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# The Emergence of Purposeful Limb Movements in Early Infancy:

## The interaction of experience, learning and biomechanics.

*by*
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## The emergence of purposeful behaviors

The process by which motor behaviors emerge throughout childhood has long been a fundamental area of study in developmental psychology (Thelen 2000 a, b) and is the foundation for pediatric neurorehabilitation (Heriza 1991). As such, the expansion of research on the development of motor skills in young children over the last 20 years has resulted in advances in pediatric neurorehabilitation (Ulrich *et al.* 2001). Significantly less is known about the process by which motor skills emerge and change in children younger than 1 year of age. As a result, there are notably fewer clinical assessments and fewer validated interventions available for clinicians working with young infants at risk for long term motor impairment. This gap in research is particularly disturbing given the increase in infants surviving significant preterm birth (Alexandar *et al.* 2003; Martin *et al.* 2003). On a more positive note, such as gap offers researchers the opportunity to advance pediatric neurorehabilitation, and ultimately improve the lives of infants and their families.

In our lab, we are interested in the initial emergence of purposeful motor behaviors in the first months of postnatal life. More specifically, we are focused on the processes by which the purposeful arm and leg movements of the five

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month old emerge from the various limb behaviors of the newborn. This basic question contains several core developmental issues. For example, what role, if any, does early **experience** play in the initial emergence of purposeful movements? What role does **learning and memory** play in this process? What role does the infant's **body mechanics** itself play? And finally, how can studying this process in the typically developing infant advance neurorehabilitation for young infants born at risk for coordination disorders? The purpose of this paper is to briefly discuss our recent work on the roles of experience, learning and memory, and limb biomechanics in the initial emergence of purposeful motor limb behaviors in very young infants.

Disembodied development: The traditional view. The most basic motor development question is simple: how do purposeful motor behaviors emerge from seemingly non-purposeful behaviors? The newborn infant flaps her arms. By five months of age she will reach with her arms to touch her mother's face, pull mother's hair and grab at toys that mother offers her. How does this amazing transformation happen!

The traditional view, represented by the classic work of Myrtle McGraw and Arnold Gesell, is that purposeful movements emerge following an orderly (McGraw 1935, 1945, 1940, 1941, McGraw and Breeze 1941) albeit non linear (Gesell 1939, 1954, Gesell and Amatruda, 1947, Gesell and Ilg 1949, 1946;cf Thelen and Adolph 1992) sequence of milestones. Behavioral principles such as 'cephalocaudal' (from head to toe) and 'proximodistal' (from trunk or pelvis outward) progressions outline the sequence by which infants acquire control of their bodies. These progressions are obvious: head control precedes reaching, and general arm movements precede fine finger movements. More importantly, this orderly sequence of behaviors reflects the singular underlying cause of developmental change: orderly nervous system 'maturation'. Taken at its simplest, this view envisions behaviors as emerging de novo as predestined by neural maturation in relative isolation from extrinsic influences such as experience, learning and changes in body properties. Here, skill emergence is thrust upon the passive infant from within. The term 'disembodied' is synonymous with this view and highlights that the child's body, if not her entire behavioral pattern, is looked past to get to the focus: the nervous system (Figure 1 left). For example, kicking behaviors in the newborn, for example, is a direct reflection of spinal circuit generation, whereas the later emergence of reaching behaviors signals the maturation of specific cortical and subcortical areas.

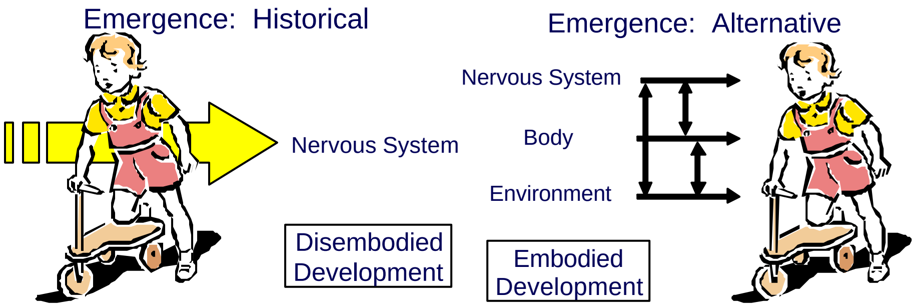


**Fig. 1**

*Figure shows schematic illustrations of the historical view (list) and alternative view (right) of motor development. In the historical view, the yellow arrow emphasizes that the child's behavior reflects the actual cause of developmental change: nervous system maturation. In the alternative view, developmental change results from the ongoing interplay of multiple factors both within and outside the child.*

