

2009

Development of Upper Body Coordination During Sitting in Typically Developing Infants

Anastasia Kyvelidou

University of Nebraska at Omaha, akyvelidou@unomaha.edu

Wayne A. Stuberg

University of Nebraska Medical Center

Regina T. Harbourne

University of Nebraska Medical Center

Joan E. Deffeyes

University of Nebraska Medical Center

Daniel Blanke

University of Nebraska at Omaha, dblank@unomaha.edu

Follow this and additional works at: <https://digitalcommons.unomaha.edu/biomechanicsarticles>

 Part of the [Biomechanics Commons](#)

Please contact the author at: https://unomaha.az1.qualtrics.com/jfe/form/SV_8cchtFmpDyGfBLE

Recommended Citation

Kyvelidou, Anastasia; Stuberg, Wayne A.; Harbourne, Regina T.; Deffeyes, Joan E.; Blanke, Daniel; and Stergiou, Nikolaos, "Development of Upper Body Coordination During Sitting in Typically Developing Infants" (2009). *Journal Articles*. 48.

<https://digitalcommons.unomaha.edu/biomechanicsarticles/48>

This Article is brought to you for free and open access by the Department of Biomechanics at DigitalCommons@UNO. It has been accepted for inclusion in Journal Articles by an authorized administrator of DigitalCommons@UNO. For more information, please contact unodigitalcommons@unomaha.edu.

Authors

Anastasia Kyvelidou, Wayne A. Stuberg, Regina T. Harbourne, Joan E. Deffeyes, Daniel Blanke, and Nikolaos Stergiou

Development of upper body coordination during sitting in typically developing infants

Running Title: Upper body development in infants

Anastasia Kyvelidou¹, Wayne A. Stuberg², Regina T. Harbourne², Joan E. Deffeyes¹,

Daniel Blanke^{1,4}, and Nicholas Stergiou^{1,3*}.

¹HPER Biomechanics Lab, University of Nebraska at Omaha, Omaha, NE, 68182 –
0216, USA

²Munroe-Meyer Institute, University of Nebraska Medical Center, Omaha, NE, 68198-
5450, USA

³Environmental, Agricultural and Occupational Health, College of Public Health,
University of Nebraska Medical Center, Omaha, NE 68198-7850, USA

⁴Health Promotion, Social and Behavioral Health, College of Public Health, University of
Nebraska Medical Center, Omaha, NE 68198-6075, USA

CORRESPONDING AUTHOR:

Dr. Nicholas Stergiou, PhD

Isaacson Professor and Director of the HPER Biomechanics Laboratory

University of Nebraska at Omaha

Omaha, NE 68182-0216, USA

Tel: (402) 5543247

Fax: (402) 5543693

E-mail: nstergiou@mail.unomaha.edu

This work was supported by NIH (K25HD047194), NIDRR (H133G040118), the Nebraska Research Initiative and the Reichenbach fellowship from the Graduate Studies Office of University of Nebraska Medical Center.

Category of Study: Clinical

Word count of abstract: 197

Word count of manuscript: 5016

1 **1. Abstract**

2 Our goal was to determine how the actions of the thorax and the pelvis are organized
3 and coordinated to achieve independent sitting posture in typically developing infants.
4 The participants were ten typically developing infants that were evaluated longitudinally
5 from first onset of sitting until sitting independence. Each infant underwent nine testing
6 sessions. The first session included motor evaluation with the Peabody test. The other
7 eight sessions occurred over a period of four months where sitting behavior was
8 evaluated by angular kinematics of the thorax and the pelvis. A physical therapist
9 evaluated sitting behavior in each session and categorized it according to five stages. The
10 phasing relationship of the thorax and the pelvis was calculated and evaluated
11 longitudinally using a one-way ANOVA. With development the infants progressed from
12 an in-phase (moving in the same direction) to an out-of-phase (moving in an opposite
13 direction) coordinative relationship between the thorax and the pelvis segments. This
14 change was significant for both the sagittal and frontal planes of motion. Clinically, this
15 relationship is important because it provides a method to quantify infant sitting postural
16 development, and can be used to assess efficacy of early interventions for pediatric
17 populations with developmental motor delays.

18 Keywords: infant sitting, coordination, dynamical systems theory, motor
19 development.

20

21

22

23

24 **2. Abbreviations**

25 **DST – Dynamical Systems Theory**

26 **MARP – Mean Absolute Relative Phase**

27

28

29

30

31

32

33

34

35

36

37

38

39

40

41

42

43

44

45

46

47 3. Text

48 Introduction

49 During the acquisition of the simplest form of a skill, such as sitting, postural control
50 is the primary goal in order to be successful. However, if we consider that postural
51 control is the complex interaction of controlling and coordinating the numerous factors of
52 the central nervous system, the task of sitting looks like an impossible skill to be
53 acquired. Therefore, investigators have been interested in identifying how we actually
54 develop this skill and several theories have been proposed to explain the development of
55 postural control. These theories elicit basically hierarchical explanations, where skill is
56 the outcome of mature executive function from the motor cortex, or a motor program
57 located at the spinal cord or at the brainstem (1,2). However, these theories have not been
58 successful in defining the relationship between the earlier and later forms of the behavior
59 or explaining the synergistic action of the various cooperating components that contribute
60 to the development of the behavior (3). The Dynamical Systems Theory (DST) provides
61 an alternative approach to the development of posture control. According to DST,
62 development of posture control, and generally movement skills, is a product not only of
63 central and cognitive information, but arises from the synergistic organization of the
64 neuromuscular system and the morphological, biomechanical and environmental
65 constraints (1,3). Utilizing this approach, Thelen and colleagues were able to explain
66 stepping performance in newborns and identify that the “disappearance” of the newborn
67 stepping response at about 2 months is not due to changes in central processes but was
68 due to the alterations that occur due to parallel development in body size and composition
69 (4). Similarly, the same group has found that newborns can elicit adult-like steps when

