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Development of reaching in infancy

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Abstract The development of reaching for stationary objects was studied longitudinally in 12 human infants: 5 from the time of reach onset to 5 months of age, 5 from 6 to 20 months of age, and 2 from reach onset to 20 months of age. We used linear mixed-effects statistical modeling and found a gradual slowing of reach speed and a more rapid decrease of movement jerk with increasing age. The elbow was essentially locked during early reaching, but was prominently used by 6 months. Differences between infants were distributed normally and no evidence of different types of reachers was found. The current work combined with other longitudinal studies of infant reaching shows that the increase in skill over the first 2 years of life is seen, not by an increase in reaching speed, but by an increase in reach smoothness. By the end of the second year, the overall speed profile of reaching is approaching the typical adult profile where an early acceleration of the hand brings the hand to the region of the target with a smooth transition to a lower-speed phase where grasp is accomplished.

Introduction

The development of human infant reaching has engendered considerable interest over the last decades. Developmentalists are interested in describing the course of the development of reaching and in using reaching as a model system with which to investigate the processes underlying development. Nondevelopmentalists are interested in understanding the development of reaching as a case of motor learning and in its implications for the understanding of how adults control their reaching movements.

The development of electronic motion-analysis systems in the last decade has led to a burst of reports analyzing the development of reaching. This research provided data that falsified earlier hypotheses about the development of reaching. For example, while it seemed reasonable that infants would reach faster as they become more proficient reachers (Halverson 1933), only Konczak et al. (1995) found an increase in reaching speed with development, and that increase disappeared when reaching speed was normalized by the distance of the reach.

While Konczak et al. (1995, 1997), Konczak and Dichgans (1997), Thelen et al. (1996), and von Hofsten (1991) provide a substantial body of data, the literature on infants reaching for stationary objects is not without controversy. For example, the number of peaks in the hand-speed profile: von Hofsten (1991) observed that the number of peaks decreases with age, but Fethers and Todd (1987) found that the number of peaks is relatively stable with age. This disagreement is important because Berthier (1996), von Hofsten (1979), and von Hofsten (1991) argued that the multiple peaks in infant hand-speed profiles indicated the presence of multiple action or movement units. This suggestion was disputed by Thelen et al. (1993) who contended that the multiplicity of peaks largely reflected the uncontrolled dynamics of the arm. Thelen et al.'s (1993) argument was supported by Berthier et al. (2005) who showed that when two or three actions were applied to a dynamical model of an infant arm, five or six peaks in the speed profile were observed.

Regardless of the controversy concerning what individual kinematic descriptors reflect, the published data conflict. While the discrepancies may reflect differences in experimental procedures (e.g., Fethers and Todd (1987) and von Hofsten (1979) used older video-based methods), they may also be the result of the small number of subjects upon which the reports are based. For example, the three long-term longitudinal studies of infants reaching for stationary objects (Konczak et al. 1997, 1995; Konczak and Dichgans 1997; Thelen et al.

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1996; von Hofsten 1991) report data from only a total of 18 infants. Even though these studies provide dense longitudinal data, the fact that they are each based on so few infants, limits their generalizability. For example, Thelen et al. (1993, 1996) intensively studied four infants over the first year and concluded that infants show different developmental trajectories. This leads to the possibility that if Thelen et al. (1993, 1996) had studied a different group of four infants, different developmental patterns would have been observed. Perhaps, a diversity of developmental patterns has led to the discrepancies in the literature. In order to obtain a more complete view of the development of infant reaching, the present paper adds 12 infants' data to the existing corpus of longitudinal data and explicitly examines the kinematics of reaching across studies.

Recent advances in statistics also provide a more powerful and informative way to analyze longitudinal data. Previously, longitudinal data were analyzed using repeated measures analyses of variance, but the development of linear and nonlinear mixed-effects models or hierarchical linear models (Goldstein 2003; Pinheiro and Bates 2000) allows for the linear and nonlinear modeling of longitudinal data without the requirement that the data be balanced. The balanced data requirement of traditional analysis of variance is particularly troubling in long-term longitudinal studies with human infants because missing sessions are common and data loss due to the lack of the infant's compliance is usually substantial. The mixed-effects models also have the important added advantage of being able to estimate the variability of the population from which the sample is drawn. This allows for an estimate of the differences in the patterns of data of different infants, an important theoretical factor that has been emphasized by Thelen et al. (1993, 1996), who concluded that different infants show different patterns of development.

Besides providing a description of the development of the kinematics of infant reaching, we also sought to deepen our understanding of how development occurs. Thelen et al. (1993) argued that the process of development of reaching involves self-organization and discovery of useful patterns, von Hofsten (1993) described development as a search of the task space for actions, while Berthier (1996) and Berthier et al. (2005) have provided models of interactive learning that discover useful patterns of reaching. While reaching in older children and adults involves the use of forward and inverse models (e.g., Jansen-Osmann et al. 2002), it seems unlikely that accurate dynamical models would be employed by 4-month-old infants at the onset of reaching (they are not necessary in simulated reaching, see, Berthier et al. 2005). More likely, action selection involves choosing movements that take the hand to the target rapidly, smoothly, accurately, and with low energetic costs. Thelen et al. (1993) suggested that actions that minimize or counteract the motion-dependent torques

that occur during reaching are preferred, a suggestion that was not confirmed by Konczak et al. (1997). Berthier (1996) has suggested that infants attempt to reach targets in minimal time. In considering these various descriptions, Engelbrecht's (2001) discussion of various criteria that could be used to evaluate reaching movements for fitness may be helpful.

Because action selection ultimately operates at the level of limb forces, two groups of investigators have used inverse dynamical models in an attempt to estimate how limb forces change with development (Thelen et al. 1993; Konczak et al. 1997, 1995; Konczak and Dichgans 1997). Those studies show that development leads to both smoother hand paths as well as smoother joint-torque profiles. In the current paper, we not only measured how hand speed and reach straightness change with development, but we also computed the jerk of movements. Jerk is the third derivative of position with respect to time and Flash and Hogan (1995, 1985) have argued that it is optimized to select movements. Jerk is also related to torque change so that computing jerk provides an indirect measure of net joint torque (Uno et al. 1989). We emphasize that we did not attempt to determine which metric is used during development because infants probably do not use a single, quantifiable metric; instead we simply computed descriptive variables that assessed the straightness, smoothness, speed, and jerkiness of reaching, qualities that would all be important to a reacher, determining which movements were good or bad.

