The relationship between spatiotemporal kinematics of the upper extremity and motor development in early infancy: an exploratory study

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1. Background

Reaching is a critical part of infant development as it allows the infant to interact with their environment and sequentially promotes play and self-care activities. In typical development, the onset of reaching, or bringing a hand to an object, occurs between 3-5 months.[1-4] Prior to the onset of reaching, infants demonstrate pre-reaching movements of their upper extremity, typically called flapping. These early, pre-reaching flapping movements contribute to the development of successful reaching. The "march to midline" in typical development describes the process in which infants begin to bring their hands closer together, eventually resulting in successful grasping of hands at midline around 3 months. This early motor milestone is considered critical, as it is an indicator of strength, as the child moves against gravity, and coordination, as the child brings their hands together successfully.

Pre-reaching upper extremity movements that occur prior to the onset of reaching, occur with or without the present of an external stimulus. Spontaneous movement of the upper extremity against gravity have been shown to relate to the development of reaching and also overall motor development.[5 6] Pre-reaching infants are able to bring their hand closer to the object and slow down their movement, increasing likelihood of successful contact with the toy. Early arm movements are typically fast, uncoordinated, and derive from the shoulder complex. As infants get older and closer to reaching onset, movement becomes slower, more coordinated, and involve the shoulder and elbow joints working simultaneously.[7-10] Their hand position in relation to an object also becomes improved with age, as the child is able to anticipate the affordance of the object (ie: open hand towards the object in preparation to touch and grasp).[1] At the onset of successful reaching, infants demonstrate high variability in their performance. They often show variability in success of reaching, trajectory, movement velocity, movement amplitude, and duration of movement. During this time there is a rapid change in movement performance, as the infant's reach becomes smoother and faster. These changes slow down after 6 months of age, and by 2 years old, reaching performance is comparable to an adult pattern.[11-13 14]

The development of reaching influences and is influenced by fine motor and gross motor skill development. Successful reaching performance affords fine motor interaction with objects in the environment. Increasing opportunity for these fine motor interactions (i.e. increasing frequency of reaching) helps to improve fine motor performance. Similarly, gross motor function and its attributes, such as postural control, are imperative to provide the proximal stability to allow for successful reaching, and in turn, successful reaching will continue to challenge and improve postural control. Development in each of these domains is interconnected and understanding their relationship to one another is critical for optimal motor outcomes.

Fine motor and gross motor developmental domains are often utilized to describe overall motor function of an infant and clinical tools have been developed to track these domains over time. Although much attention has been paid to understanding the development of reaching and motor development separately, the relationship between reaching performance and motor development, as measured by clinical outcome tools is unknown. The Bayley Scales of Infant and Motor Development, 3rd edition (Bayley-III), is a reliable and valid measurement of motor skills development and includes gross motor, fine motor, cognitive, and language subtests. The development of motor skills is often characterized utilizing this norm-referenced tool. Therefore, the purpose of this study was to describe upper extremity movement in typically developing infants and to explore the relationship between the development of reaching and motor skill development as measured by a clinical tool.

2. Methods

2.1 Participants

Twelve healthy infants between 2 and 8 months old (8 females and 4 males) were recruited to participate in this study. Infants were seen for a total of 2-4 study visits, capturing a range of development. The procedures and experiments were approved by the Research Ethics Committees of Nationwide Children's Hospital and The Ohio State University. Informed written consent to participate in the study was provided to the parent or caregiver.

Each visit lasted approximately 1 hour, and included assessment of spontaneous movements and motor development.

2.2 Procedure

Spontaneous upper extremity movement and motor development was captured at each visit. Infants were placed in supine and spontaneous movement of the upper extremities was recorded for 6-12, 30 second trials (7.7±1.9). Growth was recorded utilizing measurements of the infant's height, arm length, and weight. Motor development was assessed utilizing the Bayley Scales of Infant and Motor Development, 3rd Edition (Bayley): Gross (GM) and Fine Motor (FM) Subtests. Breaks were provided to ensure the infant remained in a quiet and alert state during the session.

