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ORIGINAL RESEARCH

Preliminary evidence of an association between spontaneous kicking and learning in infants between 3–4 months of age

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Abstract

Background: The timing and coordination of infant kicking may allow for activities that facilitate learning and cognitive development.

Objective: This study examined spontaneous kicking and associations with changes in kicking during a learning paradigm in typically developing infants.

Methods: Ten healthy full-term infants participated in two experiments at 3 months of age: spontaneous kicking and the mobile paradigm. The inter-limb, intra-limb, and spatiotemporal parameters during spontaneous kicking were collected by 3D motion capture. Learning was measured in the mobile paradigm where an infant's leg was tethered to an overhead mobile. The mobile offered visual and auditory reinforcement when the infant kicked. Changes in kicking rate indicate learning. Friedman tests were used to determine the dominant inter-/intra-limb kicking patterns. Spearman's rank correlation coefficients were used to assess the correlations between spontaneous kicking and performance in the mobile paradigm.

Results: A significant negative correlation ($r = -0.72$, $p = 0.03$) was observed between the percentages of unilateral kicking and normalized kicking rate during the extinction phase of the paradigm. There was a trend of positive correlation ($r = 0.58$, $p < 0.10$) between dissociated hip-ankle joint coupling and the last three-minute of the acquisition phase of the paradigm.

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Conclusion: Exploratory kicking behaviors elicited by visual and auditory feedback may be related to lower extremity movement control. Enhancing movement experience through appropriate external feedback may be critical in treatment programs to support infant development. Future studies to assess how exploratory motor behaviors contribute to development in motor and other domains are warranted.

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Introduction

Young infants demonstrate a multitude of spontaneous movements of their bodies including arm flapping, leg kicking, and writhing body wiggles.¹ Spontaneous kicking of the legs are present in utero and during infancy with or without external stimuli.^{2,3} The trajectory of spontaneous kicking in healthy infants is well described in the literature by decreasing kicking rates with age, high variability and flexibility, and better joint coordination as purposeful movements begin to emerge.^{4–6}

Inter-limb patterns of alternating, unilateral, and synchronous kicks are important characteristics that describe the coordination and maturity of kicking. Newborns kick with a primarily alternating pattern and then develop dominant unilateral kicking patterns at one month. Synchronous kicking patterns become more prominent after five months of age.^{7,8} Importantly, type and variability of inter-limb kicking patterns may be associated with delayed development of motor milestones. Specifically, preterm infants who demonstrated predominant unilateral kicks at two months of age and predominant alternate kicks at four months of age started to walk later than infants with typical development.^{5,9} Although, it is difficult to use kicking in isolation from other clinical tools to identify developmental delay or disability, motor coordination measured with kicking may be an important component in understanding the development of both typical and atypical motor skills.

Intra-limb coordination of hip-knee, knee-ankle, and hip-ankle joint coupling are also important measurements of kicking coordination. In general, infants demonstrate tight coupling movements of the lower extremity as the ankle, knee, and hip joints flex and extend almost synchronously. Hip-ankle joint movements start to disassociate by the second month of age, followed by disassociations of hip-knee and knee-ankle joints between four and six months of age.¹⁰ Infants who are at high-risk of motor impairments may demonstrate delayed dissociation of intra-limb coordination.^{11–13} Importantly, tighter joint coupling (less mature) at two months of age is associated with a later attainment of walking.⁵ This may also indicate an important relationship between early joint coordination during kicking and the acquisition of new motor skills.

The mobile paradigm is designed to test learning and memory in infants.¹⁴ An infant's leg is tethered to an overhead mobile, such that when the infant kicks, the mobile moves. As a result, the moving mobile provides conjugate

visual and/or auditory reinforcement to the infant. With this reinforcement, infants are able to learn the association between their kicking and movement of the mobile by showing increased kicking frequency. Full-term healthy infants learn this paradigm in one day and remember it for one week.^{15,16} Interestingly, infants also demonstrated the ability to change their inter- and intra-limb kicking coordination in fairly complex ways,^{6,16,17} such as kicking more with the tethered leg,^{16,17} or moving their legs with less hip-knee coupling and specifically choosing a range of motion to induce external feedback more efficiently during the mobile paradigm.^{6,17,18}

The existing evidence indicates that the infant's ability to adapt kicking coordination may bestow more advanced contingent learning or vice versa. Yet, it is unknown whether there is an association between the developmental status of spontaneous kicking and performance in the mobile paradigm in early infancy. This association may offer an opportunity to investigate whether the development of very early motor skills play a role in supporting the growth in other domains, such as learning and cognitive development. Therefore, the purposes of this study were to assess the relationship between inter-limb and intra-limb coordination during spontaneous kicking and contingent learning assessed by kicking rate changes in the mobile paradigm task in infants at 3–4 months of age.

