ISSN 1413-3555
Rev Bras Fisioter, São Carlos, v. 14, n. 6, p. 483-90, Nov./Dec. 2010
©Revista Brasileira de Fisioterapia

ORIGINAL ARTICLE

Ideal treadmill speed to stimulate stepping in infants*

Velocidade ideal da esteira para estimular passadas do andar em bebês*

Diana X. C. Schlittler[1], Matheus B. Sanches[2], Raquel P. Carvalho[3], José A. Barela[2,4]

Abstract

Background: The motorized treadmill elicits stepping in infants, however the effects of belt speed on treadmill-elicited stepping patterns are still unknown. Objective: To examine the effect of belt speed on treadmill-elicited infant stepping. Methods: Six normally developing infants, aged between 11 and 13 months and acquiring independent walking, were videotaped while stepping on a treadmill at four belt speeds (0.1, 0.16, 0.22, and 0.28 m/s), with passive markers affixed to the major joints (shoulder, hip, knee, and ankle). The images were digitized and analyzed using the software programs Ariel Performance Analysis System, Matlab, and SPSS (Statistical Package for Social Sciences, v.10). The analyzed variables were the descriptive, temporal, coordinative, and angular characteristics of the treadmill-elicited steps at the four speeds. Results: At 0.22 and 0.28 m/s, stride velocity and duration increased, and the duration of the stance phase decreased at 0.22 m/s. Moreover, at 0.22 and 0.28 m/s, the knee joint range of motion increased. Conclusions: The moderate and high speeds seem to be more appropriate to elicit stepping in infants who are acquiring independent walking, with 0.22 m/s being the speed that seemed the most appropriate.
Article registered in the Australian New Zealand Clinical Trials Registry (ANZCTR) under number ACTRN12609000517279.

Key words: motor development; customized treadmill; steps; infants.

Resumo

Contextualização: A esteira motorizada desencadeia passadas em bebês similares ao andar. Entretanto, os efeitos da velocidade da esteira nas características das passadas desencadeadas por ela ainda são desconhecidos. Objetivo: Examinar o efeito da velocidade da esteira em passadas desencadeadas em bebês. Métodos: Seis bebês com desenvolvimento típico, com idades entre 11 e 13 meses, iniciando o andar independente, foram filmados andando na esteira em quatro velocidades (0,10; 0,16; 0,22 e 0,28 m/s), com marcas passivas posicionadas em suas principais articulações (ombro, quadril, joelho e tornozelo). As imagens foram digitalizadas e analisadas com os softwares *Ariel Performance Analysis System, Matlab* e *SPSS (Statistical Package for Social Sciences, v.10)*. As variáveis analisadas foram as características descritivas, temporais, coordenativas e angulares das passadas desencadeadas pela esteira nas quatro velocidades. Resultados: Em 0,22 e 0,28 m/s, ocorre aumento da velocidade e duração da passada, além de uma menor duração da fase de apoio (FA) na velocidade de 0,22 m/s. Nas velocidades de 0,22 e 0,28 m/s,observa-se aumento da amplitude articular do joelho. Conclusões: As velocidades moderadas e rápidas parecem ser as mais indicadas para desencadear passadas em bebês que estão iniciando o andar independente, sendo ainda que a velocidade de 0,22 m/s parece ser a mais apropriada.
Artigo registrado no Australian New Zealand Clinical Trials Registry (ANZCTR) sob o número ACTRN12609000517279.

Palavras-chave: desenvolvimento motor; esteira motorizada; passadas; bebês.

Received: 11/07/2009 – Revised: 17/01/2010 – Accepted: 01/06/2010

[1] Physical Therapist
[2] Department of Physical Education, Institute of Biosciences, Universidade Estadual Paulista (UNESP), Rio Claro (SP), Brazil
[3] Department of Health Sciences, Universidade Federal de São Paulo (UNIFESP), Santos (SP), Brazil
[4] Institute of Physical Activity and Sports Sciences, Universidade Cruzeiro do Sul, São Paulo (SP), Brazil
Correspondence to: José A. Barela, Universidade Cruzeiro do Sul, ICAFE, Rua Galvão Bueno, 868, CEP 01506-000, São Paulo (SP), Brasil, e-mail: jose.barela@cruzeirodosul.edu.br
* Paper presented as a poster at the 4th Brazilian Conference of Motor Behavior held in São Paulo in July 2008.

Introduction

Throughout the first year of life, infants exhibit lower limb movements that can be triggered in several ways and that are similar to gait movements, which will be acquired in a few months. For example, infants up to two months display a stepping reflex when held under their arms with their feet touching a flat surface. They move their legs in a coordinated and often alternated pattern[1-3], with coactivation of extensors and flexors[4] as in infants at 12 months of age[5]. Prior to the acquisition of independent walking, this pattern can be enhanced through interventions, leading to retention of the task by the infant and allowing the transition from reflex to functional action[6].

