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The Relationship between Physical Growth and a Newborn Reflex*

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Young infants both grow at a very rapid rate and show dramatic changes in body composition. The behavioral consequences of somatic growth have been little explored. Here we report three studies on the relationship between body-build changes and a newborn reflex, stepping. Study 1 compared the number of steps and several body-build measures in 40 infants seen at 2, 4, and 6 weeks. At each age, overall arousal was the best predictor of steps. At 4 weeks, however, those infants who gained weight and became "chubby" most rapidly stepped less. Infants gained weight and added fat at the most rapid rate between 2 and 4 weeks. In Study 2, we manipulated leg mass by adding small weights to the legs. Infants stepped less and with weaker flexion movements when the legs were weighted. In Study 3, we reduced the effects of leg mass by submerging infants' legs in water. Stepping rate increased and joint flexions were greater. We proposed that muscle strength development may not be synchronous with mass increase and that peripheral as well as central nervous system factors contribute to infant behavioral development. The disappearance of stepping is better explained by asynchronous physical growth than by previous hypotheses.

stepping reflex somatic growth newborn reflex body build

During the first few months of life, humans grow at a much more rapid rate than at any other time in postnatal development (Bayley & Davis, 1935; Brandt, 1980; Visser, 1966). Indeed, the sharply accelerating velocities of weight gain plotted for the first 3 months are more like the growth curves seen in prenatal development than those characteristic of later infancy and childhood (Visser, 1966).

While these dramatic body-build changes are the subject of intense interest to parents and pediatricians, developmentalists have rarely asked whether rapid physical growth has behavioral consequences. Traditionally, researchers have focused on the development of the central nervous system (CNS) to understand early infant development. Contemporary motor theorists, however, have increasingly emphasized the importance of the dynamic qualities of the effector organs themselves in motor control. Movement, they argue, is as much a product of the mass, stiffness, and inertial properties of the limbs as of

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central neural processes (c.f. Kelso, Holt, Kugler, & Turvey, 1980; Kugler, Kelso, & Turvey, 1980, 1982; Lestienne, 1979).

During the first year, infants progress from behavior that is stereotyped and reflexive to increasingly goal-corrected and skillful movement. This is paralleled by increasing maturation of the motor cortex. These CNS changes, however, are concomitant with equally dramatic changes in muscle mass, muscle fiber characteristics, muscle tone, body composition, and body proportion, all of which are vital contributors to the final movement outcome. Yet we know very little about the impact of these growth changes on the acquisition of motor skills (Malina, 1980).

Thus, while it has been customary to ascribe both the capabilities and the limitations of newborn infant behavior to the relative maturation of only the nervous system, these non-neurological contributions may play a significant role. For example, newborn infants show a strong flexor tone of the limbs. It is likely that at least in the early neonatal period this flexed posure is maintained not by active muscle activation, but by "contractures," or mechanical limitations of joint motions, perhaps as a result of the flexed posture *in utero* (Haas, Epps, & Adams, 1973; Hoffer, 1980; Maekawa & Ochiai, 1975). By 2 weeks old, however, flexor dominance can be detected as actual differences in muscle activation strength (Thelen & Fisher, 1983). In the legs, extensor strength lags behind flexor strength even at the onset of independent gait (Sutherland, Olshen, Cooper, & Woo, 1980). These mechanical considerations may constrain behavior by limiting the movement possibilities regardless of the central mediating mechanisms.

This interaction between neurological and mechanical contributions to early behavior is dramatically illustrated by an intriguing neonatal reflex, newborn stepping. When newborn infants are held upright, they will make well-coordinated, alternating movements that look remarkably like mature locomotion. Normally, stepping can no longer be elicited after a few months of age.