Methods

Participants

Ten full-term (≥ 37 weeks of gestational age) infants, who were typically developing as reported by their parent(s), were recruited through a convenient sampling. Infants did not have a medical or developmental diagnosis or concerns for neurological, genetic, cardiopulmonary, or other medical conditions that may result in developmental delays. Infants in this study completed 2 experiments: (1) spontaneous kicking and (2) learning in the mobile paradigm. Data from the spontaneous kicking session for one infant was incomplete because of technical problems; therefore, available data from nine infants were used for kicking analysis (Table 1). This study was approved by The Nationwide Children's Hospital IRB13-00375 (Columbus, OH, United States) Institutional Review Board, and informed consent from a legal guardian was obtained before enrolling each participant in the study.

Table 1 Demographic data of infants with complete data.

	Sex	Gestational age (week/day)	Age at mobile paradigm test (month/day)
Participant 1	F	39/6	3/22
Participant 2	F	39/4	3/0
Participant 3	F	39/4	3/12
Participant 4	M	41/0	3/15
Participant 5	F	37/6	3/22
Participant 6	M	40/0	3/1
Participant 7	F	39/6	3/19
Participant 8	F	37/0	3/10
Participant 9	M	37/1	3/3

**Figure 1** Marker placements for spontaneous kicking data collection.

Experiment 1: spontaneous kicking

The spontaneous kicking experiment was performed to assess spatiotemporal characteristics and inter-/intra-limb coordination patterns, which frequently indicate the maturation of motor control of leg movement in infants. This experiment was conducted before the learning experiment to avoid any potential changes in kicking characteristics from a learning effect from the mobile paradigm task. Ten reflective markers were placed on each infants' lateral side of the mid-trunk, greater trochanter, lateral femoral epicondyle, lateral malleolus, and fifth metatarsal head bilaterally with hypoallergenic tape for kinematic data collection (Fig. 1).⁹ The kinematic data for measuring inter-limb and intra-limb coordination patterns and spatiotemporal parameters were collected by an 8-camera motion capture system (Vicon, Motion Systems, Oxford, UK) at 120 Hz sampling rate. The converted 3-D data were used to calculate inter-and intra-limb coordination patterns and spatiotemporal kinematics of kicking. The kicking movements were recorded for three, one-minute trials. Infants were placed in a supine position on a table. One investigator stood near the infants' head to gently keep a midline head position and hold the infants' hands as needed to avoid covering up markers.⁹

Marker trajectories were filtered using a 6 Hz low-pass Butterworth filter and exported for analysis. Kicking

parameters were calculated using a custom MATLAB script (MathWorks, Inc., Natick, MA). Joint angles were calculated as the angle between the vectors of the two adjoining segments, such that hip angles were the angle formed by the mid lateral trunk, greater trochanter, and knee; knee angles formed by the angle between greater trochanter, lateral knee, and lateral ankle; and ankle angles were formed by the angle between the lateral knee, lateral ankle, and 5th metatarsal head. A kick cycle was then operationally defined when hip flexion/extension was immediately followed by hip extension/flexion with a more than 15° change in angle in both directions. Intra-limb coordination patterns included dissociations of hip-knee joint, hip-ankle joint, and knee-ankle joint coupling. Dissociation of each joint coupling was defined by the percentage of time of out-phase movement (e.g. one joint moves toward flexion and the other does not move or moves toward extension) in the whole kicking cycle. Inter-limb coordination patterns included unilateral, alternating, and synchronous kicks. Unilateral and bilateral kicks were determined, with bilateral kicks occurring when right and left kicking phases occurred together for a minimum of 50% of both kicking phases. Specifically, in bilateral kicks, when the right and left hip joints moved toward the same direction (flexion or extension) for 50% or more of the overlapping time, it was defined as synchronous kick, and those which were not synchronous were defined as alternating kicks.⁹ Spatiotemporal parameters of the spontaneous kicking movement including maximum and minimum hip, knee, and ankle joint angles during each kicking phase, and peak hip flexion/extension velocities during each kicking phase were also calculated to describe the kicking performance.

