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Toy-oriented changes in hand and joint kinematics during the emergence of purposeful reaching

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Abstract

Infants first consistently reach for objects between 3 and 5 months of age. In the months before reaching, infants produce a variety of arm movements. The relationship between these early arm movements and the emergence of purposeful reaching is still unclear. The purpose of the present study was to determine how groups of non-reaching, nearly reaching, and newly reaching infants changed the kinematics of their spontaneous arm movements in the presence of a toy. Five infants in each of these groups were observed with a high-speed motion capture system during trials with and without a toy present. Kinematic analyses examined 3D hand, shoulder, and elbow motions. Our results suggest that with a toy present, non-reachers altered their movement quantity whereas near- and new-reachers altered their movement quality through spatio-temporal dissociation and reorientation of the arm. When comparing the changes across groups we observed three preliminary patterns of toy-oriented changes. Our results join other studies to strengthen the relationship between early arm movements and purposeful reaching. Future longitudinal studies are now required to begin to fully understand the complex process by which infants adapt their early arm movements for purposeful behaviors.

Keywords: Motor development; Infant; Reaching; Motor control; Arm movements; Coordination

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1. Introduction

Infants acquire the ability to reach for and contact objects between 3 and 5 months of age (Thelen, Corbetta, Kamm, Spencer, Schneider, & Zernicke, 1993). Studies have begun to identify how infants change their patterns of reaching in the months *after* their first consistent reaches. These changes are typically complex and involve many different aspects of movement and posture. For example, reaches become smoother, straighter, and accurate with development (Konczak & Dichgans, 1997; Thelen, Corbetta, & Spencer, 1996; von Hofsten, 1991). Moreover, in terms of joint coordination, shoulder motions become smoother before elbow motions (Galloway & Thelen, 2000; Konczak & Dichgans, 1997). In addition, bilateral hand movements and hand use preference also changes after the onset of reaching (Corbetta & Thelen, 1996; Hinojosa, Sheu, & Michel, 2003; van Hof, Van der Kamp, & Savelsbergh, 2002). Several studies have also showed the important role of postural control in the development of reaching skill (Fallang, Saugstad, & Hadders-Algra, 2000; Hopkins & Ronnqvist, 2002; Rochat & Goubet, 1995; Thelen & Spencer, 1998). Lastly, infants utilize reaching to contact, manipulate and learn about stationary object properties (Corbetta, Thelen et al., 2001; McCarty, Clifton, & Collard, 1999; Needham, Barnett et al., 2002) as well as to contact and explore moving objects (Savelsbergh & Whiting, 1996; von Hofsten, 1983).

In the months *before* reaching, infants produce a variety of arm movements. Although there are few empirical studies of these early arm movements, understanding how infants change these movements in the months leading up to the onset of reaching, is important for several reasons. First, recent work in the neurosciences suggests that early limb movements are important in shaping the cortical and subcortical areas that contribute to the emergence of purposeful reaching (Eyre, Miller, Clowry, Conway, & Watts, 2000; Eyre, Taylor, Villagra, Smith, & Miller, 2001; Martin, Choy, Pullman, & Meng, 2004). Similarly, work in infant development suggests that early arm movements provide the sensorimotor experiences by which infants first learn the neuromotor control required for contacting objects (Kawai, Savelsbergh, & Wimmers, 1999; Lobo, Galloway, & Savelsbergh, 2004; Out, Savelsbergh, van Soest, & Hopkins, 1997; Out, van Soest, Savelsbergh, & Hopkins, 1998; Thelen et al., 1993; Turvey & Fitzpatrick, 1993; von Hofsten, 1993). Reaching itself provides infants with their first independent exploration and manipulation of their environment and contributes to infants' overall motor (Corbetta & Bojczyk, 2002; Goldfield, 1990), social (Fogel, Dedo, & McEwen, 1992), sensory-perceptual (Corbetta, Thelen, & Johnson, 2001; Eppler, 1995; Rochat, 1989), and cognitive development (Diedrich, Highlands, Spahr, Thelen, & Smith, 2001; Thelen, Schöner, Scheier, & Smith, 2001). Lastly, the developmental trajectory to early arm movements in typically developing infants provides a normative database from which future work can begin to identify movement impairments in infants born at risk of future reaching delays.

The transition from spontaneous[1] arm movements to purposeful reaching is a complex and individualized, yet tractable process (Corbetta & Thelen, 1999; Thelen et al., 1993, 1996; von Hofsten, 1984). Studies have found that spontaneous arm movements decreased in frequency with age in the weeks before reach onset (Piek & Carman, 1994; Thelen, 1981). Studies have also noted changes in spatial and temporal characteristics of arm movements in the weeks preceding the onset of reaching. Spatially, spontaneous arm movements became located progressively more in the midline of the body from birth to the first week of reaching (Galloway & Thelen, 2003; Lew & Butterworth, 1997). When presented with a toy, infants as young as a few days old increased the number of forward directed arm movements when looking at a toy as compared to moving without a toy present (von Hofsten, 1982). When infants were

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[1] Spontaneous arm movements are those that occur without a clear external stimulus such as a toy or person.

closer to the first week of consistent reaching, infants moved their arms more frequently (Galloway & Thelen, 2003; von Hofsten, 1984) and closer to midline when a toy was presented in the midline position (Galloway & Thelen, 2003; Spencer & Thelen, 2000). Moreover, the increase in midline arm movements occurred along with an increase in proximal muscle activity at the neck and shoulder (Spencer & Thelen, 2000). Temporally, in terms of movement speed, infants with fast early arm movements slowed down in the weeks leading up to their first reaches, whereas slower infants increased their speeds (Thelen et al., 1993). Taken together, these studies suggest that spatial and temporal characteristics of early arm movements may have somewhat different developmental trajectories. Specifically, spatial characteristics, such as hand location, appear to gradually change, whereas temporal characteristics such as hand or joint speed, change along a more complex and individualized developmental trajectory.

Few studies have specifically examined how infants change their spontaneous arm movements in the presence of a toy (i.e. *toy-oriented changes*), and no study has comprehensively examined how 3D hand and joint kinematics change over the period *before* reach onset. Thus, many basic questions remain. For example, to what extent do infants *alter* the length, and speed of the hand's path in the presence of a toy? Moreover, what are the changes in shoulder and elbow excursion and speed that underlie the changes in hand motion? Therefore, the purpose of the present study was to examine the spatial and temporal changes in hand and joint kinematics of arm movements in non-reachers (8–9 weeks old), near-reachers (14–16 weeks old), and new-reachers (16–19 weeks old) both with and without a toy present.