The traditional explanation for the disappearance of stepping is that this "primitive" reflex is suppressed with the maturation of inhibitory tracts from the cortex. Persistence of the reflex is taken as a sign of central nervous system dysfunction (Dekaban, 1959; DiLeo, 1967; Fiorentino, 1981; Illingworth, 1966, McGraw, 1940; Menkes, 1980; Molnar, 1978; Peiper, 1963). The evidence supporting cortical inhibition of infantile reflexes is indirect, however, and based on the reappearance of these motor patterns in aged patients or those with lesions in the cortex (e.g., Paulson & Gottlieb, 1968). Prechtl (1981) argues that pathological reflexes only superficially resemble those of the normal infant, and that "direct experimental evidence on the suppression of transient motor patterns by specific inhibition is meagre" (p. 208).

The work of Philip Zelazo and his colleagues (Zelazo, 1976, 1983; Zelazo, Zelazo, & Kolb, 1972) presented an important challenge to this traditional view. When parents exercised their infants' stepping reflex with daily "practice" sessions, the movement patterns in fact did not disappear, but rather increased in frequency compared to control groups who received no practice or who received passive movement in the supine position. In addition, infants who received stepping practice walked independently about 1 month earlier than the control groups.

These results showed that cortical inhibition was neither necessary nor facilitatory for later locomotion. Instead, Zelazo et al. (1972) proposed that stepping was lost because of disuse, and that with practice, the reflex became converted into an instrumental activity through the reinforcing effects of the walking movements.

Recently, we proposed an alternative to both the cortical inhibition and learning hypotheses. We suggested, instead, that simple physical growth could explain the disappearance of stepping (Thelen, 1983, 1984b; Thelen & Fisher, 1982; Thelen, Fisher, Ridley-Johnson, & Griffin, 1982). First, we showed that when infants are supine, they perform *kicking* movements of the legs that are identical in kinematic, electromyographic, and motivational characteristics to upright stepping. Indeed, stepping should not be considered a "reflex" at all, but, like kicking, a manifestation of intrinsic pattern generation (Thelen & Fisher, 1982). Unlike stepping, however, supine kicking does not disappear with age (Thelen, 1979). This raised the question of why, if these are identical movement patterns, one behavior regresses and the other does not.

We reasoned that a combination of the posture of the infant during stepping and kicking and the pattern of early physical growth could explain the different developmental courses of these movements. Specifically, in the upright posture infants must lift their legs entirely against gravity. In contrast, less muscle strength is required to move their legs in the supine position, where gravity indeed aids the flexion of the legs. As infants rapidly gain weight in the first few months, there is a disproportionate increase of body fat compared to muscle tissue (Fomon, 1966). This means that slower growing muscles are required to move relatively larger and larger masses. Thus, in the more taxing upright position, infants may lack the muscle strength to lift their heavy legs and stepping "disappears." They may continue producing step-like movements, however, when their weight is supported in the supine position.

We showed that muscle strength may indeed constrain behavioral expression in a study of body build and stepping in newborn infants (Thelen et al., 1982). When infants were crying hard and their behavioral activation was presumably very high, step rate was also high and there was no relationship between movement and body build. In infants less than maximally aroused, however, those who were relatively heavier for their length stepped less than those who were less stocky in body build.

In the present paper we report three studies which further test the behavioral consequences of the rapid growth of early infancy. In Study 1, we examined the relation between differential growth rates during the early weeks and the stepping response. We reasoned that increasing mass would be especially taxing for those infants with rapid growth rates, and that these infants would show the greatest decrease in steps. Since arousal level is a strong correlate of stepping frequency (Thelen, Ridley-Johnson, & Fisher, 1983), a measure of arousal was also included. By scoring arousal at the beginning, middle, and end of the stepping test, we could additionally test the proposition that walking movements were positively reinforcing to infants (Zelazo et al., 1972). Infants who were positively reinforced should not increase their distress during the test.

In Studies 2 and 3, we experimentally manipulated the mass of the legs by first adding weights to the legs, and secondly, by testing the infants while their legs were under water. The hypothesis of Study 2 was that adding weights would decrease the number of steps and increase the maximum joint angles, indicating a weaker flexion. Reducing the mass by submersion, on the other hand, would increase the step frequency and decrease the maximum joint angles.

