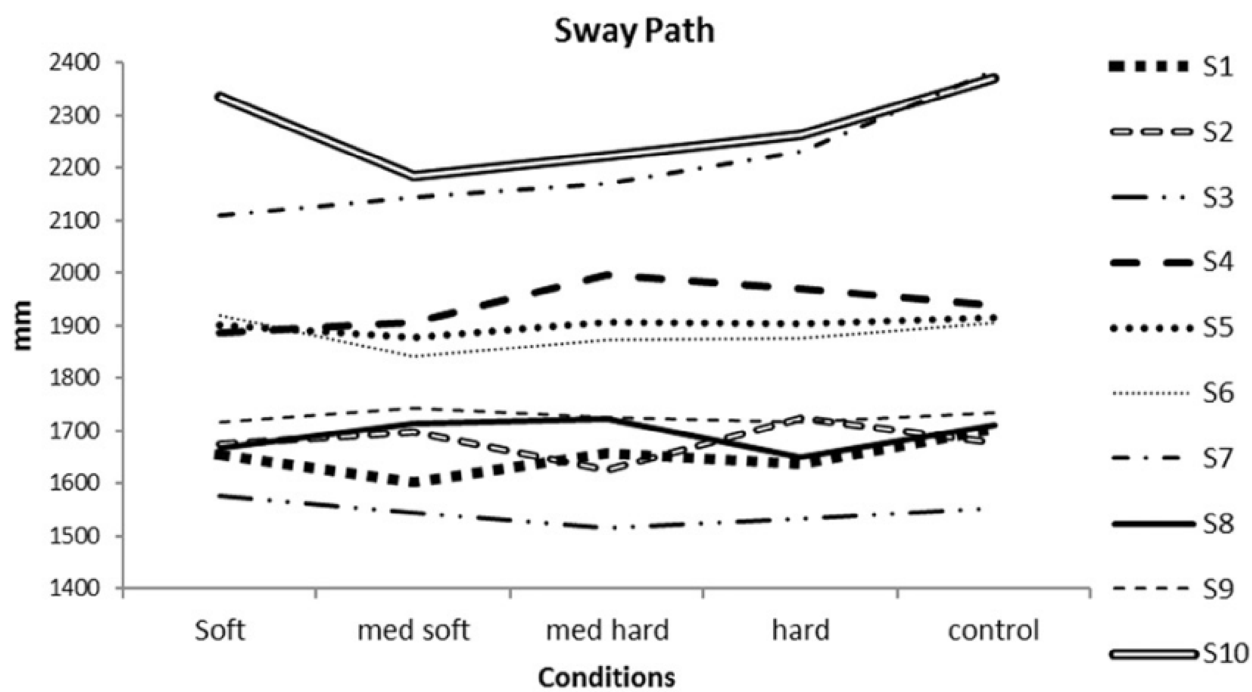

Figure 2. Sway Path trajectories across conditions per subject.

Control of infants' sitting posture across support surface contexts may be affected by growth changes

Our initial data inspection revealed large standard deviations among subjects and the formation of subgroups within our sample for two linear variables, the Sway

Path and Range of sway. We found that anthropometric features affect these linear posturography measures.