70 walking on a treadmill due to the mechanical backward stretch by the belt on the legs.
71 This stretch practically provided the necessary hip strength needed for walking which is
72 absent in newborns and eventually occurs due to development (5). Therefore, we
73 anticipate that the DST framework can provide with similar insights for another motor
74 milestone, the development of sitting posture, a skill which has not received much
75 research attention.

76 From a DST perspective, the emergence of a movement behavior can be viewed as a
77 path toward a stable attractor, which is the preferred behavioral state of the system (1,3).
78 Attractors can be described quantitatively by evaluating the order parameter. In the
79 studies mentioned above by Thelen and colleagues, interjoint and interlimb coordination
80 have been utilized as order parameters (5,6). To elicit behavioral changes and explore
81 how an order parameter differs from one attractor to another, the control parameter is
82 employed. In the studies mentioned above, hip strength as provided by a motorized
83 treadmill or changes in gravity utilizing buoyancy have been used as control parameters.
84 By scaling the control parameter, we can observe changes in behavior and we can
85 describe the different attractors of the dynamical system in question. Previous studies that
86 investigated standing postural control, used as the control parameter different support
87 surfaces (7,8) and a suprapostural tracking task (9). Previous work has also demonstrated
88 that relative phase, which describes the coordinative relationship between the segments of
89 the lower extremity, is a suitable order parameter that can elucidate the collective states
90 of the neuromuscular system during standing (7-9). Therefore, DST provides also the
91 advantage of describing the dynamic state of the neuromuscular system by
92 acknowledging a single variable, relative phase.

93 Even though the above theoretical framework can provide a basis for the exploration
94 of infant sitting postural control, limited attention has been directed towards the
95 understanding of the mechanisms involved in the postural control of sitting during
96 development (10). Most of the existing literature on postural control of infants is focused
97 on the examination of the development of postural adjustments during reaching (11-14).
98 There are only few studies that have investigated solely the development of sitting
99 postural control in infants. In these investigations, kinematic and electromyographic
100 analysis was utilized to describe sitting posture, while a movable platform was employed
101 to perturb postural control (15,16). Using a different paradigm, Harbourne and Stergiou
102 analyzed the development of sitting postural control in infants by exploring the variability
103 of the center of pressure during infant sitting using a force platform (16). The
104 development of posture was not approached as a process directed toward maximum
105 balance resulting in a rigid and motionless body over the center of the base of support.
106 On the contrary, variations present in the sitting postural sway during development were
107 viewed not as noise that needs to be removed from the system, but as a basin rich in
108 important environmental information. From this perspective, postural control develops as
109 an ongoing process of improving sitting posture by managing available degrees of
110 freedom. They also suggested that this process would enable the children at first to be
111 fairly accurate in accessing the skill of sitting independently and then to explore more
112 freely their environment. Importantly, they hypothesized that a significant component of
113 gaining the ability to sit and coordinate the superincumbent body segments over the base
114 of support includes the ability to control the thorax over the pelvis.

115 Therefore, the purpose of the present study was to implement the DST framework to
116 examine the development of sitting postural control in typically developing infants by
117 investigating the coordination of the thorax and pelvis segments. The motions of the
118 thorax and the pelvis were evaluated longitudinally in terms of their relative phase
119 relationship in typically developing infants from the first onset of sitting, and up to the
120 point that they can sit independently. For the present study, change in the physiological
121 and neuromuscular systems (natural development) served as the control parameter. We
122 hypothesized that through development, we will be able to discern a movement in the
123 opposite direction (a more out-of-phase relationship) between the thorax and pelvis
124 segment in order to achieve independent sitting. Clinically, the quantification of this
125 relationship is important because it can provide with a method to evaluate infant sitting
126 postural development and eventually to assess efficacy of early interventions for infants
127 with developmental motor delays.

128 **Methods**

129 *Subjects*

130 The participants in this study were 10 typically developing infants (Table 1). The
131 infants were followed from the age of around five months to eight months, the time when
132 infants are learning to sit independently. Infants were recruited from employee
133 announcements at the campus of the University of Nebraska at Omaha and at the
134 Munroe-Meyer Institute, University of Nebraska Medical Center.

135 The inclusion criteria for entry into the study for the typically developing infants
136 were: a) a score on the Peabody within 0.5 SD of the mean, b) age of about five months
137 at the time of initial data collection, c) the ability of the child to hold up their head when

138 supported at the thorax, d) beginning ability to reach for objects dangled in front of them
139 in supported sitting or lying on their back, e) propping on their elbows when in prone for
140 thirty seconds and f) propping on both arms to maintain sitting. The exclusion criteria
141 were: a) a score on the Peabody of greater than 0.5 SD below the mean, b) diagnosed
142 visual deficits, and c) diagnosed musculoskeletal problems. Prior to participation an
143 informed consent form was signed by the parents of the infants. The study has been
144 approved by the Institutional Review Board of the University of Nebraska Medical
145 Center.