STUDY 1

Methods

Subjects. Subjects were 40 apparently normal, full-term infants, 20 girls and 20 boys. The average birth weight was 3554 g (range 2381–4862 g). Eleven infants were delivered by Caesarian section. Parents were recruited by telephone from local published birth announcements and were paid $10.00 for participating in three biweekly sessions. The infants came from middle-class families, predominately white-collar and professional. The average age of both mothers and fathers was 30 years.

Procedure. Each infant was observed at 2, 4, and 6 weeks of age. Parents were asked to bring their infants to the laboratory about an hour before an anticipated feeding so the infants could be tested when awake, but not extremely hungry. At each visit, the infants' legs were bared. Then the examiner held and talked to the infant for 1 min. Testing of the stepping response involved the examiner supporting the infants firmly under the armpits, tilting them very slightly forward, and lowering both feet to a tabletop. Testing commenced when the infants' feet touched the table and continued for 1 min. Two observers independently counted the total number of right and left steps using hand-held counters. The examiner noted the infants' arousal state three times during the test session: immediately before testing began, at 30 s, and at 60 s. Arousal was scored on a 6-point scale: 1 (asleep); 2 (drowsy); 3 (alert, quiet); 4 (alert, gross movements of head, arms, and torso); 5 (fussy); and 6 (crying hard). The interobserver reliability correlation for arousal scoring in a previous study was .97 (Thelen et al., 1982).

After the stepping test, we removed the infants' clothing and measured the following body-build characteristics: weight, crown–heel length, crown–rump length, circumference of the right and left thighs and calves at their widest points, and subscapular fat fold. Infants were weighed on a Healthometer Pediatric Scale, and recumbent lengths recorded using a measuring board. A plastic tape measure calibrated in millimeters was used for leg circumferences, and a stainless steel caliper, also calibrated in millimeters, was used to measure subscapular fat folds taken while infants were prone.

Ponderal Index, a measure of relative stockiness, was calculated by weight/crown-heel length^3. Leg volume was estimated by assuming the leg was a cylinder with the height determined by crown-heel length minus crown-rump length and a circumference estimated by the average of the right and left thigh and calf measurements. Growth rates were determined by dividing the difference between two ages by the measure at the younger age; birth weight and length data were reported by parents.

Results

The Pearson correlation coefficients for the two observers on the number of steps was .98. Boys and girls did not differ at any age on number of steps, so data were pooled.

The means for the number of steps, total arousal score (sum of the three scores—before, during, and after the test), and various body-build measures are reported in Table 1. Six separate repeated measures analyses of variance showed a significant age effect for all the variables except arousal level, which did not change significantly over the three visits.

TABLE 1
Number of Steps, Arousal, and Body Build Characteristics as a Function of Age

	Age						*Analysis of Variance*
	2 Weeks		*4 Weeks*		*6 Weeks*		
	M	*SD*	*M*	*SD*	*M*	*SD*	*F Value (2,117)*
Total steps	18.51^{a}	10.76	13.76^{ab}	9.60	11.21^{b}	12.66	4.47*
Total arousal	13.45	2.97	12.70	3.09	12.48	2.87	1.18
Weight (g)	3812.98^{c}	458.07	4417.60^{b}	503.91	4940.98^{a}	535.49	50.95***
Ponderal index	2.55^{b}	.26	2.66^{ab}	.27	2.74^{a}	.25	5.52**
Leg volume (cc)	292.02^{c}	50.19	361.66^{b}	61.66	411.89^{a}	64.65	41.41***
Fat fold (cm)	$.85^{b}$	.21	1.07^{a}	.21	1.14^{a}	.24	18.77***

^{a,b,c} Duncan's Test: means with the same letter are not significantly different ($\alpha = .05$).
* $p < .05$
** $p < .01$
*** $p < .0001$

Growth rates expressed as the percentage increase are shown in Table 2. Growth rates were highest in the period between 2 and 4 weeks; fat fold measurement increased especially dramatically. Additionally, there was a strong negative correlation between growth rates and birth weight. The Pearson correlation coefficient between birth weight and rate of weight gain between birth and 6 weeks was $-.575$ ($p < .0001$) and between birth weight and rate of Ponderal Index increase was $-.381$ ($p < .02$). Thus, infants who weighed less or were more slender at birth gained at significantly faster rates.