The stepping reflex, as we shall refer to it in the present study, drew the attention of several authors[6-8] because, despite being present in the repertoire of the newborn, these strides are no longer displayed by the infant after the first two months of age, only returning shortly before the acquisition of independent walking. The traditional explanation for this disappearance was that the involuntary strides of the initial months are controlled by the subcortical brain and, with the approach of the acquisition of voluntary control of independent walking, these strides become controlled by the cortical brain. During this transition, the manifestation of such behavior would be suppressed[6,8], and infants no longer displayed it.

Although consistent and accepted by many authors in the field, this explanation was questioned by Thelen, Fisher, and Ridley-Johnson[9]. Initially, it was observed that the suppression of the strides occurred concomitantly with a sudden gain in leg mass, mainly due to the accumulation of adipose tissue. These authors tested this hypothesis by immersing infants in water up to the armpits and found an increase in the number of steps and in stride length. Conversely, when weights proportional to the mass of the lower limbs were added to the infant's legs, the number of steps decreased[9]. Thus, it was suggested that the disappearance of the stepping reflex is due to abrupt body changes that occur during the initial months of life and not by the change in the control of these movements by the central nervous system[9-12]. Moreover, these steps were still present in the motor repertoire of infants but "hidden", and they could be triggered if environmental conditions were appropriately manipulated[13].

From this finding that the stepping reflex can be elucidated by "facilitating agents," Thelen[12] began to study the role of the motorized treadmill as a trigger of stepping in infants in the first year of life. In general, the main finding was that the motorized treadmill elicits stepping in infants, even when they are not displaying that reflex due to the increase in leg mass. Though triggered by the treadmill, these strides show characteristics similar to the voluntary pattern of gait[3,12,13].

A key feature of the effect of the treadmill on infant stepping is that the pattern of the elicited movement is stable and simultaneously sensitive and adaptable to changes imposed by the motorized treadmill[3,12,14]. As treadmill speed increases, infants are able to adjust stepping to maintain an alternating pattern, decreasing the step cycle duration and decreasing the absolute duration of the stance phase (SP)[3,12,15-17]. Adjustments were observed even under the most intense changes, as when stepping was triggered in seven-month-old infants by treadmill belts at different speeds for each leg (0.10 and 0.20 m/s)[15]. Surprisingly, stepping was adjusted to maintain an alternating pattern: the leg in contact with the fast belt had shorter cycle duration, decreasing the SP, and the leg in contact with the slow belt had a proportionately increased SP[15].

Despite these findings, there is no standard for the use of motorized treadmills, especially regarding belt speed. Thus, the question that arises is: what would be the most appropriate belt speed to trigger stepping in infants? Such information would be of extreme importance, given that stepping is sensitive to the characteristics of the treadmill and very high or very low speeds could change both the number and characteristics of the steps elicited in the infants. Therefore, the aim of the present study was to investigate the effect of treadmill belt speed on the characteristics of infant stepping.

Methods

Participants

Six normally developing infants (two female and four male) aged between 11 and 13 months (mean 12 months and 13 days) participated in this cross-sectional study. They were starting to walk independently, but only with support. The selection of participants was by convenience and occurred by contact with friends and relatives. All procedures involved in this study were approved by the Research Ethics Committee of the Biosciences Institute, Universidade Estadual Paulista (Unesp), Rio Claro Campus (CEP-IB-Unesp), Rio Claro, SP, Brazil, protocol number

179/2007. Before infant participation, a consent form was signed by the guardian.

Procedures

The infants, accompanied by their parents, attended the laboratory once and, after an initial period of adaptation to the environment, the parents were asked to undress the infants, leaving only the diaper. Initially, spherical reflective markers (12 mm in diameter) were attached to the 5th metatarsal, lateral malleolus, lateral femoral epicondyle, greater trochanter of the femur and acromion of the infant's left side (Figure 1A).

After the markers were attached, infants were placed on a motorized treadmill specially adapted so that its speed could be controlled by a digital control. Infants wore a special harness coupled to a system of partial weight suspension (Figure 1B). This system provided postural stability to the infant so that it remained in a standing position with feet touching the treadmill surface. The relief of body weight brought by this system was minimal and similar to that provided in previous studies, when infants were held around the trunk by a researcher[12,15,16,18-28]. However, the intention was not to relieve the weight on the lower limbs.

A digital camera (Panasonic, Model AG-DVC7P) was positioned in the central region, sagittally and 4 m away from the treadmill, to allow filming during the performance of stepping on the treadmill, which was positioned within a calibrated area 1m long and 1m high, needed for the two-dimensional stride analysis. Behind the camera, a 300 W spotlight was positioned for optimal viewing of the reflective markers attached to the infant. The treadmill was adjusted so that the belt ran at speeds of 0.10, 0.16, 0.22, and 0.28 m/s, based on previous studies that used different speeds[12,15,18,21,24] . The infants were exposed to each speed for 1 min in random order. If necessary, intervals were allowed between trials.