Experiment 2: learning experiment (mobile paradigm task)

Learning was measured in the mobile paradigm over 15 min. During the task, infants were placed in a Pack-N-Play™ (portable infant bed/playground) with two white stands attached on each side of it. An overhead mobile was attached to either the right or left side stand and the infants' right leg was tethered to the right stand throughout the assessment. The first three minutes was the baseline phase, where the toy was attached to the left stand, and thus the infants were not able to move the mobile when kicking their right leg. The following nine minutes was the acquisition phase, which was composed of 3-min periods, where the toy was attached to the right stand, and thus the mobile moved in accordance with kicking (Fig. 2). The final three minutes was the extinction phase, where again the infant's kicks did not result in movement of the mobile. A more detailed description of the mobile paradigm can be found in other experiments using the same protocol.¹⁹ The definition of a kick during this task is the same as for the spontaneous kicking assessment but coded visually. Kicking was recorded using customize software with the investigator clicking "R" on the keyboard when observing a successful kick from the video recording. The intraclass correlation coefficients (ICC) showed excellent inter-rater reliability (ICC = 0.97) on kick cycle coding.

Learning was operationally defined as the normalized kicking rates of the last three minutes of acquisition (how



Figure 2 The mobile paradigm set-up. Infant's right leg is tethered to the right stand, and thus the kicking movement causes the mobile to move when the mobile is attached to the right stand during the acquisition period. The mobile is composed of five wooden blocks and five bells to provide both visual and auditory feedback.

many times the infant kicked the right leg during the 3rd acquisition period/how many times the infant kicked the right leg during the 3-min baseline phase) *and* the entire three-minute extinction phase (how many times the infant kicked the right leg during the 3-min extinction phase/how many times the infant kicked the right leg during the 3-min baseline phase) being equal or higher than 1.5. Infants who met the criteria were defined as learners.

Statistical analysis

IBM SPSS Statistics 21 (Armonk, NY: IBM Corp.) was used for statistical analyses. Shapiro-Wilk tests were used to evaluate the normality of the intra-/inter-limb kicking patterns and normalized kicking rate during the 3rd acquisition period and the extinction phase. The distributions of all parameters, except for normalized kicking rate during the 3rd acquisition period, did not reject the assumption of normal distribution. However, the small sample size may result in insufficient power to detect the deviation of the variable from normality, we therefore assessed the distribution conservatively based on the central tendency indicator (i.e. skewness and kurtosis within the absolute value of one) and identified that only two parameters fulfilled normal distribution. As a result, we used non-parametric statistics for the following analyses. Friedman tests were used to determine the dominant intra-/inter-limb kicking patterns. The post-hoc analyses were performed by Wilcoxon signed-rank tests with Bonferroni adjustments (p -value less than 0.017 indicated a significant difference). Spearman's rank correlation coefficients were used to test relationships between: (1) percent time out-phase intra-limb joint coordination of each spontaneous kicking and the normalized kicking rate of the 3rd acquisition period and extinction phase, (2) proportions of each of the three types of inter-limb kicking patterns during spontaneous kicking and the normalized

kicking rate of the 3rd acquisition period and extinction phase.

Results

Ten infants completed both experiments but one of them was excluded due to unusable kinematic data of spontaneous kicking. Available data from nine infants were used for further analyses. The spatiotemporal measures and intra-/inter-limb coordination patterns in all nine infants are described in Table 2. The hip-ankle ($71.6 \pm 5.6\%$) and knee-ankle ($68.3 \pm 6.3\%$) joint couplings showed significantly higher dissociation movement ($p = 0.008$), indicating greater percentage of time in out-phase coupling movement, compared to hip-knee joint coupling ($49.8 \pm 9.3\%$); the proportion of unilateral kicking pattern ($76.1 \pm 9.4\%$) was significantly higher than alternate ($5.4 \pm 5.6\%$, $p = 0.008$) and synchronous ($18.5 \pm 9.6\%$, $p = 0.008$) kicking patterns.

Among the nine infants, six met the criteria of learning in the mobile paradigm task and were defined as learners (66.7%); the other three infants were defined as non-learners (33.3%). The spatiotemporal measures and intra-/inter-coordination patterns in both of the groups are also listed in Table 2. There were no statistical analyses for group comparisons between learners and non-learners due to the small sample size.

The intra- and inter-limb coordination patterns and their relationships with the 3rd acquisition period and extinction phase of the mobile paradigm task are presented in Table 3. There was no significant correlation between intra-limb coordination patterns and normalized kicking rate in the mobile paradigm except a trend for a positive correlation between hip-ankle out-phase coupling movements and normalized kicking rate of 3rd acquisition period ($r = 0.58$, $p < 0.10$). There was a significant, moderate, negative correlation between percentage of unilateral kicking pattern and normalized kicking rate of the extinction phase ($r = -0.72$, $p = 0.03$).

