Relationship between Stepping Movements and Age of Walking Attainment in Full-Term Infants without Known Impairment or Pathology

Hong-Ji Luo Suh-Fang Jeng[*] Tung-Wu Lu[**] Kwan-Hwa Lin[*]

Purposes: The purposes of this study were to examine the relation between stepping movements and age of walking attainment in full-term infants who had no known impairments or pathology, and to explore the potential influencing factors for walking attainment. **Methods:** Twenty full-term infants were prospectively examined for stepping movements at a two-month interval from 7 months of age until walking attainment. Infants were supported stepping on a treadmill at 0.1 and 0.2 m/s speeds, and the stepping movements were recorded and analyzed using Peak Performance Motion Analysis System. Potential influencing factors included physical growth, skin fold thickness, and gross motor function. **Results:** Infants attained walking ability at a mean age of 11.4 months (SD 1.2 months, range 10-14.3 months). Cox's proportional hazards univariate regression analysis revealed that a long stance time, a large knee extension at foot contact, and a symmetrical interlimb coordination pattern in the stance and swing time in stepping movements at 9 months of age were associated with an increased rate of walking attainment (all $p < 0.05$). Furthermore, a small skin fold thickness at the biceps and subscapular areas together with a low percentage of total body fat and a high motor subscale and total score at 7 months of age; and a small skin fold thickness at the supra-iliac area together with a high standing subscale score at 9 months of age were also associated with an increased rate of walking attainment (all $p < 0.05$). **Conclusions:** Our findings indicate that full-term infants demonstrate gradually organized stepping movements prior to walking attainment. The developmental process of walking appears complex that may relate to changes in multiple subsystems. (FJPT 2004;29(2):67-78)

Key Words: Influencing factors, Kinematic analysis, Stepping, Walking developemnt

Department of Physical Therapy, Hung-Kuang University, Taichung, Taiwan.
* School and Graduate Institute of Physical Therapy, College of Medicine, National Taiwan University, Taipei, Taiwan.
** Institute of Biomedical Engineering, College of Engineering and Medicine, National Taiwan University, Taipei, Taiwan.
Correspondence to: Suh-Fang Jeng, School and Graduate Institute of Physical Therapy, College of Medicine, National Taiwan University, No. 1 Jen Ai Road, Section 1, 100 Taipei, Taiwan. Tel: 02-23123456- 7557 E-mail: jeng@ntu.edu.tw
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Attainment of walking ability is one of the major goals for the therapeutic intervention of children with neuromotor disorders (e.g., cerebral palsy) because walking attainment greatly enhances an infant's mobility and exploration in the surroundings that is beneficial for subsequent cognitive and psychosocial development.[1-4] Understanding the developmental process of walking and the influencing factors for walking attainment in full-term infants who have no known impairment or pathology is important to provide a basis for the comparison of walking development in children with neuromotor disorders.

Young infants manifest stepping movements when supported in an upright position. The spatial and temporal organization of the early locomotion-like movements are similar to those of mature walking and have thus been proposed as the precursory motor patterns of walking movements.[5,6] The paradigm of infant stepping study provides a useful means to help reveal the development of leg movements before children actually acquire walking ability under a similar context as upright locomotion.

A number of researchers have used biomechanical instruments to investigate the changes of stepping movements in full-term infants during early months of life.[5-8] Biomechanical instruments used included kinematics, electromyography, and kinetics. Kinematical analysis showed that there is an increase in alternate step frequency, a decrease in interjoint correlation, and a decrease in variability of interlimb coordination in infant stepping movements with advancing age.[6,9,10] Electromyographic analysis revealed that infant stepping movements undergo a transformation in muscle activation from early co-contraction pattern to subsequently reciprocal pattern.[7,11,12] Kinetic analysis illustrated that supported stepping movements become more efficient from a proximal to a distal control pattern as infants become older.[13,14]

Previous studies on stepping movement have demonstrated that developmental changes occur in the organization and coordination of stepping movements in full-term infants during early months of life. However, none of the studies followed up infants until walking attainment and neither did they examine the relationship between stepping movements and walking attainment. Therefore, the first purpose of this study was to longitudinally examine the stepping movements in full-term infants who had no known impairments or pathology until walking attainment, and to examine the relation of stepping movements with subsequent walking attainment.

The information concerning the influencing factors for walking attainment in infants is limited. Only two studies had respectively investigated the potential influencing factors for stepping movements in full-term infants and preterm infants who had low risk of developmental problems.[9,15] Thelen and Ulrich found that full-term infants who had a more matured gross motor function, a smaller flexion angle in the legs, and a smaller inward rotation angle in the feet produced more alternate steps on a treadmill than those without.[9] Davis et al observed that in preterm infants with low risk of developmental problems,[15] a heavier body build at 1 and 6 months, and a smaller flexion angle in the legs during swing phase at 1 month were each associated with more alternate steps on a treadmill.