146 *Experimental design*

147 Each infant participated in nine sessions. The first session lasted for 45 minutes and
148 was used to perform the Peabody. The Peabody is a norm-and criterion-referenced test
149 that examines gross motor function in children from birth to 83 months (17). The other
150 eight sessions were distributed over a period of four months. The infants were tested
151 twice in one week at each of the four months of the study. A physical therapist ranked
152 each infant's sitting behavior at each session according to five stages of sitting: 1) Prop
153 sitting, 1.5) Transition-moves briefly out of prop –sit, but goes back to it, 2) Variable,
154 about 10 seconds of sitting, 2.5) Not solid stage 3, but longer than 10 seconds of sitting
155 and 3) Sits upright all the time-doesn't need hands. Stage identification was always
156 performed by the same physical therapist (author RTH). Even though more than one
157 session could be identified at the same stage of sitting, the three trials required by each
158 infant for a specific stage were chosen from the same session. Stages of sitting were
159 considered the appropriate independent variable of development, because of the wide
160 variability of age at which the infants began to sit.

161 *Protocol*

162 For all sessions, the infants were allowed time to get used to the laboratory setting,
163 and were at their parent's side or on their lap for preparation. A standard set of infant toys
164 was used for distraction and comfort, accompanied by a DVD player, which presented
165 infant movies. All attempts were made to maintain a calm, alert state by allowing the
166 infant to eat if hungry, be held by a parent for comforting, or adapt the temperature of the
167 room to the infant's comfort level.

168 After the child was undressed by the mother, two sets of triangles with one reflective
169 marker in each corner were glued with a double face tape in two locations (Figure 1A):
170 around the spinous process at the level of the axilla, so as the upper side of the triangle
171 was parallel to the shoulder's mediolateral line and the second triangle was placed
172 midway between the left and right posterior superior iliac spine so as one side of the
173 triangle was parallel to the level of the pelvic crest. After positioning the reflective
174 markers, the infants were placed by their parent on the top of a force plate that was
175 covered with a special pad for warmth which was securely adhered with tape on the force
176 plate. The baby was held in the sitting position in the middle of the plate when calm and
177 happy (Figure 1B). The investigator and the parent remained at one side and in front of
178 the infant respectively during all data collection to assure the infant does not fall or
179 become insecure. The child was held at the thorax for support, and gradually the infant
180 was guided into a sitting position while being distracted by toys presented by the parent
181 or the investigator or a DVD movie. Once the examiner could completely let go of the
182 infant, data were collected continuously while the child maintained sitting (Figure 1B).
183 Data were collected until we had three trials that were acceptable for our criteria, or until

184 the infants were indicating that they were done. If the child became irritated the session
185 was halted for comforting by the parent, or a chance of feeding, and then resumed only
186 when the child was again in a calm state.

187 *Data Analysis*

188 Kinematic data were collected using a six camera motion analysis system (Vicon,
189 Oxford Metrics Group, Oxford, UK) at a sampling rate of 60 Hz. The lightweight
190 reflective markers (Figure 1) were tracked by the system, and recorded in three-
191 dimensional space. Specifically, the local coordinate systems (Figure 2) defined the
192 origin of each segment (pelvis and thorax), with respect to the global reference system of
193 the laboratory. Thereafter, the angular kinematic data were calculated relative to the fixed
194 global coordinate system of the laboratory. The movement patterns of the thorax and the
195 pelvis were viewed as inverted pendulums. Furthermore, video of each trial was collected
196 using two Panasonic video cameras (Model 5100 HS) and processed for split screen
197 video imaging using a Panasonic Digital AV Mixer (Model WJ-MX30). The cameras
198 were positioned to record a sagittal and a frontal view of the subject.

199 Three acceptable trials of 8.3 seconds were selected from each testing session using
200 the video record and the following criteria: a) infant did not move the arms (not reaching,
201 holding an object, or flapping their arms), b) infant did not vocalize or cry, c) infant was
202 not in the process of falling, d) thorax was not inclined more than 45 degrees to either
203 side, e) not being touched, f) the arm position (propping or not propping) of the infants
204 was noted during the entire trial and only trials that have the infant using consistent base
205 of support was used. Test re-test reliability of trial identification was 0.99. Out of the 240

206 trials in total required to examine infant sitting posture across stages of sitting, we were
207 able to identify 239 acceptable trials based on our criteria.

208 The six reflective markers attached in the form of two triangles, defined a two-
209 segment model comprised of the pelvis and the thorax (Figure 2). Coordination of these
210 segments was examined in the sagittal and the frontal plane. The angular kinematic data
211 acquired were used to examine the coordination pattern between the thorax and the
212 pelvis. The data were filtered using a 0.5Hz low pass, second order Butterworth filter.
213 The 0.5Hz as a cut-off frequency was selected based on power spectrum evaluation and
214 phase portrait qualitative analysis.