2.3 Kinematic analysis

A ten-camera (120 Hz) Vicon motion capture system was used to collect position-time data from the upper extremities of the infant. Circular reflective 8mm in diameter, were placed on the infant for motion tracking: 1 on the dorsal side of each hand. Upper extremity movement was then recorded in supine. The 3D position for each marker was calculated in Vicon Nexus 1.8.5 and low-pass filtered with a 4th order zero lag Butterworth filter, with a cutoff frequency of 4 Hz. The 3D linear positions and speed were calculated for each marker. The calculations for the dependent variables were performed using MATLAB (The MathWorks Inc., Natick, MA). A total of 215 trials were analyzed.

2.4 Motor development

The Bayley-III GM and FM were used to measure fine and gross motor skill development of the infants. This test was administered by a trained and reliable experimenter. Scores attained from the GM and FM subtests were recorded as raw and scaled scores, allowing for an age-equivalent of motor development to be determined. No infant scored below the 5th percentile, which would warrant referral for further follow-up. This portion of the testing session was video-recorded to ensure fidelity of the testing results.

3. Data Analysis

3.1 Movement identification

For this study, a movement was defined as a hand displacement of at least 30mm in one direction (Bhat and Galloway 2006). The end of a movement was indicated by a reversal of direction measuring 15mm or greater in length. Movements were identified using a custom MATLAB program. An experimenter then confirmed the identified movements, by viewing the graph of 3D hand position across each trial.

3.2 Dependent variables

Spatial and temporal dependent variables were included for analysis of the infant's spontaneous upper extremity movement and are presented in Table 1. Spatial variables that were measured directly included movement length, arc length, and movement displacement. Straightness index, a ratio of movement length and arc length, was calculated. Temporal variables included movement speed, peak velocity, and movements per minute. All dependent variables were calculated in MATLAB, except the straightness ratio, which was calculated using Excel (Microsoft Corporation, Redmond, WA).

Table 1. Dependent variables, units and definitions

Movement length	mm	Distance from start point to end point of a movement, measured by the distance of the hand marker from the toy marker (averaged across all movements in a trial)
Arc length	mm	Total distance travelled by the hand in X, Y, Z space from start point to end point of movement (averaged across all movements in a trial)
Straightness ratio	No units	Ratio of length of arc length/movement length (calculated using averages from each trial)
Movement displacement	mm	Distance between starting points of the movement (calculated using averages from each trial)
Movement speed	mm/s	Velocity of a movement, calculated by the movement length/movement time (averaged across all movements in a trial)
Peak velocity	mm/s	Single highest velocity of a movement recorded
Movements/minute	number	Total number of movements recorded

3.3 Statistical analyses

IBM SPSS version 23.0 was used to conduct the statistical analysis. Descriptive statistics, including mean, standard deviation, and range, for each kinematic variable was calculated for each subject. Related-samples Wilcoxon Signed Rank Test was used to determine differences between left and right upper extremity movements. Linear regression analysis was used to evaluate the relationship between kinematic variables and motor development, as measured by the Bayley-III. Spearman's rank correlation coefficient (r) was used to describe the strength of the relationship. Significance was established as p=.05.

4. Results

4.1 Kinematic analysis

Means, standard deviations, and range across all subjects for each month (2-8 months old) and for each kinematic variable and FM and GM score on the Bayley-III was analyzed and described below. Spatial variables are presented in Table 2 and temporal variables are presented in Table 3.

Table 2. Spatial kinematic variable means and standard deviations.

Spatial Variables	Movement displacement (mm)	Movement length (mm)	Arc length (mm)
	0.21±4.5	68.6±11.2	169.3±26.9

Table 3. Temporal kinematic variable means and standard deviations.

Temporal Variables	Left movements per minute	Right movements per min	Movements per minute	Average speed (mm)	Peak velocity (mm/s)
	23.3±17.6	23.6±20.7	47.0±35.9	373.2±113.6	667.5±204.9

4.2 Relationship between growth, kinematics, and motor development

Simple linear regressions were performed between measures of growth (height, arm length, and weight of the infant), each kinematic variable, and FM, GM, and combined Bayley-III scores. No relationships were found between age, height of the infant, or length of the arm and any kinematic variable of the upper extremity. All single order r values for each measure of growth in relation to score on Bayley-III are listed in Table 4. No relationships was found between movement displacement, arc length, movements per minute, average movement speed, or peak velocity and motor score on the FM, GM, or combined Bayley-III.

