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Anterior-posterior and medial-lateral control of sway in infants during sitting acquisition does not become adult-like

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1 **Anterior-posterior and medial-lateral control of sway in infants**
2 **during sitting acquisition does not become adult-like**

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ABSTRACT

We examined (1) how sitting postural control in infants develops in the anterior-posterior (A/P) and medial-lateral (M/L) directions of sway, and (2) whether this control is already adult-like during the late phase of infant’s sitting acquisition. COP data were acquired from 14 healthy infants (from the onset of sitting until independent sitting) and 21 healthy adults while sitting on a force platform. Attractor dimensionality (CoD: correlation dimension), attractor predictability (LyE: largest Lyapunov exponent), and sway variability (RMS: root-mean square) were calculated from the COP data to evaluate postural control. In the A/P direction, sitting was mastered by the infants by decreasing the active degrees of freedom of the postural system (decreased CoD), using a more predictable and (locally) stable sway (decreased LyE), and increasing sway variability (increased RMS). Control of sitting became practically simple, stable and exploratory with infant development. This may support the hypothesis that the sitting posture serves as the foundation for the development of other motor skills, as reaching. In the M/L direction, only sway variability decreased with development, possibly due to changes in the infant’s body dimensions. Taken together, these findings indicate that early in development the focus is more in the A/P than the M/L direction. Adults’ postural control was found more adaptable than the infants in both directions, involving more active degrees of freedom and less predictable sway patterns. Identifying the factors that make the dynamics of the postural system adult-like requires further research.

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1

2 **1. Introduction**

3 The achievement of independent sitting is a major motor milestone, requisite for the
4 development of other activities such as reaching, grasping, eye/hand coordination, standing
5 posture and locomotion [1-5]. Therefore, several studies have examined how this skill is
6 acquired as part of the infant's motor development [6-9]. While most of the literature on this
7 subject focuses on the processes operating within the central nervous system [e.g., 6,7], a few
8 recent studies used as a theoretical background the dynamical systems approach to motor
9 development [8,9]. This approach emphasizes the self-organizing principles underlying skills
10 acquisition over time, under the shaping influence of environmental, task, and biomechanical
11 constraints [10]. Specifically, sitting is viewed as a high-dimensional task in which the many
12 degrees of freedom (DFs) of the sensory-motor system are compressed into a low-
13 dimensional space of a few active DFs [10,11]. Maintaining sitting posture results thus from
14 mastering the active DFs.

15 Using this theoretical framework, Harbourne and Stergiou [8] used center of pressure
16 (CoP) data to show that infants achieve sitting posture in the anterior-posterior (A/P) direction
17 of sway by freezing and freeing the active DFs during the intermediate (~6-7 months) and late
18 (~7-8 months) phases of sitting acquisition, respectively. Moreover, they found that postural
19 control becomes more stable with development. They postulated that the freezing to freeing
20 strategy of the active DFs allows the infant to first assemble a safe sitting skill and second to
21 interact with the environment while sitting. A remaining issue is now to determine whether
22 infants' postural control during the late phase of sitting acquisition is already comparable to
23 that of adults. Considering that active DFs are already released in this phase, possibly to make
24 postural control more complex (perhaps for exploration purposes), we hypothesized that an
25 adult-like control of sitting posture is already present at that time.

26 Another issue of interest is whether infants achieve sitting by solving the DFs problem in
27 the medial-lateral (M/L) direction of sway the same way as they do in the A/P direction. It is
28 known that a differentiated control of sway is evident in the A/P and M/L directions in adult
29 standing [12,13]. Harbourne et al. [9] also supported the need to consider separately the A/P
30 and M/L directions of sway in infant sitting. These authors used a principal component
31 analysis and found that variables from the A/P direction loaded onto different factors than
32 variables from the M/L direction. This finding suggested that the two directions describe
33 different features of sitting postural control. Therefore, determining changes in the M/L
34 direction during the development of sitting represents an important step to improve our

1 understanding of the sitting skill acquisition. Since new skills are commonly mastered by
2 freezing and/or freeing the active DFs [10,11,14], we hypothesized that one of these pathways
3 of change will also be observed in the M/L direction, with the control of sway becoming
4 comparable to that of adults.