215 To examine the coordination between the two segments, the phase portraits for the
216 thorax and the pelvis were generated (Figure 3), which is a plot of each segment's
217 position versus its velocity (18). The phase portrait analysis follows Rosen's suggestion
218 (18) that the behavior of a dynamical system may be captured by a variable and its first
219 derivative with respect to time. Once the phase portraits were constructed, the resulting
220 phase plane trajectories were transformed from Cartesian (x, y) to polar coordinates with
221 a phase angle $\Phi = \tan^{-1}[y/x]$ and radius (19). Phase angle ranged from zero to ± 180
222 degrees. The phase angles of the segments' trajectories were used to calculate relative
223 phasing relationships between the actions of the two respective segments for the period of
224 sitting. Relative phase represents the coordinative relationship between the actions of two
225 segments at every point during a specific time domain. In other words, relative phase
226 indicates how the two segments were coupled in their movements while performing the
227 sitting task. Relative phase was calculated by subtracting the distal phase angle (thorax)
228 from the proximal phase angle (pelvis). Relative phase values close to zero designated

229 that the two segments were moving in similar fashion or in-phase, while values close to
230 180 indicated that the two segments moved exactly opposite or out-of-phase. Relative
231 phase curves were not time normalized since the time length of all sitting trials selected
232 were 8.3 seconds. The relative phase curves were also averaged and mean ensemble
233 curves were generated from all infants and for each testing session (by averaging the
234 three acceptable trials) for the evaluation of the postural control during sitting.
235 Furthermore, the mean of the absolute values for all points of the relative phase (MARP)
236 mean ensemble curve was calculated. This parameter captured in a single value the entire
237 relative phase curve. Thus, MARP values close to zero designated that the two segments
238 were moving in similar fashion or in-phase, while values close to 180 indicated that the
239 two segments moved opposite or out-of-phase. All the above analysis was performed by
240 custom written laboratory software in Matlab (The MathWorks, Natick, MA).

241 *Statistical Analysis*

242 Based on the physical therapist's evaluation of each session's sitting behavior for each
243 infant, five groups of sitting were formed and tested statistically. Group means and
244 standard deviations were calculated for the MARP for each stage and for both planes.
245 Because we had an unequal number of observations at each stage of sitting, we did not
246 perform repeated measures ANOVA. Instead, one-way between stages of sitting ANOVA
247 with a test for linear trend was performed on the subjects' means for each parameter
248 using the SPSS software. A Tukey multiple comparison post hoc analysis was also
249 performed to identify the location of the significant differences for all tests resulting in a
250 significant F-ratio. All statistical tests were evaluated at the 0.05 level for significance.

251 **Results**

252 An example of time series data for pelvis and thorax at the onset and at the last stage
253 of sitting, as well as the corresponding phase portraits, are presented in Figure 3.
254 Generally, the angular position of the thorax and the pelvis at the onset of sitting seems to
255 be very similar. Alternatively, at the end of the study the angular positions of the two
256 segments seems to be the opposite; when the angular position of the thorax decreases, the
257 angular position of the pelvis increases and vice versa. The phase portraits demonstrated
258 a cyclic movement by the formation of a closed cyclic path. Even though this pattern is
259 not a perfect circle we can reasonably conclude that pelvis and thorax segments have an
260 oscillatory nature, which in DST phraseology this constitutes a limit cycle type of
261 behavioral attractor (19).

262 MARP values at the onset and conclusion of the study are presented in Table 2 for
263 each subject. MARP values in the sagittal plane significantly increased ($F=4.406$, $df=4$,
264 $p=0.003$), demonstrating a more out-of-phase relationship, as the infants improved their
265 ability of sitting. The post hoc analysis test revealed significant differences between the
266 first and the third stage of sitting with the latter presenting larger values (Figure 4A). A
267 significantly increasing linear trend ($F=15.743$, $p<0.001$) was found for MARP in the
268 sagittal plane from stage one to stage three (Figure 4A).

269 MARP in the frontal plane of motion significantly increased ($F=2.742$, $df=4$,
270 $p=0.034$). The post hoc analysis revealed significant differences between the first stage
271 and the 2.5 stage, with 2.5 stage showing slightly larger values (Figure 4B). A
272 significantly increasing linear trend ($F=6.253$, $p=0.014$) for MARP in the frontal plane
273 from stage one to stage three (Figure 4B).

274 **Discussion**

275 The purpose of this study was to examine and identify any changes in the
276 coordination pattern of the thorax and the pelvis during sitting in infants that may take
277 place with development. The DST was used as the theoretical platform to examine
278 coordination.

279 Our results verified our hypotheses for both sagittal and frontal planes of motion. The
280 preferred behavioral state of infant sitting postural control was an out-of-phase
281 relationship between the thorax and the pelvis. This conclusion was made due to the fact
282 that at the latter stages of sitting when the infants demonstrated the ability to sit
283 independently for long periods of time, the values of relative phase were much higher
284 than the first stages of sitting and closer to 180° . These values are indicative of an out-of-
285 phase relationship and were also noticeable from the example presented in Figure 3.
286 Therefore, the DST framework was able to define the relationship between the earlier and
287 later forms of the sitting behavior and explain the synergistic action of the various
288 cooperating components that contribute to the development of the sitting posture.