For this study, we tested three hypotheses for *toy-oriented changes* based on findings of early arm movements and reaching. First, given that spontaneous arm movements appear to change throughout the weeks before reach onset, we predict that toy-oriented changes in hand and joint kinematics will differ across the three groups of infants. Second, we predict that spatial characteristics, such as hand–toy distance, will change progressively across the three groups. Specifically, older infants will show a greater decrease in hand–toy distance and different arm orientation in the presence of a toy as compared to younger infants. In contrast, we predict that temporal characteristics, such as hand and joint speed, will change in a more complex manner across the three groups. Specifically, the change in speed in the presence of a toy will differ across the three groups (no change or increase or decrease). Third, shoulder and elbow motion will display different toy-oriented changes across the three groups. The third hypothesis is based on two findings stated above. First, infants show increased proximal muscle activity with the emergence of midline reaching (Spencer & Thelen, 2000). Second, improvements in the quality of hand kinematics appear to be more clearly related to smoother shoulder motion as compared to elbow motion (Galloway & Thelen, 2000; Konczak & Dichgans, 1997).

2. Materials and methods

2.1. Subjects

Fifteen healthy fullterm infants between the ages of 8 and 19 weeks were recruited from the Newark, Delaware community through public birth announcements. There were five infants in each of the three age groups: "Non-reachers" comprised of 8- to 9-week-old infants (three males and two females), "Near-reachers" comprised of 14- to 16-week-old infants (three males and two females), and "New-reachers" comprised of 16- to 19-week-old infants (two males and three females). Four additional infants were excluded from the study because of poor data quality due to technological limitations (one infant) or excessive crying or sleeping (three infants). Infants were admitted in the study following informed parental consent as approved by the University of Delaware Human Subjects Review Board.

Each of the groups differed in how they moved their arms as well as their gross motor development. New-reachers were able to contact the toy more than five times during the experimental session (Thelen et al., 1993). Near-reachers were unable to contact the toy but displayed midline arm movements during their session. Non-reachers were unable to contact the toy and lacked significant midline arm movements. To provide additional confirmation that the three age groups were fundamentally different in their general motor skills, each infant's gross motor development was assessed using the Alberta Infant Motor Assessment Scale (AIMS) (Piper & Darrah, 1994). An experimenter who was also a pediatric physical therapist performed each assessment. A one-way analysis of variance showed that the AIMS scores of all three groups were significantly different on the day of their experiment. Specifically, non-reachers had a score of 8–9, near-reachers had a score of 12–13, and new-reachers had a score of 16–18 ($p < 0.01$). In addition to being statistically different, the range of AIMS scores for each group reflects significant differences in the general control of their movements and postures (see Appendix A for details).

2.2. Procedure

Infants were seated in a custom made chair, reclined at a 30° angle to the vertical. The design of the chair allowed free range of motion of the arms and legs (Fig. 1A). For the "*no toy*" *condition*, an experimenter was seated in front of the infant. During the "*toy*" *condition*, a midline toy was held by the experimenter at the infant's shoulder height, arm's length and at the midpoint between both shoulders. Across both experimental conditions, infants were alert and moving, but not crying. An average of six 30 s trials was recorded per condition.

2.3. Kinematic analysis

A six-camera (120 Hz) motion capture system was used to obtain position-time data from both arms (Vicon Motion Systems Inc., CA, USA). Cameras surrounded the infant chair in a semicircular fashion with two cameras on each side and two in the front of the infant. Infants were seated within a calibrated volume of 160 cm × 160 cm × 200 cm. The average measurement error ranges between 0.2 and 0.3 mm for the given calibrated volume. Arrays of three reflective, non-linear markers (8 mm in diameter) were placed on the right and left upper arm, forearm, dorsum of hand, and the toy. Three-dimensional (3D) joint motion calculations were conducted by the Singular Value Decomposition (SVD) method (Soderkvist & Wedin, 1993). The static reference position for each arm was a neutral shoulder, neutral elbow, mid prone forearm, and a neutral wrist position such that the arm was held parallel to the trunk (Fig. 1A). The calculations for hand and joint kinematics were performed for the right arm. For each trial, the 3D position for each marker was calculated and filtered at 4 Hz with a fourth order Butterworth filter. 3D linear positions and resultant speed of hand as well as 3D angular positions and resultant speeds of the shoulder and elbow joints were calculated (Fig. 1B). The 3D resultant speed of hand, shoulder and elbow was calculated using a three-point differentiation technique. The calculations for hand and joint kinematics were performed through Matlab programming (Mathworks Inc.).

An average of 3 minutes of motion data was recorded for each experimental condition per infant (see Table 1 for details on individual infants). In addition, a loss of no more than 20 consecutive frames (equal to one-sixth of a second) was interpolated using cubic spline interpolation. Following the interpolation,