5 **2. Methods**

6 *2.1. Subjects*

7 Fourteen typically developing infants (6 males, 8 females; age at onset: 150.8 ± 15.01 days)
8 and 21 healthy adults (9 males, 12 females; age: 23 ± 2.45 years, height: 1.65 ± 0.32 m;
9 weight: 63.95 ± 9.39 kg) participated in the study. The infants were followed over a period of
10 4 months (from the age of 5-8 months), the time for them to sit independently. Inclusion entry
11 criteria for the infants into the study were: (a) a score on the Peabody Gross Motor Scale
12 (PGMS) within 0.5 SD of the mean, (b) an age of about 5 months at the time of initial data
13 collection, and (c) abilities to hold up their head when supported at the thorax, to reach for
14 objects dangled in front of them in supported sitting or lying on their back, to prop on their
15 elbows for 30 s and to prop on both arms to maintain sitting. The exclusion criteria were: (a) a
16 score on the PGMS greater than 0.5 SD below the mean, (b) diagnosed visual deficits, and (c)
17 diagnosed musculoskeletal problems. The inclusion criteria for the adults were the absence of
18 any neurological, visual, vestibular, or musculoskeletal problems that might affect postural
19 steadiness. Adults were also excluded from the study if they were unable to sit on the force
20 platform surface (0.6 m x 0.4 m) without any part of them touching the floor around the
21 platform (Fig. 1). An informed consent form was signed by the parents of the infants and by
22 the adults before the experiment.

23 *2.2. Experimental design*

24 Each infant underwent nine experimental sessions. The first session lasted for 45 min and
25 was used to perform the PGMS which is a norm and criterion referenced test that examines
26 gross motor function from birth to 83 months. The other eight sessions were sitting sessions,
27 distributed every month of the 4-month period, during which the infants performed a sitting
28 skill on a force-plate (Fig. 1). Specifically, the infants were tested twice in 1 week at each of
29 the 4 months of the study. A physical therapist identified each session's sitting behavior
30 according to three stages of sitting: (1) prop sitting (i.e., early phase of sitting acquisition), (2)
31 prop sitting with periods of 10 s independent sitting (i.e., intermediate phase of sitting
32 acquisition), and (3) independent sitting (i.e., late phase of sitting acquisition). Stage of sitting

1 was considered as a more appropriate independent variable of development than the age since
2 infants presented similar sitting behaviors at different ages, and, two or more sessions were
3 identified at the same stage of sitting. Although more than one session could correspond to the
4 same stage of sitting, the data presented in the study for each infant's phase of development
5 were always chosen from the same session, considered as the best sitting performance session.

6 The adults took part in three experimental sessions of 5 min each. They were asked to sit on
7 a force-plate in a yoga style position with their hands resting comfortably in their lap and head
8 facing forward (Fig. 1).

9 *2.3. Data collection*

10 Infants' COP data in the A/P and M/L directions were obtained using an AMTI force-plate
11 (Advanced Mechanical Technology Inc., Model OR6-7-1000) interfaced with a VICON 370
12 3-D Motion Capture System (Fig. 1). Specifically, the COP coordinates were obtained (240
13 Hz) from the components forces (F_x , F_y , F_z) and moments (M_x , M_y , M_z) using the VICON 370
14 v. 2.5 software (Oxford Metrics Ltd., Oxford, UK). The sampling frequency was selected
15 based on a frequency analysis of both A/P and M/L COP data which indicated a range of
16 signal frequencies that contains the entire signal power spectral density between 1 and 30 Hz.
17 For each infant and stage of sitting, three segments of 8.3 s, corresponding to 2000 data points
18 each, were then selected over the sitting sessions for analysis.

