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Authors
Anderson, David I
Kobayashi, Yuka
Hamel, Kate
et al.

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Effects of Support Surface and Optic Flow on Step-Like Movements in Pre-crawling and Crawling Infants

David I. Anderson[1], **Yuka Kobayashi**[1], **Kate Hamel**[1], **Monica Rivera**[2], **Joseph J. Campos**[3], and **Marianne Barbu-Roth**[4]

[1]Department of Kinesiology, San Francisco State University

[2]Department of Physical Therapy, Fresno State University

[3]Institute of Human Development, University of California, Berkeley

[4]Laboratoire Psychologie de la Perception - UMR 8242 CNRS - Université Paris Descartes

Abstract

Step-like movements were examined in pre-crawling (n=9) and crawling (n=9) 6–13 month-old infants in the air and on a surface in response to a static pattern or optic flows that moved toward or away from the infant. Infants completed six 60-second trials. A significant interaction between locomotor status and support condition revealed that pre-crawling infants made more step-like movements in the air than on a rigid surface. In contrast, crawling infants made an equivalent number of step-like movements in the air and on the surface. Optic flow did not influence the number of step-like movements made by infants. The pre-crawling infant finding is consistent with a finding in a previous study in which two month-old infants were shown to step more in the air than on the ground. This finding is discussed relative to the idea that the infant stepping pattern disappears because the legs become too heavy to lift.

Keywords

locomotion; motor development; stepping; vision

1. Introduction

The disappearance of the newborn stepping pattern at approximately two months of age has attracted considerable scientific interest. Though originally attributed to the suppression of sub-cortically controlled reflex patterns by the maturing cortex (Fiorentino, 1981; Forssberg, 1985; McGraw, 1940, 1945; Peiper, 1963), the favored explanation over the last 30 years for the disappearance of the stepping pattern has been Thelen's *heavy legs hypothesis* (e.g., Thelen, Fisher, & Ridley Johnson, 1984). The hypothesis argues that stepping disappears

Address Correspondence to: David Anderson, Department of Kinesiology, San Francisco State University, San Francisco, CA 94132, Ph#: 415 338-1559, Fax: 415 338-7566, danders@sfsu.edu.

because rapid weight gain on the legs during the early weeks of life, particularly in fat mass relative to muscle mass, makes the legs difficult to lift in the upright position. The hypothesis was initially formulated following the observation that infants continued to kick in the supine position when they had stopped stepping in upright position, even though kicking and stepping looked like identical behaviors in terms of joint kinematics and underlying muscle activation patterns (Thelen & Fisher, 1982). The hypothesis gained widespread acceptance following three experiments by Thelen et al. (1984). The first showed that increases in body weight and ponderal index between two and four weeks of age were significant predictors of a decline in stepping at four weeks of age. The second showed that adding mass to the legs of four week-old infants significantly depressed stepping and the third showed that making the legs easier to lift by submerging them in a tank of water resulted in significant increases in stepping.

Despite the convincing nature of the evidence provided by Thelen and colleagues to support the heavy legs hypothesis, recent findings reported by Barbu-Roth et al. (2015) suggest the hypothesis may need modification. Barbu-Roth et al. found that two month-old infants stepped significantly more when held upright in the air than when supported upright on a rigid surface. They argued that inability to lift the legs couldn't be the only explanation for the greater amounts of stepping observed in the air than on the surface because if the legs were too heavy to lift on the surface they must have been too heavy to lift in the air. While acknowledging that heavy legs may have helped to depress stepping on the surface, Barbu-Roth et al. (2015) argued that the primary reason stepping was inhibited on the surface was not because the infants could not lift the legs, though heavy legs certainly could have factored into the explanation, but because the infants had a tendency to collapse their legs (flex the hips and knees) when lowered in the upright position onto the surface. In other words, the infants were either unable or unwilling to support their body weight on the surface and stepping was not seen because the infants didn't adopt a posture from which stepping could be initiated.