Because the aforementioned studies used the number of alternate steps as the outcome measure, whether the influencing factors remain the same for walking attainment is unclear. Therefore, the second purpose of this study was to examine the potential influencing factors that relate to walking attainment in full-term infants. The potential influencing factors examined included physical growth, skin fold thickness, and gross motor function.

METHODS

Subjects

This study included 20 full-term infants who were born at the National Taiwan University Hospital, Taipei, Taiwan, during the period from August 2000 to March 2002. The inclusion criteria were: gestational age of 38-42 weeks, birth weight within the 10th to 90th percentile of the intrauterine growth curve of Taiwanese infants,[16] 1- and 5-min Apgar scores greater than 8, absence of maternal and perinatal complications, and considered "normal" on newborn examination. The infants included 9 boys (45%) and had a mean gestational age of 39.3 weeks (SD 1.1 weeks) and a mean birth weight of 3,383 g (SD 463.4 g). This study was approved by the Institutional Review Committee of the National Taiwan University Hospital, Taipei, Taiwan. Informed consent was obtained from the parents of all infants prior to participation in the study.

Testing Procedure

Infants were prospectively examined for stepping movements and potential influencing factors at a two-month interval from 7 months of age until walking attainment. Potential influencing factors included physical growth, skin fold thickness, and gross motor development. Age of walking attainment was determined by asking the parents to monitor and record the date when the child began walking for five successive steps without support.[17] This data was collected within a week of this event and was recorded by chronological age.

Prior to stepping test, infants wore a black short to reveal the following anatomical landmarks on their right sides: mid trunk, greater trochanter, lateral femoral condyle, lateral malleolus, and fifth metatarsal head. Reflective ball-shaped markers (3M Corporation, MN, USA) with 0.7- to 1-cm diameter were placed at these landmarks to respectively define the hip, knee, and ankle angles. During stepping test, infants were supported by an examiner under the arms with their feet resting on a treadmill (Woodway Reha K1, Germany) and allowed to bear as much weight as was comfortable. Infants were encouraged to step for two minutes at 0.1 and 0.2 m/s respectively for which speed sequence was randomly assigned. These treadmill speeds have previous been used by Thelen and Ulrich[9] and Davis et al[15] for infant stepping studies.

Infants' stepping movements were recorded using two synchronized video cameras (WV-CL350 with lenses of 8-48 mm, Panasonic Broadcast & Television System Co., NJ, USA) that were positioned on their right sides. Each camera was operated at 60 Hz and was connected to a videocassette recorder (SVHS AG-1960, Panasonic Broadcast & Television System Co., NJ, USA), a time code generator (SDR-50, Horita Co., USA), and a video monitor (Sony PVM-1341, Japan). The cameras were angled at 70 degrees and were placed at a distance of 6.5 meters from the infants. The cameras were used to construct a three-dimensional analysis of the limb movements with calibration errors of smaller than 3 mm.

Infants were measured for physical growth, skin fold thickness, and gross motor function following each stepping test. Physical growth included weight, length, and leg volume. Weight was measured using a digital weight meter; length was measured using a wooden platform where a standard rule was mounted. Leg volume was calculated as the product of leg length and leg circumference.[15] Leg length was measured from baby's greater trochanter to the sole of the foot; leg circumference was measured as the average of the circumference of the mid-thigh and the mid-calf. Infants were examined for skin fold thickness at the following locations: biceps, triceps, sub-scapulae, supra-iliac, anterior and posterior aspects of thigh, and lateral aspect of shank. Skin fold thickness was measured using a caliper. The percentage of total body fat was then estimated from the skin fold data using the Pediatric Anthropo-Plicometry Software (Rel. Master version 1.0, Anthropometic Kit for Pediatric Age Group, Dietosystem MediGroup, Milano, Italy).

Infants' gross motor function was examined using the Alberta Infant Motor Scale (AIMS).[18] The scale was designated to evaluate the gross motor development of infants from birth through 18 months of age. The AIMS consists of 58 items that are organized into four subscales: prone (21 items), supine (9 items), sitting (12 items), and standing (16 items). The scoring system entails a dichotomous choice for each test item, scored as "observed" or "not observed" using three key descriptors: weight bearing, posture, and antigravity movement. Acceptable reliability and validity have been found for the AIMS to evaluate the motor development of preterm and full-term infants.[19,20]

Data acquisition and reduction

A 20-second segment of video record that best represented supported stepping movements during middle of a trial was selected for individual infant at each speed for each month. The video data were digitized and analyzed using the Peak Performance Motion Analysis System (Motus version 3.01, 4th order Butterworth filter with filtering rate at 6 Hz, Peak Performance Technologies Inc., CO, USA). An examiner coded the foot movement through viewing the 20-second video records frame by frame and specified a mark on the frame when foot contact or foot off occurred. Four infants' stepping records were used to examine the coding precision of the examiner's data analysis. The average coding error of foot contact and foot off events was less than 1 frame (0.017 sec).