19 Adults' COP data in the A/P and M/L directions were acquired by means of a Kistler force-
20 plate (Model: 9281-B11; Amherst, NY) interfaced with a Peak Technologies Motus 7.2
21 system (Englewood, CO) (Fig. 1). The sampling frequency was set at 10 Hz as the frequency
22 range of the A/P and M/L COP signals was found below 1 Hz. Three segments of 200 s were
23 selected from the 5 min collecting sessions. The 200 s duration allowed the COP time series
24 for the adults to count a similar number of points (i.e., 2000 data points) as those used for the
25 infants and eliminated any artificial differences in the nonlinear measures (see below) due to
26 uncontrolled time series length. No filtering was performed on the COP time series as has
27 been prescribed when calculating nonlinear tools [15].

28 *Please insert Fig. 1 here*

29 *2.4 Data analysis*

30 To quantify the active DFs involved in the control of sitting, the (multi-dimensional)
31 attractor underlying the postural system was first reconstructed from each scalar COP time
32 series using the time-delay method (Fig. 2A and 2B) [16]. In order to unfold the attractor with

1 no overlap in the reconstructed trajectories, the number of dimensions was selected where the
2 percentage of the global false nearest neighbors (GFNN) approached zero [17]. The GFNN
3 analysis of the COP time series was conducted using Tools for Dynamics software [18]. Five
4 and six embedding dimensions were found adequate to unfold the attractor from the infants
5 and adults COP time series, respectively. The correlation dimension (CoD) was then
6 calculated from the reconstructed attractor using the Chaos Data Analyser software [19]. CoD
7 is an estimate of the attractor's dimensionality and identifies the least number of independent
8 variables (i.e., active DFs) needed to characterize a complex system. Technically, the fraction
9 of points $C(r)$ contained within a (hyper) sphere of radius r centred about some points on the
10 attractor is evaluated for various r values (Fig. 2C). CoD is then obtained from the slope of
11 the relation between $\log[C(r)]$ and $\log[r]$ [20]. Practically, the higher the CoD value, the
12 larger the active DFs [21]. The largest Lyapunov Exponent (LyE) was also calculated from
13 the reconstructed attractor using the same software. The LyE quantifies the average
14 exponential rate of divergence of neighboring trajectories in phase space (Fig. 2D) [22]. This
15 is a direct measure of the attractor's predictability and sensitivity to infinitesimal (local)
16 perturbations of the (postural) system, with larger exponents indicating lower attractor
17 predictability and greater sensitivity to local perturbations (i.e. greater local instability)
18 [21,23].

19 *Please insert Fig. 2 here*

20 Finally, the Root-Mean Square (RMS) of the COP time series was also calculated using
21 Matlab (Matlab 7.1, The Mathworks, USA). This parameter, which measures the magnitude
22 of varying COP displacements, was included in the study since it is a standard descriptive
23 variable of postural strategies relatively independent of biomechanical factors (e.g., height
24 and weight) which are expected to change with development [24].

25 *2.5 Statistical analysis*

26 Individual mean values of CoD, LyE and RMS were calculated for the different stages of
27 sitting (i.e., stages 1 to 3 and adult's stage) and for both the A/P and M/L sway directions. To
28 evaluate changes in the development of sitting postural control, (i) repeated measures
29 analyses of variance (ANOVAs) across the stages 1 to 3 of infant sitting, and (ii) independent
30 t-tests between the stages of infant sitting and adult sitting, were performed on the above
31 dependent variables. For all ANOVAs, post-hoc Newman-Keuls tests tallied differences
32 between the infant stages of sitting. To control type I errors when performing multiple
33 independent t-tests, Bonferroni corrections were used by testing each comparison at a

1 significance level of α/n , with n the number of comparisons. Dependencies among the
2 dependent variables, for each sitting stage, were also tested by means of Pearson's correlation.
3 The level of statistical significance was set at 0.05.

