Studies in Perception and Action III
B. G. Bardy, R. J. Bootsma, and Y. Guiard (Eds.)

Development of Infant Crawling: Balance Constraints on Interlimb Coordination

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A major achievement in the first year of human infancy is the development of independent locomotion. For most infants, the first access to mobility is provided by crawling. Research in the forties and fifties (e.g., Gesell, 1939; McGraw, 1935, 1941) described the development of crawling as a stage-like progression: Infants would begin by moving on the belly before crawling on hands and knees.

In a recent longitudinal study of six infants, Freedland and Bertenthal (1994) found that crawling on hands and knees quickly falls into a uniform pattern – an alternating gait with diagonal limbs moving together (left arm and right leg, right arm and left leg). These authors suggest that this preferred pattern of interlimb coordination results from balancing constraints. We know of no description of the development of interlimb coordination or the timing of limb movements in early phases of prone progression, when infants balance on their bellies during part of each crawling cycle.

In the present study we sought to obtain a first detailed kinematic description of the entire crawling period, from the first crawling steps of infants until they begin walking bipedally. Our primary aim was to examine the effects on interlimb coordination of overall balance constraints from belly crawling to hands-and-knees crawling. We observed a large sample of crawling infants to determine whether the apparently stage-like, obligatory pattern of hands-and-knees crawling described in classic research and reported by Freedland and Bertenthal (1994) might result from highly constrained balance requirements. We hypothesized that in belly crawling, where balance requirements are less stringent, gait patterns would be more variable.

Method

Twenty-nine healthy, full-term infants participated in the study. Fifteen infants (7 girls, 8 boys) were tested every third week, from their first week of crawling until their first steps. Fourteen babies (7 female, 7 male) were tested twice, on their first and tenth week of crawling. In each session, infants crawled four times over a flat, carpeted walkway (2.44 x 0.75 m), twice in either direction. An assistant videotaped the trials with a camera oriented perpendicular to the walkway. We defined crawling onset as the first

day when infants could travel the length of the walkway on 3 of 4 consecutive attempts without a pause longer than 3 s between two phases of forward movement.

Using a computerized video-coding system (Macshapa), we defined onset time as the time a limb contacted the surface and offset time as the time the limb was lifted off the surface or slid forward. From these data, we calculated transport velocity (time to travel between two markers), average stance and swing times for each limb (periods of support and forward propulsion), and relative phasing between limbs (when right arm and legs began a swing phase compared to initiation of swing in the left arm). Inter-rater reliability was high: Out of the 1488 codes checked for reliability, inter-rater agreement was within 3 frames (.05 s) on 94.4% of codes and within 5 frames (.08 s) on 98.7% of codes.

Results and Discussion

Belly crawling. Mean age at crawling onset was 7.4 months (ranging from 4.8 to 9.7 months). Seventeen infants began crawling with their belly resting on the ground during each crawling cycle, then later switched to hands and knees; 12 infants began directly on hands and knees; and 2 babies began walking upright before passing crawling criteria. Belly crawlers started crawling at a younger age than children who skipped that phase and went directly to hands and knees ($t(27) = 2.99, p < .006$). Early crawlers tended to have more crawling experience ($r = -.64$) and early walkers tended to have less crawling experience ($r = .66$). Age at belly crawling was positively correlated with age at hands-and-knees crawling ($r = .89$). Children who belly-crawled had more total crawling experience than children who did not ($t(26) = 3.31, p < .003$), but there was no difference in the age when they began to walk.

Belly crawlers accomplished forward progression with a surprisingly wide variety of patterns, viz., propelling with all four limbs, dragging one or both legs behind as if lame, or pushing onto knees and feet and hopping forward onto the belly like an inchworm. Coordination between limbs was relatively unconstrained by balance requirements. Infants sometimes moved all four limbs at once or both arms then both legs while balancing on their belly, and sometimes moved diagonal limbs together in an alternating gait. Changes in overall style of belly gaits did not follow a stage-like progression. Rather, infants used a variety of styles within sessions, and even within trials from cycle to cycle. Speed increased across sessions, indicating improvement. However, many belly crawlers persisted with energetically inefficient and cumbersome gait patterns for weeks (mean = 6.3 weeks) and sometimes months (range from 0.9 to 16 weeks), prior to getting up on hands and knees.