## Embodied development. The alternative view

Over the last 20 years, there has been increasing focus on the process of developmental change (Thelen 2000a,b; Thelen and Smith 1994). The issues have shifted from '*what* did baby do at time A and time B?' to '*how* did she change?'. Similarly, the source of developmental change has shifted. In contrast to the isolated nervous system of the traditional view, purposeful behaviors are now seen to arise from the ongoing interplay of a wide variety of factors encompassing social, cognitive, language, perceptual and motor domains. Consequently, the modern realization is that although not all aspects of life play a major role in the emergence of a given behavior, all aspects *have the potential to*. It is not an overstatement to recognize that in a relatively short period of time the study of motor development has reversed from a field having few questions left to answer to having an unanswerable number of questions. The driving force behind this change, of course, is a change in our theoretical grounding. That is, a change in our view or concept of developmental change.

New conceptual models, such as dynamic systems theory (see Thelen and Smith 1994; Smith and Thelen 1993; for both historical references and basic tenets), are becoming well established in infant motor development. For example, dynamic systems, as outlined for infant development by Esther Thelen, has led to an appreciation of the array of potentially important factors influencing developmental change and set down general hypotheses regarding the interrelationships of these factors. In turn, empirical studies, which having increasing focused on a systems approach, have led to more specific theories of developmental change[1]. Currently, there are several guiding principles for envisioning the interplay of the overwhelming array of potential factors. In our study of the development of purposeful reaching and kicking, we have found two separate but related sets of principles to be particularly helpful.

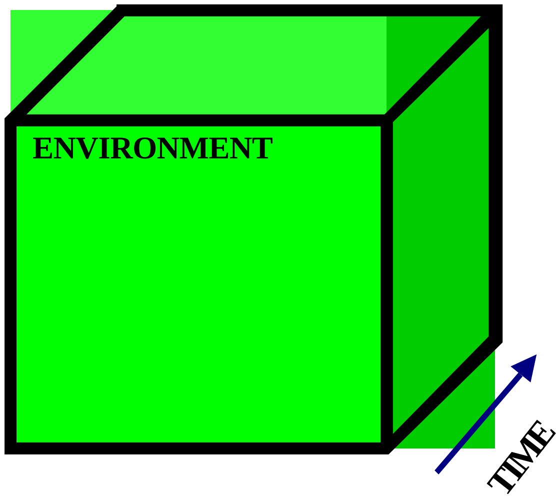


**Fig. 2**

*Figure shows the nervous system nested within the body which is then nested with the physical and social environment. The arrow shows developmental time and emphasizes the changing relationship between these components over time. (Adapted from Chiel and Beer 1997).*

The first principle views the control and development of motor behaviors as rising from the ongoing interplay of the nervous system, the body's mechanical properties and experience (Chiel and Beer 1997). The interplay of these factors is illustrated on the right of Figure 1 and stands in contrast to the disembodied model on the left. Figure 2 is a reminder that the nervous system is physically housed within a body, which in turn is housed within the immediate environment. Thus we are reminded that, at all times, the nervous system's actions are constrained by the body properties as well as the physical and social properties of the environment. From this obviously nested arrangement comes many non-intuitive implications. For example, as a group, human infants

[1] See the developmental work of Karen Adolph, Daniela Corbetta, Jane Clark, Alan Fogel, Carolyn Heriza, Jana Iverson, John Spencer, Esther Thelen, Bev Ulrich, Jill Whitall.

display motor 'milestones' (ex. reaching, sitting, walking) in a predictable sequence independent of socioeconomic, cultural or geographic factors. It is tempting to view this consistency as a 'hard-wired' sequence directed by motor development genes. The rationale being that with all the variability in external factors, the consistency must arise from nervous system maturation as directed by our genes. That is, despite many external differences, African, Indian and European infants all have similar brains, similar brain development and thus similar motor development.