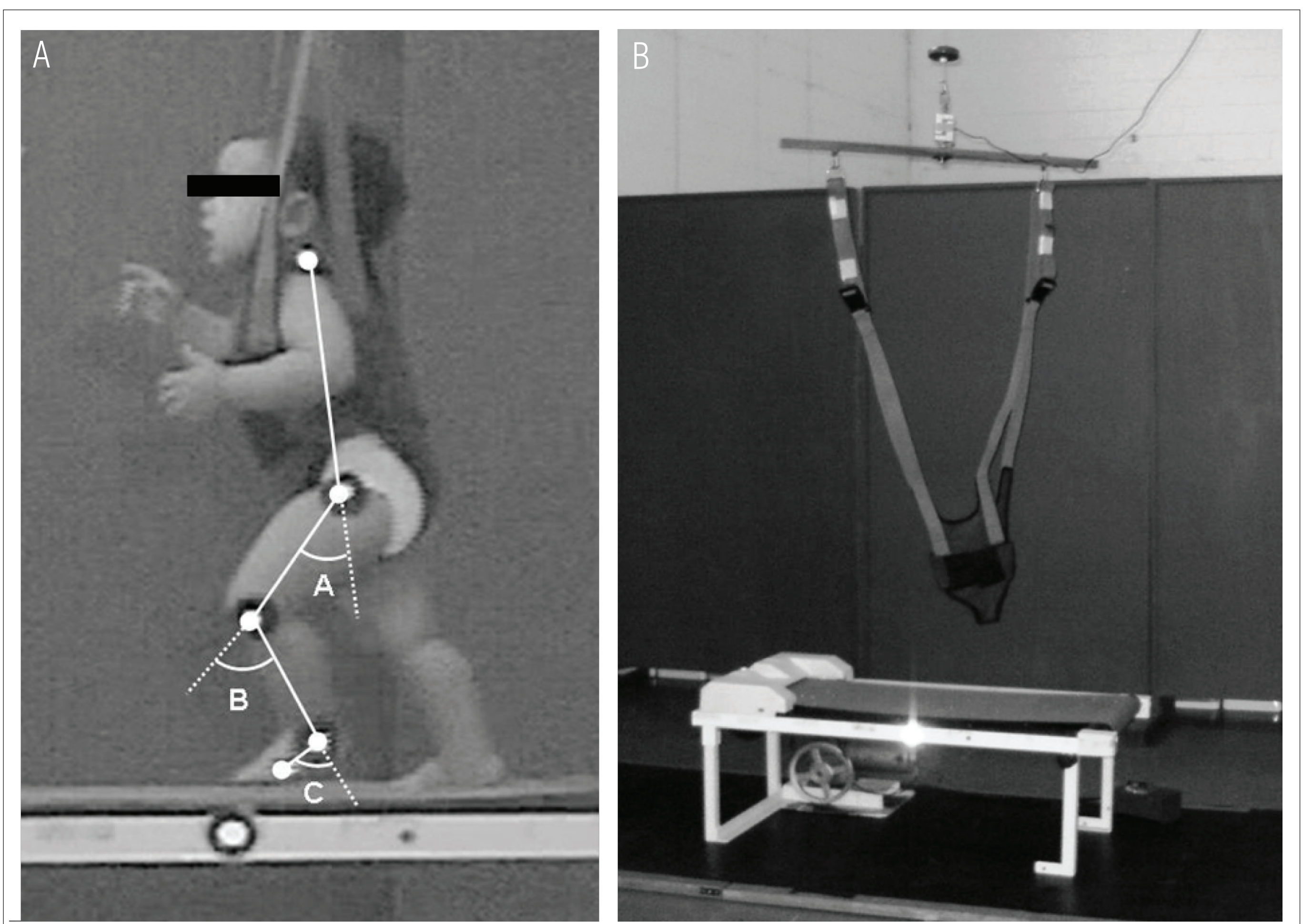


Figure 1. Picture of an infant on the treadmill with the markers on the joint centers and convention used to define the ankle, knee, and hip angles (A); photo of the treadmill, harness, and body weight support system (B).

Data decoding

After videotaping, three alternating strides at each speed were selected for digitizing. They were chosen considering the visualization of the markers and the performance of "natural" strides without any interruption or sudden movements. The joint markers of the selected strides were digitized by the software program Ariel Performance Analysis System (APAS®) to obtain the coordinates "x" and "y" for each marker. During the digitizing, the occurrence of the following events were identified: touch of the ipsilateral foot (TIF), touch of the contralateral foot (TCF), ipsilateral loss of contact (ILC) and contralateral loss of contact (CLC). In this case, the stride was defined as the period between the occurrence of two consecutive TIFs.