TABLE 2
Growth Rates of Body Build Measures

	Percentage Increase[1]			
	Birth–2 Weeks	*2–4 Weeks*	*4–6 Weeks*	*Analysis of Variance*
Weight	7.72^{c}	16.15^{a}	11.99^{b}	$F\ (2, 117) = 15.43^{**}$
Ponderal index	.33	4.56	3.44	$F\ (2, 114) = 2.23$
Leg volume		24.51^{a}	14.71^{b}	$F\ (1, 78) = 11.59^{*}$
Fat fold		29.27^{a}	7.35^{b}	$F\ (1, 78) = 17.11^{**}$

[1] Means of individual percentages.
[a,b,c] Duncan's Test; means with the same letter are not significantly different ($\alpha = .05$).
* $p < .001$
** $p < .0001$

To determine the contribution of these body-build changes and arousal to step rate, we performed a multiple regression analysis at each of the three age levels. The independent variables entered into the regression were : (a) at 2 weeks, total arousal score and growth rates for weight and Ponderal Index between birth and 2 weeks (growth rates for leg volume and fat fold could not be determined because this information was not available for birth); and (b) at 4 and 6 weeks, arousal and growth rates for weight, Ponderal Index, leg volume, and fat fold for between weeks 2 and 4 and between weeks 4 and 6.

This analysis showed that arousal was a potent predictor of amount of stepping at each age level (2 weeks; $F[1,35] = 4.65$, $p < .05$; 4 weeks: $F[1,38] = 11.8$, $p < .01$; 6 weeks: $F[1,38] = 18.4$, $p < .0001$). In addition, rate of weight gain also entered the regression model at the 4-week period ($F[2,37] = 4.31$, $p < .05$). Zero-order correlations showed that infants stepped less who gained weight most rapidly between 2 and 4 weeks ($-.334$, $p < .05$) and who showed most rapid increases in Ponderal Index between birth and 4 weeks ($-.335$, $p < .05$). A second regression using the actual values of the four body-build measures (not the rates of change) and arousal as the independent variables showed again that arousal predicted steps, but no other variables entered the regression model.

Infants' arousal increased during the stepping test at all three ages, although only at 2 and 4 weeks was this statistically significant (Table 3). Mean scores showed arousal changes from pretest states between quiet alert and moving alert to posttest scores in the clearly distressed range.

TABLE 3
Arousal Scores Before, During, and After the Stepping Test as a Function of Age

	Mean Arousal Scores			
Age (N=40)	*Before Test*	*After First 30 s*	*After 60 s*	*Analysis of Variance F (2, 117)*
2 weeks	3.725[b]	4.650[a]	5.075[a]	13.44, $p<.0001$
4 weeks	3.575[b]	4.425[a]	4.700[a]	10.59, $p<.0001$
6 weeks	3.825	4.325	4.325	2.93, $p<.0576$

[a,b] Duncan's post hoc test; means with the same letter are not significantly different ($\alpha=.05$).

Discussion

The period between 2 and 4 weeks of age was one of especially rapid weight gain in this sample of infants, and of particularly striking increases in the fat fold, a measure of the deposition of subcutaneous fat. During this time, infants also showed a 26% decline in their average number of steps. Although at each testing session, generalized behavioral arousal was the best predictor of steps, the arousal scores between 2 and 4 weeks were not significantly different, and arousal alone could not account for these declines.

