THREE-DIMENSIONAL KINEMATICS OF EYE, HEAD AND LIMB MOVEMENTS

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harwood academic publishers
Australia • Canada • China • France • Germany • India • Japan
Luxembourg • Malaysia • The Netherlands • Russia • Singapore
Switzerland • Thailand • United Kingdom (1997)

The Development of Hand Trajectory Formation and Joint Kinematics During Reaching in Infancy

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HOW IS MULTI- JOINT COORDINATION ACQUIRED?

Because human motor systems are redundant at multiple levels, movement solutions of multi-joint control during reaching are not unique (Bernstein, 1967; Hogan *et al.*, 1987; Soechting, 1989). For example, an infinite number of proximal joint angular configurations can lead to identical hand paths (joint redundancy). Or, identical joint net torques can be generated with varying patterns of motor-unit activation (muscular redundancy). Flash (1990) suggested that the nervous system masters the redundant degrees of freedom by applying coordinative constraints that lead to acceptable movement solutions. Although there is a considerable debate about the specifics of the underlying planning process, numerous studies have shown that as a consequence of these applied constraints, human adults express stereotypic kinematic patterns of the hand during reaching. Examples of such kinematic "invariants" are the scaling of hand velocity to target distance (Gordon *et al.*, 1994), or production of straight hand paths with a bell-shaped velocity profile under various speed and load conditions (Morasso, 1983).

It is not known how these coordinative patterns are acquired? The place in time to look for an answer is early ontogenesis, because it is the only period in the human life-span where basic forms of multi-joint coordination are assembled. We- know that humans are not born with consistent and efficient patterns of multi-joint coordination. When young infants attempt their first reaches about 4-5 months after birth, their hand trajectories are not characterized by a straight-line hand path (see Figure 1), and they do not exhibit a unimodal velocity profile of the hand. Their initial reaching movements are jerky, the joint paths consist of several segments. However, previous studies (Fetters and Todd, 1987; Hofsten von, 1979; Hofsten von, 1991) and our own work (Konczak *et al.*, 1995; Konczak and Dichgans, 1997) demonstrate that with increasing experience infants begin to express smoother hand and proximal joint motion.

PHASES OF DEVELOPMENT

This ontogenetic process is not stage-like, as suggested by traditional developmental theory (Piaget, 1952), nor is its direction necessarily moving from proximal to distal arm segments as proposed by neuromaturational theory (Gesell, 1946). Especially within the immediate period after reaching onset, development is rather individual among infants, and does not show a proximal to distal progression (Konczak and Dichgans, 1997).