The obtained linear and angular displacement data were used to calculate all the following kinematic variables using a customized program written in the Matlab software by the investigator (HJL) (Version 5.3, MathWorks Inc., USA). An alternate step was selected for further analysis and was defined as when the step was initiated within 20%-80% of a step cycle on the opposite leg.[9] The alternate steps data were further analyzed for kinematic variables of stepping frequency, spatiotemporal organization, interjoint coordination, and interlimb coordination.

Stepping frequency was measured as the number of alternate steps during the 20-second period and was converted into steps per minute. Spatiotemporal organization included joint angles and movement phases. Joint angles were measured as the hip, knee, and ankle joint angles of the right limb at the time when the right foot contacted the treadmill. Movement phases included stride, step, stance, and swing time. Stride time was the time duration when one foot contacted the treadmill until the same foot contacted the treadmill again; step time was the time duration when one foot contacted the treadmill until the other foot contacted the treadmill; stance time was the time duration when one foot contacted the treadmill until the same foot off the treadmill; swing time was the time duration when one foot off the treadmill until the same foot contacted the treadmill. The duration of step, stance, and swing time were each divided by the stride time to calculate the percentage of step, stance, and swing time within a step cycle. Interjoint coordination was measured by pair-wised cross-correlation of the hip, knee and ankle joint angles of the same leg during the swing phase using Pearson product-moment correlation, and was transformed into Fisher's Z scores. Interlimb coordination was measured by the asymmetry ratio of stance and swing time of the legs. Asymmetry ratio was calculated by dividing the larger value of the two limbs' parameter by the smaller one.

Statistical analysis

The stepping movements and potential influencing factors were compared within the subjects between ages using the analysis of variance (ANOVA) with repeated measures. The ANOVA model for the stepping variables was age (2) X speed (2) and for the potential influencing factors was age (2). Age of walking attainment was analyzed using the Kaplan-Meier method.[23] The relations of stepping movements and potential influencing factors with age of walking attainment were examined using Cox's proportional hazards univariate regression analysis.[23] The analysis provides the maximum likelihood estimate of rate ratio (RR) and the 95% confidence interval (CI) for individual predictive variables. A p value of less than 0.05 was considered as statistically significant. All statistical analyses were performed using the Statistical Analysis Software (SAS) program (version 8.02, SAS Institute Inc., Cary NC, USA).

RESULTS

Age of walking attainment

Survival analysis of age of walking attainment revealed that 10 infants (50%) attained walking ability by 11 months of age, 8 (40%) attained walking ability during the period of 11 to 13 months of age, and 2 (10%) attained walking ability during the period of 13 to 15 months of age. The infants attained walking ability at a mean age of 11.4 months (SD 1.2 months, range 10-14.3 months).

Development of stepping movements

Stepping test was scheduled for infants at a two-month interval from 7 months of age until walking attainment. The number of stepping test performed on individual infants varied depending on their age of walking attainment. During the follow-up period, stepping test was performed on all infants at 7 and 9 months of age; stepping test was performed on 12 infants at 11 months of age; stepping test was performed on 2 infants at 13 months of age. Table 1 illustrates the stepping movements of infants at 0.1 and 0.2 m/s at 7 and 9 months of age. Table 2 illustrates the stepping movements of infants at 0.1 and 0.2 m/s at 11 and 13 months of age.

The individual stepping variables were compared between 0.1 and 0.2 m/s and across 7 and 9 months of age. Analysis of the step frequency revealed speed [$F(1,78)=22.57$, $p<0.0001$] and age [$F(1,78)=4.20$, $p<0.05$] effects. Infants exhibited an increase in the step frequency from 0.1 to 0.2 m/sec of speed and from 7 to 9 months of age. Examination of the temporal variables showed speed effects for the stride time [$F(1,78)=56.37$, $p<0.0001$], stance time [$F(1,78)=69.64$, $p<0.0001$], percent stance time [$F(1,78)=27.57$, $p<0.0001$], swing time [$F(1,78)=69.64$, $p<0.0001$], and percent swing time [$F(1,78)=27.57$, $p<0.0001$]. Infants manifested a decrease in the stride time, stance time, and percent stance time, together with an increase in the swing time and percent swing time with increasing speed. As for the step time and percent step time, there were no differences between speeds and across ages. Analysis of the spatial variables illustrated an age effect for the hip joint angle at foot contact [$F(1,78)=8.87$, $p<0.004$]. Infants showed a smaller flexion angle at the hip joint at foot contact with increasing age. As for the knee and ankle angle at foot contact, there were no differences between speeds and across ages.