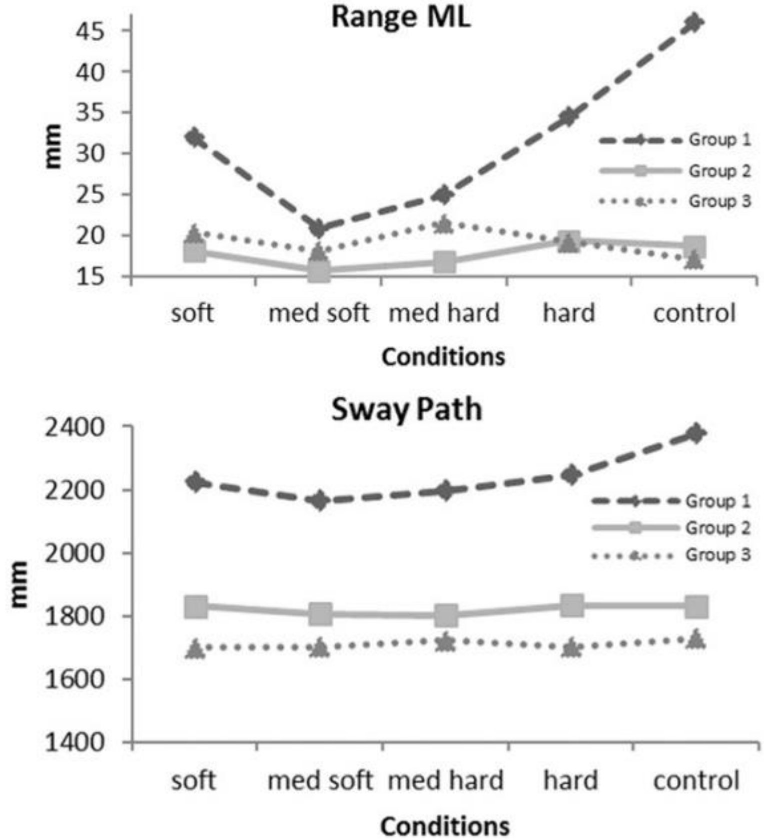

Figure 3. Distinct group trajectories for Range of sway in medial–lateral direction and Sway Path.

Table 4. Means and standard deviations for each group across conditions for Sway Path and RMS.

		Conditions				
Groups	*N*	Soft	Medium soft	Medium hard	Hard	Control
Sway Path (mm)						
1	2	2222.983 ± 159.123	2164.433 ± 29.887	2195.883 ± 38.207	2245.883 ± 22.368	2377.467 ± 11.078
2	3	1830.778 ± 136.313	1805.222 ± 94.229	1801.878 ± 152.904	1834.389 ± 96.820	1831.944 ± 134.740
3	5	1699.833 ± 114.830	1702.080 ± 139.618	1723.047 ± 174.928	1701.140 ± 164.150	1728.600 ± 137.481
RMS ML (mm)						
1	2	5.103 ± 2.239	3.456 ± 1.318	4.217 ± 1.457	4.436 ± 1.219	5.870 ± 3.306
2	3	3.574 ± 0.981	2.549 ± 0.744	3.124 ± 1.034	3.187 ± 0.964	3.283 ± 0.787
3	5	3.670 ± 0.707	3.114 ± 0.738	3.672 ± 1.152	3.654 ± 1.078	2.871 ± 0.769

Initially, other factors were examined to explain the aforementioned observations. For example, we considered that this variability within the group might be attributed to the selection of segments; however, video analysis followed the same rules for each of the three segments for each infant. Furthermore, the process was similar to the selection of segments used in previous work which has shown that there is good intra-session reliability between segments in typically developing infants especially in the later phase of sitting skill, at around 8 months, when they become experienced sitters (Kyvelidou et al. 2009). In addition, at least two more experienced laboratory members verified the correctness of the process. Thus, it was unlikely that segment selection caused these large deviations. Another follow-up examination involved the exclusion of one infant from the sample, nearly an outlier that exhibited much more motion in the segments identified compared to the other subjects. However, we still observed similar high standard deviations within our variables. Lastly, we looked at reliability of our data by comparing our variable values to previous work. RMS and Range values were similar to findings by others, especially in the ML direction (Deffeyes et al. 2009; Cignetti et al. 2011). Non-linear values were also similar. Only Sway Path values were found to be larger in our study. Based on our finding that anthropometric features such as mass have an effect on Sway Path possibly explains this difference.

Our aforementioned examinations led to the conclusion that there was possibly another factor responsible for this inter-subject variability that could not be identified by behavioral observation from the videos. Our next step, the plotting of individual posturography data, clearly demonstrated the presence of statistically different subgroups in our sample for two linear variables, Sway Path and Range of sway (Figures 2 and 3). Sway Path is the summed total displacement of the COP throughout the identified segment. Results on Sway Path may be interpreted as some infants sway more or sway faster (since they are able to cover more distance at the same time) than others although they are of the same age and sitting skill level. More importantly, it seems that mass defines those groupings which possibly cause this inter-subject variability when considering all subjects as one group. Regression analysis in this case confirmed the suggestion that infants with less body weight are more movable than the heavier ones (Figure 4). An alternative thought might also be that more physically active infants may have less mass which leads to more movement, so increased Sway Path values. In line with our results, others have observed that Sway Path decreased as age was increasing during the development of sitting posture (Harbourne and Stergiou 2003). Although they did not find this to be statistically significant, it can be explained by the fact that mass also increases with age; therefore, Sway Path values decrease, which couples quite well with our current findings.