4 **3. Results**

5 In the A/P direction, ANOVA results showed significant differences for both CoD and LyE
6 values between the stages of infant sitting ($F_{(2,26)}=4.31$, $p=.02$; $F_{(2,26)}=35.55$, $p<.001$;
7 respectively) (Fig. 3). The post-hoc analyses revealed (i) a higher CoD value in stage 1 as
8 compared to stage 3, and (ii) a significant decrease of the LyE values from stage 1 to 3 (Fig.
9 3). In addition, the t-tests indicated significant differences between the infant stages and adult
10 sitting. Both the CoD values at stages 2 and 3 and the LyE values from stages 1 to 3 were
11 lower than the values observed for the adult stage (Fig. 3). Regarding the RMS values,
12 significant difference was only identified between the infant sitting stages and adult sitting.
13 Specifically, the values from infants were higher than that from adults (Fig. 3). At last, no
14 significant correlations were observed between the dependant variables per sitting stage, with
15 a range of r-values between -0.16 and 0.23 for all stages.

16 *Please insert Fig. 3 here*

17 The results in the M/L direction were different from those in the A/P direction. Only the
18 LyE values from the infant sitting stages were lower than those from the adult sitting stage
19 (Fig. 4). On the other hand, significant differences were present for the RMS, with (i)
20 decreased values from the stages 1 to 3 of infant development ($F_{(2, 26)} = 7.98$, $p = .001$), and,
21 (ii) lower values for the infant stages as compared to the adult stage (Fig. 4). As in the A/P
22 direction, no correlations were found to be significant between the dependent variables per
23 sitting stage, with a range of r-values between -0.48 and 0.44 for all stages.

24 *Please insert Fig. 4 here*

25 **4. Discussion**

26 The aims of the present study were to investigate how sitting posture develops in the A/P
27 and M/L directions of sway during infancy and to examine whether an adult-like control of
28 the sway is already present during the late phase of sitting acquisition in infants. Changes in
29 the control of postural sway were approached within the framework of “the active DFs
30 problem” that accompanies motor development, exploring variations in attractor dynamics of
31 the postural system.

1 In the A/P direction the decreased CoD that was observed during the sitting skill
2 acquisition, reflected an attractor that was becoming lower-dimensional, indicating a skill that
3 was mastered by decreasing the active DFs. This pathway of organizational change has been
4 commonly observed in motor learning and motor development [10,11]. From a dynamical
5 systems theoretical perspective, this renders the postural system much simpler to control, with
6 fewer collective variables (or order parameters) [10]. Consequently, in contrast with the
7 findings of Harbourne and Stergiou [8], a freezing to freeing strategy of the active DFs does
8 not underlie infant sitting acquisition so that postural control is not becoming more complex
9 in the late phase of sitting acquisition. Instead, the lower LyE values revealed in this late
10 phase indicated a COP path that was more predictable with much more convergence in the
11 attractor's trajectories, a strategy reminiscent of a process of fine tuning to a most successful
12 solution as shown in reaching, clapping and walking [25-29]. More importantly, this finding
13 shows that sway became more (locally) stable. This replicates a finding of Thelen and
14 Spencer [3] who concluded that the postural system in infancy is working on stability, to
15 promote reaching. However, their results favored a motionless behavior of the postural system
16 while the increased RMS observed here with infant development reflects a higher amount of
17 sway variability. Considering that sitting and reaching are 'embedded', a more variable and
18 stable sway would represent a proficient solution, allowing the infant to increase the reaching
19 area as well as counteract the inertial effects of arm movements that may cause to miss the
20 intended target. Another important finding in the A/P direction is that infants' postural control
21 at the time of independent sitting is drastically different to adults, with higher CoD and LyE
22 values found in the latter group. In contrast to our hypothesis, adults are then more skilful (i.e.
23 flexible) in sitting, controlling simultaneously more active DFs and exploring more sway
24 patterns. Such a difference certainly results from changes in variables associated with age as
25 body dimensions, motor competence, perceptual acuity, and intentional constraints that shape
26 attractor dynamics throughout the lifespan [26].