The explanation put forward by Barbu-Roth and colleagues is consistent with the idea that the limbs become progressively more relaxed over the first months of life as the strength of the upright righting response decreases (e.g., Amiel-Tison, Gosselin, & Kurjak, 2006; Dargassies, 1987) and it suggests that changes in body weight and ponderal index may predict the decline in stepping not because of asynchronous development of fat and muscle in the legs, but because an increase in body weight will make it more difficult to support the body weight on one leg and potentially accentuate the tendency to collapse the legs when the infant is lowered toward a surface. Thus, body weight and ponderal index may still predict whether or not infants will step, but these variables may influence whether the infant can support its weight rather than whether it can lift its legs. Alternately, these variables may influence whether the infant can support its weight *and* whether it can lift its legs.

Barbu-Roth et al. (2015) also examined whether air stepping in their two month-olds was influenced by approaching and receding optic flows, following earlier studies that showed newborns engaged in more air stepping in response to terrestrial optic flows than to a static pattern (Barbu-Roth, Anderson, Desprès, Provasi, Cabrol, & Campos, 2009; Barbu-Roth et al., 2013). Their findings on two month-olds were difficult to interpret. No differences in the amount of stepping were seen in the approaching and receding optic flow conditions relative to the static condition, suggesting a lack of responsiveness to optic flow; however, significantly more air stepping was seen in the receding optic flow condition than in the approaching optic flow condition. Curiously, the amount of air stepping in the approaching optic flow condition was the lowest in the three air stepping conditions, just the opposite of what was observed in newborns (Barbu-Roth et al., 2009, 2013), and seemingly inconsistent with recent reports of enhanced tactile stepping frequency and quality in infants as young as two months of age (with and without disabilities) when optic flow is added to the treadmill on which they are stepping (Pantall, Teulier, Smith, Moerchen, & Ulrich, 2011; Pantall, Teulier, & Ulrich, 2012; Teulier, Barbu-Roth, & Anderson, 2014). Barbu-Roth et al. (2015) did not have a tenable explanation for the effects of optic flow they observed in their two month-olds.

The current exploratory study sought to extend the methodology used by Barbu-Roth et al. (2015) to older infants with and without hands-and-knees crawling experience using a balanced design in which two levels of postural support (Air and Surface) were crossed with three levels of optic flow (Static, Approaching, and Receding). We were interested in whether older infants would continue to make more step-like movements in the air than on a surface and whether the infant’s locomotor status would influence their behavior in the two contexts. We were also interested in whether the infant’s responsiveness to approaching and receding optic flows, relative to a static pattern, would be more clear-cut than those of two month-olds, particularly in infants with crawling experience. We predicted that infants without crawling experience would make more step-like movements in the air than on the surface and that they would respond more to the receding optic flow than the approaching optic flow (consistent with the Barbu-Roth et al., 2015 findings). We predicted that the infants with crawling experience would make equivalent numbers of step-like movements in the air and on the surface because they were more likely to have the capacity to lift one leg while supporting the body weight on the other leg when they were positioned upright on the surface. Crawling experience likely would have contributed to improved strength in the lower limbs and torso (Adolph, Vereijken, & Denny, 1998) and reinforced the pattern of alternation between the legs. In addition, we speculated that crawling infants would step more in response to the approaching optic flow than to the receding optic flow and static condition because they would have had more experience coupling approaching optic flow with forward locomotion during crawling. We were not sure whether the responsiveness to optic flow would be more apparent in the air or on the surface in the crawling infants.

2. Methods

2.1 Participants

A total of 33 infants were originally tested. However the data were not analyzed if the infant was too fussy to complete all six experimental trials (6 infants) or cried for more than 30 s during a single trial (5 infants) or did not look at the optic flow pattern for more than 30 s during a single trial (4 infants). Consequently, the final sample consisted of eighteen 6- to 13-month-old infants (13 females and 5 males, 9 were Caucasian, 2 were Asian, 1 was Hispanic, and 6 were of mixed heritage). Infants were classified into prelocomotor (n=9;

Mean Age = 8.5 months, SD=1.09 months) and locomotor (n=9; Mean Age = 11 months, SD=1.9 months) groups. All of the infants classified as locomotor were reported to be crawlers by their parents and could crawl on hands-and-knees for a distance of 2.5m within 2 minutes without stopping, as determined by a locomotor test administered at the start of the experiment. None of the locomotor infants were able to walk. The duration of crawling experience was not recorded. All parents provided written consent for their infants to participate in the experiment.