But given the dynamical complexity of human limbs, what mechanisms are used by the infants to achieve smooth reach profiles? Bernstein (1967) realized that simple random search would fail because of the large number of possible actions and because of the nonlinear mapping of motor commands to actions. To address this problem, Bernstein (1967) suggested that novices would limit the dynamical complexity of the task by stiffening joints, a simplification that would reduce the nonlinearity of movement as well as reduce the number of possible actions. Joint stiffening in novices has been observed in studies of adults (Vereijken et al. 1992; Newell and van Emmerik 1989) and infants (Berthier et al. 1999; Spencer and Thelen 2000). In infants, Berthier et al. (1999) showed that during the first week of successful reaching, little change in elbow angle was observed during reaching and Spencer and Thelen (2000) showed that early reaching movements were controlled by the proximal musculature of the shoulder. Halverson (1933) had also previously noted that early reaching is largely accomplished by shoulder movement. Of course, joint stiffening reduces the capabilities of the arm and increases the energetic cost of movement so we can expect to observe joint stiffening only in the initial phases of learning. Our last major goal of the current work is to describe the developmental time course over which infants begin to use the elbow joint in reaching.

Methods

Subjects

Twelve infants participated as subjects in the current experiment. All infants were the result of full-term pregnancies and were in good health on the day of testing. Data from some of these infant's first reaching sessions were reported in Berthier et al. (1999). Families received a small gift for each experimental visit (usually a small toy or book). The experimental procedure was reviewed and approved by the institutional human subjects committee. Informed consent was obtained from the infants' parents.

Equipment and procedure

Young infants were seated on one of their parent's laps during experimental sessions. The parent was asked to hold their infant firmly around the hips so as to support the infant and allow for free movement of the infant's arms. The parent was further asked to refrain from attempting to influence the infant in any way. Depending on the infant's level of comfort, older infants were seated in an infant booster seat with the seat belt fastened. In both situations, infants reached naturally and because the target object was held within arm's length of the infant, little trunk flexion was observed.

Data was obtained from two longitudinal studies. The first was designed to study reaching for the first several weeks after reach onset and five infants were tested at least once a week in the laboratory from several weeks before to 4 or 5 weeks after reach onset. Typically, infants were tested from 9 to 22 weeks of age in this study. A second study was intended to study the development of reaching from 6 to 20 months of age. Five infants participated in this study and were tested in the laboratory at monthly intervals until a year of age and quarterly intervals thereafter. Lastly, two infants were enrolled in the first study and were also studied until 20 months of age. As with other studies of infants, missing sessions occurred with sickness, vacation, noncompliance of the infants, obstructed motion analysis markers, and fussiness.

Infants younger than 160 days reached exclusively for a colorful plastic toy (Sesame Street's Big Bird, 7 cm length). The toy was attached to a rattle and held by an experimenter who sat facing the infant. Because older infants quickly became uninterested in the single toy, older infants reached for a group of small plastic toys and infants over a year of age were also asked to reach for small oat breakfast cereal (Cheerios). At the beginning of each trial, the presenter attracted the attention of the infant to the toy and slowly brought it forward to a position 15–25 cm away from the infant. To encourage use of the right hand, the toy was presented approximately 30° in the horizontal plane to the infant's right.

In all cases, the target object was presented as still as possible when the infant was reaching.

Infants were videotaped throughout the session at 30 frames/s with an infrared camera (Panasonic WV1800) placed to the right of the infant for a side view of the reaches. In addition to the videotape, the reaches were monitored using an Optotrak motion-analysis system. This system consisted of three infrared cameras that generated estimates of a marker's position in three-dimensional coordinates. In the current experiments, four infrared emitting diodes (IREDs) were used as markers. The Optotrak system estimated the positions of these markers at a rate of 100 Hz. Position data were acquired during 10–20 s trials. Two IREDs were taped on the back of the infant's right hand, one just proximal to the joint of the index finger and one on the ulnar surface just proximal to the joint of the little finger. These two IREDs were used on the hand in order to keep at least one in camera view if the infant rotated his or her hand during the reach. Infants tended to ignore the IREDs once they were in place. One IRED was also placed on the apex of the infant's shoulder and one on the lateral edge of infant's elbow. The Optotrak cameras were placed above and to the right of the infants.

The video camera output was fed through a date-timer (For-A) and into a videocassette recorder (Panasonic Model 1950), and a video monitor (Sony Model 1271). The Optotrak system and the date-timer were triggered simultaneously by a second experimenter in order to time-lock the IRED data with the video-recorded behavior for later scoring. The second experimenter was seated out of view, triggered the data collection by the motion analysis system, and observed the infant on the video monitor.

Kinematic data analysis and computational methods

Videotapes were first examined for any significant movement of the hand that was made in the presence of the goal object. We defined a reach as a forward movement of the hand toward the goal object that was accompanied by the attention of the infant to the goal object, usually visual attention, and by the viewer's judgment that the infant was in fact attempting to reach for the toy, not simply batting at it or touching it incidentally in a movement toward the mouth, body, or contralateral hand. We also eliminated small arm movements where the infant obtained the goal object through experimenter errors when the presenter presented the object too close to the infant so as to almost place the object in the infant's hand without significant movement on the infant's part.

Reach onset was defined as the point in time when the hand started to move forward toward the goal object as judged by frame-by-frame observation of the videotape. Backward, upward, or other preparatory movements before forward movement were not considered part of the reach proper. These preparatory movements were

easy to score because they often involved large movements, such as an upward movement from the infant's thigh to their shoulder. The end of the reach was defined by the time of contact with the target object. In practice, segments of the video were scored for when infants made contacts with the target and then the videotape was re-wound, frame-by-frame, until the point where the infant's hand first made a discernible forward movement to the target.

The data obtained from the Optotrak system are estimates of the true IRED position at the time of the sample. The dynamic programming method of Busby and Trujillo (1985) was used to estimate the position, velocity, and acceleration of the hand. The algorithm assumes that the marker is a point moving through space and computes a smooth path based on a minimal input control. We used the criteria suggested by Busby and Trujillo for selecting the parameter B and used $B = 1 \times 10^{-11}$ (Berthier 1996; Milner and Ijaz 1990). While exact comparisons are difficult because of the algorithm, the data reported here are similarly smoothed to traditional low-pass filtering with a cutoff frequency of 30–50 Hz.