27 In the M/L direction, the CoD values and thus the active DFs remained the same during
28 infant sitting development. Although this result was unexpected and opposed to other findings
29 revealing DFs variations with motor development [10,11], it is not irrational. Indeed, Mégrot
30 and Bardy [30] reported that in some learning cases, it is not only the dimension of the
31 intrinsic dynamics of the movement per se that is modulated (from complex to simple or
32 simple to complex). Learning can be manifested also in changes of the spatio-temporal
33 characteristics of the movement itself. In the present case, the geometrical structure of the
34 postural attractor in the M/L direction remained the same, with patterns equivalently

1 predictable through sitting development (i.e., unchanged LyE values). However, sway became
2 less variable in the late phase of sitting acquisition with a decreased RMS. Potentially this
3 may be the result of changes in the infant's body composition with age due to changes in the
4 base of support. The infant's base of support is affected during development through changes
5 in the amount of body fat stored around the hips. Finally, while the active DFs were found to
6 be similar between infants and adults, their postural control differed with less predictable (i.e.,
7 higher LyE) and more variable (i.e., higher RMS) sway patterns in the adults. As in the A/P
8 direction, adult postural control in the M/L direction was more flexible than the infants,
9 allowing more proficiency in producing goal-directed actions.

10 From a methodological standpoint, the absence of a correlation between the dependent
11 variables (i.e., CoD, LyE, and RMS) within each sitting stage, in both A/P and M/L directions,
12 provided evidence that these variables are complementary and quantify different aspects of
13 postural sway control. This supports the contemporary view that changes in the behavioral
14 organization that occur during the development of sitting postural control should be captured
15 by incorporating multiple levels of analysis (dimensionality, predictability, and variability) of
16 postural sway [8,9].

17 **5. Conclusion**

18 In conclusion, infant sitting posture develops differently in the A/P and M/L directions of
19 sway. In the A/P direction, a major finding is that the sitting skill is progressively mastered by
20 decreasing the active DFs, relying on a more predictable and (locally) stable sway, and
21 increasing sway variability. This pathway of change would promote the acquisition of new
22 skills, as reaching. Determining the health of the developing postural control system in this
23 direction may then be critical for the early diagnosis of motor disability. In the M/L direction,
24 only the sway variability was found decreased, so that an early monitoring of sitting
25 development in this direction appears to be less important.

26 Moreover, infant sway control at the time of independent sitting is not adult-like, lacking in
27 adaptability. Further studies are then needed to delineate the factors (e.g., neuro-maturation,
28 motor experience) responsible for such a difference, in order to get a more complete account
29 of sitting posture development throughout the lifespan.

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4 **Conflict of interest**

5 None of the authors have any financial or other interests relating to the manuscript.

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Figures and captions

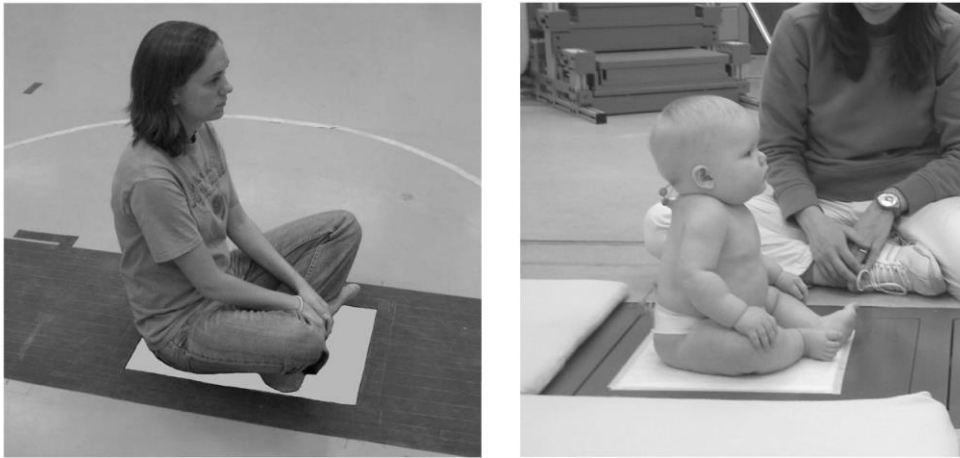


Fig. 1. Illustration of the experimental set-up for an adult and an infant during the late phase of sitting acquisition (i.e., stage 3 of sitting).