Table 1. Stepping movements of infants at 7 and 9 months of age

Variable	7 Months of Age (N=20)		9 Months of Age (N=20)	
	0.1 m/s	0.2 m/s	0.1 m/s	0.2 m/s
Number of alternate steps	3.3 ± 2.4	5.9 ± 3.1	4.3 ± 1.7	7.2 ± 2.5
Percent alternate steps (%)	52 ± 30	57 ± 29	74 ± 22	80 ± 23
Step frequency (cycles/min)	9.9 ± 7.3	17.6 ± 9.4	13.0 ± 5.1	21.5 ± 7.6
Spatiotemporal organization				
Stride time (sec)	2.69 ± 0.49	1.91 ± 0.42	2.99 ± 0.70	1.97 ± 0.42
Step time (sec)	1.16 ± 0.23	1.26 ± 1.41	1.29 ± 0.46	0.93 ± 0.26
Percent step time (%)	44 ± 9	48 ± 5	45 ± 8	47 ± 6
Stance time (sec)	2.11 ± 0.55	1.38 ± 0.30	2.36 ± 0.55	1.38 ± 0.30
Percent stance time (%)	78 ± 7	72 ± 6	79 ± 5	70 ± 5
Swing time (sec)	0.59 ± 0.19	0.53 ± 0.18	0.63 ± 0.23	0.59 ± 0.17
Percent swing time (%)	22 ± 7	28 ± 6	21 ± 5	30 ± 5
Angle at foot contact (°)				
Hip joint	138.9 ± 10.9	139.1 ± 12.5	132.3 ± 9.5	131.8 ± 6.9
Knee joint	145.1 ± 13.3	145.4 ± 13.9	140.2 ± 14.1	142.8 ± 12.1
Ankle joint	118.1 ± 13.5	111.5 ± 15.2	114.6 ± 13.1	110.6 ± 13.1
Interjoint coordination (Z)				
Hip-Knee coupling	0.34 ± 0.71	0.23 ± 0.62	0.14 ± 0.68	-0.12 ± 0.38
Hip-Ankle coupling	0.59 ± 1.02	1.07 ± 0.45	1.13 ± 0.80	1.07 ± 0.37
Knee-Ankle coupling	0.21 ± 0.74	0.22 ± 0.87	0.20 ± 0.82	-0.11 ± 0.46
Interlimb coordination				
AR of stance time	1.36 ± 0.30	1.33 ± 0.26	1.21 ± 0.12	1.26 ± 0.17
AR of swing time	1.55 ± 0.25	1.65 ± 0.42	1.67 ± 0.54	1.43 ± 0.19

The data are presented as Mean ± SD.
AR= asymptry ratio.

Table 2. Stepping movements of infants at 11 and 13 months of age

Variable	11 Months of Age (N=12)		13 Months of Age (N=2)	
	0.1 m/s	0.2 m/s	0.1 m/s	0.2 m/s
Number of alternate steps	5.3 ± 2.5	9.0 ± 2.7	5.0 ± 1.4	9.0 ± 1.4
Percent alternate steps (%)	69 ± 28	88 ± 21	93 ± 10	94 ± 8
Step frequency (cycles/min)	16.0 ± 7.6	27.0 ± 2.7	15.0 ± 1.4	27.0 ± 1.4
Spatiotemporal organization				
Stride time (sec)	2.41 ± 0.83	1.81 ± 0.47	3.02 ± 1.26	1.81 ± 0.28
Step time (sec)	1.16 ± 0.42	0.96 ± 0.28	1.49 ± 0.84	0.97 ± 0.28
Percent step time (%)	49 ± 7	53 ± 1	47 ± 7	53 ± 8
Stance time (sec)	1.87 ± 0.88	1.33 ± 0.33	2.4 ± 1.1	1.41 ± 0.23
Percent stance time (%)	77 ± 9	74 ± 4	80 ± 2	77 ± 0
Swing time (sec)	0.54 ± 0.30	0.48 ± 0.16	0.59 ± 0.19	0.40 ± 0.05
Percent swing time (%)	23 ± 9	26 ± 4	20 ± 2	23 ± 0
Angle at foot contact (°)				
Hip joint	137.1 ± 10.3	135.8 ± 10.2	136.2 ± 2.7	136.7 ± 2.1
Knee joint	137.0 ± 9.0	138.9 ± 12.2	148.7 ± 10.6	146.9 ± 4.4
Ankle joint	108.1 ± 16.1	110.5 ± 13.8	94.8 ± 16.5	100.8 ± 14.8
Interjoint coordination (Z)				
Hip-Knee coupling	0.56 ± 0.66	0.17 ± 0.62	0.50 ± 0.41	-0.01 ± 0.27
Hip-Ankle coupling	1.04 ± 0.75	0.99 ± 0.48	0.24 ± 1.21	0.50 ± 0.77
Knee-Ankle coupling	0.25 ± 0.72	0.07 ± 0.39	-0.08 ± 0.01	0.37 ± 0.59
Interlimb coordination				
AR of stance time	1.42 ± 0.29	1.46 ± 0.66	1.23 ± 0.02	1.24 ± 0.07
AR of swing time	1.64 ± 0.29	1.38 ± 0.12	1.87 ± 0.42	1.57 ± 0.14