Discussion

This work joins others in demonstrating that the spatial and temporal characteristics of spontaneous kicking in young infants are measurable. Fetters et al.¹² showed mean values of peak hip angle (106.8°), hip flexion excursion (40.5°), and hip extension excursion (40.8°) in full-term infants at five months of age. These results are similar to our findings in infants between 3–4 months of age. However, the peak hip flexion and extension velocities (204.4 m/s and 289.3 m/s) tended to be higher in the study by Fetters et al.' compared to our results. In comparison, Heriza²⁰ showed smaller range of hip flexion excursion (62.02°) and extension excursion (59.30°) than results of the present study, but slightly slower peak hip flexion velocity of ($148.31^\circ/\text{s}$) in full-term infants at three days old. Therefore, we speculated that hip flexion/extension velocities may continuously increase from birth to at least five months of age, while the total excursion, or amplitudes of hip movement, may tend to decrease from birth to a few months later.

In our study, hip-ankle and knee-ankle joint coupling showed dissociated movement prior to hip-knee coupling

Table 2 Characteristics of spontaneous kicking in learners, non-learners, and all infants.

	Learners (n = 6)	Non-learners (n = 3)	Total (n = 9)
Max. hip angle (°)	104.9 ± 19.1	92.4 ± 9.8	100.7 ± 17.0
Min. hip angle (°)	59.3 ± 17.9	46.2 ± 4.5	54.9 ± 15.8
Hip excursion (°)	76.2 ± 15.1	74.1 ± 9.8	75.5 ± 13.0
Peak hip extension velocity (m/s)	160.4 ± 57.9	119.9 ± 55.4	146.9 ± 57.2
Peak hip flexion velocity (m/s)	171.9 ± 50.3	138.4 ± 88.1	160.8 ± 61.7
Max. knee angle (°)	113.5 ± 11.9	117.0 ± 9.9	114.7 ± 10.8
Min. knee angle (°)	60.9 ± 15.6	65.3 ± 15.4	62.3 ± 14.7
Max. ankle angle (°)	77.6 ± 16.5	87.8 ± 17.6	81.0 ± 16.5
Min. ankle angle (°)	50.9 ± 11.9	60.2 ± 14.9	54.0 ± 12.9
Hip-knee out-phase coupling (%)	50.7 ± 11.6	48.1 ± 1.4	49.8 ± 9.3
Hip-ankle out-phase coupling (%)	69.6 ± 6.1	65.9 ± 7.2	68.3 ± 6.3 ^a
Knee-ankle out-phase coupling (%)	72.2 ± 6.6	70.4 ± 3.4	71.6 ± 5.6 ^a
Unilateral inter-limb pattern (%)	75.1 ± 10.9	78.1 ± 7.0	76.1 ± 9.4 ^b
Alternate inter-limb pattern (%)	5.7 ± 6.7	4.7 ± 3.3	3.6 ± 5.4
Synchronous inter-limb pattern (%)	19.2 ± 11.8	17.2 ± 13.9	18.5 ± 9.6

^a Significantly predominant out-phase intra-limb coordination pattern.^b Significantly predominant inter-limb coordination pattern.**Table 3** The relationships between intra-/inter-limb coordination patterns during the 3rd acquisition period and extinction phase of the mobile paradigm task.

		<i>r</i> (p-Value) 3rd Acquisition	<i>r</i> (p-Value) Extinction
Intra-limb	Hip-knee out-phase	0.55 (<i>p</i> = 0.13)	0.48 (<i>p</i> = 0.19)
	Knee-ankle out-phase	0.28 (<i>p</i> = 0.46)	0.05 (<i>p</i> = 0.90)
	Hip-ankle out-phase	0.58 (<i>p</i> = 0.10)**	0.23 (<i>p</i> = 0.56)
		3rd Acquisition	Extinction
Inter-limb	Unilateral	−0.23 (<i>p</i> = 0.55)	−0.72 (<i>p</i> = 0.03)*
	Alternate	0.28 (<i>p</i> = 0.47)	0.44 (<i>p</i> = 0.24)
	Synchronous	−0.10 (<i>p</i> = 0.80)	0.56 (<i>p</i> = 0.12)

* Significant relationship tested by Spearman Spearman's rank correlation coefficient (*p* < 0.05).** Trend relationship tested by Spearman Spearman's rank correlation coefficient (*p* = 0.1).

