

Brief report

Toy-oriented changes in early arm movements III Constraints on joint kinematics

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Abstract

The purpose of this study was to identify invariant features of shoulder and elbow kinematics during prereaching arm movements with and without a toy present. Invariant movement features may reflect the presence of constraints that reduce the complexity of learning to reach and provide a link between early arm movements and reaching. Joint excursion and smoothness were consistently greater at the shoulder than the elbow suggesting strong organismal constraints on prereaching movements. Speed became greater in the shoulder than the elbow only with a toy present during the 4 weeks leading up to reach onset suggesting the introduction of task related constraints. We propose that organismal constraints on joint coordination throughout the prereaching period provide a foundation for the overlay of task related constraints closer to reach onset. We also suggest that the coordinative structures of early arm movements and later reaching may be much more similar than currently thought. This similarity would significantly reduce the elements needing to be actively controlled, and simplify the learning process.

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1. Introduction

Between 3 and 5 months of age, infants begin to contact, explore, and manipulate their immediate physical environment through reaching and grasping. The extended prereaching period reflects the many cognitive, perceptual, and motor abilities to be mastered before reaching emerges. One basic perceptual-motor problem for infants is how to adapt the shoulder-elbow coordination of non-reaching movements for purposeful reaching. Bernstein (1967) and others (Kugler, Kelso, & Turvey, 1980, 1982; von Hofsten, 1979) reasoned that constraints on coordination exist, which limit the components needing to be actively controlled. Constraints would assist the emergence of purposeful reaching by reducing the available shoulder-elbow coordination patterns. The general aim of this study was to look for evidence of constraints at the level of joint kinematics during the initial emergence of reaching.

Constraints can be categorized in a number of ways, such as based on origin (Newell, 1986) or effect (Flach & Smith, 2000). Newell (1986) proposed that functional coordination emerged from the interaction of three broad categories of constraints: *task related constraints*, such as object properties (Corbetta, Thelen, & Johnson 2000; Fagard & Lockman

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2005; Newell, Scully, McDonald, & Baillargeon, 1989; van Hof, van der Kamp, Calijouw & Savelsbergh 2005; van Hof, van der Kamp, & Savelsbergh 2002) *environmental constraints*, such as external forces (Jensen, Thelen, Ulrich, Schneider, & Zernicke, 1994; Kawai, Savelsbergh, & Wimmers, 1999; Out, van Soest, Savelsbergh & Hopkins, 1998) or social context (Fogel, Dedo, & McEwen, 1992), and *organismal constraints*, such as body properties and mechanics (Newell, McDonald, & Baillargeon, 1993; Out, Savelsbergh, van Soest, & Hopkins, 1997; Thelen, Fisher, & Ridley-Johnson, 1984). In terms of the initial emergence of reaching, the idea being that over the first months of life, infants discover the cascade of constraints that ultimately result in the shoulder-elbow coordination necessary for consistent reaching.

Organismal and environmental constraints are active beginning prenatally, whereas task related constraints for reaching become active when the infant's view of the toy changes from simply an environmental stimulus to something that affords contacting. Organismal constraints may be reflected in the consistency of a movement variable or relationship between variables over time or across context or task. Although not widely studied, there are examples of organismal constraints linking the arm movements of newborns with those of older infants. For example, spontaneous arm movements of newborns displayed movement units with speed-curvature features similar to that of 5-month-old reachers (von Hofsten, 1993; von Hofsten & Ronnqvist, 1993), and also displayed bimanual symmetry similar to older infants (Thelen et al., 1993). Given the high levels of neural, mechanical, and behavioral changes as well as individual variability during the prereaching period (von Hofsten, 1993; von Hofsten & Ronnqvist, 1993, Thelen et al., 1993; Thelen, Corbetta, & Spencer, 1996), features that remain consistent reflect strong constraints and should be relatively easy to identify during this period. Moreover, these constraints may be particularly helpful to the infant in terms of limiting the solutions to be actively learned.

Given the redundancy of degrees of freedom, the complexity of joint coordination would be one level of organization where constraints would be particularly helpful. Indeed, recent studies suggest that organismal constraints are active in the relationship between the shoulder and elbow kinetics as well as kinematics early in the prereaching period. Thelen and coworkers (Zaal, Daigle, Gottlieb, & Thelen, 1999) noted that certain combinations of joint torques were linearly related between the shoulder and elbow in the reaches of young infants as they were in adult reaching (Gottlieb, Song, Almeida, Hong, & Corcos, 1997). Interestingly, this 'linear synergy' was also noted throughout the prereaching period, suggesting that this feature was not a reflection of task related constraints. Preliminary data from these same infants suggested that the smoothness, directness, and accuracy of shoulder motion were each greater than of elbow motion (Galloway & Thelen, 2000). As with the linear synergy, this proximal to distal pattern was not unique to reaching, but was seen throughout the prereaching and reaching periods of the first year. In both these studies, infants appeared to capitalize on inherent properties of the arm to produce their first reaches. Both these studies focused on 2D motion data under the single context of movement with a toy present, thus investigating how constraints active during spontaneous movements change with a toy present was not possible.