The data are presented as Mean ± SD.
AR= asymmetry ratio.

Analysis of the interjoint coordination revealed no differences in the hip-knee, hip-ankle, and knee-ankle couplings between speeds over ages. As for the interlimb coordination, there was an age effect [$F(1,78)=4.51$, $p<0.04$] for the asymmetry ratio of stance time. Infants exhibited a lower value of asymmetry ratio, indicating a more symmetrical pattern, in the stance time from 7 to 9 months of age.

Changes in physical growth, skin fold thickness, and gross motor function

Infants' physical growth, skin fold thickness, and gross motor function at 7 and 9 months of age are presented in Table 3. Significant age effects were found for the length [$F(1,38)= 8.61$, $p<0.006$], the skin-fold thickness at anterior thigh [$F(1,38)=73.17$, $p<0.01$] and lateral calf areas [$F(1,38)= 5.55$, $P=0.03$], and all the AIMS subscale (prone, supine, sitting, and standing) and total scores [$F(1,38)=17.57$, $p<0.0002$; $F(1,38)=7.70$, $p<0.009$; $F(1,38)=24.91$, $p<0.0001$; $F(1,38)=39.46$, $p<0.0001$; $F(1,38)=30.39$, $p<0.0001$]. That is, infants demonstrated an increase in the length, the skin-fold thickness at anterior thigh and lateral calf areas, and all the AIMS subscale and total scores from 7 to 9 months of age.

Table 3. Physical growth, skin fold thickness, and gross motor function of infants at 7, 9, 11, and 13 months of age

Variable	7 Months of Age (N=20)	9 Months of Age (N=20)	11 Months of Age (N=12)	13 Months of Age (N=2)
Physical growth				
Weight (g)	8327.8 ± 1067.3	8949.0 ± 1139.6	9696.5 ± 1595.8	10050.0 ± 9040.6
Length (cm)	69.8 ± 2.6	72.3 ± 2.8	75.1 ± 3.7	75.2 ± 5.9
Leg volume (cm^3)	1044.1 ± 192.9	1166.6 ± 246.1	1907.0 ± 1000.0	1490.5 ± 705.0
Skin fold thickness (mm)				
Biceps	6.8 ± 1.9	7.0 ± 1.3	7.1 ± 1.4	8.0 ± 1.7
Triceps	9.0 ± 2.1	9.8 ± 1.7	10.0 ± 2.1	12.0 ± 2.5
Subscapulae	6.6 ± 1.4	6.5 ± 0.8	6.5 ± 2.0	7.5 ± 2.4
Supra-iliac	5.4 ± 1.2	5.8 ± 1.1	5.8 ± 1.9	6.9 ± 1.0
Anterior thigh	13.7 ± 3.8	16.4 ± 2.3	17.0 ± 2.2	18.0 ± 2.6
Posterior thigh	14.0 ± 3.7	15.4 ± 2.3	14.9 ± 2.1	16.5 ± 1.8
Lateral calf	12.0 ± 2.9	13.9 ± 2.2	19.8 ± 2.2	14.6 ± 9.7
Percent total body fat (%)	17.3 ± 4.7	18.4 ± 3.1	18.6 ± 9.6	21.0 ± 5.6
AIMS scores (points)				
Prone subscale	14.1 ± 3.6	18.6 ± 3.3	20.9 ± 1.0	21.0 ± 0.0
Supine subscale	8.6 ± 0.6	9.0 ± 0.2	9.0 ± 0.0	9.0 ± 0.0
Sitting subscale	8.7 ± 2.2	11.4 ± 1.2	12.0 ± 0.0	12.0 ± 0.0
Standing subscale	3.7 ± 1.3	7.8 ± 2.6	10.3 ± 1.2	10.5 ± 0.7
Total score	34.9 ± 6.9	46.7 ± 6.6	52.1 ± 1.9	52.5 ± 0.7

The data are presented as Mean ± SD.
AIMS= Alberta Infants Motor Scale.