Based on this and on coordinates obtained from the digitizing process, the following stride descriptive variables were calculated: a) stride length, obtained by the difference in the position of the lateral malleolus in the sagittal plane between two consecutive TIFs, given in meters; b) stride duration, obtained by the time between two consecutive TIFs, given in seconds; c) cadence, obtained by the number of strides per second (strides/s); d) stride velocity, obtained by the ratio of stride length to stride duration in meters per second (m/s). Based on the occurrence of these events, the duration of the following temporal variables of the stride were obtained: a) SP, obtained by the time between the TIF and ILC; b) first double support (DS1), obtained by the time between the TIF and the CLC; c) single support (SS), obtained by the time between the CLC and the TCF; d) second double support (DS2), obtained by the time between the TCF and ILC. All those times were normalized in relation to the total duration of the respective stride, and therefore these variables were expressed as percentage of total stride duration. The relative phase between lower limbs, indicating the coordination between them, was calculated by the ratio of TIF-TCF interval to total stride duration. This variable was also normalized in relation to the total stride duration.

Finally, based on digitized coordinates, the complementary joint angles of the hip, knee, and ankle were calculated by the APAS® software program by means of the tangent arc of the vectors formed by adjacent segments. The convention for the calculation of these angles is shown in Figure 1A. After the angles for each trial were obtained, they were normalized in relation to the total stride duration, with an increase of 1%, using a specific Matlab® routine (MathWorks, Inc. - version 6.5). After this procedure, the mean angle for each infant at each speed and the mean for all infants at each speed were calculated. Hip, knee, and ankle range of motion for the SP were calculated by subtracting the smallest angular value from the greatest angular value in the respective temporal series.

Statistical analysis

For statistical analysis, three multivariate analyses (MANOVA) and two analyses of variance (ANOVA) were used, and in both cases, the four speeds were treated as repeated measures factor. In the first MANOVA, the dependent variables were the descriptive variables of the stride: length, duration, cadence, and velocity. In the second MANOVA, the dependent variables were the duration of DS1, SS, and DS2. In the third MANOVA, the dependent variables were the range of motion of the hip, knee, and ankle. In the first ANOVA, the dependent variable was the SP duration, and in the second, the relative phase. Univariate analysis and Tukey's post hoc tests were performed for the variables stride velocity, stride length, and SP duration. All statistical analyses were performed using SPSS (Statistical Package for Social Sciences for Windows®, version 10.0). In all analyses, the significance level was set at 0.05.

Results

As expected, the motorized treadmill triggered alternated stepping in all infants in the study. With the aim of distinguishing the alternated strides, the descriptive, temporal, coordinative, and angular characteristics are shown below.

Descriptive characteristics of alternated stepping

The MANOVA revealed differences between the descriptive variables of stride (Wilks' Lambda = 0.205, $F_{[12,32]} = 2.18$, $p<0.05$). However, univariate tests indicated a difference only for stride velocity ($F_{[3,15]} = 8.875$, $p<0.005$) and marginality for stride duration ($F_{[3,15]} = 3.105$, $p=0.05$). Post hoc tests indicated that stride velocity at 0.22 and 0.28 m/s belt speed was greater than at 0.10 m/s and also that the stride velocity at 0.22 m/s belt speed was greater than at 0.16 m/s. Post hoc tests indicated that stride duration at 0.10 m/s belt speed was greater than at 0.22 m/s (Table 1).

Temporal characteristics of alternated stepping

ANOVA revealed a significant difference in SP percentage at the different treadmill speeds ($F_{[3,15]} = 3.303$, $p<0.05$). Post hoc tests indicated that the SP duration at 0.22 m/s was shorter than at 0.10 m/s (Figure 2A).

Table 1. Mean and standard deviation of stride length, duration, cadence, and velocity at the four treadmill belt speeds.

Descriptive Variables	0.10 m/s	0.16 m/s	0.22 m/s	0.28 m/s
Stride length (m)	0.28 (0.09)	0.33 (0.07)	0.35 (0.03)	0.30 (0.06)
Stride duration (s)	1.71 (0.75)a	1.54 (0.66)	1.20 (0.30)a	1.21 (0.32)
Stride cadence (stride/s)	0.73 (0.44)	0.78 (0.38)	0.91 (0.33)	0.88 (0.32)
Stride velocity (m/s)	0.19 (0.12)b,c	0.24 (0.12)d	0.33 (0.15)b,d	0.28 (0.12)c

Same letters indicate statistical difference between belt speeds (p<0.05).