The specific purpose of this study was to test for the existence of invariant shoulder-elbow relationships in arm movements over the preteaching period. This project expanded on previous reports by searching for constraints within 3D motion data in two movement conditions: with and without a toy present. Our previous work identified numerous ways in which prereaching infants altered their hand and joint kinematics during spontaneous movements (no toy condition) when they are offered a toy (toy condition), which we termed 'toy-oriented' changes (Bhat, Heathcock, & Galloway 2005; Bhat & Galloway 2006; Bhat, Lee, & Galloway, in press). For the present study, we longitudinally compared arm movements with and without a toy present to test specific hypotheses about the interaction of organismal and task related constraints on shoulder and elbow kinematics. To be clear, organismal constraints would result in consistent features early in development and with little difference between conditions. Although we hypothesized joint differences, as detailed below, these constraints could be revealed in either consistent differences or similarities between joints. Task related constraints would result in consistent features emerging with a toy present and most clearly in the weeks approaching reach onset.

Specifically, we predicted consistent shoulder-elbow differences in joint excursion, speed and smoothness without a toy present, which would reflect organismal constraints (Newell, 1986) or action constraints (Flach & Smith, 2000). We also predicted that, at some point during the prereaching period, shoulder-elbow differences during the toy condition would increase or decrease as compared to the no toy condition, which would reflect the emergence of task related constraints (Newell, 1986) or constraints imposed by the value of the toy (Flach & Smith, 2000). By comparing the degree of joint differences in these two conditions, we could test the proposition that the action of reaching is built, in part, from task related constraints being superimposed on constraints inherent in much earlier spontaneous movements.

2. Methods

Thirteen healthy, full-term infants (eight females and five males) were recruited from the Newark, Delaware community through public birth announcements. Infants visited the laboratory every other week from 8 weeks of age up to the onset of reaching, defined as the first week that total toy contacts were three times greater than any previous week (mean 19.5 weeks, range 16–22 weeks). Infants were admitted in the study following informed parental consent as approved by the University of Delaware Human Subjects Review Board. Infants were seated in a custom made chair that 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 and spoke to the infant. During the “toy” condition, an experimenter held a midline toy at the infant’s shoulder height, arm’s length, and in the midline while speaking to the infant (for additional details see Bhat, Heathcock, & Galloway, 2005; Bhat & Galloway, 2006). The order of experimental conditions was alternated between visits. Across both experimental conditions infants were alert and moving, but not crying. Six 30 s long trials were recorded for each condition. A six-camera (120 Hz) motion analysis system (Vicon Motion Systems Inc., CA,