Relations of stepping movements and potential influencing factors with age of walking attainment

Cox's proportional hazards univariate regression analysis of the relations between stepping movements and age of walking attainment illustrated that none of the stepping variables at 7 months of age had significant relations with age of walking attainment (all $p > 0.05$) (Table 4.). Whereas, a long stance time at 0.2 m/s, a large percentage of stance time at 0.1 m/s, a large knee extension angle at foot contact at 0.1 m/s and 0.2 m/s, and a symmetric pattern in the stance and swing time at 0.2 m/s at 9 months of age were each significantly associated with an increased rate of walking attainment ($p < 0.05$).

Univariate regression analysis of the relations between potential influencing factors and age of walking attainment illustrated that a small skin fold thickness at the biceps and subscapular areas, a low percentage of total body fat, and a high AIMS subscale and total score at 7 months of age were significantly correlated with an increased rate of walking attainment ($p < 0.05$) (Table 5.). Furthermore, a small skin fold thickness at the supra-iliac area and a high AIMS standing score at 9 months of age were also significantly correlated with an increased rate of walking attainment ($p < 0.05$).

DISCUSSION

This study examined the relationship between stepping movements and age of walking attainment in full-term infants who had no known impairment or pathology, and explored the potential influencing factors for their walking

Table 4. Cox's proportional hazards univariate regression analysis of stepping movements for age of walking attainment in infants

Variable	7 Months of Age		9 Months of Age	
	0.1 m/s	0.2 m/s	0.1 m/s	0.2 m/s
Stepping frequency (per cycle/min increase)	1.12 (0.91-1.38)	1.07 (0.93-1.24)	0.83 (0.60-1.16)	1.05 (0.82-1.34)
Spatio-temporal organization				
Stride time (per sec increase)	1.00 (0.38-2.63)	0.52 (0.16-1.66)	1.53 (0.65-3.56)	3.46 (0.77-15.6)
Step time (per sec increase)	1.58 (0.16-15.3)	0.88 (0.60-1.27)	1.10 (0.29-4.14)	4.64 (0.54-39.6)
Percent step time (per % increase)	1.37 (0.01-270)	0.18 (0.00-599)	2.14 (0.00-100)	6.65 (0.01-6646)
Stance time (per sec increase)	0.92 (0.38-2.21)	0.38 (0.08-1.89)	2.40 (0.89-6.48)	10.28 (1.36-77.7)*
Percent stance time (per % increase)	0.98 (0.91-1.06)	0.99 (0.91-1.09)	1.12 (1.01-1.24)*	1.07 (0.98-1.16)
Swing time (per sec increase)	2.46 (0.17-35.6)	0.36 (0.02-5.82)	0.22 (0.02-2.37)	0.98 (0.07-14.5)
Percent swing time (per % increase)	1.02 (0.95-1.10)	1.01 (0.92-1.10)	0.89 (0.81-0.99)*	0.93 (0.86-1.02)
Angle at foot contact (per ° increase)				
Hip joint	0.97 (0.92-1.02)	0.99 (0.96-1.03)	0.99 (0.95-1.05)	1.04 (0.96-1.12)
Knee joint	1.01 (0.98-1.05)	1.02 (0.98-1.05)	1.04 (1.00-1.09)*	1.09 (1.03-1.15)*
Ankle joint	1.03 (0.99-1.08)	1.03 (0.99-1.07)	0.99 (0.96-1.04)	1.02 (0.98-1.05)
Interjoint coordination (per Z score increase)				
Hip-Knee coupling	0.78 (0.35-1.71)	0.44 (0.15-1.32)	0.54 (0.25-1.16)	0.55 (0.18-1.66)
Hip-Ankle coupling	1.84 (0.99-3.40)	1.85 (0.68-5.04)	0.87 (0.45-1.69)	1.50 (0.39-5.78)
Knee-Ankle coupling	0.95 (0.44-2.04)	0.54 (0.19-1.50)	0.71 (0.35-1.45)	0.63 (0.25-1.56)
Interlimb coordination (per 1 increase)				
AR of stance time	2.24 (0.43-11.7)	0.22 (0.03-1.86)	8.11 (0.07-968)	0.01 (0.00-0.38)*
AR of swing time	3.34 (0.51-21.9)	0.76 (0.25-2.31)	1.34 (0.45-4.01)	0.04 (0.01-0.70)*