Table 2. Mean and standard deviation of joint displacement (degrees) of ankle, knee, and hip during stance on treadmill at 0.10, 0.16, 0.22, and 0.28 m/s belt speeds.

	0.10 m/s	0.16 m/s	0.22 m/s	0.28 m/s
Ankle	12.47 (3.67)	14.74 (3.80)	15.37 (3.78)	14.81 (9.86)
Knee	12.34 (4.81)a,c	11.84 (4.34)b,d	24.59 (8.42)a,b	22.82 (7.32)c,d
Hip	14.12 (6.25)	19.81 (7.68)	19.65 (7.41)	16.92 (5.42)

Same letters indicate statistical difference between belt speeds (p<0.05).

Regarding the stance subphases, MANOVA showed no difference in the duration of DS1, SS, and DS2 at the different belt speeds (Wilks' Lambda = 0.342, F [9,32] = 1.95, p=0.07; Figure 2B).

Coordenative characteristics of alternated stepping

ANOVA showed no difference for the coordination between legs at the different belt speeds (F [3,15] = 1.04, p>0.05; Figure 2C).

Angular characteristics of alternated stepping

Figure 3 shows the angular displacement of the ankle, knee, and hip joints during alternated stepping. As can be seen, in the initial touch of the foot and during the SP, the ankle is at an angle of about 50 degrees. Considering the convention used to calculate the ankle angle, this value indicates full support of the foot on the ground. That fact is expected because infants acquiring independent walk place the whole foot on the floor at the initial touch.

Regarding the knee, the 0.22 and 0.28 m/s belt speeds clearly triggered patterns with a well-defined peak of flexion during the swing phase. At slower belt speeds (0.10 and 0.16 m/s), this definition was not as clear, and the temporal series of knee angle showed variations during the entire step cycle. Finally, the temporal series of the hip joint shows that this joint showed variations due to belt speed similar to those observed for the knee joint.

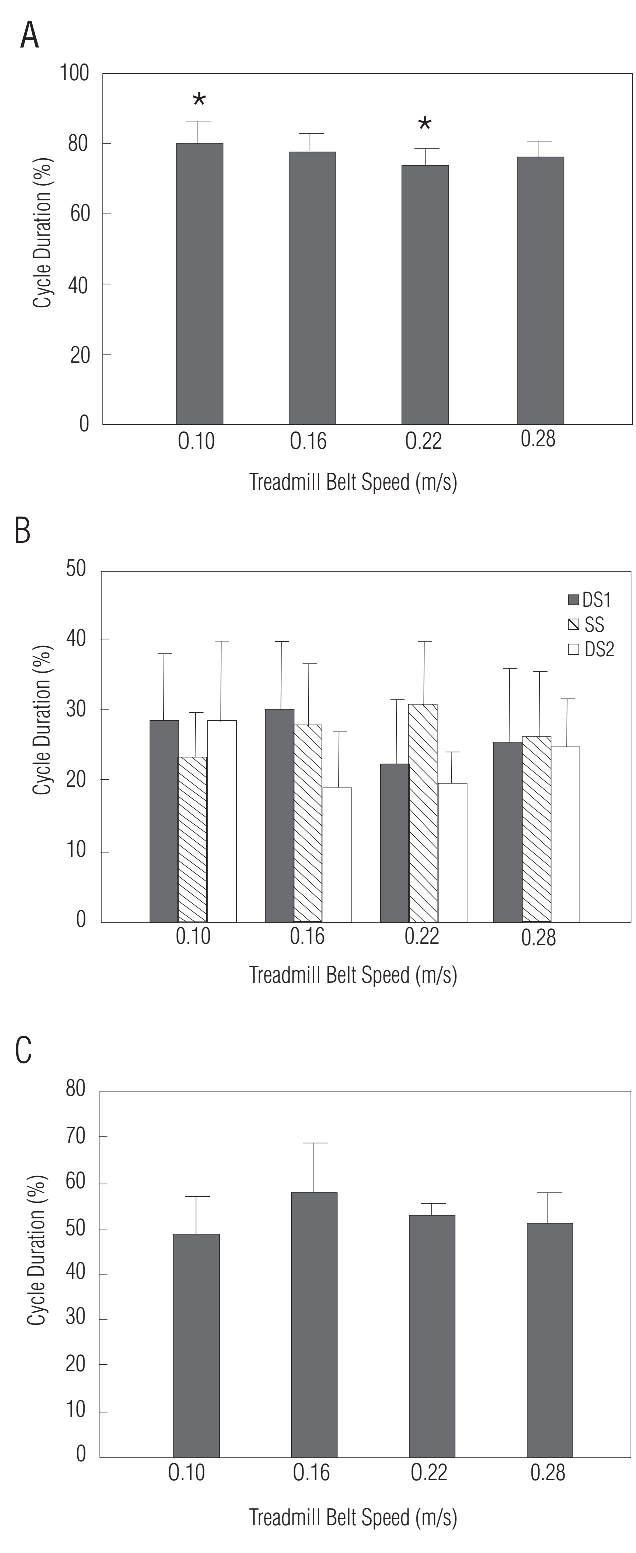
Table 2 shows the range of motion at the different belt speeds for the hip, knee, and ankle joints. MANOVA revealed that the range of motion was different between the belt speeds (Wilks' Lambda = 0.238, F [9,32] = 2.836, p<0.005). Univariate analysis indicated that only the knee range of motion was influenced by speed manipulation (F [3,15] = 9.227, p<0.005), and the range of motion of this joint was greater at 0.22 and 0.28 m/s than at 0.10 and 0.16 m/s.