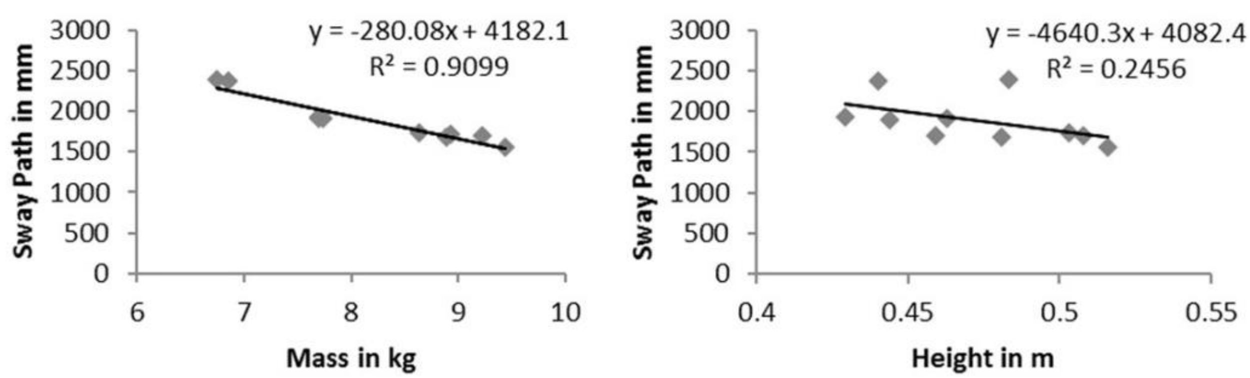

Figure 4. Relationship of Sway Path with mass and height in control condition.

In addition, these groups were significantly different for Range of sway, however, only in the ML direction (Table 4). This value represents the range (max – min) of distance covered in this specific direction. This result indicated also that heavier infants presented less Range of sway from lighter infants but only in the side to side direction. This can be explained by the fact that infants have most of their mass concentrated in their buttocks which while sitting and especially with their legs outstretched leads to a bigger base of support and so less freedom of movement in this direction.

Lastly, it seems that the different infant growth characteristics also contribute to different responses across different surface contexts (Figure 5). Lighter infants demonstrated a bigger distribution of (and larger) Sway Path values across conditions. Heavier infants demonstrated more similar (and lower) Sway Path values across conditions. Accordingly, infants with low body mass seem to be more affected from the different conditions. These results also suggest that for infants with large body mass, Sway Path is probably not the most suitable variable to identify differences across the conditions used here. Research studies in adult posturography also support our results of the effects of anthropometric features on linear measures. It has been found that Sway Path and Range in the ML direction are affected by biomechanical factors such as weight and height in adults while standing (Chiari et al. 2002). Our analyses did not show this strong dependence on height as mass. This may be attributed to the characteristics of sitting posture itself that involves a wider base of support in relation to body height while sitting (pelvis to head) compared to the narrow base of support in relation to total body height in upright stance. In addition, the distance between the center of mass and the point of ground support is lower in sitting infants compared to that of standing adults. Therefore, it seems that height does not significantly affect infants' body sway while sitting.