289 In addition, we hypothesized that at the onset of sitting, we had a different behavioral
290 state or attractor. Infants presented a more in-phase relationship between the two
291 segments both in the sagittal and frontal planes. The value of MARP for stage 1 in the
292 sagittal plane was approximately 75° . Even though the value is not 0° , in order to indicate
293 an absolute in-phase relationship of thorax and pelvis at the onset of sitting, it can be
294 concluded that it is a rather in-phase relationship at the onset of sitting behavior.
295 Moreover, as the infants matured physiologically and became more experienced, the
296 value of MARP increased and reached 120° which is closer to 180° and rather an out-of-
297 phase relationship of the two segments. This demonstrates a clear behavioral transition

298 for the sagittal plane of movement. Similarly, in the frontal plane the values of MARP
299 presented a significant trend to increase with development. However, the values of
300 MARP for the frontal plane on the third stage of sitting dropped to approximately 105°,
301 similar to stage two, while the range of change in MARP was not as large as in the
302 sagittal plane. It can be speculated that at the onset of sitting skill infants were not able to
303 control efficiently the thorax and the pelvis motion and the activation of the postural
304 muscles. In contrast, with development and experience infants accomplish to
305 synergistically self-organize the most appropriate degrees of freedom and conclude to the
306 appropriate sitting pattern. This result may be due to biomechanical and/or
307 neuromuscular constraints, such as the fat tissue stored around the pelvis of the infants,
308 which may limit the movement of the upper body in the frontal plane.

309 Theoretical mechanical aspects of sitting postural control should also be considered
310 (20), regarding the results of the present study. To achieve independent sitting posture,
311 the body center of mass must remain within the base of support. When there is an in-
312 phase relationship between two segments this will lead to an unstable behavioral state.
313 This instability does not allow the system to counteract and keep the center of mass
314 (COM) within the stability limits (Figure 5). Specifically, when both the thorax and the
315 pelvis move in the same direction, they move as one segment which has its axis of
316 rotation at the pelvis. Thus, as the gravity and the force produced from the
317 neuromuscular system pushes the system in one direction, the center of mass steps out of
318 the base of support, and falling occurs. The opposite holds true with an out-of-phase
319 relationship, which is more stable behavioral state. Particularly, when the thorax and the
320 pelvis move in the opposite direction, the axis of rotation is located between the two

321 segments. Hence, as the gravity and the force produced from the neuromuscular system
322 pushes the segments in the opposite direction, the center of mass is prohibited from
323 stepping out of the base of support, and sitting occurs (Figure 5). This synergistic action
324 of the cooperating components contributes to the development of the sitting posture.

325 The results of the present study could not be compared directly with other studies
326 because there are no investigations examining coordination of thorax and pelvis in
327 infants. Woollacott et al (21) reported that infants as young as five months produce
328 directionally postural responses as a result to perturbation in the trunk, while other infants
329 did not. This result suggests that the organization of postural responses is not
330 predetermined but arises from the synergistic interaction of the neuromuscular system as
331 well as other constrains (21). Therefore, the coordination of the trunk and pelvis
332 segments in infants acquiring the sitting skill should be governed by the same principles.
333 An interesting observation of our data is that individual patterns have emerged regardless
334 of the average picture of the statistical analysis, especially in the frontal plane of motion.
335 Specifically, four out of the 10 infants presented decreasing values of MARP in the
336 frontal plane, when comparing the onset with the last stage. Interestingly, these infants
337 were the ones that appeared to have greater weight initially and at the last stage from
338 almost all the other infants. Therefore, biomechanical constraints, such as weight, may
339 have influenced the acquirement of the sitting skill in those infants and eventually
340 regulated appropriate coordination of the thorax and pelvis mostly through the sagittal
341 plane of motion. Variation between subjects, but also within subjects is one of the main
342 characteristics of infant motor development and it has been observed in multiple studies
343 (14, 15).

344 A limitation of the present study is that data were analyzed on the basis of the infant's
345 motor behavior, i.e. the infant's ability to sit. This means that the developmental changes
346 in MARP reflect the developmental changes in what the child is doing, i.e. the data
347 mainly reflect whether the child sits with support of the arms (first 2 stages) or without
348 support of the arms. It is well known that even minimal support of the arms induces large
349 changes in postural control (28). However, we decided to utilize this approach because
350 this is the natural behavioral response by the infant while developing the ability to sit and
351 thus we did not want to exclude it from the analysis.

352 In conclusion, the preferred behavioral state of infant sitting postural control was an
353 out-of-phase relationship between the thorax and the pelvis for the sagittal and frontal
354 planes. In addition, at the onset of sitting, we had a different behavioral state. We believe
355 that the investigation of sitting postural control through the coordination of the thorax and
356 the pelvis can assess the development of infant sitting posture and can quantify
357 objectively, by means of a single variable, incremental change through the development
358 of infant sitting postural control. Furthermore, there is lack of knowledge on which
359 treatments are most efficacious for children that present developmental delays at an early
360 age. Hence, the proposed method of evaluating sitting postural control could be a
361 valuable tool for the study of therapeutic interventions directed at improving the postural
362 control of infants with motor delays.

363

364 **4. References**

365 1. Clark J 1995 On becoming skillful: Patterns and Constraints. Res Q Exerc Sport
366 66: 173-183.