Hands-and-knees crawling. All infants eventually crawled perched on all fours, beginning, on average, at 8.3 months of age (range = 5.0 to 11.8 months), and ending an average of 7.0 weeks later upon beginning to walk (range = 1.7 to 31.6 weeks). Again, babies displayed variability in overall gait patterns – balancing on both knees, both feet, or one knee and one foot – within sessions and within trials from step to step.

Skill improved over weeks of hands-and-knees crawling so that arm and leg movements became larger and faster. Locomotion speed increased, as the number of limb movements decreased and the cadence increased. Overall duration of swing phases, with the limb off the ground or sliding forward, was relatively constant over weeks of crawling. Between-infant variability decreased, however, as indicated by a general convergence across infants on an average swing time of 0.2 s. Duration of stance phases, with the arm or the leg weight bearing, decreased with crawling experience. Here again between-infant variability decreased with crawling experience, with the average stance time converging on 0.5 s.

In contrast to the high variability of interlimb coordination during belly crawling, between-limb relative phasing showed a striking consistency in infants that balanced on their four limbs. As reported by Freedland and Bertenthal (1994), most babies used an alternating gait even in their first week of hands-and-knees crawling. Left arm and right leg moved nearly simultaneously, and right arm and left leg swung forward together. In general, arm swings were initiated slightly before leg movements. The alternating gait was not an obligatory pattern, however. Several babies occasionally used a lateral gait – moving the two left, then the two right limbs together – and one infant persisted with this lateral gait over months of crawling.

Infants that began crawling on hands and knees showed more improvement in limb alternation than infants that belly crawled before balancing on hands and knees, suggesting that practice with the alternating gait pattern during the belly-crawling period may transfer to crawling under more stringent balance constraints on hands and knees.

In sum, balance constraints may affect different patterns of interlimb coordination. In belly crawling, where balance requirements are minimal, infants showed striking variability in gait patterns. Some babies used an alternating gait, but most found individual, idiosyncratic solutions to the forward-locomotion problem. In hands-and-knees crawling, where balance requirements are more stringent, infants showed more consistency in overall crawling style and interlimb coordination. In keeping with Freedland and Bertenthal's (1994) report, most infants were found to converge on alternating gait. Development, however, is not merely the unfolding of a maturational blueprint: No gait pattern was found to be obligatory at any point in development. Instead, the discovery of various gait patterns by infants appears to be function-driven and is constrained – rather than produced – by balance requirements.

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Ecological Theory and Experimental Studies of Children's Drawings

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The issue that has dominated experimental research on children's picture production is the apparent shift in middle childhood from Intellectual Realism to Visual Realism. The pictures of young children appear to be conceptually based whereas those of older children are more perceptually based, in the sense that they show perspective. Many researchers have tended to assume that Visual Realism (in particular linear perspective) is the "correct" end point in graphic development. Young children's drawings are then interpreted in terms of their "errors" in failing to portray perspective.

In relation to this issue, Costall (1994) has recently claimed that much of the recent experimental research is both methodologically and theoretically unsound, and offered an alternative based on Gibson's (1979) ecological theory of perception. The fundamental weakness in current theories of child art, according to Costall, is that they are based on theories of vision that appeal to a "sensory core (...) a basic level of visual experience (...) corresponding to the perspectival appearance of things" (Costall, 1994, p. 17). Given that the sensory core is low level, the paradox is why this information is not present in children's earliest pictures. Costall claims that stage theories of child art surmount this problem by assuming that portrayal of perspective is "repressed" (until the age of 8-9 years) by knowledge.

One area of research that Costall considers to have had a damaging effect on our understanding of drawing is recent experimental assessment of children's pictures. In the typical paradigm, children are presented with a model, such as a cup, in a particular orientation so that the handle is out of sight. The aim has been to manipulate various factors, including contrast in the array or social context, to explore their effects on children's inclusion or omission of the invisible feature. Costall (1994) claims that "these studies are supposed to show that children can easily be induced to be visual realists and hence 'prove' that the old stage theories are wrong" (p. 20). He argues that these studies are both methodologically flawed and over-interpreted.

The first criticism is that since children rarely draw from a model, the task will produce artefactual findings and tell us little about the "normal contexts" in which children draw. However, do children rarely draw from models? We know of no empirical evidence bearing on this. But even supposing that Costall's claim is correct, can we dismiss these findings as artefacts? He rightly points out that in these situations children grapple to make sense of what is going on, by asking directly or non-verbally