The data are presented as rate ratio (95% CI).
A rate ratio of greater than 1 indicates that the level under consideration may lead to an increased rate of walking attainment. A rate ratio of less than 1 indicates that the level under consideration may result in a decreased rate of walking attainment.
AR= asymmetry ratio.
* $p < 0.05$.

attainment. Our results showed that infants attained walking ability at a mean age of 11.4 months (SD 1.2 months, range 10-14.25 months). The age of walking attainment of our infants were close to the data reported by Capute et al [24] but were younger than the data reported by de Groot et al[25] and Gorga et al.[26] The discrepancy in age of walking attainment in full-term infants between studies may be due to differences in sampling method and definition of walking attainment.

Infants manifested changes in a number of stepping variables prior to walking attainment. From 7 to 9 months of age, infants exhibited more alternate steps, a smaller hip flexion angle at foot contact, and a more symmetrical interlimb coordination pattern in the stance time when supported stepping on a treadmill. When the treadmill speed was changed from 0.1 m/s to 0.2 m/s, there was an increase in alternate steps, a decrease in the stance time and the percentage of stance time together with an increase in the swing time and the percentage of swing time. Our findings indicate that with advancing age, infants altered their stepping movements in the spatiotemporal organization and the interlimb coordination pattern on the treadmill. In response to an increase in treadmill speed, their stepping movements showed modulation through a shortening of the temporal phases, particularly the durations of stance and swing time. Similar findings have previously been reported by Thelen

Table 5. Cox's proportional hazards univariate regression analysis of potential influencing variables at 7 and 9 months of age for age of walking attainment in infants

Variable	7 Months of Age	9 Months of Age
Physical Growth		
Weight (per g increase)	1.00 (1.00-1.00)	1.00 (1.00-1.00)
Length (per cm increase)	1.02 (0.87-1.20)	1.01 (0.86-1.18)
Leg volume (per cm³ increase)	1.00 (0.99-1.00)	1.00 (0.99-1.00)
Skin fold thickness		
Biceps (per mm increase)	0.67 (0.50-0.90)*	0.95 (0.65-1.39)
Triceps (per mm increase)	0.86 (0.68-1.08)	0.85 (0.65-1.11)
Subscapulae (per mm increase)	0.70 (0.49-1.00)*	0.95 (0.58-1.56)
Supra-iliac (per mm increase)	0.87 (0.59-1.28)	0.55 (0.31-0.99)*
Anterior thigh (per mm increase)	1.01 (0.90-1.13)	0.97 (0.79-1.18)
Posterior thigh (per mm increase)	0.95 (0.85-1.08)	0.90 (0.73-1.10)
Lateral calf (per mm increase)	0.99 (0.87-1.14)	0.93 (0.77-1.12)
Total body fat (per % increase)	0.90 (0.81-1.00)*	0.95 (0.78-1.07)
AIMS scores (per point increase)		
Prone subscale	1.18 (1.02-1.38)*	1.06 (0.91-1.23)
Supine score	1.42 (0.70-2.88)	1.45 (0.19-11.1)
Sitting score	1.56 (1.11-2.18)*	1.18 (0.78-1.80)
Standing score	2.36 (1.40-3.97)*	1.44 (1.71-1.92)*
Total score	1.14 (1.04-1.25)*	1.70 (0.98-1.18)

The data are presented as rate ratio (95% CI).
A rate ratio of greater than 1 indicates that the level under consideration may lead to an increased rate of walking attainment. A rate ratio of less than 1 indicates that the level under consideration may result in a decreased rate of walking attainment.
AIMS= Alberta Infants Motor Scale.
* $p<0.05$

and Ulrich[9] and Davis et al[15] in full-term infants and preterm infants who were at low risk of developmental disorders.

Besides the maturation in stepping movements, infants showed changes in the subsystems of physical growth, skin fold thickness, and gross motor function prior to walking attainment. From 7 to 9 months of age, infants manifested an increase in the body length, the skin fold thickness at the anterior thigh and lateral calf areas, and all the AIMS subscale (prone, supine, sitting, and standing) and total scores. The results implicate that changes have simultaneously occurred in multiple subsystems (ie physical growth, skin fold thickness, and motor function) during this time period.