The data filtering resulted in estimated velocity and acceleration vectors in three-dimensional space for each data sample. The instantaneous jerk (third derivative of position) was estimated by taking the temporal differences of the acceleration vectors. The speed (tangential velocity or resultant speed) was calculated as the magnitude of the velocity vector and the total squared jerk of a movement was estimated by summing the squared instantaneous jerk over the time of the reach.

As we and others have found, young infants reach toward targets using multiple accelerations and decelerations of the hand. We analyzed the amplitude and timing of these individual peaks to determine if there were any dependencies in the peak amplitudes. To determine the time of a speed peak, we smoothed the speed data with a three-point moving average filter. We then defined peaks as times when the two previous samples of the smoothed speed function had positive slopes and the two succeeding samples of the smoothed speed function had negative slopes. Typically, each reach contained a number of distinct speed peaks and the times and amplitudes of these speed peaks were then noted.

Two other variables were calculated from the peaks in the hand-speed profile. First, the largest peak in a reach was identified. One variable was then calculated as the time of that peak in milliseconds from the start of the reach. A second variable, percent peak, was calculated by dividing the time of the largest peak by the movement time of the reach. The value of the latter would be 0.50 if the peak occurred in the middle of the reach and 0.25 if the largest peak occurred one quarter of the way through the reach.

Because our infants made unconstrained reaches in three dimensions, we computed kinematic measures that were relatively reliable, direct, and did not assume any

particular kinematic or dynamical model of the arm. For example, instead of attempting to estimate the elbow angle, which would have been difficult with our marker arrangement, we simply used the difference of the hand marker from the shoulder marker. Because the arm is composed of essentially rigid links, the hand–shoulder distance is an increasing monotonic function of the elbow angle.

Previous work showed that the elbow was relatively fixed at the developmental onset of reaching (Berthier et al. 1999; Spencer and Thelen 2000). Because a major goal of the current work was to determine the development of elbow utilization in infants, we computed the change in hand–shoulder distance during a reach as an index of the change in elbow angle during that reach. To this end, we subtracted the shortest hand–shoulder distance during the reach from the largest hand–shoulder distance during that reach. If the elbow was locked during a reach, that difference was zero, if the elbow angle showed a large change during a reach, that difference was large.

The straight-line distance from the position of the hand marker at the start of the reach to the position of the same hand marker at the end of the reach was calculated. The hand-path length was calculated by summing the differences in hand-marker position during the reach. A straightness measure was computed by dividing the path length of the reach by the distance of the reach. Path curvature was not used as a measure of straightness because it is strongly dominated by changes in the direction of the hand and noise of the measurement system at low speeds.

Results

Infants typically started reaching at about 16 weeks of age. Apart from missed sessions due to illness or vacation, data acquisition with infants over a year of age was especially challenging because some infants would not tolerate the Optotrak markers placed on their hands (this is the reason data collection stopped for infants 1 and 3 and why the session is missing at 16 months for infant 5). When Optotrak data was collected, 35.1% of the reaching trials were lost because the motion-analysis system lost sight of the markers. Overall, data was obtained from 82 experimental sessions from infants of 95–653 days of age. Table 1 describes the usable data set.

We computed 11 variables that are typically used to assess infant reaching with the purpose of determining whether all of these variables were necessary to provide a full accounting of how infant reaches develop. Was there a smaller set of variables that provides an adequate description of the development of reaching? For example, do average and peak speed furnish us with independent information and thus both need to be used in our description or do they present highly correlated information that only informs us about a single under-

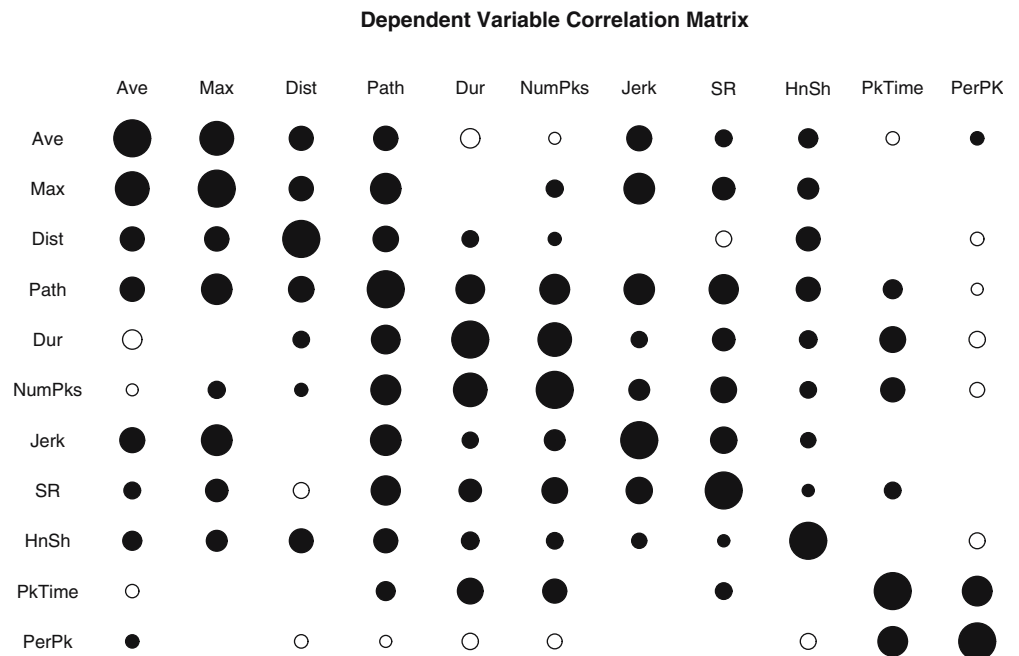
Table 1 Description of the sample of usable Optotrak data

Infant	Age range (days)	Sessions with usable data	Total number of trials with usable data
1	174–394	7	60
2	114–482	13	67
3	191–299	4	46
4	197–381	6	41
5	168–653	7	48
6	123–616	14	94
7	98–651	12	47
8	95–121	5	11
9	121–135	3	10
10	118–146	4	14
11	126–154	4	21
12	130–142	2	3

lying variable? If variables do not give independent information, how do we determine the key variables that supply critical information? By eliminating redundant information from our computed variables we hope to uncover the underlying processes undergoing developmental change.