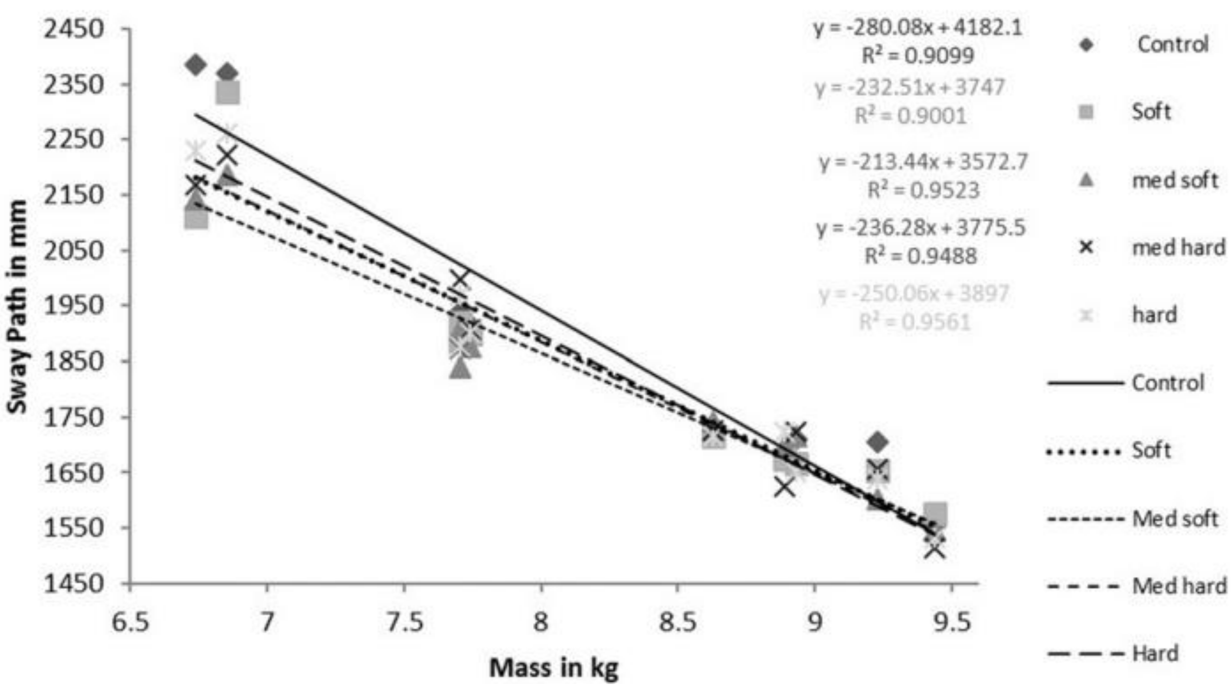

Figure 5. Regression analysis shows negative relationship between Sway Path and mass across conditions.

Based on the above findings, body characteristics should be taken into account when considering these variables to describe postural sway even when studying sitting posture in infants in which height and mass differences are considerably much less than in adults while standing. This information can be used accordingly when studying sitting development, as infants' bodies change rapidly from the beginning to the final stage of the skill. Lastly, even though there is a definite distinction between groups for Sway Path and Range of sway, still no significant differences were identified across conditions confirming the null hypothesis one more time. However, the small group size of just two, three, and five subjects is not adequate to make inferences for the whole population. Rather the current evidence should be taken as an indication, providing the basis for further investigation.

We can consider many new aspects to expand our study. Firstly, we can explore the effect of the same selection of foam properties on infants with sensorimotor impairments. Secondly, try a different selection of foam properties that might be able to induce changes on the postural sway of typically developing infants. Furthermore, the same type of somatosensory manipulation can be applied in younger infants that have not mastered the sitting skill and follow them longitudinally through the whole progress of the skill. Another interesting finding would be to see if locomotor experience, in our case through crawling, affects their sensorimotor relationship. Although in our study one infant with crawling experience was found not to have differences from the rest of our sample, still no inferences to the whole population can be made considering one subject alone. Lastly, the effect of vision and vestibular input should be evaluated to identify how sensory information is utilized to achieve the sitting posture in infants.

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Disclosure statement

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ORCID Elena Kokkoni http://orcid.org/0000-0003-4337-9455

References

Abarbanel H. 1996. Analysis of observed chaotic data. New York: Springer Verlag.

Assaiante C, Amblard B. 1995. An ontogenetic model for the sensorimotor organization of balance control in humans. Hum Mov Sci 14:13–43.

Barela JA, Godoi D, Freitas PB, Polastri PF. 2000. Visual information and body sway coupling in infants during sitting acquisition. Infant Behav Dev 23:285–297.

Barela JA, Jeka JJ, Clark JE. 1999. The use of somatosensory information during the acquisition of independent upright stance. Infant Behav Dev 22:87–102.

Bertenthal BI, Rose JL, Bai DL. 1997. Perception–action coupling in the development of visual control of posture. J Exp Psychol 23:1631–1643.