Several features of stepping movements were found to have significant relations with age of walking attainment in infants. A long stance time at 0.2 m/s, a large percentage of stance time and a small percentage of swing time at 0.1 m/s, a large knee extension angle at foot contact at 0.1 m/s and 0.2 m/s, and a symmetrical interlimb coordination pattern in the stance and swing time at 0.2 m/s at 9 months of age were each associated with an increased rate of walking attainment. The identified stepping variables have primarily involved the characteristics of spatiotemporal organization and symmetry of interlimb coordination at 9 months of age. Thelen and Ulrich[9] and Davis et al[15] respectively reported on full-term infants and preterm infants who were at low risk of developmental disorders that a more extended leg posture was associated with the production of more alternate steps on a treadmill. Our findings suggest that the spatiotemporal organization and the symmetry of interlimb coordination pattern in stepping movements may be important for the attainment of walking ability in full-term infants. Future studies are necessary to investigate the mechanisms that explain the relations between these stepping features and walking attainment.

Changes in certain subsystems during the age period of 7 to 9 months also had significant relations with age of walking attainment in infants. Specifically, a small skin fold thickness at the biceps and subscapular areas, a low percentage of total body fat, a high gross motor subscale and total score at 7 months of age; and a small skin fold thickness at the supra-iliac area and a high standing score at 9 months of age were associated with an increased rate of walking attainment. The findings of this study suggest that changes in multiple subsystems ie, skin fold thickness, total body fat, and gross motor function, may relate to the attainment of walking ability in infants.

Our findings concerning the influencing factors for walking attainment in full-term infants were consistent with the results of Thelen and Ulrich that maturation of gross motor function is correlated with the development of upright locomotion.[9] Furthermore, our results appear to coincide with the observations of Thelen et al that asynchronous physical growth,[27] as reflected by an increase in the percentage of total body fat but no change in muscle mass, might contribute to the disappearance of stepping movements in full-term infants during early infancy. This might explain why a high percentage of total body fat is not in favor of early walking attainment in this study. Our data have contradicted to the findings of Thelen and Ulrich,[9] however, that showed no relation between body build characteristics and stepping movements. This might be partly due to the use of a small sample size (only 9 infants) in their study.

In conclusion, the results of this study demonstrated that full-term infants who had no known impairment or pathology exhibited changes in stepping movements and multiple subsystems prior to walking attainment. The stepping features i.e., a long stance time, a large knee extension at foot contact and a symmetrical interlimb coordination pattern in the stance time and the swing time at 9 months of age were associated with an increased rate of walking attainment. Furthermore, a small skin fold thickness at the biceps and subscapular areas, a low percentage of total body fat, and a high gross motor subscale and total score at 7 months of age; and a small skin fold thickness at the supra-iliac area and a high standing score at 9 months of age were also correlated with an increased rate of walking attainment. Our findings suggest that full-term infants demonstrate gradually organized stepping movements prior to walking attainment. The developmental process of walking appears complex that may relate to changes in multiple subsystems. The obtained data could be used as a reference for further study on the development of stepping movements and the influencing factors for walking attainment in those infants who are at risk of developmental disorders.

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無損傷或病變之足月兒的跨步動作與行走達成年齡的相關性研究

羅鴻基 鄭素芳* 呂東武** 林光華*

研究目的：本研究的目的有二：(一)探討無損傷或病變之足月兒的跨步動作與行走達成年齡的相關性，以及(二)探索可能和行走達成有關之影響因子。**研究方法**：本研究包括20名足月兒，於年齡7個月開始每兩個月接受跑步機跨步動作評估(速度0.1與 0.2 公尺/秒)直至行走達成為止，跨步動作以Peak Performance動作分析系統記錄與分析，可能之影響因子包括身體成長、皮脂厚度、與粗動作功能。 **結果**：嬰兒之平均行走達成年齡為11.4個月(標準差1.2個月，範圍10-14.3個月)。Cox's比率危險單變項迴歸分析顯示，年齡9個月時的跨步動作具較長之著地期、較大之著地時膝關節伸直角度、以及兩腳間較對稱之著地期和離地期，則明顯有利於較早之行走達成($p<0.05$)。另外，年齡7個月時較小之二頭肌與肩胛下皮脂厚度、較低之全身脂肪比率、與較高之粗動作分項分數和總分；以及年齡9個月時較小之恥骨上皮脂厚度、與較高之粗動作站立分項分數，亦明顯有利於較早之行走達成($p<0.05$) 。**結論**：本研究的結果顯示，足月兒於行走達成前呈現逐漸統整之跨步動作，而且其行走發展的過程相當複雜，可能和多系統的變化有關。(物理治療2004;29(2):67-78)

關鍵詞：運動學分析、跨步動作、行走發展、影響因子

弘光大學物理治療學系
* 台灣大學物理治療學系暨研究所
** 台灣大學醫學工程研究所
通訊作者：鄭素芳 台灣大學物理治療學系暨研究所 台北市仁愛路一段一號 電話：(02)23123456-7557
E-Mail: jeng@ntu.edu.tw
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