movements. This result is consistent with Thelen's observation that the hip-ankle joint coupling shows the earliest dissociated movement from tight intra-limb joint coupling during kicking.¹⁰ Jeng et al.⁹ also showed higher hip-knee joint coupling, indicating less dissociated movement, in full-term infants who are at 2 and 4 months of age. Similarly, van der Heide et al.¹³ using medians of correlation coefficients to investigate intra-limb coordination patterns, found a trend of tighter hip-knee joint and knee-ankle coupling compared to hip-ankle joint coupling in full-term infants at 3 months of age. Based on previous and the current studies, dissociation of intra-limb joint coupling during kicking seems to start from the most distal joint. A better control of dissociated lower extremity joint coupling may enhance the efficiency of kicking, which decreases energy consumption, while interacting with the mobile to show positive impact on the learning process.⁶ However, the disassociated intra-limb kicking pattern at any pairs of lower extremity joint coupling was not associated with changes of kicking rate in the mobile paradigm in our study. This finding might be due to our definition of a kick, when the hip joint flexed

and then extended $\geq 15^\circ$ and vice versa without additional requirement for knee joint movement. In this case, we may miss counting the kicks that moved the mobile mainly by dissociated knee movements. However, we found a trend for a positive correlation between the out-phase movements of hip-ankle joint coupling and the normalized kicking rate of 3rd acquisition period, during which infants demonstrated highest kicking rate throughout the mobile paradigm task. Therefore, the demand for more efficient motor control may be important in supporting infants' explorative behaviors during a challenge. We speculate that the first dissociation of the lower extremity intra-limb joint coupling (i.e. hip-ankle joint coupling) may produce a less constrained and more energy saving option when infants try to increase the number of kicks. Please note that the infants in this study were developing in a typical manner; the natural variation of maturity of intra-limb kicking patterns may not be large enough to impact kicking rate changes in the mobile paradigm task.

Previous studies showed variable results on the development of inter-limb kicking patterns in young infants.

In our study, a unilateral kicking pattern was the dominant inter-limb coordination pattern. This is consistent with van der Heide et al.'s¹³ findings in full-term infants at 3 months of age. Our result showed a negative moderate correlation between the normalized kicking rate of extinction phase and unilateral inter-limb kicking pattern. This means that infants who showed relatively fewer unilateral kicks had a higher normalized kicking rate in the extinction phase (i.e. learning). During the extinction phase, infants were no longer receiving visual and auditory feedback, and thus these infants may exaggerate and increase their kicking frequency or change kicking patterns to try to move the mobile. We speculate that without sufficient variability of movements, such as in infants with a mono-type of inter-limb kicking pattern (caused by delayed or impaired motor function), infants may demonstrate a reduction in exploratory kicking movements in the mobile paradigm task. We therefore suggest that a smaller percentage of a unilateral kicking pattern (and therefore more variability) at this age may indicate more mature leg control allowing for diverse kicking movements in reaction to the extinction phase. In contrast, infants who "failed" to learn the cause-and-effect relationship during the acquisition phase may be less motivated to explore new or less frequently used movement strategies to move the mobile. These speculations support the perception-action perspective that cognitive elements, such as perception, interaction with the environment, learning, and memory, may drive the development of motor domain by eliciting new movement strategies and vice versa.^{6,17}

At this stage, our preliminary findings have two clinical implications. First, we consider that greater capacity of voluntary movement control may offer a better opportunity for explorative behaviors and cognitive learning in infants. For high-risk infants, especially those who may have global delays like preterm infants, adequate motor experience with enriched external feedback may be considered as an essential component in treatment programs. Second, when conducting early assessment in infants with motor and cognitive risk factors, we suggest careful selection of the appropriate task to ensure the result of the targeted domain will not be unduly influenced by the constraints of another domain. If this is not feasible, the assessment results should be interpreted in a more cautious and comprehensive manner.

The inherent limitations of a preliminary study with a small sample prevent strong conclusions. First, the natural variation of maturation of kicking movement may not interfere with the exploratory activities and learning in the mobile paradigm task in infants with typical development. Therefore, we cannot conclude how impairments or delay in one developmental domain affect the other domain. Second, the cross-sectional design of this study may not allow distinguishing the impact of motor development on cognitive outcome, such as learning the cause-and-effect relationship, in this study. Future studies to compare infants with and without motor developmental delays or impairments, including atypical kicking movements, and the use of a longitudinal study design may provide opportunities to further understand the development of high-risk infants.

Conclusion

Our findings provide preliminary evidence to support the importance of motor explorative behaviors in infant development. These results may provide valuable insight to inform future larger scale studies aiming to investigate the influence of motor development on different developmental domains. Moreover, the validity of using mobile paradigm task to reflect learning ability in infants should be assessed in infants who are at risk of or showing motor impairments. In the future, studies to extensively understand how different body systems influence the development of each other with a larger sample and longitudinal design are also warranted to support and enhance growth and development in high-risk infants.

Conflicts of interest

The authors declare no conflicts of interest.

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