Chen LC, Metcalfe JS, Jeka JJ, Clark JE. 2007. Two steps forward and one back: Learning to walk affects infants' sitting posture. Infant Behav Dev 30:16–25.

Cherng RJ, Su FC, Chen JJ, Kuan TS. 1999. Performance of static standing balance in children with spastic diplegic cerebral palsy under altered sensory environments. Am J Phys Med Rehabil 78:336–343.

Chiari L, Rocchi L, Cappello A. 2002. Stabilometric parameters are affected by anthropometry and foot placement. Clin Biomech 17:666–677.

Cignetti F, Kyvelidou A, Harbourne RT, Stergiou N. 2011. Anterior–posterior and medial–lateral control of sway in infants during sitting acquisition does not become adult-like. Gait Posture 33:88–92.

Deffeyes JE, Harbourne RT, Kyvelidou A, Stuberg WA, Stergiou N. 2009. Nonlinear analysis of sitting postural sway indicates developmental delay in infants. Clin Biomech 24:564–570.

Dingwell JB, Cusumano JP, Sternad D, Cavanagh PR. 2000. Slower speeds in patients with diabetic neuropathy. J Biomech 33:1269–1277.

Hadders-Algra M, Brogren E, Forssberg H. 1996. Ontogeny of postural adjustments during sitting in infancy: variation, selection and modulation. J Physiol 493:273–288.

Harbourne RT, Stergiou N. 2003. Nonlinear analysis of the development of sitting postural control. Dev Psychobiol 42:368–377.

Hoon AH, Jr., Lawrie WT Jr, Melhem ER, Reinhardt EM, Van Zijl PC, Solaiyappan M, Jiang H, Johnston MV, Mori S. 2002. Diffusion tensor imaging of periventricular leukomalacia shows affected sensory cortex white matter pathways. Neurology 59:752–756.

Kyvelidou A, Stuberg WA, Harbourne RT, Joan E, Blanke D, Stergiou N. 2009. Development of upper body coordination during sitting in typically developing infants. Pediatr Res 65:553–558.

McLaughlin JF, Felix SD, Nowbar S, Ferrel A, Bjornson K, Hays RM. 2005. Lower extremity sensory function in children with cerebral palsy. Pediatr Rehabil 8:45–52.

Metcalfe JS, Clark JE. 2000. Sensory information affords exploration of posture in newly walking infants and toddlers. Infant Behav Dev 23:391–405.

Metcalfe JS, McDowell K, Chang TY, Chen LC, Jeka JJ, Clark JE. 2005. Development of somatosensory-motor integration: an event-related analysis of infant posture in the first year of independent walking. Dev Psychobiol 46:19–35.

Patel M, Fransson PA, Lush D, Gomez S. 2008a. The effect of foam surface properties on postural stability assessment while standing. Gait Posture 28:649–656.

Patel M, Fransson PA, Lush D, Petersen H, Magnusson M, Johansson R, Gomez S. 2008b. The effects of foam surface properties on standing body movement. Acta Oto-Laryngologica 128:952–960.

Pincus S, Goldberger A. 1994. Physiological time-series analysis: what does regularity quantify? Am J Physiol 266:H1643–H1656.

Rachwani J, Soska KC, Adolph KE. 2017. Behavioral flexibility in learning to sit. Dev Psychobiol 59:937–948.

Rochat P, Goubet N. 1995. Development of sitting and reaching in 5- to 6-month-old infants. Infant Behav Dev 18:53–68.

Saxena S, Rao BK, Kumaran S. 2014. Analysis of postural stability in children with cerebral palsy and children with typical development: an observational study. Pediatr Phys Ther 26:325–330.

Stergiou N, Harbourne RT, Cavanaugh JT. 2006. Optimal movement variability: a new theoretical perspective for neurologic physical therapy. J Neurol Phys Therap 30:120–129.

Tixard JP, Paine RS, Crothers B. 1954. Disturbances of sensation in children with hemiplegia. J Am Med Assoc 155:628–632.

Twitchell TE. 1966. Sensation and the motor deficit in Cerebral Palsy. Clin Orthopaed 46:55–62.

Yentes JM, Hunt N, Schmid KK, Kaipust JP, McGrath D, Stergiou N. 2013. The appropriate use of approximate entropy and sample entropy with short data sets. Ann Biomed Eng 41:349–365.