At 4 weeks of age, stepping frequency was related to weight and Ponderal Index rate *gain*, not absolute body size. Those infants who had gained most stepped less. In addition, infants who were lightest and most slender at birth gained significantly faster during the first month. This supports the hypothesis that rapid increases in body mass may outstrip concomitant development of muscle strength, especially in a period when there is a rapid acquisition of fat tissue.

No effect of physical growth rate was found at either the 2- or 6-week test. Although this sample of infants was not tested for stepping at birth, the mean number of steps of a previous sample of 65 neonates tested between 1 and 3 days of age was 15.6 (mean arousal score 12.8) (Thelen et al., 1982). Since the present sample of 2-week-old infants performed an average of 18.5 steps (arousal score 13.45), stepping may not in fact decline during the first 2 weeks. This period showed only a modest increase in body-build variables as well (Table 2). The lack of relationship at 6 weeks is more puzzling. One possibility is that after the period of most rapid fat acquisition, the burden of the weight/strength disparity was not *differentially* detectable.

The results of this study showed that infants gained body mass, and particularly fat, especially rapidly between 2 and 4 weeks, and that at 4 weeks, those infants with the most rapid weight gain stepped less. Since muscle increments lag behind overall weight gain, it seemed likely that, in 4-week-old infants, movement outcome would be especially sensitive to changes in limb mass. Thus, we used infants of this age to experimentally manipulate leg mass to assess the effect on stepping directly. In Study 2, we added small weights to the legs to simulate the average gain in the legs between 4 and 6 weeks. We hypothesized that this additional weight would tax the comparatively weaker muscles and reduce stepping. Additionally, we proposed that infants would be unable to lift their weighted legs as high as without weights, resulting in larger (less flexed) joint angles.

STUDY 2

Methods

Subjects. Subjects were 12 apparently normal infants, 9 girls and 3 boys, recruited by telephone from published birth announcements. All were within 4 days of 4 weeks old when tested. Birth weights averaged 3374 g (range, 2381–4026); mean weight at testing was 4397 g (range, 3289–5592).

Procedure. We used the anthropometric data gathered in Study 1 to estimate the mean amount of weight gained in the legs by infants between 4 and 6 weeks. First, Winter's (1979) formula for body density based on Ponderal Index was used to determine total body volume at each age. Using our estimates of leg volume at each age, we could then determine the increase in volume gained by the legs as a percentage of total volume gained. This volume percentage was then applied to the weight gain means. These calculations resulted in an estimated average gain in the legs of 163 g between 4 and 6 weeks. This amount of mass was distributed evenly by sewing small lead shot into four cotton fabric strips with Velcro fasteners which could be wrapped around the infants' thighs and calves.

When infants were brought into the laboratory, they were consecutively assigned to one of two order conditions, either stepping test without weights first or stepping test with weights first. Infants' legs were bared for all tests. To facilitate kinematic analysis of movement amplitude, the joints of the infants' right legs were marked with 3-mm white tape squares affixed to strips of black tape at the following sites: lateral border of the base of the fifth toe, lateral malleolus, lateral femoral condyle, and lateral thigh at the hip crease. For the condition with weights, the weighted strips were attached securely to the legs. Stepping was elicited in both conditions in a manner identical to that used in Study 1. In this study, however, stepping was also videotaped using a Sony VO 2800 videorecorder with the camera focused on a lateral view of the infants' right legs. Arousal was monitored every 16⅔ s (1000 video frames) using the same 6-point scale as Study 1. Each infant was tested for 1 min in both conditions, with a 5-min rest and comforting period between conditions.

Step rate was determined as in Study 1, with two observers counting the total number of right and left steps at each session. Interobserver reliability was .901. Joint angles at maximum flexion for each right leg step were determined by frame-by-frame scanning of the videotapes for the point of maximum flexion for each step. At maximum flexion, coordinates for the hip, knee, ankle, and toe were read from a transparent grid placed over the videomonitor. Joint angles for hip, knee, and ankle were calculated from the coordinate data using trigonometric formulas.