Our first step in this analysis was to compute the correlation matrix across the variables for all infant reaches. These calculations did not attempt to remove variance that was due to individual infants or due to age, but simply aggregated all the reaches together in a single data set. If the resulting correlation matrix shows correlations that were small in magnitude, we would conclude that the variables provided independent information and informed us about different aspects of infant reaches. On the other hand, if particular variables showed high correlations, we would suspect that those correlated variables might be informing us about single underlying variables.

Fig. 1 Dependent-variable correlation matrix with the magnitude of the correlation represented by the area of each disk, with filled disks being positive correlations and open disks being negative correlations. For scale, the diagonal displays correlations of 1.0. *Ave* average speed, *Max* peak speed, *Dist* straight-line distance of the hand to the target at the start of the reach, *Path* hand path length, *Dur* movement time, *NumPks*, number of speed peaks, *Jerk* total squared jerk, *SR* straightness ratio, *HnSh* hand-shoulder distance change, *PkTime* time of peak speed in ms, *PerPk* time of peak speed in percent movement time



Because the distribution of the jerk-dependent variable was strongly skewed to the right, movement jerk was log-transformed for the current analysis. Fig. 1 shows the resulting correlation matrix in graphical form. In the figure, the magnitude of each pair-wise correlation is given by the area of the corresponding disk, with filled disks representing positive correlations and open disks representing negative correlations. For reference, the diagonal of the matrix displays autocorrelations of the variables which are necessarily 1.0. Correlations that were not significant at the 0.05 level are not displayed.

Inspection of Fig. 1 indicates that many of the dependent variables were substantially correlated with each other. For example, average speed (*Ave*) and peak speed (*Max*) were correlated at the 0.83 level, and the path length (*Path*), temporal duration (*Dur*), and number of speed peaks (*NumPks*) were correlated between 0.60 and 0.68.

The high correlation between the number of speed peaks and the temporal duration and path length suggested that speed peaks were occurring at relatively consistent intervals. Subsequent analysis of peak timing showed that the peaks occurred with a median temporal interval of 190 ms with the central 50% of the inter-peak intervals ranging from 140 to 270 ms.

The large number of nonzero correlations in the matrix indicated significant dependence among our dependent variables and suggested that the observed pattern could be the result of variation in a smaller set of underlying variables. To determine whether a smaller set of underlying variables could be discovered, we performed a maximum-likelihood factor analysis. Factor analysis was chosen over principal component analysis because the aim was more to discover the underlying factors than to generate a compact representation of the data.

We performed our analysis using the factorial procedure in the R statistical package (<http://www.cran.r-project.org>). The analysis standardized each variable so that scale differences were eliminated. We used a standard varimax rotation and started our analysis with three factors and increased the number of factors until a good model of the data was obtained. The fit of the statistical model to the data was assessed by comparing the model's correlation matrix with the correlation matrix computed from the data. This procedure was used instead of using the overall proportion of variance explained because it assessed the fit of the model at the level of the pair-wise correlations between the variables. A good model of the data would be one that preserves these pair-wise correlations, whereas a model with overall good fit in terms of proportion of variance explained might be deficient in that it distorted the pair-wise relationship between two variables.

With three factors in the model, the largest discrepancy between the two matrices was 0.42, with four factors the largest discrepancy was 0.10 and with five, 0.06. The results of the analysis with five factors are presented in Table 2. The factor analytic model explained 84% of the variance of the data with all the dependent variables being well modeled by the analysis except the variability in hand-shoulder distance which had a high uniqueness (0.74). The first factor heavily loaded on the variables that measure the speed and jerk of the reach; the second, the temporal duration of the reach and the number of speed peaks; the third, the time of peak speed; the fourth, the distance covered by the reach; and the fifth, the straightness of the reach.

In sum, the current 11 dependent variables did not provide independent information and a factor analysis found that infant reaches could be described by a smaller set of five underlying variables. While some of these relationships were expected, others were not. For example, while it is possible that the peak speed of a reach could be independent of the average speed of a reach, a high correlation between the two would be expected. On the other hand, there is no a priori reason to expect that the number of speed peaks in a reach would be highly correlated with the length of the hand

path or with the temporal duration of a reach as we observed.

Changes in reach kinematics with age

Because of the unbalanced nature of our longitudinal data, we used mixed-effects models to analyze the data. Mixed-effects models consider the within- and between-subject variability and produce population and individual regression coefficients that can be tested for significance. We used data from individual reaches in estimating the regression coefficients. In the current work, the nlme package in the R statistical program was used to estimate the regression coefficients.

Mixed-effects modeling allows for both linear and nonlinear regressions. Apart from the hand-shoulder variability measure where we expected an increase and a leveling off with age, we had no strong theoretical reason to assume either a linear or nonlinear model for development. Thus, we explored several types of models in the initial phases of our analysis. We found that nonlinear models did not improve the fit over a standard linear model so linear mixed-effects models were used in the current analyses. The hand-shoulder variability-dependent variable was analyzed separately (see below).

In plotting the prediction residuals of the linear fits, we discovered significant departures from normality. Because normality of the residuals is a requirement of mixed-effects models and because the residuals were positively skewed, we recomputed the linear fits after logarithmic transformation of the data (i.e., $\ln(y) = b + ax$) This procedure normalized the residuals while at the same time producing approximate homogeneity. Viewed in the untransformed, original coordinates, the logarithmic transformation produces exponential fits of the form: $y = e^b \cdot e^{ax}$, with the y -intercept given by the value of e^b and the decay of the exponential function given by a . While these exponential fits could in principle show significant curvature in the original coordinate system, the regression curves resulting from the current analysis only slightly departed from straight lines (see Fig. 2). The advantage of this procedure was not that it

Table 2 Results of the factor analysis

DV	Uniqueness	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5
Average speed	0.13	0.80	-0.32		0.33	0.13
Maximum speed	0.08	0.90			0.30	0.14
Distance	0.16	0.22			0.87	-0.16
Path length	0.09	0.51	0.54		0.44	0.41
Duration	0.08		0.92		0.21	0.15
Number of speed peaks	0.17	0.16	0.88			0.17
Jerk	0.17	0.87	0.25			0.13
Straightness ratio	0.01	0.30	0.32		-0.16	0.88
Hand-shoulder distance	0.74	0.24	0.19	-0.12	0.39	
Time of speed peak	0.18		0.46	0.78		
Percent MT speed peak	0.005	0.10	-0.21	0.96	-0.14	
Cumulative variance		0.25	0.47	0.61	0.74	0.84

allowed for curvilinear fits of the data, but that it normalized the regression residuals.