There were significant, strong, and positive relationships between height and FM score (r=0.85, p=<0.001), height and GM score, (r=0.84, p=<0.001), and height and combined Bayley-III (Figure 1).

All single order r values for each kinematic variable in relation to score on Bayley-III are listed in Table 5.

Table 4. Spearman's rank correlation coefficient (r) and significance (p) for each measure of growth in relation to scores on FM, GM, and combined Bayley-III.

Measure of Growth		FM Score	GM Score	Bayley-III Combined Score
Height	r	0.85*	0.84*	0.86*
	p	0.<001*	<0.001*	<0.001*
Arm length	r	0.19	0.39	0.31
	p	0.37	0.06	0.15
Weight	r	0.18	0.08	0.13
	p	0.43	0.71	0.57

**Measures of growth and Bayley were completed at each visit*

There was a significant, moderate, and positive relationship between movement length of the upper extremities and FM score (r=0.41, p=0.04), movement length and GM score (r=0.52, p=0.01), and movement length and combined Bayley-III (r=0.50, p=0.01) (Figure 2). There was a significant, moderate, and negative relationship between straightness index and GM score (r=-0.46, p=0.02) and straightness index movement length and combined Bayley-III (r=-0.44, p=0.03) (Figure 3).

5 Discussion

This exploratory study describes spontaneous upper extremity movement in infants with typical development and explores the relationship between these underlying movements, growth, and motor development. Motor development is often studied to better understand overall development because of the unique ability to see and record when they occur.[15] Understanding pre-reaching and reaching behaviors of infants with typical development has implications for informing the design of successful neurorehabilitation interventions for children with atypical development.

5.1 Relationship between growth, kinematics, and motor development

Table 5. Spearman's rank correlation coefficient (r) and significance (p) for each kinematic variable in relation to scores on FM, GM, and combined Bayley-III.

Kinematic Variable		FM Score	GM Score	Bayley-III Combined Score
Movement displacement	r	-0.01	-0.13	-0.08
	p	0.95	0.53	0.70
Movement length	r	0.41*	0.52*	0.50*
	p	0.04*	0.01*	0.01*
Arc length	r	0.26	0.34	0.32
	p	0.21	0.10	0.11
Straightness index	r	-0.36	-0.46	-0.44*
	p	0.74	0.02*	0.03*
Movements per minute	r	-0.23	-0.10	-0.14
	p	0.30	0.65	0.51
Average speed	r	-.05	0.09	0.03
	p	0.80	0.69	0.88
Peak velocity	r	-0.08	0.14	0.04
	p	0.69	0.50	0.85

This study explored the relationship between measures of growth, including height, arm length, and weight, and motor skills attainment motor skill attainment and development, as measured through the Bayley-III. The results from this study suggest that height is significantly and positively related to motor skill development. Overall height, compared to arm length or weight, may be the best indicator of motor development and skill attainment over time.

This study also explored the relationship between underlying spontaneous movement and their relationship to motor skill attainment and development. The results from this study suggest that increased movement length of the upper extremity and better straightness indices, a measure of trajectory, are associated with better fine and gross motor development.

Movement length. Longer upper extremity movement lengths were significantly associated with better scores on the FM, GM, and combined Bayley-III. The kinematic variable of movement length considers the distance from the start and end point of a movement. Since the infants were placed in supine, the movement of the upper extremity was most often in an anti-gravity direction. Upper extremity movements in the anti-gravity direction have been considered an indicator of strength. Increases in strength may be foundation for motor skill development.

Straightness index. This kinematic variable is a ratio between arc length and movement length and is an indication of the smoothness of the infant's trajectory. An adult would have a straightness index of 1, as their arc length and movement length are the same. Straightness ratios larger than 1, as seen in infant movement of the upper extremities, indicates immature movement patterns and decreased coordination. Infants with smoother upper extremity trajectories demonstrated significantly higher GM score and combined Bayley-III score. This suggests that coordination, or efficacy of a movement, influences motor skill development.