In contrast, a nested, embodied view expands our search of the cause of this regularity. First must be the confession that although infants as a group display milestones in a regular sequence, individual infants achieve their milestones in a individualized manner both in terms of sequence and timing across milestones and the development of each milestone. Second, not only do all infants share a brain of similar capacity but each also shares a body with similar parts and properties. Thus, if one were to want a singular cause, musculoskeletal changes such as skeletal growth, changes in skeletal muscle force generation, or muscle to adipose tissue ratio would be as likely a rate-limiting step in the emergence of motor skills as neural maturation. Moreover, given that the nervous system does not move the body, but rather must work with the cardio-vascular-musculo-skeletal systems to produce movement – a singular cause is quite simply a flawed --or worse, a completely unhelpful view.

The second model is actually an amalgam of several different constructs that emphasizes the exploration-selection process underlying the emergence of a particular motor behavior or 'state' (see Thelen and Smith 1994; Gibson 1988, 1997, 2000). First, any purposeful motor behavior can be viewed as the current state selected from a constrained set of potential states. Second, the selection of this current state is a function of distant and recent experiences, current task demands, and the physical and social environment. Third, during development, it is through ongoing exploration that the infant learns the relationship between herself and her environment (i.e. discovers affordances), which in turn leads to progressively more specific purposeful behaviors and new exploratory abilities. Lastly, behavioral states can be highly stable and resist change, or highly unstable and moved by change. The level of stability reflects the ongoing interplay of the multiple, 'causal' factors. It is important to note that, although pediatric rehabilitation of the very young infant lacks a foundation of research, it continues to benefit from this rich theoretical grounding as it patiently awaits the empirical data necessary to validate these theoretical foundations (Heriza 1991).

## Feet reaching: a test of developmental principles

The use of the arms and the legs for reaching presented an interesting test of several classic views of the infant motor development. Historically, control of the arms and the legs have been viewed as fundamentally different. Leg movements in early infancy are reflexive, non-volitional expressions of spontaneously active central pattern generator circuitry located in the spinal cord (Forssberg, 1985; Lamb and Yang 2000). The planning and execution of purposeful arm movements, such as reaching, however, involves a variety of supraspinal centers (Kalaska *et al.* 1997; Shadmehr and Holcomb 1997; Lawrence and Kuypers 1968 a, b). As outlined previously, infants gain control of their bodies from their head to their toes (i.e. cephalcaudal progression). Thus, in terms of both traditional neurophysiology and developmental psychology, infants purposefully control their arms before they can control their legs. This is seemingly obvious, as infants first reach between 3-5 months of age, yet do not sit, crawl or walk until after 6 months.

In the alternative view, control of the arms or the legs emerges from the interplay of nervous system development, experience, biomechanics and the 'drive' to explore and discover the body's functionality. From this view, I propose that indeed the legs and arms differ, but with the advantage to the legs for the initial emergence of purposeful reaching. First, the pattern of early leg and arm movements are different. Compared to early arm movements, early leg movements are relatively stereotypical in their alternating movement pattern (Thelen, 1979, Thelen, 1985 and Thelen and Fisher, 1983), and their muscle activation patterns (Spencer and Thelen, 2000). The resulting perceptual-motor mapping for the legs would also be more constrained compared to the arms. Given this perceptual-motor constraint, infants may find it easier to adapt the leg's well-established pathways for purposeful activities when an opportunity arises. Second, the anatomy and resulting biomechanics of the arms and legs are different. The hip joint is both deeper, more mechanically stable as compared to the shallow, mobile shoulder joint. As a result, the legs have fewer anatomical degrees of freedom than the arms. Specifically, hip joint anatomy may softly constrain the legs from moving freely in lateral workspaces, which reduces the amount of motion to be actively controlled. Without this anatomical guidance, infants can move their arm more freely through a wider range of motion, which increases the degree of control required to place the hand on a toy. Of course, such freedom is what provides for the functional flexibility of the arms we enjoy as adults.