2.2 Apparatus

A custom MatLab software program (Mathworks Inc., Natick, MA, USA) was used to generate the optic flow patterns. The visual stimulus was a black-and-white checkerboard pattern with squares 0.127m by 0.127m in size (approximate spatial frequency of 0.06 cycle/ degrees relative to the infants' eyes; the same spatial frequency used by Barbu-Roth et al., 2009). The visual pattern was presented in three different conditions: 1) approaching the infant (Toward); 2) Receding from the infant (Away); and 3) static (Static). The pattern moved at a velocity of 0.27m/s^{-1} in the Toward and Away conditions, faster than the average crawling speed (0.2 m/s^{-1}) of nascent hands-and-knees crawlers but lower than that of experienced hands-and-knees crawlers (0.4 m/s^{-1}) (Adolph et al., 1998).

The MatLab program was run on a PC that was connected to a video projector mounted onto the wall approximately two meters above the ground. The optic flow patterns were projected onto a 0.75 m by 1.15 m white screen on the floor. The left edge of the flow pattern was bounded by the laboratory wall onto which the projector was mounted and the right edge was bounded by a 1.2 m high x 2 m long barrier to prevent the infant from being distracted by equipment and furniture in the laboratory. The infant and the white screen on the floor in front of the infant were literally in a tunnel without a ceiling (the laboratory ceiling was actually the ceiling). One 30-Hz digital video mounted to a tripod 0.75 m above the ground was positioned within the tunnel on the other side of the screen on the floor. It was located 2.5 m in front of the infant and captured a frontal plane view of the infant. The camera was used to record the infant's movements. The barrier helped to keep the infants focused on the optic flow patterns but prevented us from using a second camera to capture a sagittal view of the infant.

2.3 Procedure

Experimenters played with the infants for approximately 10 min to familiarize them with the laboratory environment and the experimenters at the start of the experiment. Because the infants were tested in the dark and dark adaptation takes time (Patla & Vickers, 1997), the lights in the room were dimmed approximately five minutes prior to the start of the trial. The lights were turned off completely three minutes prior to the start of the trial and the infants were undressed to their diapers or one piece undergarment so that their legs could be clearly seen. The room was not completely dark because of the light from the projector, which reflected off the screen on the floor and illuminated the infant.

Infants were tested in six randomly ordered 1-min trials. They were exposed to the three optic flow conditions while supported upright at the edge of the screen in two postural support conditions: 1) with their feet in contact with the laboratory floor (Surface), and 2) with their feet suspended approximately 0.05 m above the floor (Air). In both conditions the infants were held under the arm pits, though the arms were free to move, and tilted slightly forward to facilitate viewing of the visual stimuli. The infants were not permitted to move forward in the Surface condition. The break between trials was 10 s, unless the infant was fussy or agitated and had to be comforted by the parent. A second experimenter, positioned in front of the infant but to the right of the camera, used a variety of toys to attract the infant's attention at the start of each trial to the surface onto which the visual stimuli were projected.

2.4 Data Coding and Analysis

The videos were analyzed frame by frame. Step-like movements were defined as any upward vertical movement of the ankle that was accompanied by knee flexion and hip flexion followed by a downward movement of the ankle that was accompanied by knee extension and hip extension within two seconds of the pause at the end of the flexion phase. The frames at which infants started looking at the optic flow patterns and away from the patterns were recorded so that total viewing time could be determined. The frames at which infants started and stopped crying were also recorded so that infants who cried more than 30 s in any trial could be excluded from the analyses. Once those infants were excluded, the amount of crying was extremely low and did not differ significantly across conditions. All the trials were coded by one experimenter and a second experimenter coded a randomly chosen 20% of the trials. The percentage agreement was 85.9% for the step counts and the intraclass correlation for the viewing time was 0.88.