Discussion

In the present study, infants were supported over a motorized treadmill in order to identify the most suitable belt speed to elicit alternated stepping through the analysis of descriptive, temporal, coordinative, and angular stride characteristics. The motorized treadmill can be used to elicit alternated stepping in infants who are not walking independently. Considering the results of the present study, the four speed parameters were able to trigger alternated stepping in infants. The alternating pattern is their preferred pattern, and its frequency improves with age[12] and training[23], especially during moderate and high belt speeds[12,23].

By analyzing the characteristics of alternated stepping, we noted that the higher belt speeds led to faster strides, and the 0.22 m/s belt speed elicited shorter stride and SP duration than the 0.10 m/s belt speed. Moreover, 0.22 and 0.28 m/s led to increased peak of knee flexion compared with other belt speeds, and the knee range of motion was greater at these two speeds than those observed at lower belt speeds. Thus, the results suggest that the higher speeds favor an appropriate alternated stepping pattern for infants in the acquisition phase of independent walking.

In the study by Thelen[12], normally developing seven-month-old infants were supported over a treadmill at two speeds, slow (0.10 m/s) and fast (0.19 m/s). The results showed that the treadmill elicited the alternating movements of the lower limbs and that there was an increase in the number of steps



* indicates statistical difference between treadmill belt speeds (p<0.05).

Figure 2. Temporal and coordinative characteristics of stepping at the four treadmill speeds: (A) mean and standard deviation of the stance phase in percentage of the cycle; (B) mean and standard deviation of the first double support (DS1), single support (SS), and second double support (DS2) phases; (C) mean and standard deviation of the relative phase between the lower limbs.

at the higher speed. The infants' response to increased speed led to a decrease in the time of foot contact on the SP and a slight decrease in the swing phase. In the present study, similar results were seen in infants who had a decrease in SP with increasing belt speed.

According to Ferreira and Barela[18], the preferred step pattern of children with cerebral palsy (CP) at a 0.29 m/s treadmill speed is the alternating pattern. The durations of the SP and the swing phase were 60-70% and 30-40% of the step cycle, respectively. Regarding the duration of the DS1, SS, and DS2 subphases, the values were 18%, 31%, and 17.5%, respectively[18]. Comparatively, in the present study, at different speeds, the SP ranged between 71.8% and 79.9% of the step cycle, but without indication of significant difference between different speeds, and the behavior of the stance subphases showed no significant differences between the different belt speeds. One explanation for this lack of difference is the ability of the infants to adapt the step behavior to maintain an alternating pattern, regardless of the speed[15]. Interestingly, the coordination between legs observed in the present study was similar to the pattern shown by infants and children walking on the ground and on the treadmill, respectively[18,29], which was around 50%.

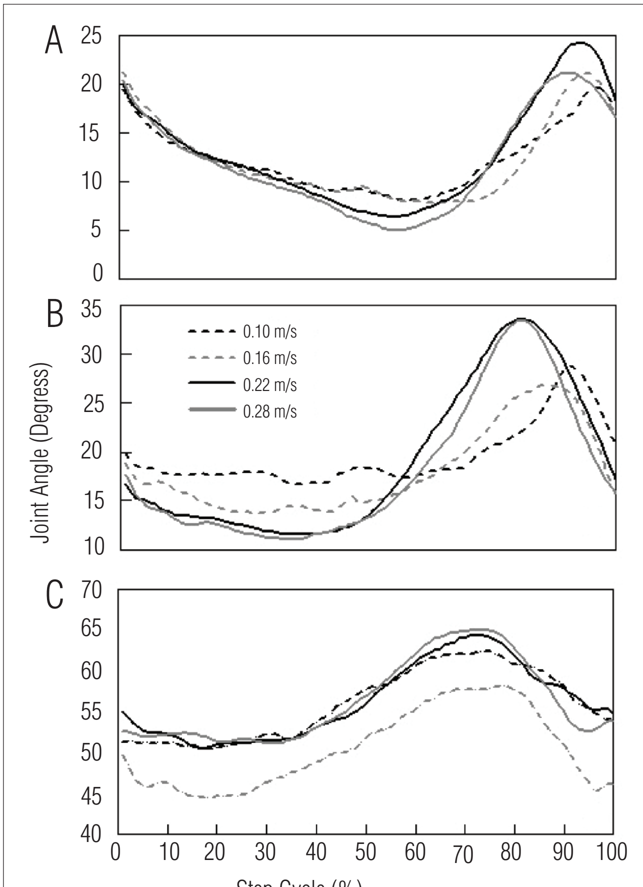


Figure 3. Time series of the mean hip (A), knee (B), and ankle (C) joint angles throughout the step cycle at the four treadmill belt speeds.