**Fig. 3**

*Figure shows a split screen view of feet reaching behavior in a young infant in the lab. This infant was 4 weeks from contacting this same toy with her hands.*

This alternative view led Esther Thelen and I to propose an experiment with a novel hypothesis: young infants would purposefully contact toys with their feet before their hands (Galloway and Thelen 2003). Indeed, our results suggested that infants, as young as 8 weeks of age, purposefully contacted toys with their feet an average of four weeks before they contacted toys with their hands (Figure 3). This rapid adaptation of leg movements for a novel task suggests that a) early leg movements can come under precise purposeful control; b) that motor behaviors need not develop in a strict cephalocaudal pattern. Moreover, because none of these young infants had feet reaching experience prior to coming into the lab, these results suggest that certain purposeful behaviors can 'develop' online when the opportunity presents itself without the need for lengthy task-specific practice.

## Role of movement experience

The role of experience in the emergence of purposeful behaviors is a fundamental issue for the developmental sciences (Adolph and Eppler, 2002) and, of course, for pediatric neurorehabilitation (Ulrich *et al.* 2001; Willis *et al.* 2002). The role of experience in altering the performance of motor behaviors once these skills are already present is well established throughout the lifespan. What is much less clear, and potentially more telling in terms of the developmental process, is which experiences influence the initial emergence of early behaviors. Moreover, past work suggests that any influence of experience is likely to be complex and often non-intuitive such that empirical data is required in even the clearest of cases (Gottlieb 2002).

We recently began to address the need for a systematic assessment of the role of different types of movement experiences in the initial emergence of reaching. The development of reaching is particularly interesting as an infant's first independent exploration of her immediate environment is through reaching. As such, the ability to contact objects expands opportunities for further motor, cognitive and social development (Gibson, 1988; Thelen and Smith, 1998; von Hofsten, 1997, Fogel *et al.* 1999).

**Fig. 4**

*Figure shows a picture of parent providing task related movement experiences to her young infant. Pare nts in both the task related experience group and the general movement experience group provided daily experiences to both the arms and the legs for 2 weeks.*

As outlined by Gilbert Gottlieb (1983), experience can advance the initial emergence of a behavior (induction), advance the development of a behavior already present (facilitation), or preserve a behavior already present from declining over time (maintenance; Gottlieb, 1983). Our results provide an interesting example of the facilitative and inductive effects of enhanced movement experiences on the initial emergence of reaching. Specifically, in collaboration with Geert Savelsbergh of the Vrije University in Amsterdam, we showed that two fundamentally different types of movement experiences, general experience (GE) and task-related experience (RE), advanced the onset of reaching in comparison to a control group (Lobo *et al*. 2004). Infants in the GE group were provided with 2 weeks of daily play that encouraged general arm flapping to move a distant toy similar to the mobile paradigm (see **Role of learning and memory** section below). Infants in the RE group were provided with the same amount of play that encouraged reaching for and contacting a toy (Figure 4). Both experiences advanced the onset of reaching. Interestingly, GE advanced feet reaching greater than RE, and RE advanced hand reaching greater than GE.

The effect of GE supports the theoretical stance that early limb movements not involving direct object contact provide experiences that are important in the emergence of reaching (Turvey, 1993). The effects of RE suggests that experiences specific to moving towards and touching objects may be an effective strategy to advance purposeful reaching in infants at risk for delayed reaching. We are now utilizing these findings in the development of novel interventions for young infants at risk for long term disability such as preterm infants and those born with brachial plexus birth palsy (Duff *et al*. 2004).

## Role of learning and memory

The ability to learn and retain basic cause-effect relationships (i.e. associative learning and memory) is an important factor in the emergence of purposeful behaviors in both typical development and in pediatric neurorehabilitation. Young infants display basic learning and memory abilities within the first month of postnatal life, well before they display adult functional skills such as reaching.