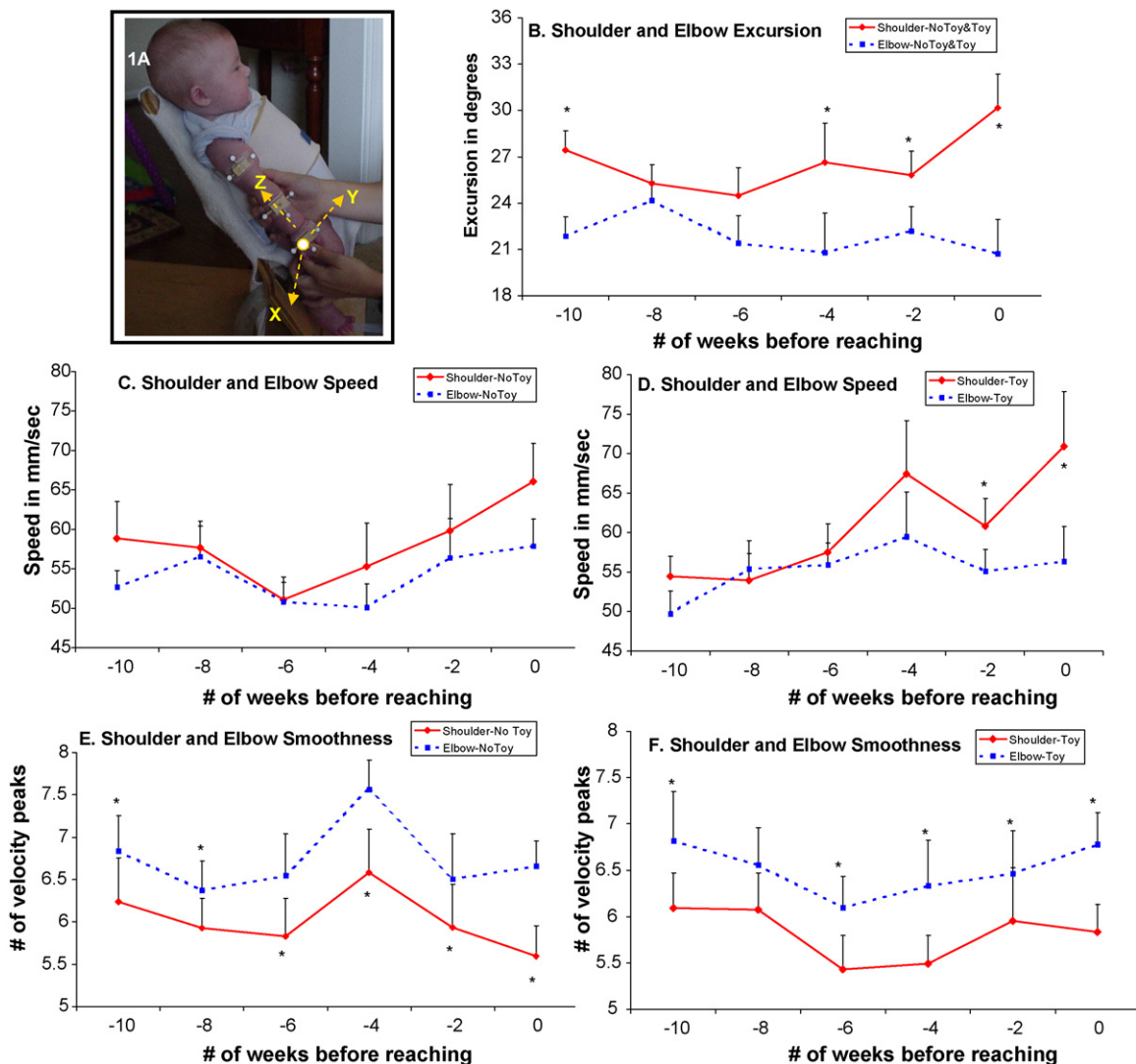


Fig. 1. (A) shows an infant in the custom made chair with conventions for calculating joint motions. The remaining graphs show average data (mean \pm standard error) for the shoulder and elbow for each week. Specifically, Fig. 1B shows joint excursion when no toy and toy conditions are combined. 1C and D show joint speed separately for no toy and toy condition, respectively. 1E and F show joint smoothness during no toy and toy conditions, respectively. *reflects significant differences ($p < 0.008$) between joints for a given week.

USA) captured position-time data from arrays of three reflective, non-linear markers (8 mm in diameter) placed on the right and left upper arm, forearm, dorsum of hand, and the toy (Fig. 1A). Three-dimensional (3D) joint motion calculations were conducted by the Singular Value Decomposition (SVD) method (Soderkvist & Wedin, 1993) for each arm, however here we report data from the right arm. For each trial, the 3D position for each marker was calculated and filtered at 4 Hz with a 4th 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 were calculated.

A “movement” was defined as a hand displacement ≥ 30 mm in length (Bhat et al., 2005). A reversal of direction of ≤ 15 mm, half the movement threshold was included within a movement. A movement reversal of ≥ 15 mm denoted the end of the preceding movement and the start of the next movement. For each movement, the following joint variables were calculated. *Joint excursion* (degrees): the 3D excursion of the shoulder and elbow between the start and the end of a movement. *Joint speed* (deg/sec): the average 3D speed of the shoulder and the elbow per movement. *Joint smoothness*: the average number of local maximums or peaks in the 3D speed profile of the shoulder and the elbow per movement. Fewer peaks reflect increased movement smoothness (von Hofsten, 1979, 1991).