Preliminary analyses revealed no significant differences attributable to the infant's sex or the leg (right or left) on which they made step-like movements and so these two variables were collapsed across the other dependent variables in subsequent analyses. Step-like movements and viewing time were analyzed using 2 (Locomotor Status) x 2 (Support Condition) x 3 (Optic Flow Condition) mixed model ANOVAs. Significant main effects and interactions were followed up with Tukey post hoc tests. The alpha level was set at 0.05. Because the variances of the counts of step-like movements were unequal in some of the conditions, the counts were square-root transformed. The transformation solved the unequal variance problem. The descriptive statistics for the untransformed step-like movements are presented in Table 1 and Figure 1.

3. Results

3.1 Total Step-Like Movements

The infant's locomotor status and the condition in which they were tested had a clear influence on step-like movements. The ANOVA revealed a significant main effect for Support Condition, $F(1, 81) = 12.26$, $p < 0.05$, $\eta^2 = 0.07$, however, the main effect was superseded by a significant interaction between Locomotor Status and Support Condition $F(1, 81) = 6.82$, $p < 0.05$, $\eta^2 = 0.04$. The post hoc tests revealed that pre-crawling infants made significantly fewer step-like movements on the surface than in the air. Even though the infants tended to make fewer step-like movements in the Toward optic flow condition in the air, the main effect of Optic Flow Condition was not significant, nor were the interactions between Optic Flow Condition and the other variables.

3.2 Viewing Time

The mean duration of time (and standard deviation) spent looking at the visual stimuli collapsed across the pre-crawling and crawling infants in the Air-Toward, Air-Away, Air-Static, Surface-Toward, Surface-Away, and Surface-Static conditions was 59.1 s (1.9), 57.2 s (5.4), 58.8 s (2.7), 58.2 s (3.1), 57.5 (3.6), and 57.3 (4.4) respectively. The mixed model ANOVA found no differences in viewing time as a function of any of the three factors included in the analysis or their interactions.

4. Discussion

Consistent with expectations, the infants' locomotor status and the support condition in which they were tested influenced the number of step-like movements they made. Step-like movements were depressed when pre-crawling infants were supported upright with their feet contacting the floor compared to when they were suspended in the air with their feet above the floor. In contrast, infants with crawling experience made an equivalent number of step-like movements when supported in the air and on the floor.

The behavior of the pre-crawling infants is consistent with the behavior of the two month-old infants reported by Barbu-Roth et al. (2015), who took significantly more steps when they were supported upright in the air than when they were supported upright on a surface. Consequently, the current findings are inconsistent with the notion put forward by Thelen and colleagues (e.g., Thelen et al., 1984) that the stepping pattern is difficult to elicit in infants after the first few weeks of life because asynchronous growth in fat and muscle mass makes the legs too heavy to lift. If the legs are too heavy to lift then they should be too heavy to lift regardless of whether the infant is supported on a surface or in the air.

What then inhibits stepping on a surface in prelocomotor infants? Barbu-Roth et al. (2015) ventured that their two month-olds stepped less on the surface because they were unwilling or unable to support their body weight when they were lowered onto the surface. Many times the infants' legs simply collapsed downward when their feet touched the surface. The two month-old infants' response to the surface is consistent with the reports of other researchers who have attempted to elicit stepping in infants at approximately two months of age (e.g., Forssberg, Hirschfeld, & Stokes, 1991; Lamb & Yang, 2000) and could be explained by the progressive relaxation of limb tonus that occurs over the first months of life (e.g., Amiel-Tison et al., 2006). However, the relaxation of limb tonus and accompanying unwillingness or inability to support the body weight on one leg cannot account for the current findings because all of the pre-crawling infants except one extended their legs upon contact with the surface and all except one were capable of supporting their body weight on the surface with the assistance of the experimenter. The assistance from the experimenter primarily helped the infant to balance rather than to support its own body weight. In their attempt to support themselves in the upright position, these pre-crawling infants extended both legs forcefully onto the surface and appeared to be frozen in the upright posture. Consequently, we believe that stepping on a surface in our pre-crawling infants may have been inhibited by this strong bilateral extensor-supporting response, stimulated by tactile contact between the feet and the surface, which contributes to the emergence of independent standing.