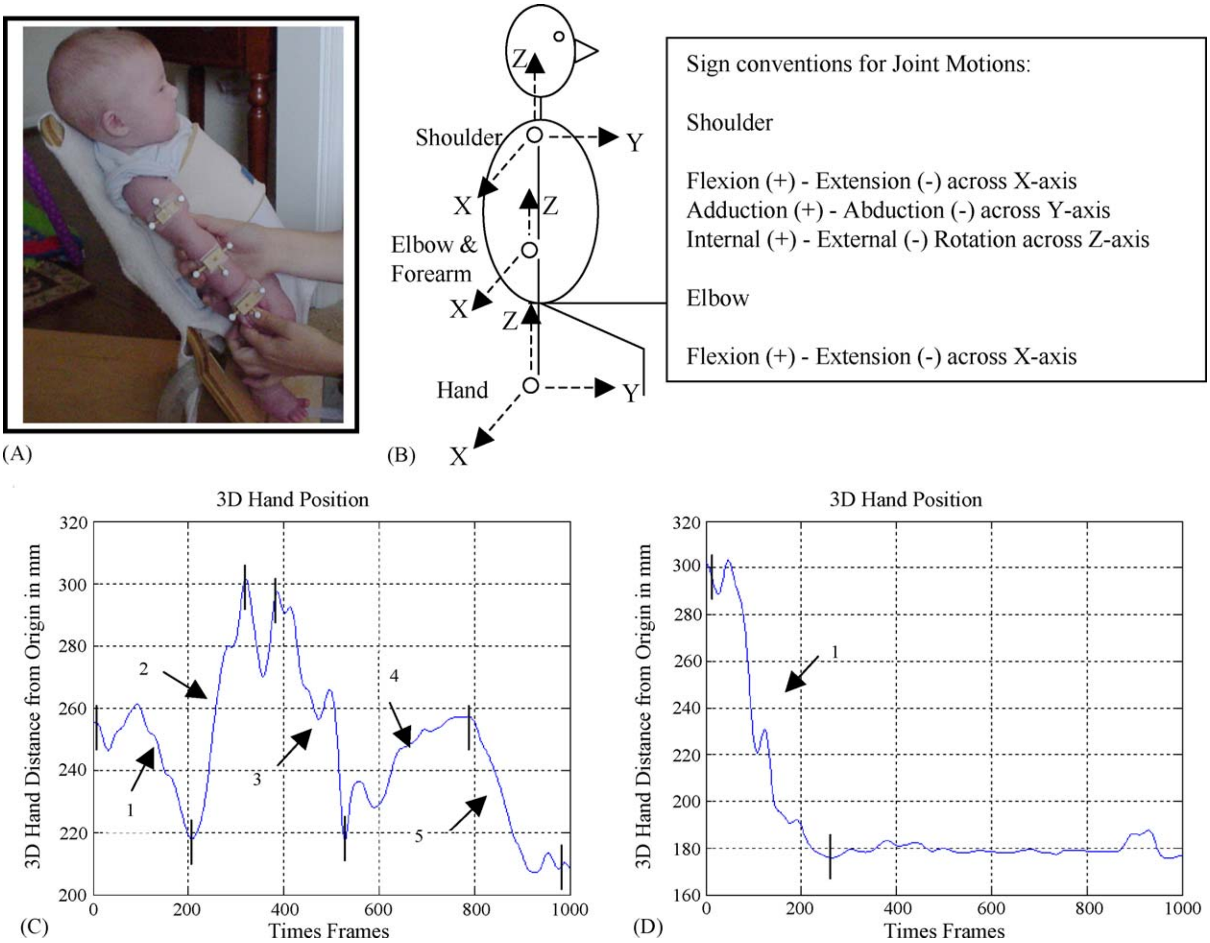


Fig. 1. Experimental set up, kinematic model, and movement identification. (A) An infant in the setup with his arm in the static reference position. (B) A schematic of shoulder, elbow, and hand kinematic model with the sign conventions for joint motions. (C) 3D hand position with respect to the origin of the coordinate system over a 1000 frames. Five movements were identified in (C) and one movement in (D).

87% or more of the recorded data per experimental condition per infant was used for further analysis. This equals or exceeds the amount of data used by similar studies (Konczak, Borutta, Topka, & Dichgans, 1995; Thelen et al., 1993; von Hofsten & Ronnqvist, 1993).

3. Data analysis

3.1. Movement identification

A “movement” was defined as 3D hand displacement ≥40 mm in length (Berthier, Clifton, McCall, & Robin, 1999). A movement reversal of ≥20 mm denoted the end of the preceding movement and the

Table 1
Details of infant data: describes the total number of trials, total number of minutes, and the total number of movements obtained per infant across non-, near-, and new-reachers

Groups	Infant	Number of trials of data		Total minutes of data		Total movement number	
		No Toy	Toy	No Toy	Toy	No Toy	Toy
Non-reachers	1	7	6	4.32	3.94	72	79
	2	6	5	2.88	2.70	74	103
	3	6	7	3.29	3.83	105	165
	4	5	7	2.06	3.75	61	117
	5	5	6	2.71	3.22	111	62
Near-reachers	1	6	4	3.24	1.99	82	46
	2	6	7	3.21	3.64	111	114
	3	6	6	3.29	3.28	104	156
	4	6	7	3.28	3.63	59	126
	5	6	6	3.02	3.26	88	147
New-reachers	1	5	5	2.61	3.13	73	56
	2	7	7	3.68	3.62	51	80
	3	5	6	2.73	3.24	103	146
	4	6	6	3.18	3.09	241	110
	5	6	5	3.28	2.72	89	75

start of the next movement (Fig. 1C and D). A custom Matlab program selected the movements and an experimenter also visually confirmed each selection by observing the 3D hand position profile. Our goal was to capture all types of movements, small as well as large. We selected a movement threshold of 40 mm as this length represented approximately 10^0 of motion of a single joint system with a limb segment length of 20 cm, which is the average arm length of our infants. Moreover, a movement threshold of 40 mm was indeed capturing most movements, as the average movement length was 120 mm across all infants. For each movement, multiple hand and joint variables were calculated, as described below.

4. Dependent variables

4.1. Hand variables

4.1.1. Movement number per minute

The total number of hand movements normalized by the total duration in minutes for each experimental condition.

4.1.2. Length of hand movement

The 3D distance between the start and end of a movement in millimeters (mm).

4.1.3. Speed of hand movement

The average 3D speed of hand motion over the entire movement in mms/s.

4.2. Joint variables

4.2.1. Joint excursion

The 3D excursion in degrees of the shoulder and elbow between the start and the end of each movement.

4.2.2. Shoulder to elbow excursion ratio

The ratio of the difference in excursions of the shoulder and of the elbow within a movement over the sum of both excursions

$$\text{Excursion ratio} = \frac{\text{shoulder excursion} - \text{elbow excursion}}{\text{shoulder excursion} + \text{elbow excursion}}$$

4.2.3. Joint speed

The average 3D speed in degrees/second of the shoulder and the elbow over the entire movement.

4.2.4. Shoulder to elbow speed ratio

The ratio of the difference in speeds at the shoulder and at the elbow within a movement over the sum of both speeds.

$$\text{Speed ratio} = \frac{\text{shoulder speed} - \text{elbow speed}}{\text{shoulder speed} + \text{elbow speed}}$$

The excursion and speed ratios reflect the contribution of shoulder and elbow excursion or speed within a movement. This ratio equation was selected as it bounded range of values between -1 and +1. A value closer to +1 indicates greater contribution of shoulder excursion or speed, a 0 indicates equal excursion or speed, and a -1 indicates greater contribution of elbow excursion or speed. Moreover, an excursion ratio of +0.5 indicates that shoulder excursion is three times that of the elbow, whereas a +0.3 indicates that shoulder excursion is two times that of the elbow.

4.2.5. Hand and joint orientation

4.2.5.1. Minimum hand to toy distance. The distance of the hand from a standardized toy location in millimeters (mm) at the end of movements that occurred in the direction of the toy, also termed "*forward*" *arm movements*. This distance was compared with the distance of the hand from the same standardized toy location during ‘no toy’ trials.

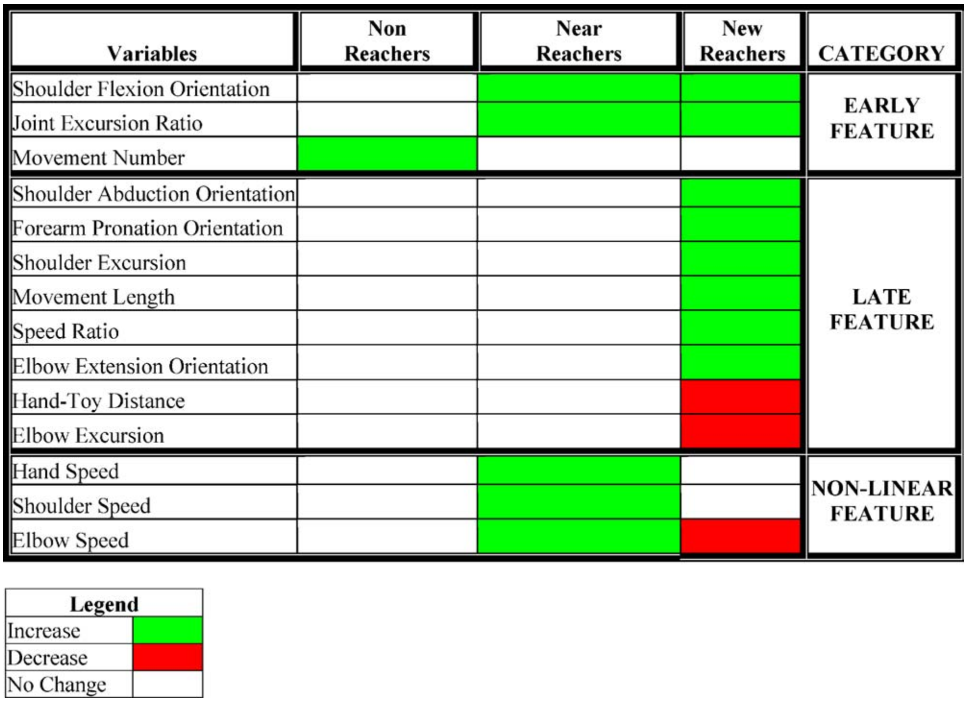
4.2.5.2. Standardized toy location. The average X, Y, and Z position of the toy, during the ‘toy’ condition trials, was used as the toy location for the "no toy" condition trials.