- 367 2. Hirschfeld H, Forssberg H 1994 Epigenetic development of postural responses for
368 sitting during infancy. *Exp Brain Res* 97:528-540
- 369 3. Thelen E, Smith LB 1994 A dynamic systems approach to the development of
370 cognition and action. MIT Press, Massachusetts, pp 1-340
- 371 4. Thelen E, Fisher DM 1982 Newborn stepping: an explanation for a “disappearing
372 reflex.” *Dev Psychol* 18: 760-775
- 373 5. Thelen E 1986 Treadmill-elicited stepping in seven-month-old infants. *Child Dev*
374 57: 1498-1505
- 375 6. Thelen E, Ulrich BD, Wolff PH 1991 Hidden skills: A dynamic systems analysis
376 of treadmill stepping during the first year. *Monogr Soc Res Child Dev* 56: 1-104
- 377 7. Marin L, Bardy BG, Baumberger B, Fluckiger M, Stoffreger TA 1999 Interaction
378 between task demands and surface properties in the control of goal-oriented
379 stance. *Hum Mov Sci* 18:31-47
- 380 8. Oullier O, Bardy BG, Stoffregen TA, Bootsma RJ 2004 Task-specific
381 stabilization of postural coordination during stance on a beam. *Motor Control*
382 8:174-187
- 383 9. Bardy BG, Marin L, Stoffregen TA Bootsma RJ 1999 Postural coordination
384 modes considered as emergent phenomena. *J Exp Psychol Hum Percept Perform*
385 25:1284-1301
- 386 10. Shumway-Cook A, Woollacott M 1995 *Motor Control: Theory and practical*
387 applications, Williams & Wilkins, Baltimore, pp 143-166.

- 388 11. Van der Heide J, Fock J, Otten B, Stremmelaar E, Hadders-Algra M 2005
389 Kinematic characteristics of postural control during reaching in preterm children
390 with cerebral palsy. *Pediatr Res* 58:586-593
- 391 12. Van der Heide J, Otten B, Van Eykern L, Hadders-Algra M 2003 Development of
392 postural adjustments during reaching in sitting children. *Exp Brain Res* 151:32-45
- 393 13. Fallang B, Oien I, Hellem E, Saugstad O, Hadders-Algra M 2005. Quality of
394 reaching and postural control in young preterm infants is related to neuromotor
395 outcome at 6 years. *Pediatr Res* 58:347-353
- 396 14. Harbourne R, Giuliani C, Mac Neela J 1993 A kinematic and electromyographic
397 analysis of the development of sitting posture in infants. *Dev Psychobiol* 26:51-64
- 398 15. Hadders-Algra M, Brogren E, Forssberg H 1996a Ontogeny of postural
399 adjustment during sitting in infancy: variation, selection and modulation. *J*
400 *Physiol* 493:273-288
- 401 16. Harbourne R, Stergiou N 2003 Nonlinear analysis of the development of sitting
402 postural control. *Dev Psychobiol* 42:368-377
- 403 17. Folio MR, Fewell RR 2000 Peabody Developmental Motor Scales, 2nd Edition,
404 Pro-ed Inc, Austin, pp 1-125
- 405 18. Kurz M, Stergiou N 2003 Applied dynamical systems theory for the analysis of
406 movement. In: Stergiou N (Ed) Innovative Analyses of Human Movement.
407 Human Kinetics, Champaign, pp 93-120.
- 408 19. Clark JE, Phillips SJ 1993 A longitudinal study of intralimb coordination in the
409 first year of independent walking: A dynamical systems analysis. *Child Dev*
410 64:1143-1157

- 411 20. Assaiante C., Mallau S., Viel S., Jover M. and Schmitz C. (2005). Development
 412 of postural control in healthy children: a functional approach. Neural Plast 12:
 413 109-118.
- 414 21. Woollacott MH, Debu B, Shumway-Cook A 1986 Children’s development of
 415 posture and balance control: changes in motor coordination and sensory
 416 integration. In: Gould D, Weiss M (Eds) Advances in pediatric sport sciences:
 417 behavioral issues. Human Kinetics, Champaign, pp 166-186.
- 418 22. Cordo PJ, Nashner LM 1982 Properties of postural adjustments associated with
 419 rapid arm movements. J Neurophysiol 47: 287-302
- 420

Subjects	Weight (kg)		Age (Weeks)		Gender
	<i>Start</i>	<i>End</i>	<i>Start</i>	<i>End</i>	
1	8.26	9.48	22.14	35.00	Male
2	7.24	8.16	18.29	31.43	Female
3	6.42	7.55	22.29	38.43	Female
4	5.81	6.42	18.14	32.57	Female
5	7.85	8.87	20.29	32.43	Female
6	7.14	8.57	22.14	34.29	Female
7	7.24	8.06	22.29	34.43	Female
8	8.16	8.97	24.00	37.00	Female
9	7.34	7.85	18.29	30.29	Female
10	6.73	7.34	22.57	32.57	Female
Mean	7.22	8.13	21.04	33.84	
SD	0.76	0.90	2.13	2.51	

421
 422 **Table 1** – Descriptive characteristics of the subjects at onset and conclusion of the study.