We aligned each infant’s data by the week of reach onset prior to analysis. A 6 (week: 0 versus -2 versus -4 versus -6 versus -8 versus -10) \times 2 (condition: no toy versus toy) \times 2 (joint: shoulder versus elbow) multifactorial ANOVA with repeated measures on all three factors was used for all dependent variables (Field, 2000). Two types of post hoc analyses were conducted via paired *t*-tests. First, when there was a main effect of joint and a week \times joint interaction, data was pooled across conditions for each joint and for each week, and the joints were compared each week. Second, when there was a main effect of joint, a week \times joint interaction, week \times condition, and/or a week \times condition \times joint interaction, joints were compared at each week separately for each condition. For main effects and interactions, *p*-values < 0.05 were considered statistically significant and *p*-values ≤ 0.1 were considered a statistical trend. Due to the multiple *t*-tests used to compare no toy and toy conditions for each week, we set the *p*-value for significance at < 0.008 , which is 0.05 divided by six paired *t*-tests per variable.

3. Results

3.1. Joint excursion

Shoulder and elbow excursion across weeks is shown in Fig. 1B. Shoulder excursion (range 24–30°) appeared to be larger than elbow excursion (range 20–24°) for both no toy and toy conditions with an increase in this difference in the last 6 weeks leading up to reach onset. There was a main effect for joint, $F(1, 12) = 30.58$, $p < 0.01$ and a week \times joint interaction, $F(5, 60) = 4.34$, $p < 0.01$. There were no effects for condition; hence, data were pooled across the no toy and toy conditions at each week (note pooled data in Fig. 1B). Post hoc analyses for shoulder-elbow differences across weeks suggested shoulder excursion was significantly greater than elbow excursion for all weeks except week -8 and -6 .

3.2. Joint speed

Shoulder and elbow speed across weeks for the no toy and toy condition is shown in Fig. 1C and D, respectively. Shoulder speed appeared to be consistently higher than elbow speed over the last 4 weeks leading up to reach onset, with a greater difference in the toy condition as compared to the no toy condition. There was a main effect for joint, $F(1, 12) = 10.90$, $p < 0.01$, a statistical trend for a week \times joint interaction, $F(5, 60) = 2.1$, $p = 0.08$, a week \times condition interaction, $F(5, 60) = 2.71$, $p = 0.03$, and a statistical trend for a week \times condition \times joint interaction, $F(5, 60) = 1.85$, $p = 0.1$. Hence, post hoc analyses for shoulder-elbow differences across weeks were conducted separately for the no toy condition and the toy condition. For the no toy condition, there were no significant differences between joints. For the toy condition, shoulder speed was significantly greater than elbow speed for week -2 and for the week of reach onset (week 0).

3.3. Joint smoothness

Shoulder and elbow smoothness across weeks for the no toy and toy condition is shown in Fig. 1E and F, respectively. Shoulder smoothness appeared to be greater than elbow smoothness each week with or without a toy present.

There was a main effect for joint, $F(1, 12) = 137.38$, $p = 0.00$, a week \times joint interaction, $F(5, 60) = 2.42$, $p = 0.046$ and a statistical trend for a week \times condition effect, $F(5, 60) = 1.95$, $p = 0.09$. Hence, post hoc analyses for shoulder-elbow differences across weeks were conducted separately for the no toy condition and the toy condition. For both conditions, shoulder smoothness was significantly greater than elbow smoothness for all weeks except week -8 in the toy condition.

4. Discussion

This longitudinal study identified consistent differences in movement features between the shoulder and elbow during the prereaching period with and without a toy present. Despite significant developmental changes in hand and joint kinematics (Bhat & Galloway, 2006; Bhat et al., *in press*), the infants in this study moved their shoulder with greater excursion, speed, and smoothness than the elbow for various amounts of time leading up to reach onset. These joint differences however were not uniform across weeks, conditions and variables. Joint differences in excursion and smoothness were noted 10 weeks before reach onset, and occurred with or without a toy present. These results suggest that strong organismal constraints on excursion and smoothness are active in very early arm movements. In contrast, speed differences between joints were noted much closer to reach onset, and only in movements with a toy present. Thus, strong organismal constraints resulting in speed differences between joints were not found, however, there do appear to be task related constraints on joint speed beginning 1 month before reach onset.

4.1. *What are the developmental origins of these constraints?*

This is a key developmental question and requires further study; however, an interplay of arm mechanics with emerging purposeful control seems a reasonable speculation (Out et al., 1997; Thelen et al., 1993; Turvey & Fitzpatrick, 1993). The early emergence and consistency of our results suggests a significant influence of arm mechanics on excursion and smoothness. That is, joint differences in excursion and smoothness were noted months before the first week of reach onset, and in movements with or without a toy present. On the other hand, the specificity of speed differences in movements with a toy present, and the increasing excursion difference in the weeks leading up to reach onset suggest that changes associated with emerging toy-oriented action were laid upon the existing mechanical constraints. It is important to note here that there are multiple important perceptual changes also occurring during early infancy, such as the emergence of binocularity (van Hof, Van der Kamp, & Savelsbergh, 2006; von Hofsten, 1986). These and others perceptual changes provide important constraints on information pickup which influence toy-oriented actions in early infancy (see special issue on action and perception in infancy, *Infant Behavior and Development* Vol. 23). Below we briefly discuss the potential origins of the developmental changes in excursion, smoothness and speed.