4.2.5.3. Shoulder, elbow, and forearm orientation. The shoulder flexion–extension, abduction–adduction, internal–external rotation, elbow flexion–extension, and forearm pronation–supination angle in degrees, at the end of forward arm movements. The joint angle convention was such that flexion, adduction, internal rotation, and pronation were positive and their counterparts were negative (Fig. 1B).

5. Statistical analysis

The focus of this study was to compare toy-oriented changes in arm movements for each group; hence we compared movements of the "no toy" and the "toy" condition per group. For hand movement number, we conducted a chi-square test across condition for each group. Due to a relatively small sample size and uneven number of movements within and across infants, we used the Mann–Whitney test, a conservative non-parametric test, to compare the remaining variables across the two experimental conditions. Median value for each dependent variable is reported via figures. Table 2 shows results summary. For all analyses, *p*-values <0.05 were considered significant. Due to the individual nature of infant movements we also required that a majority of infants in a group followed the group finding for a toy-oriented change to be termed significant. Where this was not the case, we denoted 'no clear change' for that variable. The chi-square test was conducted using Minitab software (Minitab Inc.) and the Mann–Whitney tests were conducted using SPSS software (SPSS Inc.).

Table 2
Summary of toy-oriented changes: summarizes and compares the toy-oriented changes within and across groups



Variables	Non Reachers	Near Reachers	New Reachers	CATEGORY
Shoulder Flexion Orientation		🟩	🟩	EARLY FEATURE
Joint Excursion Ratio		🟩	🟩	
Movement Number	🟩			
Shoulder Abduction Orientation			🟩	LATE FEATURE
Forearm Pronation Orientation			🟩	
Shoulder Excursion			🟩	
Movement Length			🟩	
Speed Ratio			🟩	
Elbow Extension Orientation			🟩	
Hand-Toy Distance			🟥	
Elbow Excursion			🟥	
Hand Speed		🟩		NON-LINEAR FEATURE
Shoulder Speed		🟩		
Elbow Speed		🟩	🟥	

Legend	
Increase	🟩
Decrease	🟥
No Change	

Vertical columns under each group show whether there was an increase, decrease or no toy-oriented change in each variable *within* that group. Each category (far right column) compares the different toy-oriented changes *across* group. An "Early Feature" reflects a cluster of variables for which non-reachers were different than near- and new-reachers. A 'Late Feature' reflects a cluster of variables for which non- and near-reachers were different from new-reachers. A 'Non-linear Feature' reflects a cluster of variables in which all groups differed.

6. Results

6.1. Hand movement number, length and speed

Fig. 2A–C show hand movement data for each group. In the presence of a toy, non-reachers increased their movement number ($\chi^2 = 12.1$, d.f. = 4, $p = 0.02$) with no change in movement length or movement speed as compared to their spontaneous arm movements. In the presence of a toy, near-reachers increased their movement speed (Mann–Whitney U (U) = 99 040, $p < 0.01$) with no change in movement number or movement length. Note that the near-reachers did, however, show a statistical trend for increase in movement number in the presence of a toy ($\chi^2 = 6.8$, d.f. = 4, $p = 0.1$). In contrast, new-reachers increased their movement length ($U = 111\,238$, $p < 0.01$) with no changes in movement number or movement speed. In summary, in the presence of a toy, non-reachers increased their movement number, near-reachers increased their movement speed, and new-reachers increased their movement length.

6.2. Individual and relative joint excursion

Fig. 3A and B show individual joint excursion data for each group. In the presence of a toy, non-reachers and near-reachers did not change their shoulder or elbow excursion as compared to their spontaneous arm movements. Note that near-reachers did, however, show a statistical trend for an increase in shoulder excursion in the presence of a toy ($p = 0.07$). Interestingly, new-reachers *increased* their shoulder excursion ($U = 52\,962$, $p < 0.01$) and *decreased* the elbow excursion ($U = 102\,019$, $p = 0.02$) in the presence of a toy. Fig. 3C shows shoulder to elbow excursion ratio for each group. Non-reachers did not alter their shoulder excursion relative to elbow excursion in the presence of a toy. In contrast, both near- and new-reachers increased their shoulder excursion relative to the elbow (Near-reachers, $U = 73\,229$, $p = 0.01$ and New-reachers, $U = 49\,532$, $p < 0.01$, respectively). In summary, non- and near-reachers showed no changes in individual joint excursion, whereas new-reachers showed a toy-oriented increase in shoulder excursion and a decrease in elbow excursion. In terms of relative joint excursion, both near- and new-reachers increased their shoulder excursion relative to the elbow.

6.3. Individual and relative joint speed

Fig. 4A and B show individual joint speed data for each group. In the presence of a toy, non-reachers showed no differences in shoulder or elbow speeds as compared to their spontaneous arm movements. Near-reachers, however, increased their shoulder speed as well as their elbow speed (shoulder, $U = 62\,727$; elbow, $U = 63\,578$; for both joints, $p < 0.01$). Interestingly, new-reachers *decreased* their elbow speed ($U = 63\,842$, $p < 0.01$) with no changes in shoulder speed. Fig. 4C shows shoulder to elbow speed ratio for each group. Neither non-reachers nor near-reachers altered their shoulder speed relative to the elbow speed in the presence of a toy. In contrast, new-reachers increased their shoulder speed relative to the elbow ($U = 51\,616$, $p < 0.01$). In summary, non-reachers showed no toy-oriented changes in joint speed, whereas near-reachers increased both shoulder and elbow speed. In contrast, new-reachers showed no changes in shoulder speed and *decreased* their elbow speed. In terms of relative joint speed, only new-reachers increased their shoulder speed relative to the elbow.