Results

These 4-week-old infants averaged 14.17 steps in the no-weight condition (*SD* $=8.94$), similar to the 13.76 steps averaged by the 4-week-olds in Study 1. Stepping in the weight added condition declined significantly to 9.58 steps ($SD=7.12$; dependent t-test [two-tailed], $t[11]=3.496$, $p<.01$). Each of the 12 infants showed a reduction of steps with weights ranging from 1 to 16 steps. There were no arousal differences between the weight and no-weight conditions (average arousal score in the no-weight condition was 4.03 and in the weight-added condition, 4.11; dependent $t[11]=-.522$, n.s.). Stepping decline could not be attributed to arousal changes from the experimental manipulation.

Table 4 contains the average hip, knee, and ankle angles for the weight and no-weight conditions. (The data for one infant were not used because he showed no steps at all in the weighted condition.) Both the knee and hip angles increased, indicating less strong flexion, although only in the hip did this approach statistical significance. There was a nonsignificant decrease in ankle flexion, but since the foot was not weighted, we would not expect an effect on the ankle joint.

TABLE 4
The Effects of Adding Weights to the Leg on the Joint Angles at Maximum Step Flexion

	Joint Angles					
	Hip		*Knee*		*Ankle*	
Condition ($N=11$)	*M*	*SD*	*M*	*SD*	*M*	*SD*
Without weights[1]	108.7*	14.1	98.0	20.3	103.0	13.5
Weights added[2]	114.9	8.1	101.5	16.2	99.2	14.4

[1] Based on all the right leg steps (94) in this condition.
[2] Based on all the right leg steps (57) in this condition.
*Dependent t $(10)=-.2112$, $p<.06$

This discovery that there were behavioral consequences from the addition of a small amount of mass to the legs of 4-week-old infants led us to ask whether we could confirm these strength limitations by a manipulation in the opposite direction—the reduction of the effects of leg mass. In Study 3, we repeated the stepping test, but substituted a condition where the infants stepped while their legs were under water. We hypothesized that infants would increase their step rate under water, and additionally, that the degree of flexion would be greater, resulting in smaller joint angles at maximum flexion.

STUDY 3

Methods

Subjects. Another sample of 12 apparently normal infants served as subjects. The 6 boys and 6 girls had an average birth rate of 3550 g (range, 2637–4281 g), and weights at times of testing averaged 4356 g (range, 3572–5514 g). Infants were within 4 days of 4 weeks old when tested.

Procedure. All infants were tested both in-water and out-of-water, with the order consecutively assigned. Joints were marked as in Study 2. For the out-of-water condition, infants' legs were bared and diapers removed; for the in-water condition, all their clothes were removed. Stepping was videotaped and arousal monitored exactly as in Study 2.

The in-water condition used a 32-gallon rectangular aquarium (92 × 32 × 45 cm) filled with comfortably warm water. The infants were held under the arms and lowered into the tank in the upright position until their feet touched the bottom. (The water level came to about the middle torso.) As soon as their feet made contact, the 1-min step period commenced.

In Study 3, the count of step frequency was from the videotape to insure accurate step counts in the in-water condition. All tapes were scored by two observers; reliability was .985. Joint angles at maximum flexion of the right leg were determined as in Study 2.

Results

The infants in this sample showed dramatic increases of step rate when the mass of their legs was lightened by submerging in water. The average number of steps in the out-of-water condition was 10.41 (*SD* 8.48); this increased to 20.27 steps (*SD* 8.80) in the water test (dependent $t[11] = -2.370$, $p < .05$). Arousal scores between conditions were not different (out-of-water arousal = 4.30; in-water arousal = 4.66, $t[11] = -.962$, n.s.). Submersion did not increase step rate indirectly through increasing arousal.