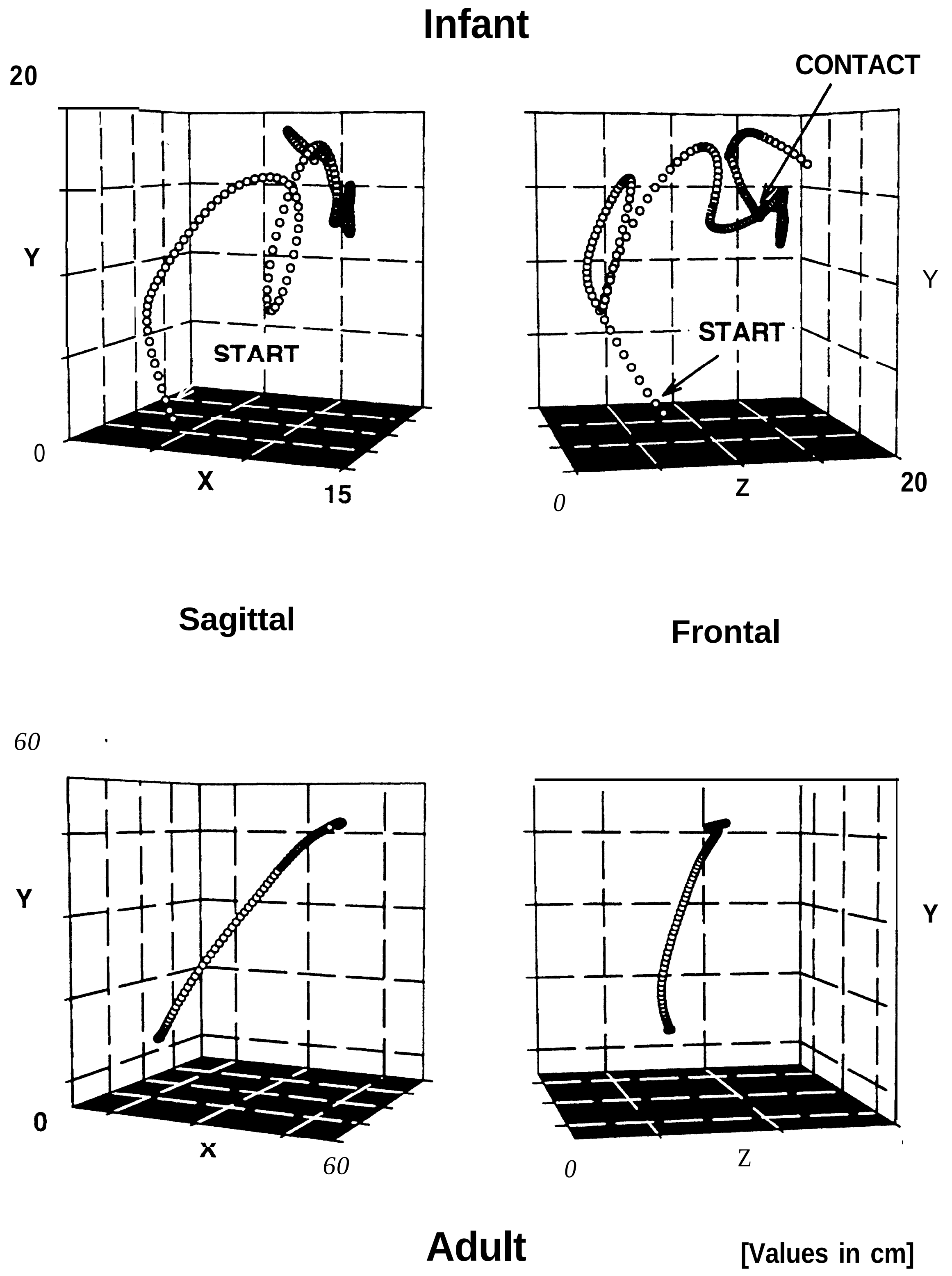

Figure 1 Top: Hand path of a 20-week old infant in one of his first goal-directed reaches. Reaching onset had occurred three days prior to recording. Bottom: Adult hand path. Time interval between successive data points is 10 ms.