Table 3 shows the results of the linear mixed-effects modeling for our dependent variables. Of primary interest in our investigation was whether the dependent variable varied as a function of age of the infant. A test of this is provided in the test of the a against 0. The P -values for these tests are given in the fourth column of the table. Of the ten regressions, four of the decay parameters were significantly different from 0 and all of these were negative in sign indicating a decreasing function of age. Even though these parameters were small in magnitude, because of the nature of the exponential fit the parameters indicate substantial decreases with age. Plots of the overall fits for across infants are given in Fig. 2 and inspection of that figure shows significant downward trend in the prediction with age for some of the dependent variables. Table 3 numerically gives the effect of age in the fifth (intercept) and sixth

(2 years) columns which gives the model's predicted value at age 0 and at 2 years of age. For example, the predicted peak speeds of the reaches decreases from 535 to 223 mm/s over the first 2 years of life.

Significance test of the decay parameters (fourth column) showed that the average and peak speed and the total jerk of the reach decreased as the infant aged, and that the straightness of the reach increased with age, and that the time of peak speed decreased with age. Fig. 2 shows population plots of the fitted functions for the dependent variables as a function of the infant's age.

The preceding information describes the development of the average infant, but mixed-effects modeling also provides information about the infant-to-infant variability in development. Fig. 3 shows plots of changes in peak speed, jerk, straightness, and time of the peak speed for the four infants in the study whose data spanned the most time. The plotted lines are the individual regression curves for the four infants and the dots

Fig. 2 Plots of regressions for the dependent variables

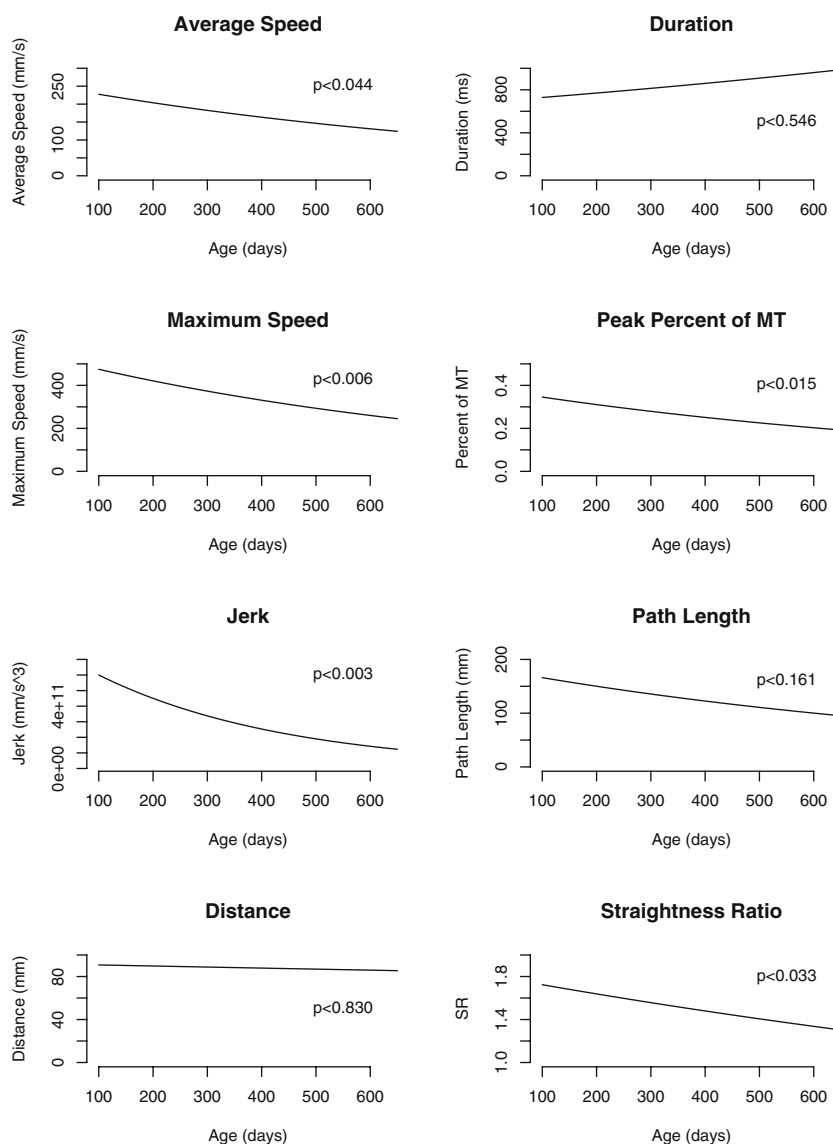


Table 3 Estimated regression parameters with *P*-values for tests of the parameters against a null hypothesis that they equal 0

Dependent variable	<i>a</i>	Between <i>S</i> variability	<i>p</i>	Intercept (e^b)	Value at 2 years	Between <i>S</i> variability	<i>p</i>
Average speed (mm/s)	-0.0011	0.00125	0.044	254	114	185–353	0.000
Maximum speed (mm/s)	-0.0012	0.00088	0.006	535	223	410–690	0.000
Distance (mm)	-0.0001	0.001	0.830	92	86	68–120	0.000
Path length (mm)	-0.0010	0.00125	0.161	184	89	116–263	0.000
Duration (ms)	0.0006	0.00078	0.546	689	1068	436–944	0.000
Speed peaks (n)	-0.0002	0.00025	0.238	2.67	2.31	2.18–3.36	0.000
Jerk (mm/s ³)	-0.0029	0.0024	0.003	$e^{27.5}$	$e^{25.4}$	$e^{26.6}$ – $e^{28.1}$	0.000
Straightness ratio	-0.0005	0.00055	0.033	1.81	1.26	1.39–2.16	0.000
Time of peak Speed (ms)	-0.0004	0.00067	0.247	256	191	175–375	0.000
Time of peak speed (%)	-0.0011	0.000938	0.015	.384	0.172	0.266–0.556	0.000

The fits were performed on log-transformed data so that the fit equation was $\ln(y) = b + ax$. The column labeled between *S* variability after the *a* coefficient is the estimated standard deviation of the *a* coefficient across the subjects and that labeled between *S* variability after the intercept column is the mean plus and minus one standard deviation of the intercept across subjects back-transformed to the original units of the data

are the means for that dependent variable for that testing session. While the same general trend in the fit can be observed across infants, differences are apparent when different infants are compared. For example, the third infant in each panel showed a dramatic decrease in the speed and jerk of reaching during development, but the other three infants showed more modest decreases in these measures.