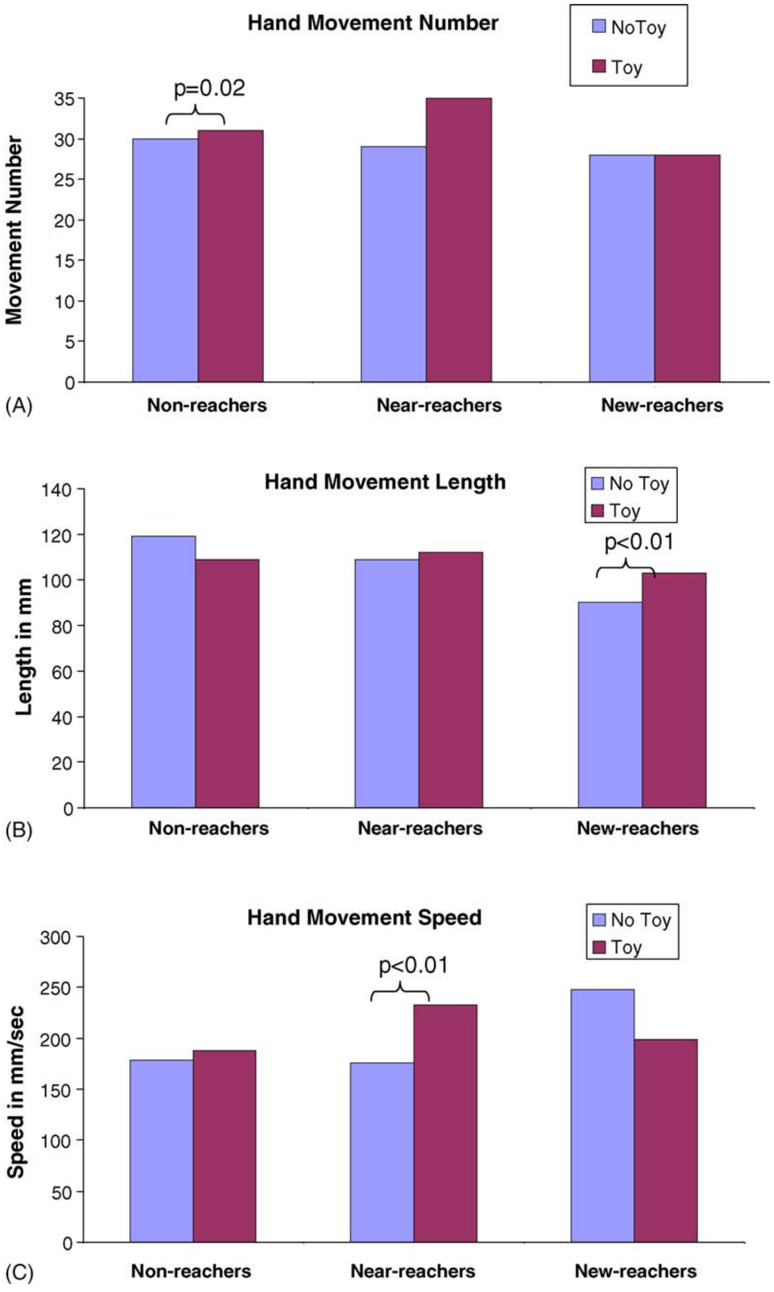


Fig. 2. Hand variables: (A) movement number, (B) hand movement length, and (C) hand movement speed during No Toy and Toy conditions for each group. *P*-values reflect within group comparisons.

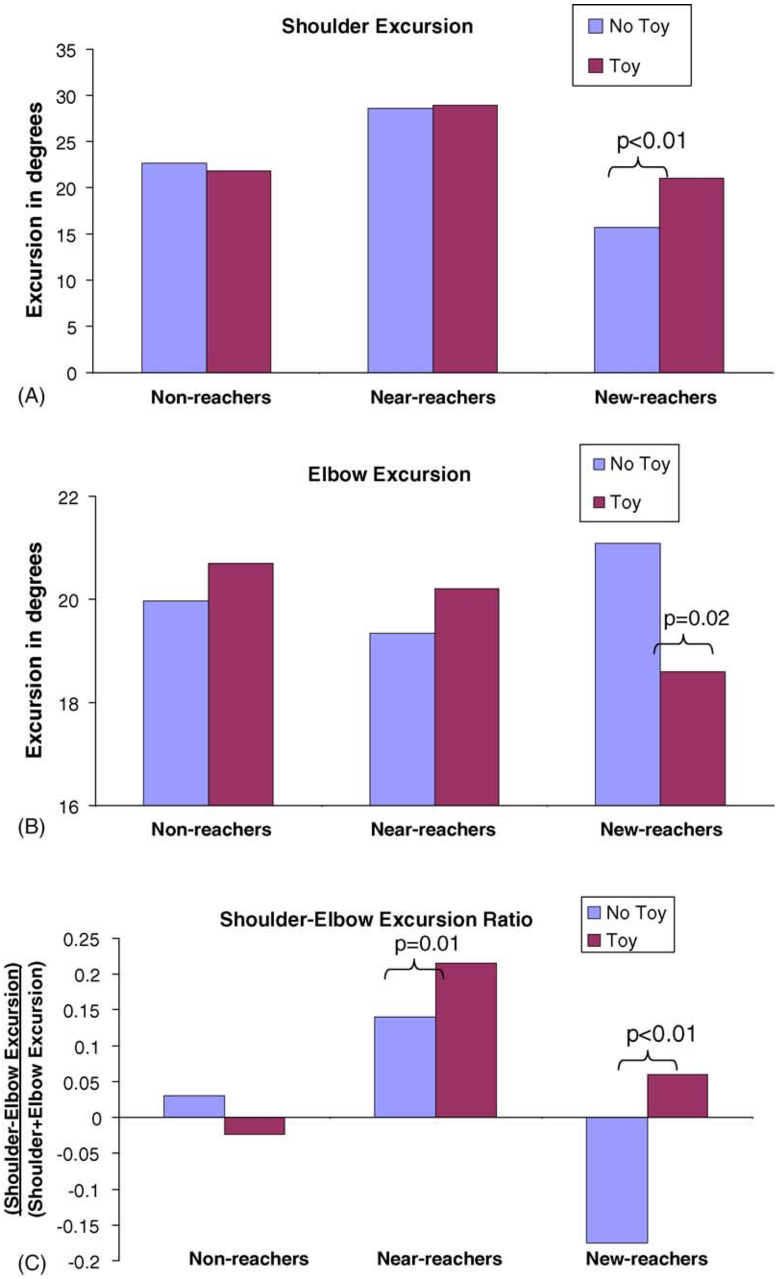


Fig. 3. Individual and relative joint excursion: (A) shoulder excursion, (B) elbow excursion, and (C) shoulder–elbow excursion ratio during No Toy and Toy conditions for each group. *P*-values reflect within group comparisons.