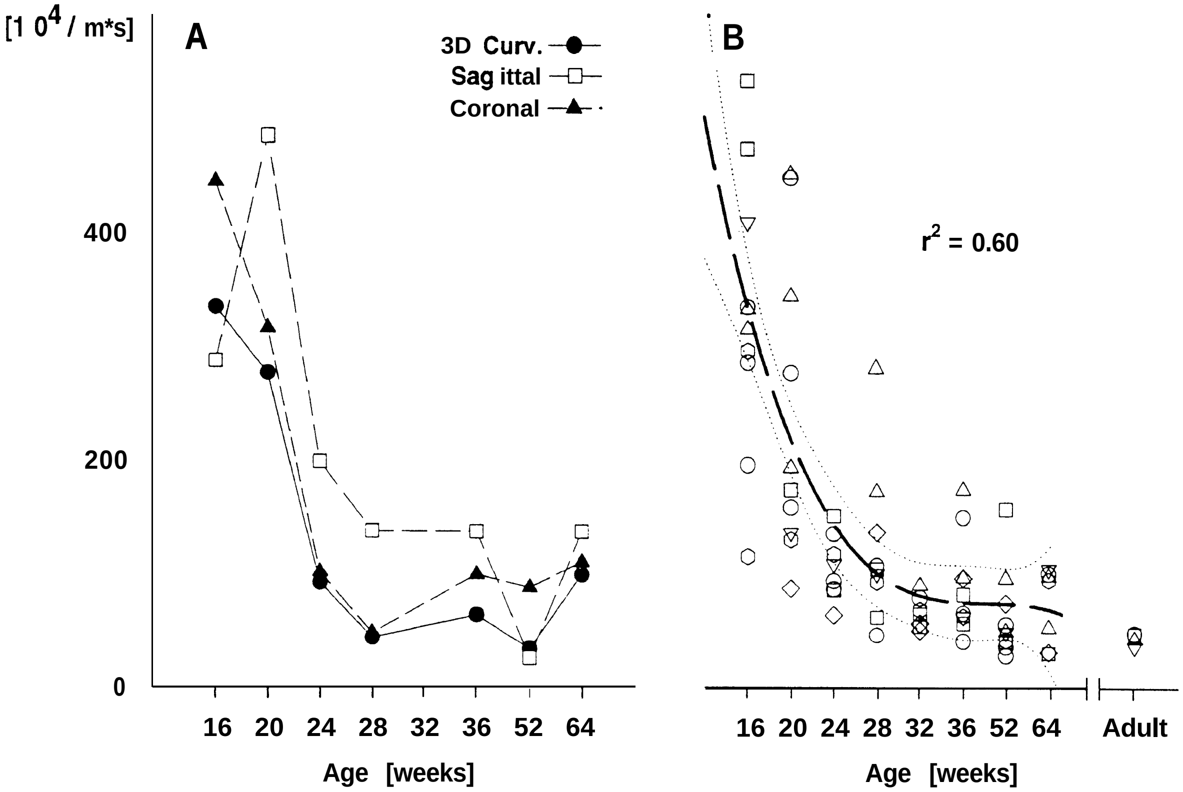

Figure 2 Development of hand curvature. We computed the curvature integral between start and object contact. Because the value of the integral depends on movement duration, we normalized it by movement time. The normalized curvature integral provides a measure of the "straightness" of the hand path. High values indicate a curvy path. (A) Individual development of one infant. Data are means of a particular recording session. Note that reduction of curvature is not restricted to one movement plane. (B) 3D-curvature of nine infants. Data are individual subject means. Solid line represents the fit of a cubic regression on the infant data. Coefficient of determination (r^2) indicates that 60% of the variance in curvature is explained by "age".

However, on a gross scale two phases of development may be identified. Within the first *4-8* weeks after reaching onset, we see rapid improvements in many kinematic measures of both hand and joint space. In this time period the number of endpoint and joint-related movement units (Brooks *et al.,* 1973) are nearly halved. At the end of this phase, infants reach reliably for objects in their surrounding. In a second phase of "fine-tuning", kinematic patterns change more gradually. The. acquired basic gross-motor patterns are refined and trial-to-trial variability is reduced. This phase lasts well within the second and third year of life. Most kinematic parameters do not assume adult-like levels before the age of 2 years. At that time, about 75% of observed reaches reveal a single-peak velocity profile of the hand, while *98%* of comparable adult trials are unimodal (Konczak and Dichgans, 1997). The increasing efficiency of infant arm movements is also demonstrated by various other kinematic measures. For example, infants minimize endpoint curvature during ontogenesis, which results in more straight-line hand paths (see Figure 2). These data also illustrate that the straightening of the hand path is not restricted to the sagittal plane but is improved in 3D-space.

Mechanics dictate that improvements in endpoint space must be related to improvements of inter-joint coordination. However, on what basis does a developing motor system