Our lab studies associative learning and memory as well as limb coordination using the 'mobile paradigm'. In the mobile paradigm, supine infants from 2 to 6 months of age have one leg tethered to an overhead toy mobile, such that their kicking is associated with mobile movement (Figure 5). Within one 15-minute session, typically developing infants are able to learn to adapt the timing and amplitude of their kicking to directly control the mobile's movement (Rovee and Rovee 1969, Heathcock *et al*. 2004, in press). In a classic basic science-clinical science information gap, in the 40 year history of the mobile paradigm's use in infant developmental psychology, there had been only one study with infants born preterm, a group at known risk for learning and coordination impairments in later childhood (Cherkes-Julkowski 1998; Drummond and Colver 2002, Han *et al*. 2002; deVries and deGroot 2002; Saigal *et al*. 2000; Sommerfelt 1998).

**Fig. 5**

*Figure shows a 3 month old infant performing in the mobile paradigm in her home crib. This photo was taken during the initial baseline period, thus the mobile is hanging from the stand that is not tethered to the infant. Following the baseline period, the mobile is switched to the other mobile stand such that her right leg kicks move the mobile.*

In a recent pair of studies, we compared the performance of healthy, full term infants, preterm infants at moderate risk for developing learning and coordination impairments with a full term control group. Full term infants learned the association between their kicks and mobile movement within the one session and retained this association at both 24 hours (short term memory) and 7 days (long term memory). Preterm infants, however, did not display learning despite 12 sessions conducted over six weeks (Heathcock *et al.* 2004).

Infants typically kick their left and right legs at an equal rate. In the mobile paradigm, however, only kicks with the tethered leg move the mobile. Thus, the paradigm offers the opportunity to test for the ability to alter the typical bilateral pattern to produce a 'task specific' pattern as well as associative learning and memory. Our results suggest that full term infants preferentially kicked more frequently with the leg that was tethered to the mobile within the first session and remembered this specific pattern for 24 hours. In contrast, preterm infants kicked with equal frequency with both legs throughout the six weeks similar to control group infants (Heathcock *et al.* in press). These findings suggest a) that preterm infants, a group at known risk for learning impairments by school age, perform much differently in the mobile paradigm, b) a potential link between coordination and learning abilities in young infants, and c) that the mobile paradigm can provide clinically useful information on learning and coordination abilities within the first months of an infant's life.

**Role of biomechanics**

In their now classic work on the stepping reflex, Esther Thelen and Donna Fisher showed that, in contrast to the neural maturational explanation, the disappearance of this reflex reflected a simple, non-neural scaling of the infant's body composition during early development (Thelen and Fisher 1982, 1983). Historically, stepping behaviors of a newborn held vertically were viewed as a direct reflection of the activity of isolated spinal cord circuitry. Within the first postnatal month, these spinal centers are inhibited by maturing supraspinal centers and the reflex disappears. Thelen and Fisher showed that, in fact, this behavior 'disappeared' as the adipose/muscle mass ratio increased. Thus, infants actually decrease their early stepping behavior because their temporarily weak leg muscles make it difficult to lift their legs against gravity. This work dramatically illustrated that multiple factors, including the body itself, influence the changes in motor behaviors seen during development.

Our lab is also interested in the role that the body's properties play in early motor development. One example of such a role is in the how infants change their shoulder-elbow coordination during the months leading up to the onset of purposeful reaching. Adults coordinate their shoulder and elbow joints such that the hand's path is relatively straight, has a bell-shaped velocity profile, and little or no overshoot at the target (Morasso 1981). Shoulder and elbow excursions are also typically smooth, direct and accurate in adults. In contrast, an infant's first reaches at 3-5 months of age are neither direct nor smooth, but show a winding hand path with many velocity changes (Thelen *et al.* 1993). Over the first year, the path becomes markedly more straight, smooth and accurate. Few studies have investigated how infants coordinate their shoulder and elbow joints to produce these improvements in hand path (Konczak *et al.* 1995; Konczak *et al.* 1997; Konczak and Dichgans 1997). Even less is known about how shoulder-elbow coordination emerges during the arm movements in the weeks before onset of reaching.