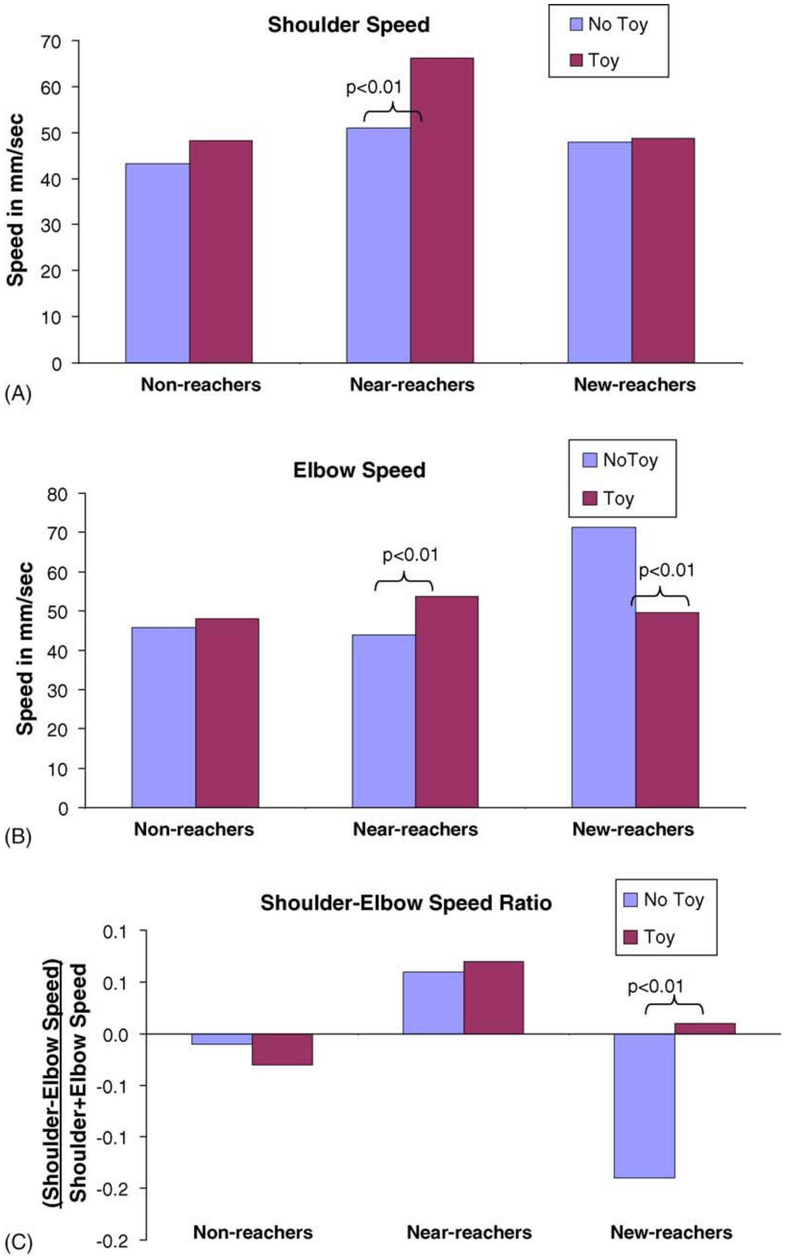


Fig. 4. Individual and relative joint speed: (A) shoulder speed, (B) elbow speed, and (C) shoulder–elbow speed ratio during No Toy and Toy conditions for each group. *P*-values reflect within group comparisons.

6.4. Minimum hand–toy distance and joint orientation

Fig. 5A shows hand–toy distance data for each group. Neither non-reachers nor near-reachers changed their hand–toy distance in the presence of a toy. In contrast, new-reachers were the only group to move

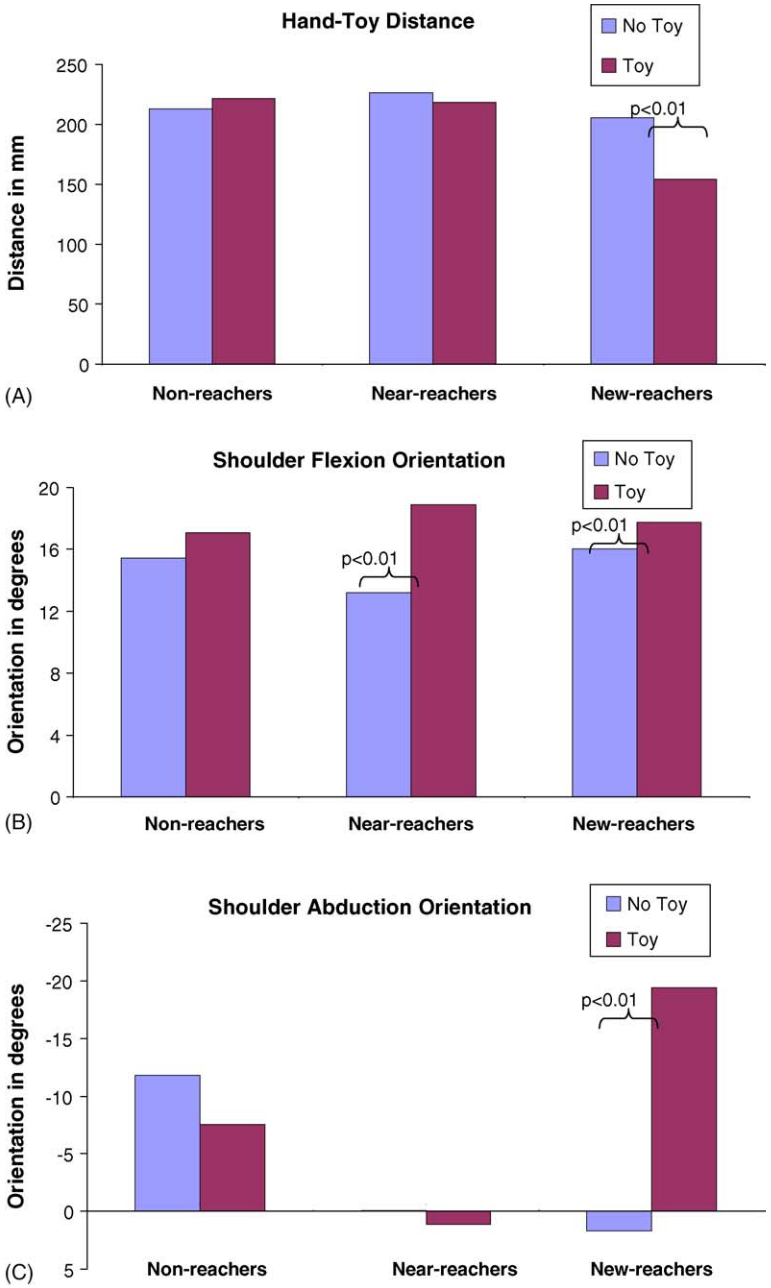


Fig. 5. Hand and joint orientation: multiple variables reflecting the orientation of the arm at the end of forward arm movements during No Toy and Toy conditions for each group. The variables include (A) hand to toy distance and joint orientations of (B) shoulder flexion, (C) shoulder abduction, (D) elbow extension, and (E) forearm pronation. *P*-values reflect within group comparisons.