Our explanation is consistent with the U-shaped developmental trajectory that characterizes the extensor-support response (Amiel-Tison et al., 2006). Amiel-Tison and colleagues note that antigravity straightening is present in the newborn as a "tactile reflex", but disappears completely between four and seven months of age as a bias towards flexor tonus increasingly dominates, only to reappear as a self-initiated pattern when the child is able to stand independently. The exact timing of the re-emergence of antigravity straightening is unclear as it is preceded by a transitional period in which flexor tone and extensor tone dominate alternately and temporarily before working together synergistically to support the child in the upright position (Dargassies, 1987).

Our argument seems contradictory at first blush because we argue that the extensor-supporting response facilitates stepping in the newborn (as have others, e.g., Dargassies, 1987), yet inhibits stepping in the older prelocomotor infant. How do we resolve this contradiction? We speculate that it can be resolved by considering the functional goals that an extensor bias enables the newborn (and fetus) versus the older infant to achieve and to the movement patterns most easily expressed in the viscoelastic environment of the uterus versus the terrestrial environment of the infant.

Human fetuses are able to make alternating stepping movements to somersault in the uterus at 10 weeks post conception (de Vries, Visser, & Prechtl, 1982). Alternating stepping movements seem to be a particularly effective way to locomote in the uterine environment and they are likely reinforced by the elastic properties of the uterine wall, which make alternating leg movements more energetically efficient than simultaneous leg movements due to the force required to displace the uterine wall with a single point of contact versus two points of contact (Brumley & Robinson, 2010). Thus, alternating stepping can be viewed as an ontogenetic adaptation (Oppenheim, 1981) to the unique properties of the uterine environment and to the actions that have functional value to the fetus. The newborn stepping pattern is a vestigial behavior when viewed from this perspective; a temporary behavior that was functional in the uterus but that requires considerable modification to have functional value on the rigid surfaces that comprise the terrestrial environment. Though locomotion is clearly important in a terrestrial environment, the infant must master upright static balance before independent bipedal locomotion will emerge. In contrast to the fetus and newborn, for whom standing has little functional value, standing has considerable value to the older infant who can now use this action to maintain an orientation to the environment from a new vantage point that considerably expands the field of view (Kretch, Franchak, & Adolph, 2014). Consequently, the extensor-supporting response that reemerges after the stepping pattern has initially disappeared, but before the onset of independent locomotion, may function to promote standing at the expense of stepping. This could then explain why we observe a strong tendency to extend both legs in a rigid posture in the pre-crawling infants: a posture that is suitable for stability in standing but not for alternated stepping.

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Though the extensor-supporting response explanation is speculative, it is notable that four of our crawling infants engaged in repeated bouts of bouncing when their feet were in contact with the floor in the surface conditions, whereas only one pre-crawling infant engaged in repeated bouncing. In other words, locomotor infants either made step-like movements or bouncing movements on the surface, suggesting either freedom from extensor dominance or less concern with standing, whereas prelocomotor infants rarely made step-like movements and rarely bounced on the surface. Little is known about the relation between self-initiated standing (with and without support) and stepping, however, the developmental phase in which self-initiated standing emerges is thought to be characterized by competition among motor patterns that support different goals (Touwen, 1976).

When infants transition to independent crawling and then cruising and walking, they must have the capacity to overcome a strong bias towards extension of both legs so that they can flex one leg while extending the other. This complex pattern of coordination is even more demanding in the upright position given that the infant must also be capable of balancing on a single narrow base of support in the upright position. Thus, the onset of crawling and the ability to step with support while standing may emerge at the same time. Alternately, stepping with support may emerge shortly after the onset of crawling because crawling also helps to develop strength in the lower limbs (Adolph et al., 1998), which likely contributes to the infant's ability to support the whole body in the upright position on one limb.