423
 424
 425
 426

427

MARP				
Subjects	Start		End	
	<i>Sagittal</i>	<i>Frontal</i>	<i>Sagittal</i>	<i>Frontal</i>
1	115.9	74.0	137.8	119.6
2	133.7	158.3	151.6	126.5
3	85.0	75.5	79.4	117.5
4	66.7	85.3	128.4	93.7
5	58.7	63.4	105.4	83.4
6	121.4	127.9	127.2	118.6
7	92.5	127.5	152.4	96.4
8	52.7	100.7	88.0	78.4
9	40.1	59.7	88.1	72.6
10	61.3	70.9	114.7	134.7
Mean	82.8	94.3	117.3	104.1
SD	32.1	33.2	26.6	21.9

428

429 **Table 2** – MARP values in the sagittal and frontal planes at onset and conclusion of the

430 study.

431

432

433

434

435

436

437

438

439

440

441

442

443

444 **5. Figure Legends**

445 **Figure 1A** - Rear view of the position of the infant during data collection.



446

447 **Figure 1B** - Side view of the position of the infant during data collection.

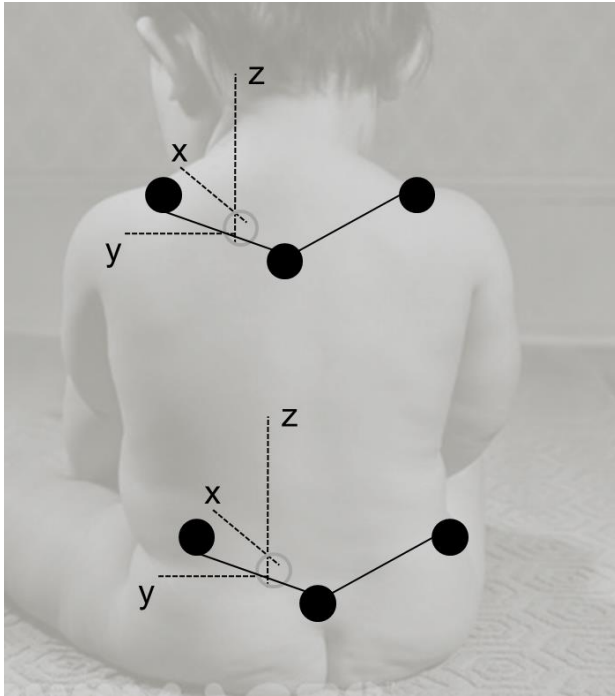


448

449

450

451 **Figure 2** - Schematic representation of the pelvis and the thorax segments.



452

453

454

455

456

457

458

459

460

461

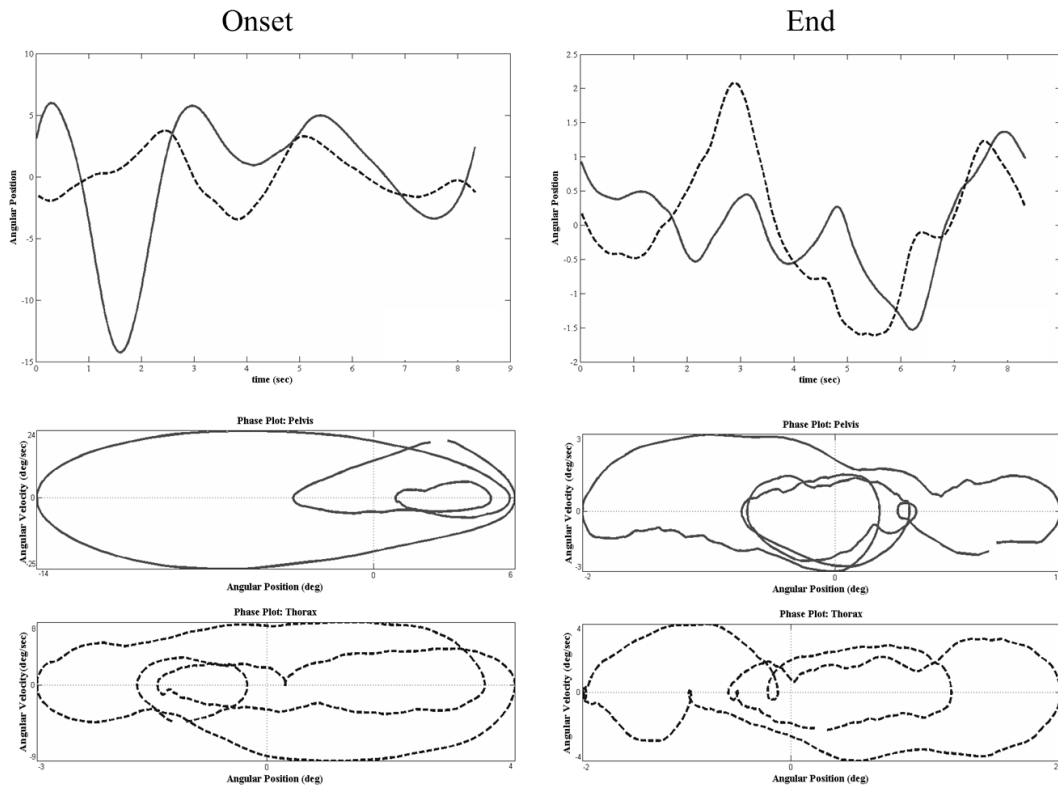
462

463

464

465

466 **Figure 3** – Example of time series data for pelvis and thorax at the onset and end of the
467 study as well as the corresponding phase portraits. Phase portraits provide a qualitative
468 picture of the organization of the neuromuscular system. Solid line represents the pelvis
469 while the dotted line represents the thorax.