Table 5 contains the changes in joint angles of the right leg steps that occurred as a result of the water test. (Again, the data for one infant were dis-

TABLE 5
The Effects of Reducing Leg Mass by Submersion on the Joint Angles at Maximum Step Flexion

	Joint Angles					
	Hip		*Knee*		*Ankle*	
Condition (N = 11)	*M*	*SD*	*M*	*SD*	*M*	*SD*
Out-of-Water[1]	111.5	18.2	101.5*	11.7	100.9	12.2
In-water[2]	104.7	14.3	87.2	8.0	101.7	11.7

[1] Based on all the right leg steps (80) in this condition.
[2] Based on all the right leg steps (156) in this condition.
* Dependent t (10) = 4.683, $p < .001$

carded because there were no steps in the out-of-water condition.) Both hip and knee angles decreased, the knee significantly so, indicating a stronger final flexion when underwater. Again, the ankle showed a small increase in angle.

GENERAL DISCUSSION

The results of these three studies suggest that rate of stepping is limited by muscle strength. At 4 weeks, infants who gained weight and chubbiness most rapidly performed the fewest steps. In our earlier study of newborn infants, we found that body build was constraining only in infants who were not highly aroused. High arousal may have compensated for the difficulty of lifting heavy legs, presumably through increased motoneuron recruitment and/or increased firing rates (Thelen et al., 1982). In the present study on older infants, however, we detected an effect of body build on stepping despite individual differences in arousal level during the test. These results point especially to an asynchrony between mass and strength gains, because at the newborn period, infants who were the most slender stepped more (Thelen et al., 1982). These infants were most likely to show very rapid weight increases, perhaps as a "catch-up" phenomenon from the intrauterine limitations on growth (Fergusson, Horwood, & Shannon, 1980). The fact that it was *rate* of growth rather than absolute size that influenced stepping decline also argues against the possibility that larger infants were simply more neurologically mature and thus showed earlier stepping inhibition.

When we added weights simulating 2 weeks of growth to the legs of 4-week-old infants, their stepping declined 32%, more than the natural 19% decline between 4 and 6 weeks seen in the infants in Study 1. Infants might be expected to gain somewhat in both muscle mass and strength between 4 and 6 weeks, but as we suggest, not at a rate sufficient to overcome the nonmuscle increases, especially in the demanding upright position. When infants were experimentally presented with entirely nonmuscle mass increases, their strength was especially taxed, and although their overall arousal was equally high, they did not lift their legs either as often or with as great an amplitude as when unweighted. In contrast, submerging infants' legs and thus reducing the effects of mass had a dramatic impact on infants' ease of stepping, nearly doubling the average step rate. Thus, experimental manipulations of mass of the legs supported the predictions of step frequency and amplitude in both directions, adding and subtracting weight. Although the joint angle data were not statistically as strong as the rate results, the weighted joints showed changes in the predicted directions.

The interdependence of physical growth, especially muscle strength, and neurological maturation suggested by this research has also been demonstrated in nonhuman studies. For example, patterned locomotor or grooming movements could be elicited in young rodents prior to their usual ages of performance by appropriate postural support or by placing the animals in water to minimize the effects of weak muscles and lack of balance (Bekoff & Trainer, 1979; Fentress, 1978). In other words, the *expression* of a behavioral capability was limited by non-neurological factors. In chicks, Provine (1981) found that the ratio of wing area to body weight was a crucial determinant in the onset of functional flight. Although the neurological substrate for drop-evoked wing flapping was present immediately after hatching, a rapid increase in flapping frequency was correlated with the spurt in wing area, providing increased lift. When wings were unilaterally weighted (Provine, 1982), the preflight flapping rate decreased, again emphasizing the sensitivity of the moving system to the biodynamic qualities of the limb.

The results of these three studies provide additional support to our earlier hypothesis that the "disappearance" of newborn stepping can be explained by asynchronous changes in body build and muscle strength. Although these studies do not directly test this hypothesis, we believe the weight of the evidence favors this parsimonious, physical growth explanation over those invoking either cortical inhibition or learning.