Again, it is important to stress here that our explanation for less stepping on the surface than in the air in the pre-crawling infants is speculative. A limitation of our study is that we did not measure each infant's body weight or ponderal index and so we cannot comment on how these variables were related to the patterns of stepping we observed on the surface and in the air. We suggested previously that the accumulation of fat mass relative to muscle mass may still prove to be an important factor in the disappearance of stepping on a surface in two month-old infants (Barbu-Roth et al., 2015) and it is just as likely that the ratio of fat mass to muscle mass continues to plays a role in the continued lack of stepping on a surface we observed in the older pre-crawling infants in the current study. Another limitation of our study was that the crawling infants were older than the pre-crawling infants and so the differential stepping we saw in the two groups of infants may be connected to age rather than to locomotor experience. Clearly more research is warranted to explore whether the *heavy legs hypothesis* or the interpretation we have offered provides a better explanation for the initial disappearance of stepping on a surface and the continued difficulty of eliciting stepping on a surface in older pre-crawling infants. This represents an exciting opportunity to revisit a phenomenon that has not been discussed in the research literature for quite some time, despite its centrality for understanding and promoting the emergence of independent locomotion.

The prediction that crawling infants would make more step-like movements in response to the approaching optic flow than the receding optic flow was not supported by the data, regardless of whether the infant was supported in the air or on the surface, nor was the prediction that pre-crawling infants would respond more to the receding than the approaching optic flow. Although the difference between the step-like movements in the receding and approaching optic flows was not supported by a significant interaction between locomotor status and optic flow condition, it is noteworthy that the pre-crawling infants made approximately twice as many step-like movements in the Air-Away condition (12) than in the Air-Toward condition (6.5) and in the Surface-Away condition (4.7) than in the Surface-Toward condition (2.2). Currently, we don't have a viable explanation for the increased responsiveness of the pre-crawling infants to receding optic flows, but we believe it is important to note that the finding is consistent with the findings reported by Barbu-Roth et al. (2015) in two month-olds. It is also consistent with the greater postural responsiveness to receding optic flows than approaching optic flows documented in pre-crawling *and* crawling infants when they are exposed to a global optic flow (including movement of the floor) in a moving room (Lejeune, Anderson, Campos, Witherington, Uchiyama, & Barbu-Roth, 2006).

The lack of responsiveness to terrestrial optic flow in the current crawling infants seems inconsistent with recent studies showing that the frequency and quality of stepping in infants as young as two months of age (with and without disabilities) can be enhanced by adding optic flow to the treadmill on which they are stepping (Pantall et al., 2011, 2012; Teulier et al., 2014). The inconsistency may be explained by the additional tactile and proprioceptive information provided by the treadmill. Stepping appears to be enhanced by a treadmill because the leg is passively extended by the treadmill belt and the stretch across the hip flexors then triggers the initiation of the swing phase of a step (Thelen & Ulrich, 1991). Optic flow may have an effect on treadmill stepping because it enhances the stepping that is already taking place on the treadmill. The congruence between the visual, vestibular, tactile, and proprioceptive information on the treadmill may heighten the infant's experience of forward locomotion and reinforce a pattern that is initiated mechanically by the treadmill belt. In contrast, optic flow may have little effect when the infant stands on a static surface (or is held in the air) because the information picked up visually about the surface is incongruent with the information picked up tactilely and proprioceptively. This explanation is clearly speculative and awaits confirmation from future research.

Several more simple explanations could also account for the failure to see effects of optic flow on step-like movements in the current study. For example, the size of the optic flow may have been too small or the velocity of the flow might not have been optimal to induce step-like movements in the contexts in which we tested the infants. Either of these explanations is plausible, reinforcing the need for additional research to disentangle the effects of optic flow on step-like movements in prelocomotor and locomotor infants.