4.2. *Joint excursion*

The greater excursion at the shoulder as compared to the elbow may be most parsimoniously explained by the larger anatomical range of motion. That is, if infants were exploring the full range of joint motion throughout the arm, they would produce greater shoulder excursion due to the greater kinematic degrees of freedom. Although elbow excursion was consistently less than the shoulder, we did not find evidence of a restriction on elbow motion during the prereaching period as has been noted in newly reaching infants (Berthier, Clifton, McCall, & Robin 1999).

4.3. *Joint speed*

Interestingly, the importance of the differences in speed may be related to different speed-excision relationships at each joint. In adults, an increase in joint excursion often occurs with a proportional increase in joint speed (Buneo, Soechting, & Flanders, 1994; Freund & Budinggen, 1978). At the shoulder, there were significant linear relationships between excursion and speed in movements with and without a toy present ($R^2 = .60$ and $.67$, respectively). Thus, infant's exploration of shoulder mobility may well have resulted in greater speed at the shoulder compared to the elbow in movements with a toy present. Interestingly, there was no such linear relationship between excursion and speed at the elbow. Impairments in this relationship have been noted in adult neurological patient populations, such as Parkinson's disease (Farley & Koshland, 2005). Thus, different speed-excision relationships supports the proposal

the shoulder and elbow have different developmental trajectories (Bhat et al., in press) based, in part, on the difference in joint dynamics outlined below.

4.4. Joint smoothness

Neither shoulder nor elbow smoothness was linearly related to its own excursion or speed suggesting that smoothness differences were not simply a result of excursion or speed differences. There was, however, a relationship between elbow smoothness and shoulder motion as outlined below, which led us to speculate that the mechanics of moving a multijointed arm may well be the source of the organismal constraints on smoothness. First, larger inertial masses are inherently more stable against perturbation. Thus, the fewer number of velocity peaks (i.e. increased smoothness) at the shoulder versus elbow may well have resulted from the shoulder's larger inertial mass and its attachment to the even more massive upper trunk and head. Second, the motion of this large proximal mass may be related to elbow smoothness. Shoulder and elbow motion are each influenced by motion of the other joint, however, the influence is larger at the elbow. Large shoulder excursions and speeds, such as in our results, produce large interaction torques at the elbow (Galloway et al., 2003; Galloway & Koshland, 2002; Gottlieb et al., 1997), which if poorly predicted by young infants would result in jerky elbow motion. If true, one prediction of our data would be a relationship between elbow smoothness and *shoulder* excursion. Indeed, post hoc analysis found a significant linear relationship but only in the *no toy* condition ($R^2 .65$). Thus, we propose that the mechanical effects of shoulder motion are a factor in elbow smoothness during spontaneous movements, but that infant purposefully influenced these mechanical effects when offered toys. It is important to note that although changes in smoothness of successful reaches during the first 3 years may primarily reflect more skillful control (Berthier & Keen, 2006; Konczak & Dichgans, 1997; von Hofsten, 1991), smoothness during the prereaching period would appear to reflect a more complicated interplay of changing biomechanics and emerging control (Out et al., 1997).

In conclusion, taking our results in total, we propose that important organismal constraints influence arm movements throughout the prereaching period, and provide a foundation for the overlay of task related constraints leading to the emergence of purposeful reaching. One important implication is that the coordinative structure of early flapping may well be much more similar to that of early reaching than currently suspected. If true, this similarity would significantly reduce the elements needing to be actively controlled, and simplify the learning process during the prereaching period. It is important to note, however, that even the most consistent features are best described as reflecting 'soft' constraints versus 'innate' or 'hardwired'. For example, joint differences were less consistently displayed during weeks -8 and -6. Constraints increase the tendency for infants to move in a certain manner but are rarely obligatory nor truly independent of the physical and social context in which the movement is produced. The emergence of even the earliest motor behaviors results not from a few dominant constraints but from the ongoing interplay of an array of constraints both internal and external to the infant. Thus, the importance of shoulder-elbow differences as a feature of the development of reaching can only be determined in relation to the interaction of the 'confluence of constraints' (Newell, Liu & Mayer-Kress, 2003) active throughout the prereaching period.

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