Estimates of the infant-to-infant variability are numerically provided in mixed-effects modeling by estimates of the variability of the regression coefficients in the population. This is an estimate of the variability of the data in the population from which the subjects are randomly drawn and should not be confused with confidence limits or error bars around the estimates of the group coefficients. These estimates of variability between subjects in the population are provided in Table 3 in the columns labeled “Between *S* Variability.” The column after the one labeled “*a*” is the estimated standard deviation of the decay parameter across infants, and the one after the column labeled “intercept” is the group average plus and minus one standard deviation of the intercept parameter back-transformed to the original scale of measurement. The latter was done because of the logarithmic transformation of the data.

These estimates of variability between randomly sampled infants are fairly large and confirm that the developmental changes in reach kinematics are quite different from infant to infant. While the variability in the coefficients is considerable, when the individual coefficients were plotted the distribution appeared roughly normal without any grouping or categorical differences between infants. That is, no evidence was found for groups of “slow reachers” and “fast reachers,” but rather reaching speeds varied normally across infants.

The dependent variable that measured the use of the elbow degree-of-freedom was analyzed differently. Berthier et al. (1999) had shown that the distance between the hand and shoulder was almost constant when infants

began to reach indicating that the elbow was relatively fixed at the onset of reaching. Because the change in the hand–shoulder distance was negligible for most reaches at the onset of reaching, we hypothesized that the change in the hand–shoulder distance would be minimal at the very onset of reaching and increase with increasing age, perhaps leveling off at some point when the elbow was fully employed by infants. Because we expected an increase followed by a leveling off, we used piecewise linear or “broken-stick” regression when modeling the change in hand–shoulder distance with age. Initial regressions indicated a skewed distribution of residuals so the data were again log-transformed. Regressions were then performed with two linear segments and the break point between the segments being varied from 150 to 250 days of age in steps of 10 days. We found that the best fit of the data using the AIC criterion was obtained for a break point at 180 days.

The best-fit regression equation with a break at 180 days was

$$y = e^b e^{a_1 x}, x \leq 180$$

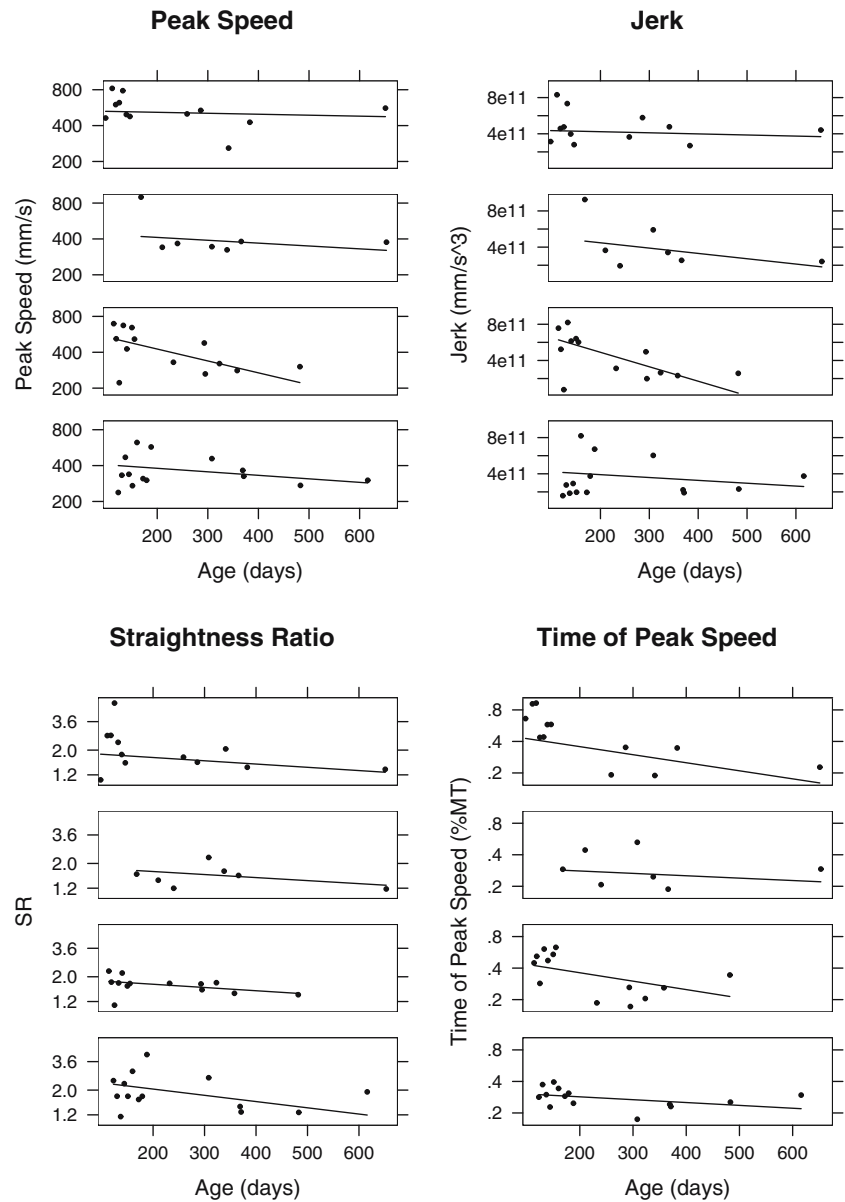
$$y = e^b e^{a_2 x}, x > 180$$

where $b = 3.530$, $a_1 = 0.013$, and $a_2 = -0.0024$. The *P*-values for the three coefficients were 0.0001, 0.0043, and 0.179, respectively, indicating a statistically significant increase in hand–shoulder distance variability up to 180 days of age followed by relatively constant hand–shoulder distances over the next year and a half. A plot of the hand–shoulder variability fit as a function of age is shown in Fig. 4.

Discussion

With the addition of the current data, there are now four studies using modern motion-analysis systems that have longitudinally studied a total of 30 infants in infancy. These studies all agree that successful, goal-directed

Fig. 3 Fits of HLM regression lines for four individual subjects on peak speed, movement jerk, straightness ratio, and time of peak speed as a fraction of movement duration. Each panel shows the fit for the four subjects with the broadest range of data. The subjects displayed are numbers 7, 5, 2, and 6, from top to bottom. Because the fits were preformed on log-transformed data, each point in the figure is the geometric mean for that individual's testing session



reaching is observed in infants starting at about 16 weeks of age. A summary of the data sets of these studies and relevant cross-sectional studies is provided in Table 4 organized by the first five factors in the factor analytic model given in the results section above.