Moreover, this pattern does not change with the variation of belt speed, thus constituting an organization that is stable to such manipulation.

Despite this similarity in the temporal organization, the results of the present study clearly indicate that the belt speed of 0.22 m/s elicits different stride velocity and duration compared to lower belt speeds. Although stride velocity and duration were not statistically different at 0.22 and 0.28 m/s, there is a tendency for reduction in both at the highest speed. Thus, considering the lack of effect on the temporal stride characteristics in relation to the belt speed and this effect on the stride velocity and duration at 0.22 m/s, it seems that this would be the ideal speed to elicit infant stepping that is closer to the voluntary overground pattern of infants who are acquiring independent walk, with a mean speed around 0.6 m/s[30], taking into account differences between overground and treadmill walking[31].

This suggestion is corroborated when we observe the temporal series of lower limb joints during stepping. The alternating steps carried out by infants at the higher belt speeds (0.22 and 0.28 m/s) are characterized by trajectories of movements with a clearer definition of the main peaks that characterize voluntary overground stepping. This finding indicates greater range of joint motion during stepping. According to Yaguramaki and Kimura[32], the increase in joint range of motion influences the increase in stride velocity, which produces a more efficient gait. It may be that young infants prefer slower belt speeds because they have difficulty in contracting the muscles properly. However, older infants prefer moderate belt speeds of around 0.20 m/s[33], and the data from the present study undoubtedly confirm this suggestion. Moreover, the speed cannot be too high otherwise stepping may be compromised and may not show an appropriate response to increasing belt speed, as seems to be the case or at least a tendency regarding the speed of 0.28 m/s, as observed here.

The present study had some limitations due to the small number of participants evaluated. Therefore, more effort should be made to carry out new studies to verify the possible effects of treadmill characteristics not only on elicited stepping patterns, but mainly on the use of this intervention to promote and facilitate gait acquisition in infants with or without neuromuscular and/or sensory and motor impairment.

Conclusion

Belt speeds of around 0.22 to 0.28 m/s seem to be the ideal speeds to trigger stepping in infants who are acquiring independent walk. They elicit stepping with characteristics similar to those observed in the stepping patterns of infants who are acquiring independent walking. However, the results of the present study also indicate that the speed of 0.28 m/s seems to compromise the quality of stepping, therefore it is safer to use the 0.22 m/s belt speed.

Acknowledgements

To Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP) for funding the master's scholarship of the first author (process 07/53131-4).

References

1. Thelen E, Fisher DM, Ridley-Johnson R, Griffin NJ. Effects of body build and arousal on newborn-infant stepping. Dev Psychobiol. 1982;15(5):447-53.
2. Thelen E. Learning to walk: Ecological demands and phylogenetic constraints. In: Lpsitt LP, Rovee-Collier C, editors. Advances in infancy research. 3ª ed. Norwood, NJ: Ablex; 1984. p. 213-50.
3. Ulrich BD, Jensen JL, Thelen E. Stability and variation in the development of infant stepping: Implications for control. In: Patla AE, editor. Adaptability of human gait implications for the control of locomotion: Elservier Science; 1991. p. 145-61.
4. Chang CL, Kubo M, Buzzi U, Ulrich B. Early changes in muscle activation patterns of toddlers during walking. Infant Behav Dev. 2006;29(2):175-88.
5. Chagas PS, Mancini MC, Fonseca ST, Soares TB, Gomes VP, Sampaio RF. Neuromuscular mechanisms and anthropometric modifications in the initial stages of independent gait. Gait Posture. 2006;24(3):375-81.
6. Zelazo PR, Zelazo NA, Kolb S. "Walking" in the newborn. Science. 1972;176(4032):314-5.
7. Thelen E. Learning to walk is still an "old" problem: a reply to Zelazo (1983). J Mot Behav. 1983;15(2):139-61.
8. McGraw MB. The neuromuscular maturation of the human infant. New York, NY: Hafner; 1949.
9. Thelen E, Fisher DM, Ridley-Johnson R. The relationship between physical growth and a newborn reflex. Infant Behav Dev. 1984;7(4):479-93.
10. Ulrich BD. Development of stepping patterns in human infants: a dynamical systems perspective. J Mot Behav. 1989;21(4):392-408.
11. Thelen E, Fisher DM. Newborn stepping: An Explanation for a "disappearing" reflex. Dev Psychol. 1982;18(5):760-75.
12. Thelen E. Treadmill-elicited stepping in seven-month-old infants. Child Dev. 1986;57(6):1498-506.
13. Thelen E, Ulrich BD. Hidden skills: a dynamic systems analysis of treadmill stepping during the first year. Monogr Soc Res Child Dev. 1991;56(1):1-98; discussion 9-104.
14. Ulrich BD, Ulrich DA. Dynamic systems approach to understanding motor delay in infants with Down Syndrome. In: Savelsbergh GJP, editor. The development of coordination in infancy. North-Holland: Elsevier Science Publishers B.V.; 1993. p. 445-59.
15. Thelen E, Ulrich BD, Niles D. Bilateral coordination in humam infants: stepping on a split-belt treadmill. J Exp Psychol Human Percept Perform. 1987;13(3):405-10.
16. Ulrich BD, Ulrich DA, Angulo-Kinzler RM. The impact of context manipulations on movement patterns during a transition period. Hum Mov Sci. 1998;17(3):327-46.