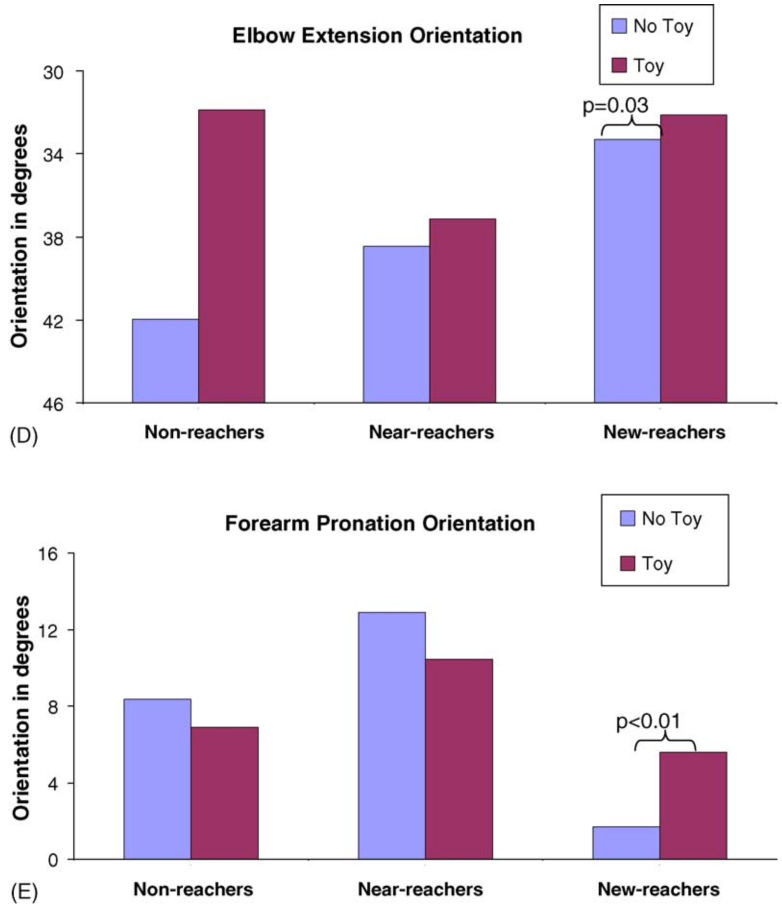


Fig. 5. (*Continued*).

their hands closer to the toy, during the “toy” condition ($U = 21\,060$, $p < 0.01$). Fig. 5B–E shows the 3D orientation of the shoulder, elbow, and forearm at the end of forward arm movements. Non-reachers showed no change in shoulder or elbow orientation. Note that non-reachers did, however, show a statistical trend for an increase in elbow extension in the presence of a toy ($p = 0.06$). Near-reachers showed greater shoulder flexion ($U = 15\,715$, $p < 0.01$) with no other changes. New-reachers showed greater shoulder flexion, abduction as well as greater elbow extension and forearm pronation (shoulder flexion, $U = 16\,194$, $p < 0.01$; shoulder abduction, $U = 8909$, $p < 0.01$; elbow extension, $U = 17\,078$, $p = 0.03$; forearm pronation, $U = 15\,828$, $p < 0.01$) with no clear change in shoulder rotation. In summary, only new-reachers moved significantly closer to the toy. Near-reachers and new-reachers, however, showed a toy-oriented increase in shoulder flexion and new-reachers showed additional changes in shoulder, elbow, and forearm orientation.

7. Discussion

The discussion focuses on the toy-oriented changes within and across the non-, near- and new-reachers. A within-group view provided the first comprehensive profile of how infants of different ages changed their spontaneous arm movements in the presence of a toy. An across-group view allowed, for the first time, a preliminary categorization of toy-oriented changes in arm movements over developmental time. We will address each hypothesis and also elaborate on how our results fit with studies on stable reaching later in the first year as well as the broader issue of coordination in early infancy.

7.1. Toy-oriented changes within each group

7.1.1. Non-reaching infants

The non-reaching group consisted of 8- to 9-week-old infants. Non-reachers showed only one type of toy-oriented change (Table 2, Non-reacher column). They increased the number of movements in the presence of a toy similar to previous studies (Thelen, 1981; von Hofsten, 1982, 1984). Non-reachers showed no changes in hand length or speed, joint excursion or speed, or hand or joint orientation. These infants also did not change the relative excursion or speed of either joint in the presence of a toy. These results suggest that non-reaching infants increased their arm movement number by moving the arm as a unit. That is, a lack of change in the relative joint excursion or speed suggested that the non-reachers lacked both spatial and temporal dissociation between joints. A lack of dissociation between joints or limbs (Heathcock, Bhat, Lobo, & Galloway, 2005; Piek, 1998; Thelen, 1985; Vaal, van Soest, Hopkins, & Sie, 2002) along with considerable muscle co-activation (Hadders-Algra, 1992) is a common feature of limb movements in early infancy. In summary, 8- to 9-week-old infants increased their arm movements in the presence of a toy yet lacked joint dissociation as is typical in early infancy.

7.1.2. Near-reaching infants

The near-reaching group consisted of 14- to 16-week-old infants who were probably within a month from consistent reaching. They displayed several toy-oriented changes in hand and joint motion (Table 2, Near-reacher column). First, near-reachers showed no clear changes in hand movement number or length. Second, they increased their hand speed along with both shoulder and elbow speed. There was no change in the shoulder to elbow speed ratio suggesting these infants increased the speed of the arm as one unit and not one joint more than the other. Third, near-reachers increased their shoulder excursion relative to that of elbow excursion when presented with a toy. Thus, near-reachers showed increased *spatial* dissociation between shoulder and elbow but not *temporal* dissociation in the presence of a toy. The ability to dissociate joints and/or limbs (Chen, Fetters, Holt, & Saltzmann, 2002; Heathcock et al., 2005; Piek, 1998; Thelen, 1985; Vaal, van Soest, & Hopkins, 2000) and an increase in reciprocal muscle activation patterns (Hadders-Algra, 1992) are two features of limb movements of infants in whom purposeful control of the body is emerging. Thus, the toy-oriented dissociation noted in the arm movements of infants in the present study may well be part of a more general increase in body control. Lastly, near-reachers produced forward arm movements that ended in greater shoulder flexion similar to purposeful reaching, which further suggests that these infants produced task oriented changes in their arm movements, weeks before the emergence of purposeful reaching (Galloway & Thelen, 2003; Lobo et al., 2004; Needham, Barnett, & Peterman, 2002; von Hofsten, 1984). In summary, 14- to 16-week-old infants showed toy-oriented increases in hand and joint kinematics as well as the first signs of spatial dissociation.

7.1.3. Newly reaching infants

The new-reaching group consisted of 16- to 19-week-old infants who were each able to contact the toy at least five times in one experimental session. This age range fits within the 3- to 5-month age often cited for the initial emergence of reaching (Thelen et al., 1993; von Hofsten, 1991). These new-reachers displayed a variety of expected as well as unexpected toy-oriented changes (Table 2, New-reacher column). First, in contrast to non- and near-reachers, new-reachers increased their hand movement length, which supports previous work (von Hofsten, 1991). They did not, however, change movement number or speed in the presence of a toy. Second, new-reachers displayed a toy-oriented increase in shoulder excursion in absolute terms as well as in relation to the elbow. Studies of reaching in infants older than 6 months have also noted a relative difference in shoulder and elbow kinematics (Galloway & Thelen, 2000; Konczak & Dichgans, 1997). Third, also in agreement with previous work, new-reachers placed their hands closer to the toy as compared to their spontaneous movements (Galloway & Thelen, 2003). Moreover, changes in hand position resulted from forward arm movements that ended with greater shoulder flexion, abduction, elbow extension, and forearm pronation orientation. These multiplanar changes in the arm's orientation were displayed only by new-reachers. Thus, such changes may be specifically related to purposeful reaching.