First, there is no direct evidence that stepping is inhibited by the maturing cortex, and the fact that step-like kicking is maintained throughout the first 6 months in the supine posture contradicts the idea that stepping is suppressed. Submersion in water should not be expected to release cortical inhibition, yet such a treatment restores high step rates in 4-week-old infants and in 3-month-old infants as well. (Thelen, 1984a).

Thus, our evidence supports the Zelazo et al. (1972) conclusion that stepping patterns are not inhibited when they "disappear." However, we believe our results suggest a more satisfactory explanation for the maintenance of stepping than instrumental conditioning. The daily practice given to the experimental group infants by Zelazo exercised leg muscles under overload conditions, that is, against gravitational resistance they normally did not encounter. Experimental infants developed muscle strength in their legs not attained by infants kept on their backs, and thus they were able to sustain their stepping movements despite increasing leg mass. The control infants and those exercised passively *on their backs* were not subjected to these overload conditions and developed no increased strength.

Zelazo et al. (1972) have claimed that practice enhanced stepping through the reinforcing effects of the walking movements. Yet, there is no direct evidence *except the increase of stepping,* that these actions were indeed reinforcing. In fact, at the same ages, 2 to 6 weeks, that exercised infants were showing an increase in stepping in the Zelazo study, our arousal data indicated that the stepping test was in fact distressing (in our scoring system, a score of 4 or 5 indicated distress). Infants of this age have poor control of their heads and trunks, and behaviorally, do not appear to enjoy being dangled by their armpits. Although an increase of response rate is a measure of learning, learning is not the only means by which a behavioral response may be increased. Infants also show dramatic increases in supine and prone kicking movements over the first 2 months without any supplemental training; they kick more and in a wider variety of contexts (Thelen, 1979, 1981). Thelen (1981) proposed that in the early months, such behaviors were elicited in situations which increased generalized behavioral arousal. Zelazo et al. (1972) did not monitor arousal during the training, but they reported that after 6 weeks of training, infants showed an increase of smiling and laughing during the stepping test. It is unknown, however, whether their pleasure was a result of the reinforcing effects of stepping per se, or their increased comfort in the social situation as a result of better head control and stronger backs.

Finally, a large body of literature (recently reviewed by Rovee-Collier & Gekoski, 1979; Rovee-Collier & Fagen, 1981) leaves little doubt that leg movements *can* be used as operants. But infants learn to use kicks to control an overhead mobile, for example, in a matter of minutes. Increases in step rate, in contrast, occur over many weeks of training, even in infants who begin training at ages comparable to those used in the mobile studies. This is much more consistent with a gradual augmentation of strength than with the rapid learning seen in the operant task. In summary, Zelazo's important training effect is more simply explained by an increase in strength than by proposing operant learning in these very young infants.

These demonstrations that muscle strength can constrain movement during infancy are not meant to minimize the importance of developmental changes occurring at all levels of the neuromuscular system. Newborn stepping appears to be an automatized and stereotyped behavior, likely controlled by lower levels of the motor control hierarchy (Forssberg & Wallberg, 1980; Peiper, 1963; Thelen, Bradshaw, & Ward, 1981). The integration of these patterns into environmentally responsive, coordinated, and flexible activities requires the maturation of higher centers. But the corticalization of behavior proceeds only in concert with subcortical and physical growth. Newborn stepping may stand as an especially dramatic illustration of the effect of non-neurological factors on behavior; it is, however, premature to extend these speculations to other so-called "primitive reflexes." Nonetheless, the contemporary emphasis on biomechanical factors in movement control suggests these may be important in other movement contexts. The possibility that different levels of the neuromotor system may mature asynchronously or even asymmetrically (Thelen et al., 1983) may offer clues to understanding previously puzzling developmental phenomena.

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