Although these spatial variables, movement length and the straightness index, were associated with motor development, no temporal kinematic variables were found to have a relationship with motor development. One possibility of why this occurred is due to the nature of the clinical test that was used to measure motor development over time, the Bayley-III. This assessment seeks to capture motor development by analyzing different motor skills, however, there is no need for speed (temporal component) when completing these tasks. It does not matter how long it takes the child to complete the task, only that they are able to complete it. This may unintendedly emphasize strength (or spatial components) as an underlying measurement of motor development.

5.2 Kinematic variables

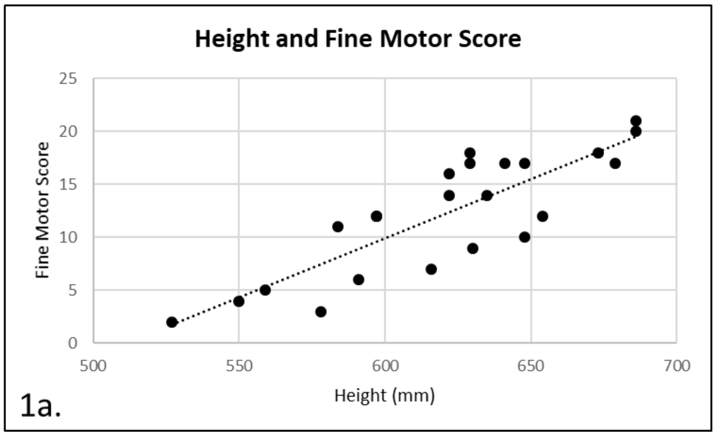
The descriptive kinematic data from this study contribute to normative values for spatial and temporal measurements commonly used in rehabilitation research to study the upper extremity in the pediatric population. The kinematic variables of interest included in this study have been used in many other studies to examine kinematics of the upper extremity for infants and children. [8 16] Previous studies have described spatial and temporal kinematics for the upper extremities, however no study has identified normative values. Advancements in establishing a normalized data set for spatial and temporal kinematics for infants can aide in earlier identification of infants with abnormal movement patterns, as they will fall outside of these normative values. As technology becomes more sophisticated, motion capture may play an increasing role in diagnosis of movement disorders. It is therefore critical to understand movement of infants with typical development to facilitate recognition of abnormal movement in infants with atypical development.

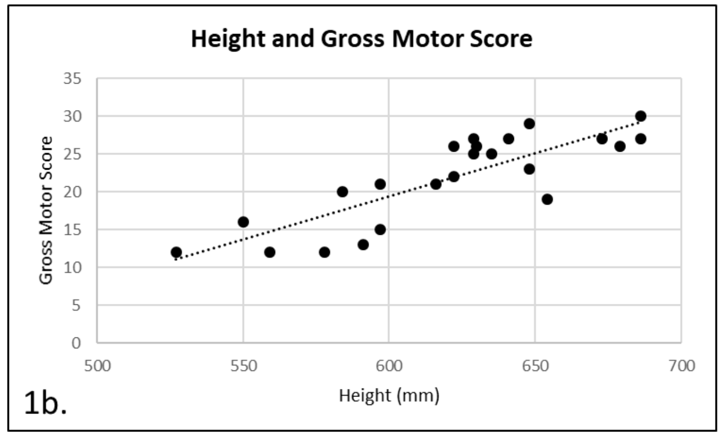
This study examined spontaneous movement recorded while the infants were in supine. This position and technique is utilized in the General Movements Assessment (GMA) to diagnose cerebral palsy (CP) in very young infants.[17-19] The GMA has been identified as the most effective assessment to aide in diagnosis of children at risk for CP and has been included in the battery of assessments for early diagnosis of CP in the United States, along with magnetic resonance imaging (MRI) and the Hammersmith Infant Neurological Assessment (HINE). The GMA takes a gestalt approach for observing and identifying infant movement patterns in supine and then classifying these patterns as “normal” or “abnormal”, with abnormal patterns being highly predictive of CP. [19 20] Since this assessment is based on a gestalt approach, there are currently no objective measurements of “normal” and “abnormal” movement patterns. The results from this study can inform future studies and aide in identification of kinematic variables of interest that may be used to objectively quantify the movement patterns identified in the GMA.