Interestingly, new-reachers decreased their elbow speed and excursion in the presence of a toy. This supports Berthier et al.'s proposal that new-reachers employ an "elbow constraint strategy" to simplify arm control in order to produce repeated toy contacts. Lastly, new-reachers increased their shoulder speed relative to the elbow in the presence of a toy suggesting temporal dissociation of the shoulder and elbow. In summary, 16- to 19-week-old infants produced the greatest number of toy-oriented changes. They produced longer movements that were completely reoriented in the presence of a toy.

7.2. *Toy-oriented changes across groups*

Comparing the toy-oriented changes *across* non-, near-, and new-reachers was expected to reveal several different patterns of developmental change with a complex, yet meaningful order (Out et al., 1998; Piek & Carman, 1994). It is important to note that in a cross sectional study there can be no definite developmental trajectories drawn. We were, however, able to categorize, for the first time, three preliminary patterns of toy-oriented changes across groups, which we termed Early, Late, and Non-linear Features (Table 2).

Early Features were those variables that (a) displayed a toy-oriented change for non-reachers (increase, decrease or no change) that differed from the near- and new-reachers and (b) displayed similar toy-oriented changes across near- and new-reachers. That is, the major group difference in toy-oriented changes for these variables occurred relatively early—between non- and near-reachers. There were three early features (Table 2). Both near and new-reachers showed an increase in shoulder excursion in relation to the elbow along with forward arm movements that ended in greater shoulder flexion in the presence of a toy whereas non-reachers did not. In contrast, non-reachers showed increase in movement number as opposed to no clear changes in the other two groups. This suggests that the non-reaching group only altered their movement quantity whereas near- and new-reachers were also able to alter movement quality such as spatial dissociation as well as reorienting the arm in the presence of a toy. These results suggest that the spatial dissociation of shoulder and elbow observed during purposeful reaching emerges during early arm movements between 8 and 14 weeks of age, a month or more from the actual onset of consistent reaching.

Late Features were those variables that (a) displayed a toy-oriented change for new-reachers (increase, decrease or no change) that differed from the non- and near-reachers and (b) displayed similar toy-oriented changes across non- and near-reachers. That is, the major group difference in toy-oriented changes for these variables occurred relatively late—between near- and new-reachers. There were multiple late features that fell into two different patterns (Table 2). First, hand–toy distance and elbow excursion decreased in new-reachers with no changes in the non- and near-reachers. Second, movement length, shoulder to elbow speed ratio, shoulder abduction orientation, and forearm pronation orientation increased in the new-reachers with no such changes in the younger age groups. The finding of increase in shoulder to elbow speed ratio suggests that temporal dissociation emerges between 14 and 19 weeks of age, a few weeks before or during the first reaching movements.

Early Features involved changes in certain shoulder variables only whereas Late Features involved changes in the remaining shoulder variables and all the elbow variables. These findings support and extend multiple studies suggesting different developmental trajectories for the control of shoulder and elbow motion such that shoulder kinematics change earlier than elbow. First, as infants approach the first week of reaching they increase the amount of shoulder and neck muscle activity (Spencer & Thelen, 2000) and produce arm movements with smoother, more accurate, and more direct shoulder motion as compared to elbow motion (Galloway & Thelen, 2000). Second, newly reaching infants typically use shoulder and/or trunk motions as compared to the elbow to contact a toy (Berthier et al., 1999). Third, infants throughout the first 2 years of life increase the smoothness of shoulder motion earlier than elbow motion (Konczak & Dichgans, 1997). Such differential development of shoulder and elbow control may be related to findings in adult reaching in which joint dynamics are more complex at the elbow as compared to the shoulder (Dounskaia, Ketcham, & Stelmach, 2002; Galloway, Bhat, & Heathcock, 2003; Galloway & Koshland, 2002; Galloway & Thelen, 2000; Koshland, Galloway, & Nevoret-Bell, 2000). Moreover, Early and Late Features of toy-oriented change suggested that the majority of spatial variables such as hand–toy distance and shoulder and elbow orientation changed in a linear and progressive fashion. Lastly, Early and Late Features also suggest that temporal dissociation of the shoulder and elbow occurs after their spatial dissociation and much closer to onset of reaching.

Non-linear Features were those variables that displayed a different toy-oriented change for each group. That is, no group showed the same type of toy-oriented change for these variables (Table 2). Non-linear Features were only seen for speed-related variables and changed along a non-linear developmental trajectory. For example, elbow speed did not change in the presence of a toy for non-reachers, increased for near-reachers, and decreased for new-reachers. These results join other studies to suggest that the control of speed has a complex if not extended developmental trajectory (Berthier et al., 1999; Thelen et al., 1993, 1996).

8. Conclusions

Our findings provide empirical support for the proposal that a tractable developmental continuity exists between early arm movements and the emergence of purposeful reaching (Corbetta & Thelen, 1996; Lobo et al., 2004; Needham et al., 2002; Thelen, 1981, 1993, 1996; von Hofsten, 1984). Here, non-, near- and new-reachers showed a variety of toy-oriented changes in hand, shoulder, and elbow kinematics, which clustered over developmental time into mutually exclusive categories. Moreover, this cross sectional study provides a foundation for more specific hypotheses about how infants adapt their 3D hand and joint motions during the development of purposeful arm movements. These results also suggest that the development of reaching encompasses many months. In general, longitudinal studies beginning in the first post natal months, if not prenatally, will be necessary to fully understand the initial emergence of reaching. Specifically, longitudinal studies are necessary to validate this categorization as well as to determine the developmental trajectories at both the group and individual level in typically developing infants and those born at risk for long term reaching impairments.

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Appendix A. Behaviors observed for non-reachers, near-reachers, and new-reachers during AIMS scoring

In prone, non-reachers lacked the mobility seen in the near-reachers and new-reachers who showed similar prone mobility and upper body support with full forearm support and active neck flexion. In supine, non-reachers lacked midline arm movements whereas near-reachers displayed midline movements. New-reachers showed advanced skills in supine such as “Hands to Knees”. In sitting, non-reachers were unable to prop on their hands even briefly whereas near- and new-reachers were able to do so.

Body position	Non-reachers	Near-reachers	New-reachers
Prone	Prone lying in physiological flexion		
	Prone lying with asymmetrical head lift		
	Prone prop with elbows behind shoulders		
		Forearm support, elbows in line with shoulders	
		Prone mobility, head at 90° to horizontal, uncontrolled weight shifts	
			Forearm support, chin tuck, elbows in front of shoulders
Supine	Supine lying with random arm and leg movements		
	Supine lying with head in midline and arms at side		
		Supine lying with chin tuck and brings hands to midline	
			Hands to knees due to active abdominals
Sitting	Sitting with support, head in midline briefly		
		Sitting with propped arms briefly	Sitting with propped arms briefly
			Pull to sit
			Unsustained sitting
Supported standing	Supported standing with no weight bearing, trunk flexion		
	Supported standing, head in midline, hips behind shoulders		

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