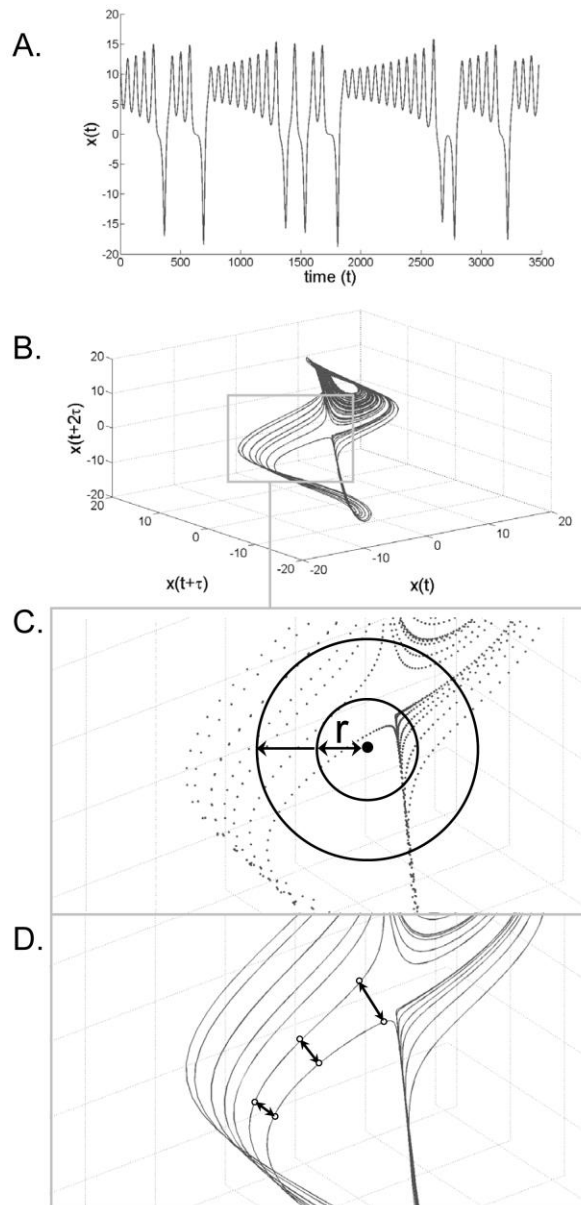


Fig. 2. Schematic representation of the attractor-based analysis. (A) A time series data, $x(t)$, plotted as a function of time t (arbitrary units). (B) Reconstruction of the attractor from $x(t)$ using the time delay method. As an example, the attractor presented here is three-dimensional $[x(t), x(t+\tau), x(i+2\tau)]$. (C) Calculation of the correlation dimension (CoD) by evaluating the way in which the fraction of points contained within a (hyper) sphere of radius r centred about some points on the attractor scales with r . (D) Calculation of the largest Lyapunov exponent (LyE) by measuring the (average exponential) rate of divergence of neighboring trajectories of the attractor.