17. Thelen E, Skala KD, Kelso JAS. The dynamic nature of early coordination: Evidence from bilateral leg movements in young infants. Dev Psychol. 1987;23(2):179-86.

18. Ferreira JN, Barela JA. Passadas desencadeadas por esteira rolante em crianças portadoras de paralisia cerebral. Revista da SOBAMA. 2000;5(1):39-44.

19. Wu J, Looper JE, Ulrich BD, Ulrich DA, Angulo-Barroso RM. Exploring effects of different treadmill interventions on walking onset and gait patterns in infants with Down syndrome. Dev Med Child Neurol. 2007;49(11):839-45.

20. Angulo-Barroso RM, Wu J, Ulrich DA. Long-term efect of different treadmill interventions on gait development in new walkers with Down syndrome. Gait Posture. 2008;27(2):231-8.

21. Davis DW, Thelen E, Keck J. Treadmill stepping in infants born prematurely. Early Hum Dev. 1994;39(3):211-23.

22. Jensen JL, Schneider K, Ulrich BD, Zernicke RF, Thelen E. Adaptive dynamics of the leg movement patterns of human infants: II. Treadmill stepping in infants and adults. J Mot Behav. 1994; 26(4): 313-24.

23. Vereijken B, Thelen E. Training infant treadmill stepping: the role of individual pattern stability. Dev Psychobiol. 1997;30(2):89-102.

24. Ulrich DA, Ulrich BD, Angulo-Kinzler RM, Yun J. Treadmill training of infants with Down syndrome: evidence-based developmental outcomes. Pediatrics. 2001;108(5):E84.

25. Bodkin AW, Baxter RS, Heriza CB. Treadmill training for an infant born preterm with a grade III intraventricular hemorrhage. Phys Ther. 2003;83(12):1107-18.

26. Ulrich DA, Lloyd MC, Tiernan CW, Looper JE, Angulo-Barroso RM. Effects of intensity of treadmill training on developmental outcomes and stepping in infants with Down syndrome: a randomized trial. Phys Ther. 2008;88(1):114-22.

27. Wu J, Ulrich DA, Looper J, Tiernan CW, Angulo-Barroso RM. Strategy adoption and locomotor adjustment in obstacle clearance of newly walking toddlers with Down syndrome after different treadmill interventions. Exp Brain Res. 2008;186(2):261-72.

28. Angulo-Barroso R, Burghardt AR, Lloyd M, Ulrich DA. Physical activity in infants with Down syndrome receiving a treadmill intervention. Infant Behav Dev. 2008;31(2):255-69.

29. Clark JE, Phillips SJ. A longitudinal study of intralimb coordination in the first year of independent walking: A dynamical systems analysis. Child Dev. 1993;64(4):1143-57.

30. Sutherland DH, Olshen R, Cooper L, Woo SL. The development of mature gait. J Bone Joint Surg Am. 1980;62(3):336-53.

31. Stolze H, Kuhtz-Buschbeck JP, Mondwurf C, Boczek-Funcke A, Jöhnk K, Deuschl G, et al. Gait analysis during treadmill and overground locomotion in children and adults. Electroencephalogr Clin Neurophysiol. 1997;105(6):490-7.

32. Yaguramaki N, Kimura T. Acquirement of stability and mobility in infant gait. Gait Posture. 2002;16(1):69-77.

33. Yang JF, Stephens MJ, Vishram R. Infant stepping: a method to study the sensory control of human walking. J Physiol. 1998;507(Pt 3):927-37.