6 Conclusion

Underlying spontaneous infant movement of the upper extremities is related to fine and gross motor development in early infancy. The results from this study suggest that the length of the upper extremity movement and the smoothness of the movement, regardless of the presence of a toy, are related to better fine and gross motor development, as measured by a commonly used clinical outcome measure. Understanding these inherent underlying movements has implications for improved diagnostics for infants with abnormal movement patterns and targeting neurorehabilitation interventions to improve motor development.

7 Figures





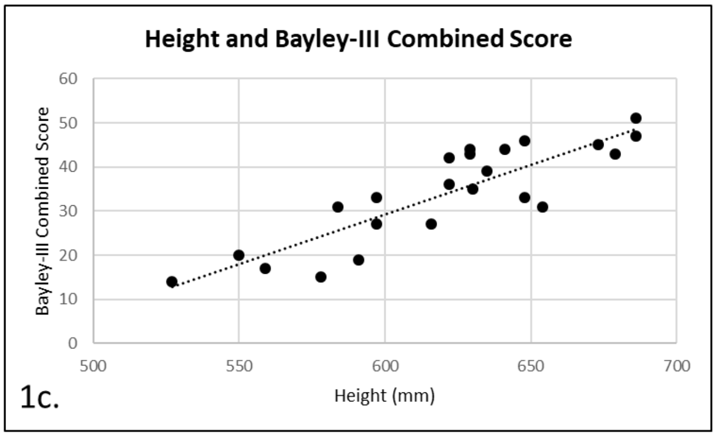
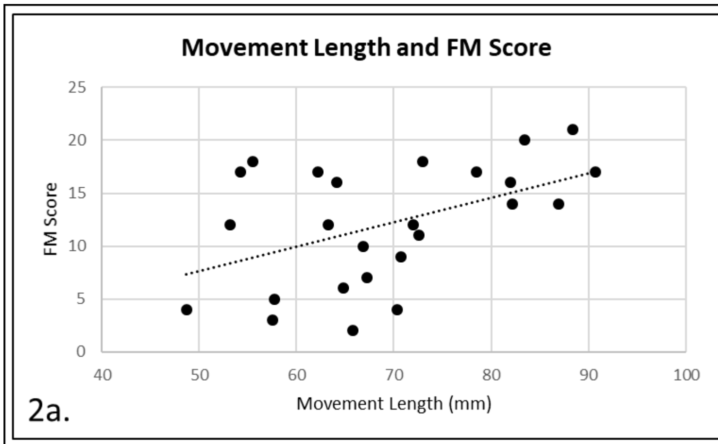
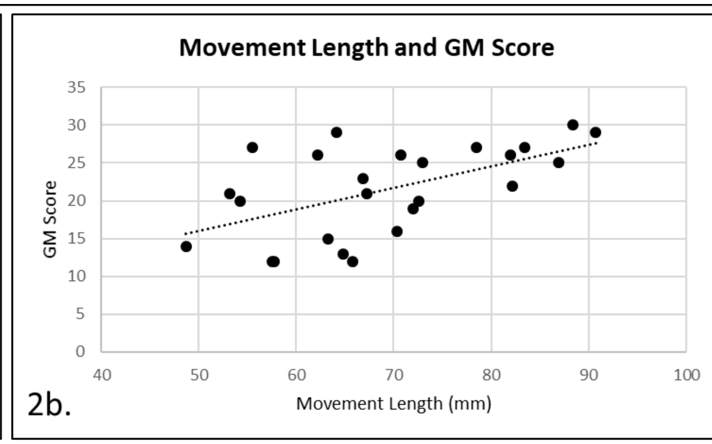


Figure 1: Height compared to scores on the Bayley-III.

1a. Graph depicting a significant, strong, and positive relationship between height and FM score (r=0.85, p=<0.001).
1b. Graph depicting a significant, strong, and positive relationship between height and GM score (r=0.84, p=<0.001).
1c. Graph depicting a significant, strong, and positive relationship between height and Bayley-III combined score (r=0.86, p=<0.001).