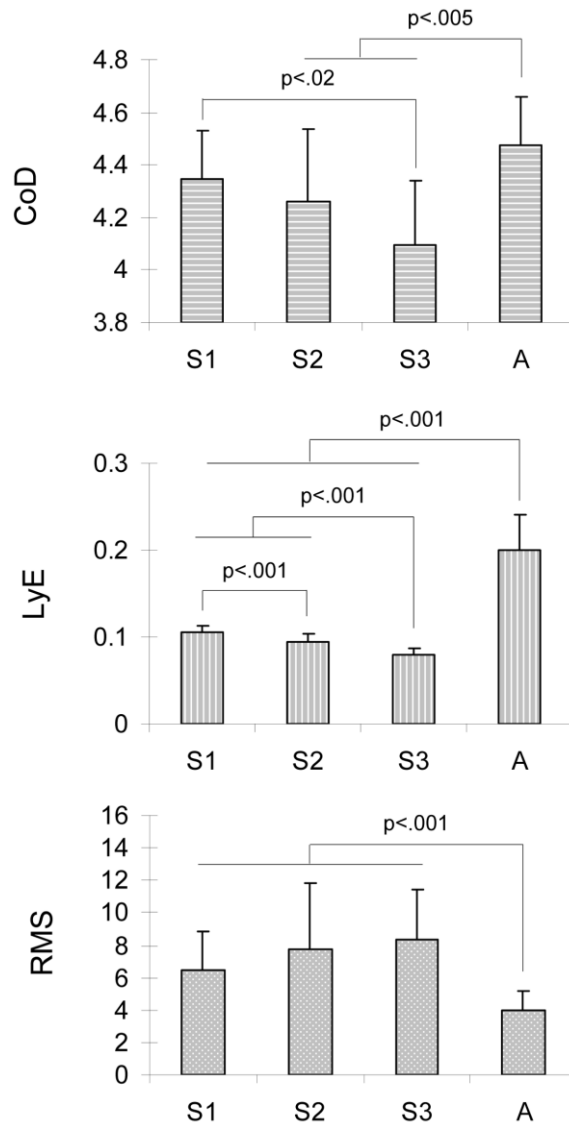


Fig. 3. Evolution of the sway dimension (CoD), predictability (LyE) and variability (RMS) as a function of stage of sitting (from S1 to A) in the A/P direction. S1: stage 1 of infant sitting. S2: stage 2 of infant sitting. S3: stage 3 of infant sitting. A: adult sitting.

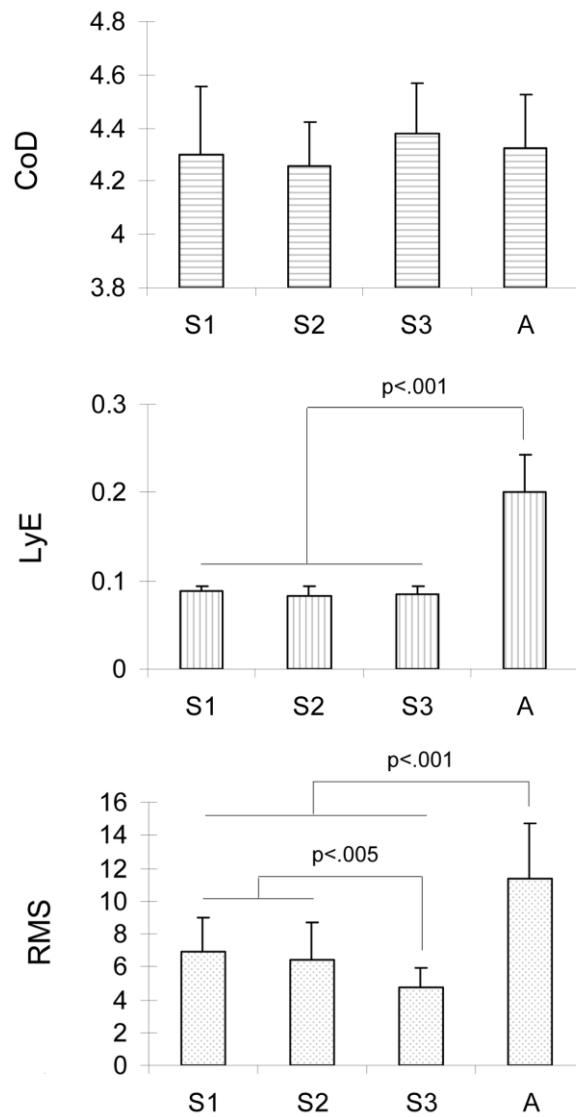


Fig. 4. Evolution of the sway dimension (CoD), predictability (LyE) and variability (RMS) as a function of stage of sitting (from S1 to A) in the M/L direction. S1: stage 1 of infant sitting. S2: stage 2 of infant sitting. S3: stage 3 of infant sitting. A: adult sitting.