Esther Thelen and I conducted a longitudinal study to characterize the pattern of directness (number of joint reversals), smoothness (number of joint velocity peaks) and accuracy (ratio of total joint excursion/maximum-minimum joint excursion) at the shoulder, elbow and wrist from the first month of life across the first year. Adult typically display no joint reversals, one joint velocity peak and an accuracy ratio of 1. Our results showed a) infant reaches displayed a consistent proximal to distal pattern in which the shoulder was more direct, smooth and accurate than the elbow, and the elbow more than the wrist (upper graph, Figure 6), b) that this proximodistal pattern was maintained as infants improved control in all three joints as they approached the end of the year, and most importantly, c) that infants displayed this proximodistal pattern in their spontaneous arm movements in the weeks prior to reach onset (lower graphs, Figure 6) . These results suggest that purposeful reaching does not arise de novo, but is fashioned within the biomechanical constraints of the multisegmented limb. That is, we believe that the proximodistal pattern display in during non reaching arm movements in the 'pre reaching' period reflected biomechanical differences in the shoulder, elbow and wrist. Purposeful shoulder and elbow control was then laid upon this mechanical foundation (lower graph, Figure 6). The biomechanical analysis of early arm movements has significant implications on how purposeful arm movements develop as well as understanding the interaction between biomechanics and neuromotor aspects of adult reaching (Koshland *et al.* 2000; Galloway and Koshland 2002; Galloway *et al.* 2004).

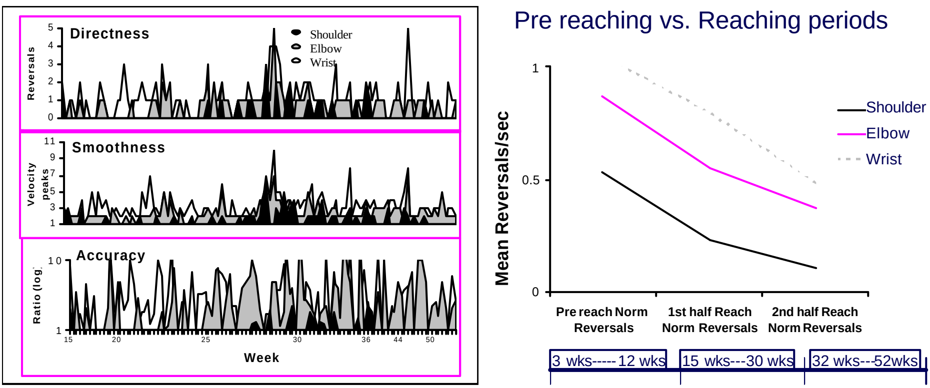


**Fig. 6**

*Figure 6 shows shoulder, elbow, wrist data from the reaches of one infant. The top figure shows directness, smoothness, and accuracy for each trial from the first week of reach onset throughout the 52nd week of the year. The lower figure shows the average joint reversals/second at the shoulder, elbow and wrist for the weeks leading up to reach onset (prereaching period) as well as the first and second half of the reaching year.*

## Conclusion

In summary, my lab's recent work suggests that purposeful behavior develops from the confluence of physiological, anatomical and biomechanical constraints, experiential history, and contextual opportunities (Edelman, 1988; Gibson, 1997; Gottlieb, 2002; Michel and Moore, 1995; Oyama, 2000; Thelen and Smith, 1994). We are currently conducting the first study of the effects of early postural experience on the emergence of reaching. We are also conducting the first study of the role of intensive early movement experience on the associative learning, limb coordination and emergence of reaching in infants born preterm and with low birth weight. In terms of reaching development, we recently completed the first comprehensive longitudinal study of 3D hand and joint kinematics over the months leading up to the onset of reaching. Ultimately, it is our hope that by understanding the roles of experience, learning and biomechanics we can advance the early assessment and intervention specifically for very young infants at high risk for long-term disability.

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