The factor analysis produced several results. First, the analysis showed that the large number of typically computed descriptive variables are highly intercorrelated and that they do not produce independent information about infant reaching. Second, the analysis informed us that infant reaches vary only along about five dimensions: speed/jerk, number of speed peaks/duration, time of peak speed, distance of the reach, and straightness of the reach. The variability along these dimensions is due to both changes with age and differences among infants. To assess how infants differ, we need only to use these five dimensions. Lastly, the analysis provided unex-

pected information about kinematic differences in that the number of speed peaks was linearly related to the temporal duration of the reach.

Several developmental trends are apparent in the results. First, and not surprisingly, infant reaches are significantly curved at the youngest ages and they become substantially straighter by 2 and 3 years of age. Straightness ratios are generally around two at reach onset and decrease to about 1.3–1.4 by 2 and 3 years of age. The straightness ratio at the end of infancy approaches, but is still substantially different from adult straightness ratios, which are typically close to 1.0 for unobstructed reaching (e.g., Churchill et al. 2000).

The second consistent developmental trend is that the time of maximum hand speed during the reach moves closer to the beginning of the reach with age. The current results together with Konczak et al. (1995, 1997)

Fig. 4 Regression of hand–shoulder distance variability on age. The plot is with the right-hand side slope coefficient equal to 0 because the *P*-value did not indicate a difference of the fit coefficient from 0

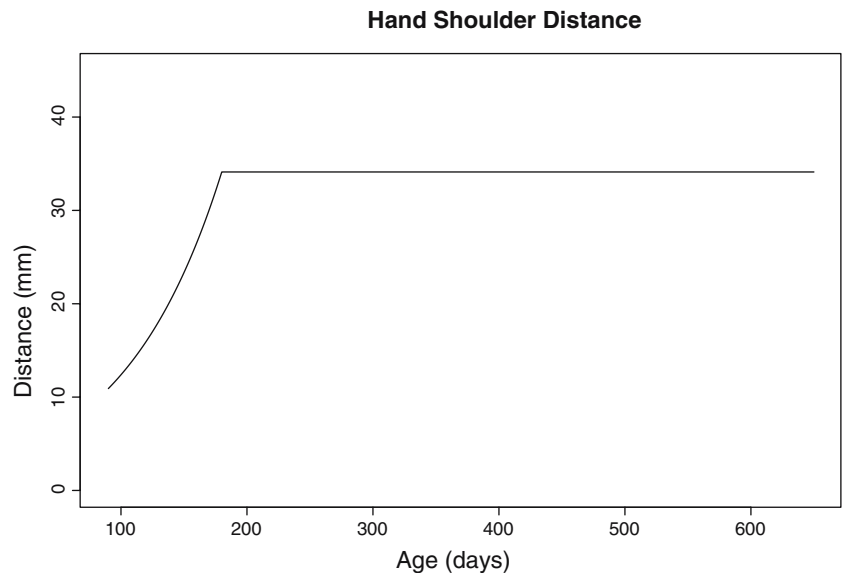


Table 4 Results of previously published studies of the development of reaching in human infants

Paper	Number of subjects	Ages (weeks of age)	Speed (mm/s)	NumPks	MaxSpeed time	Distance	Straightness
<i>Longitudinal</i>							
von Hofsten (1979) (videotape)	5	12–36					4.5–2.0
Fetters and Todd (1987) (film)	10	21–41	Decreases	2.7			2.1
von Hofsten (1991)	5	19–31	406–426 (Max; ns)	4.02–2.44			2.19–1.29
Thelen et al. (1993, 1996, 2000)	4	3–52	236–186 (Ave) 473–348 (Max)	2.38–1.58			1.29–1.15
Konczak et al. (1995, 1997)	9	18–156	560–1,170 (Max) 520–760 (Norm; ns)	5.2–1.5 1.2–0.9 (Norm)	0.50–0.40	Increases	3.1–1.3
Current	12	14–93	240–140 (Ave) 490–250 (Max)	2.5	0.35–0.20		1.75–1.38
<i>Cross-sectional</i>							
Matthew and Cook (1990) (videotape)	30	20, 26, 34	102, 131, 173 (Ave) 877, 974, 806 (Max)	5.6–3.1 3.5–2.4 (Norm)		Increases	2.6–1.6
Berthier and McCarty (1995)	48	22.5, 31.5, 40.5	389, 338, 378 (Ave)	1.4, 1.1, 0.8			
McCarty and Ashmead (1999)	48	22.5, 31.5, 40.5	389, 338, 378 (Ave)	2.5–2.3			2.25–1.6
Newman et al. (2001)	39	22.5–75	432, 301, 382 (Max)		0.40–0.34		

When a hyphenated range is given, the initial number is for the youngest age and the second number is for the oldest age. Berthier and McCarty (1995) and McCarty and Ashmead (1999) are the result of the analysis of the same set of data

and Newman et al. (2001) show that the time of the peak hand speed is between 0.35 and 0.50 of the reach at the onset of reaching and that at the oldest ages the time moves to 0.20–0.40 of the reach. Related to this is the finding of von Hofsten (1991) who found that the largest movement unit of a reach moves closer to the beginning of the reach with age. Together, these results are consistent with the development of a transport phase similar to that of adults where the hand moves toward the target and a grasp phase where grasp is accomplished (Jeannerod 1997).

Two other developmental trends are not as consistently observed across studies. While Halverson (1933) concluded that the speed of reaching increases with age in the infant, modern long-term longitudinal studies

either find a significant decrease in the average or maximum speed during the reach with age (Fetters and Todd 1987; Thelen et al. 1996), or no change (von Hofsten 1991; Konczak et al. 1995, 1997; Konczak and Dichgans 1997). We note the close agreement of Thelen et al.'s (1996) observed average speed of 186 mm/s and peak speed of 348 mm/s at 1 year of age, with the predicted values of, 170 mm/s for average speed at 1 year and of 345 mm/s for peak speed for the current regressions. This agreement is remarkable in that the infants were supported differently in the two studies, reached for different toys, and likely reached different distances. Comparison of the straightness ratios and numbers of speed peaks between the two studies at 1 year showed less agreement (1.51 vs. 1.15 and 2.48 vs. 1.58,

respectively) and indicated that the current infants reached more circuitously than those of Thelen et al. (1996).