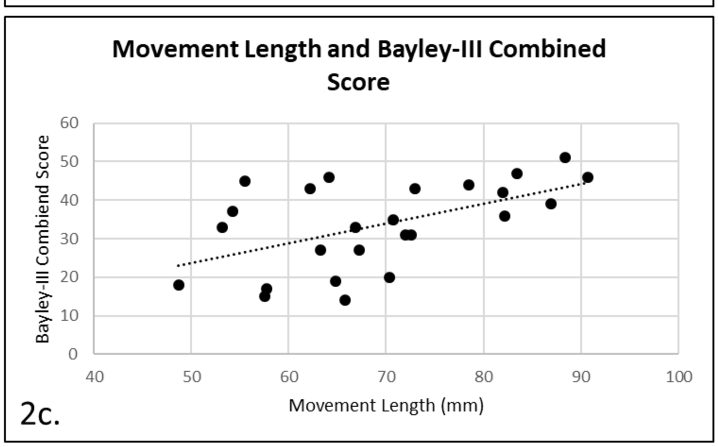
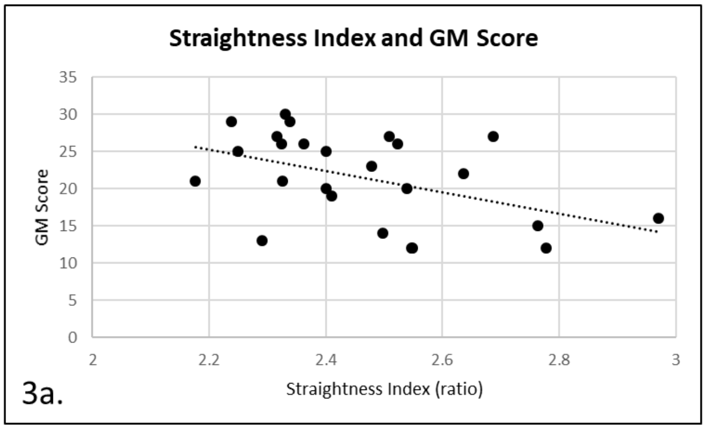


Figure 2: Movement length compared to scores on the Bayley-III.

2a. Graph depicting a significant, moderate, and positive relationship between movement length of the upper extremities and FM score (r=0.41, p=0.04).
2b. Graph depicting a significant, moderate, and positive relationship between movement length of the upper extremities and GM score (r=0.52, p=0.01).
2c. Graph depicting a significant, moderate, and positive relationship between movement length of the upper extremities and combined Bayley-III score (r=0.50, p=0.01).



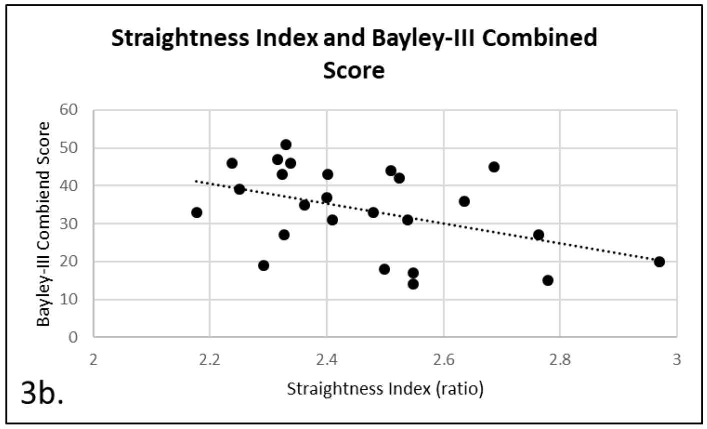


Figure 3: Straightness Index compared to scores on the Bayley-III.

3a. Graph depicting a significant, moderate, and negative relationship between straightness index and GM score ($r=-0.46$, $p=0.02$).

3b. Graph depicting a significant, moderate, and negative relationship between straightness index and Bayley-III combined score ($r=-0.44$, $p=0.03$).

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