470
471
472
473
474
475
476
477
478

479 **Figure 4 A** - Group mean values and standard error for MARP in the sagittal plane. **B** -
480 Group mean values and standard error for MARP in the frontal plane. The dotted line
481 indicates statistically significant linear trend. Asterix indicates significant differences.
482 The sample size for each stage was the following: Stage 1(6), Stage1.5 (3), Stage 2 (4),
483 Stage 2.5 (7), Stage 3 (10).

484

485

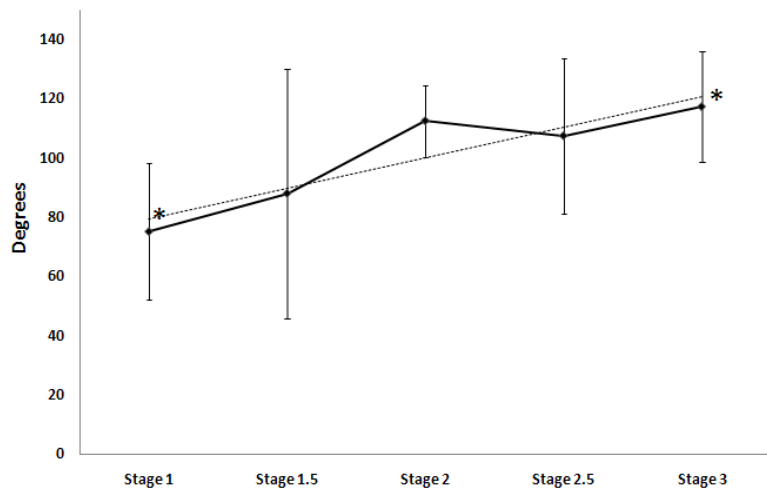
486

487

488

489

490



491

492

493

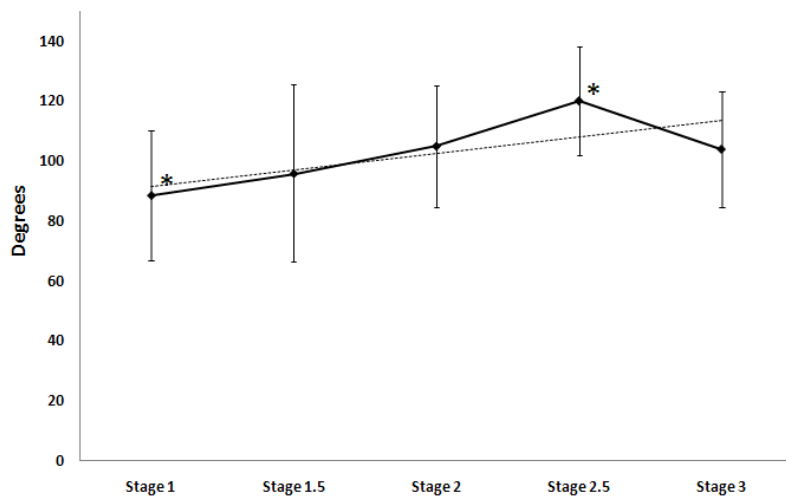
494

495

496

497

498



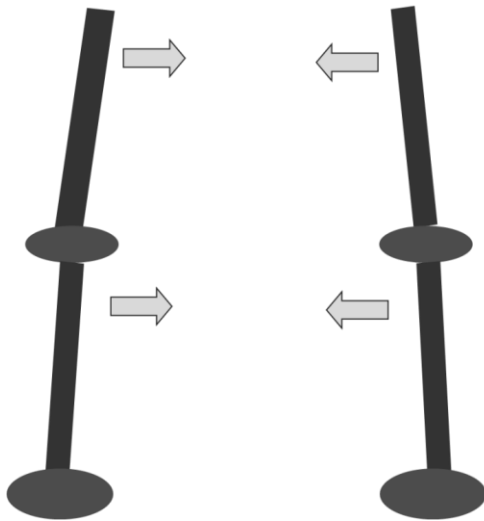
499

500

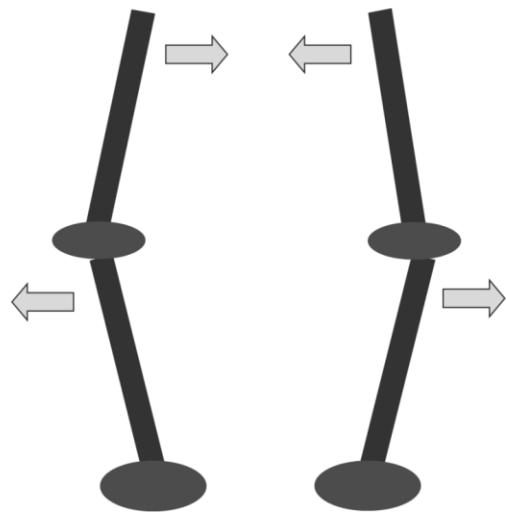
501

502 **Figure 5** - Schematic representation of the in-phase and the out-of-phase coordinative
503 relationships between two connected segments.

In-Phase



Out-of-Phase



504