Interpretation of differences in reach speed is complicated by that fact that adults show linear increases in reaching speed with increasing distance (e.g., Berthier et al. 1996), and while this relationship was not observed at the very onset of reaching (Berthier et al. 1999), the correlation coefficient between average or maximum speed and distance was 0.42 and 0.43, respectively, in the current data set. Because of this scaling of speed with distance, studies where the distance of the reach increases with age will likely find increases in hand speed with age. For example, Konczak et al. (1995) found that the significant increase in maximum hand speed observed with age become nonsignificant when the speeds were normalized by the distance of the reaches. Thus, the existing data support the conclusion that reaching speed is either stable or decreasing during infancy.

While one might think that a decrease in reaching speed is exactly opposite to what would be expected with an increase in reaching skill, the decrease seems to reflect an increase in the smoothness of reaching. In the current data, average and peak speeds were highly correlated with total jerk of the movement ($r = 0.61$ and 0.76 , respectively) and the total jerk decreased more dramatically with age than either average or peak speeds. The observed decrease in reaching speed and jerk is likely the result of increasing ability to modulate net joint torque through anticipation of motion-dependent torques and by more appropriately timing muscle contractions (Konczak et al. 1995, 1997; Konczak and Dichgans 1997).

The overall trend toward a decrease in reaching speed over the first years of life does not discount the possibility that short-term increases and decreases might be observed with development. Indeed, Thelen et al. (1996) concluded that the few weeks around the onset of reaching is a time when reaching speed increases and then decreases, and Berthier and McCarty (1996) and Newman et al. (2001) observed a significant decrease in reaching speed at 7 months followed by a subsequent increase in speed. These results illustrate that development is not a simple monotonic approach to an ideal, but a complex process that depends on the ability, motivation, and goals of the infant.

The current literature also disagrees on how the number of speed peaks or number of movement units change with development. While von Hofsten (1979, 1991), Mathew and Cook (1990), and Konczak et al. (1995) found that the number of movement units and temporal duration of infant reaching decreases dramatically with age; others have found more modest decreases or relatively good stability in the number of speed peaks (Fetters and Todd 1987; Thelen et al. 1996; Berthier and McCarty 1996). Part of the discrepancy is surely due to subtle differences in the filtering of the data and in the definition of a speed peak or movement unit, but even the decreases observed by Mathew and Cook

(1990) and Konczak et al. (1995) become minimal when the data are normalized by the increase in reach distance that was observed with age.

The finding of relative stability in the number of speed peaks/movement units combined with the high correlation of number of peaks and duration of the reach ($r=0.77$) is consistent with the finding of von Hofsten (1991) who argued that the movement units reflect on-line corrections to the reach, and that the primary or transport- movement unit becomes larger and earlier with development. Von Hofsten (1979) also apparently observed a high correlation between the number of movement units and duration when he observed that both decline over the first 6 months of age. Ample data are available that infants can make on-line corrections and that by and large, the hand changes direction between movement units in a way that corrects the hand's heading (Berthier 1996; von Hofsten 1991). However, the fact that the number of peaks is highly correlated with the temporal duration of the reach and that the number is relatively stable with development suggests that either corrections are applied at regular intervals during reaching or that the timing reflects the natural dynamic frequency of the arm. It is clear that not all of speed peaks/movement units reflect corrections because a single action applied to the arm can result in multiple movement units (Berthier et al. 1999, 2005).

Previously, we found that infants at the onset of reaching adopt a way of reaching that minimizes elbow-flexion and -extension (Berthier et al. 1999). Because we wanted to minimize the errors associated with estimating elbow-joint angle, we used the variability of hand-shoulder distance to assess the elbow movement. At the onset of reaching, this variability was in the order of 1 or 2 cm for a typical reach. Because infants seem highly unlikely to be able to anticipate motion-dependent torques, we concluded that infants were likely employing co-contraction about the elbow to maintain relative fixation. This locking of the elbow was not obligatory as some arm movements showed significant changes in hand-shoulder distance. Spencer and Thelen (2000) showed that infants learning to reach primarily rely on the shoulder musculature to extend the hand to the target. Others have observed limb stiffening in individuals learning to control movements during acquisition of new motor skills (Vereijken et al. 1992; Spencer and Thelen 2000; Newell and van Emmerik 1989).

A key question for the current work was to determine how rapidly after reaching onset, infants begin to use the elbow in reaching movements. We found that the use of the elbow gradually increased, reaching a plateau at about 6 months of age. This period of increasing use of the elbow coincides with the "rapid phase" of motor learning observed by Konczak et al. (1995) and the "active phase" of learning observed by Thelen et al. (1996). The former was a time where the average kinematics across infants showed rapid change and the latter was a time where the speed of reaching increased and then decreased. Particularly in regard to Thelen et al.

(1996), our results suggest that early reaching is a time of high speed, high jerk reaches followed by a slowing of the reach over the period of a few weeks. As the latter slowing occurs, our data shows that the elbow is increasingly employed in executing reaches during this period.

As anticipated by Bernstein (1967), the early fixation followed by later use of the elbow may represent a solution to the degrees-of-freedom problem of motor learning. Thelen et al. (1996) concurred and proposed that the “active phase” of motor learning at 6 months where high reaching speeds were observed represented “an enhanced exploration in the speed-parameter space allowing infants to discover a more globally stable and appropriate speed metric both for reaching movements and for movements prior to reaching.” (p. 1072). Our results provide the first direct data that the elbow is initially fixed at the onset of reaching and becomes increasingly used in reaching by 6 months of age.

Lastly, our mixed-effect models provide a broad summary of infant kinematics with development and necessarily smooth out week-to-week deviations in kinematics. One benefit of these mixed-effects models is that they estimate the infant-to-infant variation in the dependent variables. As seen in Table 3, this variability can be substantial. However, the between-infant variability was normally distributed in our data and did not support the hypothesis that infants differ categorically in their developmental patterns.

Overall, infant reaching shows dramatic increases in straightness and smoothness over the first 2 years of life, with concomitant decreases in reaching speed and jerk. Kinematics change rapidly over the first 2 or 3 months of reaching with infants gradually employing the distal joints to move the hand to the target object. Development is protracted with kinematic change slowing over the second year of life. Significantly, our results agree with Konczak and Dichgans (1997) in showing that reaching skill must show substantial improvement in smoothness and straightness after 2 years of age to achieve adult levels of control.

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