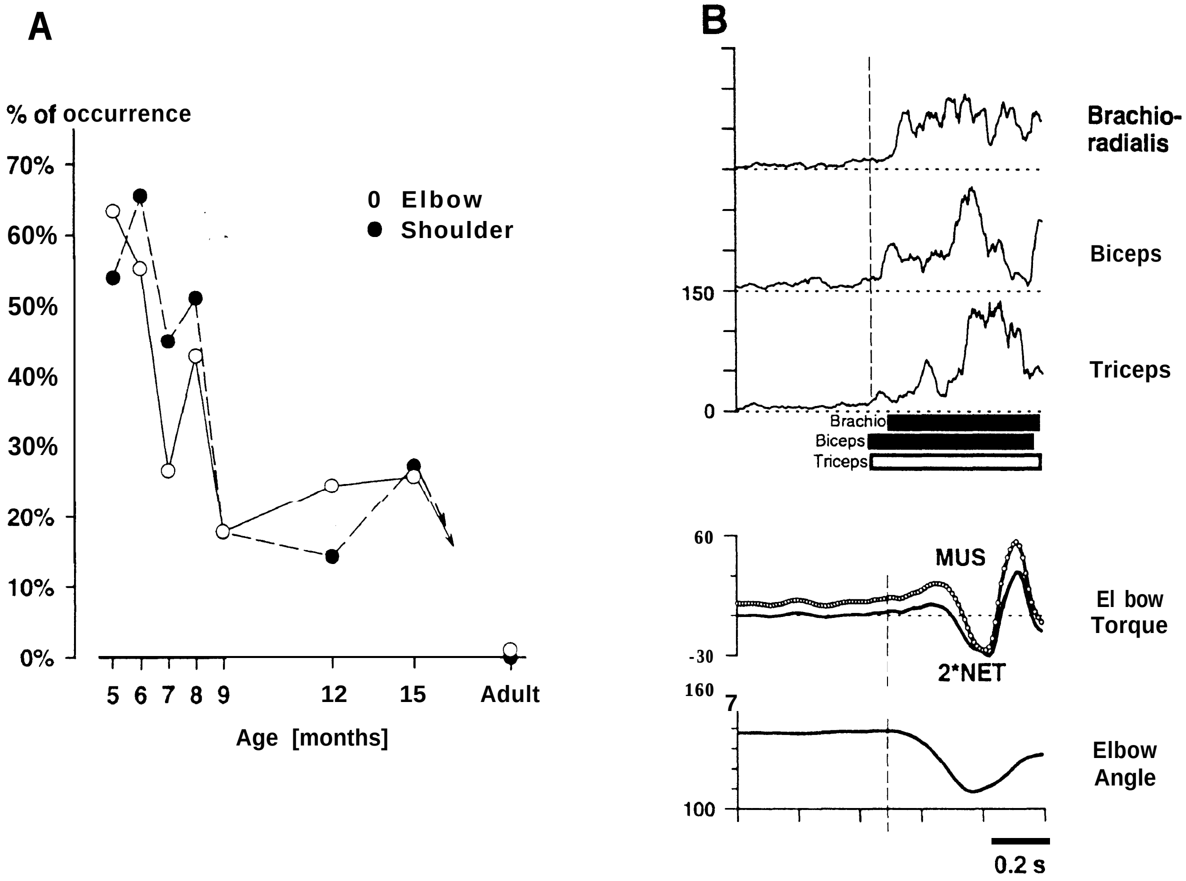

Figure 3 Evidence of improved skill economy of goal-directed reaching during ontogenesis. Data are from our longitudinal study on infant reaching (N=9). Infants performed vertical reaching movements to a target (toy) presented at shoulder height. (A) Percentage of trials exhibiting extensor muscle torque at the shoulder and elbow joint. Note that with increasing age, infants reduced the number of trials in which they generated extensor muscle torque to extend the elbow. (B) Exemplar trial of a 24-week old infant showing active elbow extension. Dashed vertical line indicates start of the reach. Note that muscle torque (MUS) exhibited positive (flexor) and negative (extensor) influence throughout the reach. Elbow extension (increase in elbow angle) was initiated by extensor MUS. The underlying muscular innervation pattern revealed coactivation of elbow flexors and extensors with the triceps becoming dominant during the extension phase of the elbow. NET is total joint torque. Because NET is small relative to MUS, it is multiplied by 2 for better readability of the graph. Torque values were normalized by body weight. Units are [Nm/N*10^{4}]. Elbow angle is the planar angle between humerus and ulna. Units are in degrees.

select a given hand trajectory, given that it can select from an infinite number of possible joint trajectories? Likely, there is not a single cause responsible for shaping endpoint control in infancy. Yet, our kinematic data clearly indicate that an overriding concern of infant motor systems is to select those joint trajectories that fulfill at least two criteria. First, the selected trajectories should provide a reasonable guarantee of obtaining the movement goal (e.g., grasping the object), and second, they should contain as few force reversals as possible (Konczak *et al.*, 1997; Konczak and Dichgans, 1997). Consequently, the increasing efficiency of infant movements is observable in kinematic space and their associated intersegmental kinetics. The improved efficiency in joint force control is not reflected by a minimization of net or muscle torque, which would imply that infants generate excessive amounts of joint force in the initial phase after reaching onset. We could demonstrate that this is not the case (Konczak *et al.,* 1995). Instead, improved skill economy is achieved by beginning to exploit external forces (gravity and reactive torques) during movement execution. When infants begin to reach at about 20 weeks of age, elbow extension is performed by actively generating extensor muscle torque in over 60% of their reaches (Konczak *et al.,* 1997). By the age of 15 months only 25% of the reaches reveal extensor muscle torque and the size of the extensor impulse yet observed has decreased threefold when compared to their early performance (see Figure 3). The extension of the elbow is now carried out by letting gravity pull down the forearm and by "regulating" the amount of necessary flexor muscle torque, so the hand does not drop below the desired target object.

OUTLOOK

Previous research e.g. (Hofsten von, 1991; Thelen *et al.,* 1993) and our recent findings support the interpretation that the emergence of co-ordination in infancy is not a single-cause phenomenon. Sufficient evidence exists to stress that the acquisition of co-ordination is tied to growth of the neuromuscular system and to neural development. Yet, our data and those of others (Schneider *et al.,* 1990) argue that development and learning cannot be considered outside their biomechanical context. That is, in order to produce co-ordinated movement among linked arm segments, motor systems need to have an advance "knowledge" about the physics of the movement (muscular forces in relation to the expected external forces). Considering that the interaction of muscular and external torques across multiple joints are difficult to predict in detail, it seems unlikely that this advance "knowledge" is genetically determined. Given that the acquisition of multi-joint co-ordination is a learning process, future research needs to address the question of how changes in central structures innervating the muscles are matched to peripheral changes (e.g., changes in anthropometrics) (Spoms and Edelman, 1993). The theory of neuronal group selection (Edelman 1987) and empirical findings in animal studies (Bekoff *et al.,* 1989) suggest that basal brain circuits form functional neuronal groups during development that ultimately lead to the progressive formation of a task-related movement repertoire. Although our data on human motor development cannot be conclusive in that respect, they are congruent with such an interpretation.

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