In summary, this exploratory study suggests a need to reexamine the *heavy legs hypothesis* for the disappearance of the infant stepping pattern. Pre-crawling infants made more step-like movements when supported in the air than when supported on a surface, consistent with previous findings with two month-old infants. We argue that stepping on a surface at birth is facilitated by previous alternating stepping experience in the womb and a strong antigravity straightening response that allows the newborn to support its body weight on one leg. Stepping then disappears initially because the older infants' bias towards flexion results in a tendency for their legs to collapse when they are lowered onto a surface resulting in an inability to support their body weight. The continued inhibition of stepping by a surface, however, may reflect the reemergence of a bilateral extensor bias, which supports the body in the upright position and makes hip and knee flexion more difficult. Clearly more research is needed to support or refute this hypothesis and to clarify the effects of optic flow on the stepping pattern during the first year of life. Researchers have already noted that multiple morphological, psychological, and social factors influence the expression of the stepping pattern (e.g., Thelen & Smith, 1994; Thelen & Ulrich, 1991). Moreover, the sensory contributions to stepping are known to interact in complex ways (Dietz, 2003). Despite the considerable amount of research that has been dedicated to studying infant stepping, many aspects of the development of stepping remain a mystery. This represents an important opportunity to redouble our efforts to understand this important phenomenon.

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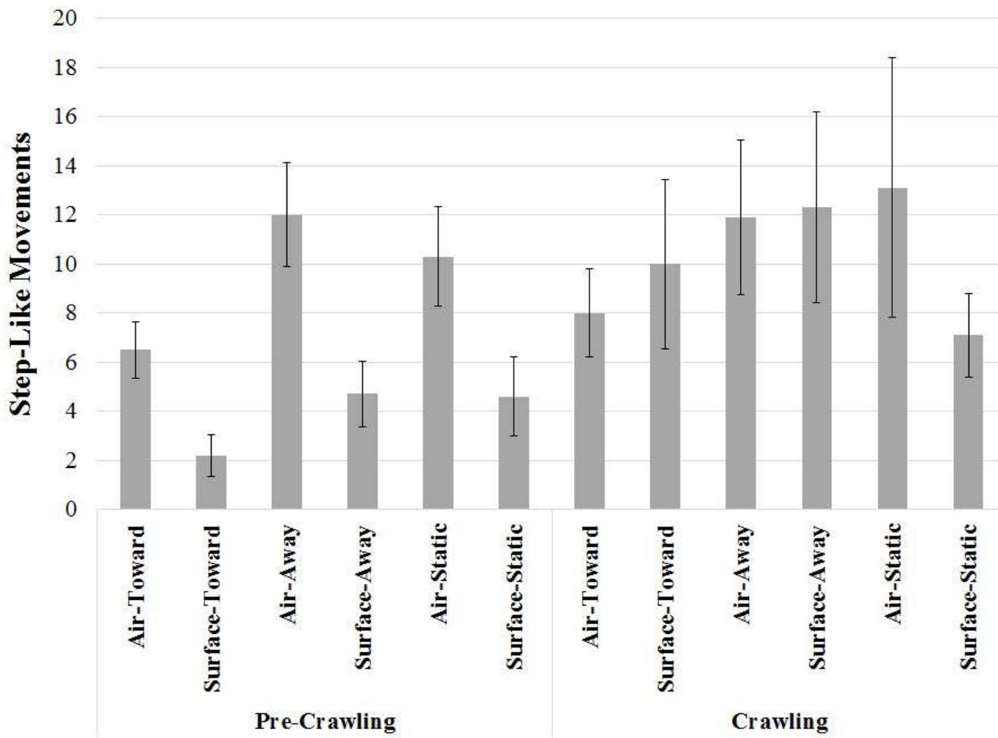

Figure 1.

Means and standard errors of the step counts for the pre-crawling and crawling infants in each of the experimental conditions.

Table 1

Mean counts for step-like movements, along with minimum values, maximum values, and standard deviations for the pre-crawling and crawling infants in each of the experimental conditions.

Locomotor Status	Condition	Mean	Min	Max	Std. Dev.
Pre-Crawling	Air-Toward	6.5	1	14	4.6
	Surface-Toward	2.2	0	9	3.4
	Air-Away	12	0	28	8.5
	Surface-Away	4.7	0	14	5.4
	Air-Static	10.3	2	26	8.1
	Surface-Static	4.6	0	20	6.4
	Air-Toward	8	1	22	7.2
	Surface-Toward	10	0	40	13.8
Crawling	Air-Away	11.9	0	34	12.6
	Surface-Away	12.3	1	47	15.6
	Air-Static	13.1	3	65	21.1
	Surface-Static	7.1	0	20	6.8