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The effect of treadmill walking on the stride interval dynamics of children

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ABSTRACT

Treadmills are commonly implemented in rehabilitation and laboratory settings to facilitate gait analysis and training. However, while this locomotor modality is often used with children, its effect on pediatric stride interval dynamics is unknown. This study investigated the stride interval persistence of 30 asymptomatic children after completion of three to six 10-min walking trials comprised of: (i) overground walking (OW), (ii) unsupported treadmill walking (UTW), and (iii) handrail-supported treadmill walking (STW). The primary outcome measure was α, a quantifier of stride interval persistence obtained from detrended fluctuation analysis. Preferred walking speed, number of strides taken, stride interval duration, and stride interval coefficient of variation were also assessed. Stride interval persistence was significantly diminished during both treadmill walking conditions, compared to overground walking, with the largest decrease in α during UTW. Preferred speed, number of strides, and stride interval duration also differed between overground and treadmill walking, and older children demonstrated reduced stride interval variability compared to younger children. The observed treadmill and age effects on stride parameters may be due to a combination of differing locomotor constraints between overground and treadmill walking and developmental differences in sensory processing, cerebellar plasticity, and corticospinal involvement in locomotion.

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1. Introduction

Close examination of the human stride interval, the time between consecutive heel strikes of the same foot, reveals complex fluctuations that are correlated over hundreds of strides (Delignières & Torre, 2009; Hausdorff, Peng, Ladin, Wei, & Goldberger, 1995). However, the mechanisms responsible for this stride interval persistence remain unclear. Current locomotor theories suggest that the most basic moving rhythms are achieved by specialized neural networks in the spinal cord, with higher neural centers playing an important role in locomotor control as well (Dietz, 2003; Forssberg, 1999).

Investigation of stride interval persistence among different populations has revealed diminished correlation with advanced aging and in the presence of certain neuromuscular pathologies (Chau & Rizvi, 2002; Hausdorff et al., 1997, 2000). Within a cohort of individuals with higher-level gait disorder, these dynamics provided the only distinguishing feature among fallers and non-fallers (Herman, Giladi, Gurevich, & Hausdorff, 2005). Furthermore, when walking is paced to a metronome, stride interval dynamics demonstrates anti-persistent fluctuations as opposed to the persistent behavior typical of regular overground walking (Delignières & Torre, 2009). Given that stride dynamics has shown these sensitivities to locomotor maturity, disfunction and constraint, quantification of stride interval persistence seemingly provides important insight into the central mechanisms driving human locomotor control.

The finding of altered stride interval dynamics during metronomic walking (i.e., walking at a step frequency dictated by the constant beat of a metronome) raises some concern within rehabilitation and scientific communities, where treadmills are commonly implemented to promote restoration of gait function (Damiano & DeJong, 2009; Hesse, 2008; Kurtais, Kutlay, Tur, Gok, & Akbostanci, 2008) and to facilitate gait analysis and training (Marsh et al., 2006; Siler, Jorgensen, & Norris, 1997). Although treadmill walking does not impose the same constraint on stride interval duration as metronomic walking, both locomotor modalities enforce a tempo constraint. Specifically, treadmill walking necessitates maintenance of the average speed dictated by the treadmill belt, while allowing for some fluctuation in stride frequency, duration and length. Considering the significant effect of metronomically-constrained gait on stride interval persistence, it is also imperative to study the effect of treadmill walking, another gait-constraining modality, on the persistence of stride interval time series.

Recently, Chang, Shaikh, and Chau (2009) suggested that the afferent influences of treadmill walking on the locomotor control system are distinctly different from those of metronomic walking, after treadmill walking was not found to significantly alter the stride interval persistence of healthy young adults. Nonetheless, it would be naïve to assume that the same is true for children. To date, a single study has quantified the stride interval persistence of a pediatric population, identifying greater complexity in their stride-to-stride fluctuations when compared to those of adults (Hausdorff, Zemany, Peng, & Goldberger, 1999). It is suggested that these elevated dynamics reflects a less mature locomotor control system (Hausdorff et al., 1999). Indeed, there is considerable evidence to suggest that neuromaturation and locomotor development continues well beyond the age of three (Assaiante, 1998; Barnea-Goraly et al., 2005; Beck, Andriacchi, Kuo, Fermier, & Galante, 1981; Dusing & Thorpe, 2007; Forssberg, 1999), at which time a seemingly coherent locomotor pattern is produced (Hausdorff et al., 1999). As such, while the stride interval dynamics of adults appears robust to treadmill walking, it is conceivable that pediatric stride dynamics may be more susceptible to the external influences presented by this locomotor modality.

From a rehabilitation perspective, a treatment regime that fails to promote (or at the very least preserve) a certain extent of stride interval complexity, would seem to oppose the natural neuromuscular rhythms of healthy human gait. Given that many emerging rehabilitation techniques make use of treadmills to train children (Cherng, Liu, Lau, & Hong, 2007; Damiano & DeJong, 2009; Dodd & Foley, 2007), our primary research objective was to investigate the implication of treadmill walking, both with and without handrail support, on the natural stride interval dynamics of children. Additionally, other gait parameters typically provided in the gait literature (e.g., Hausdorff et al., 1996, 1999; Herman et al., 2005), were extracted for comparison purposes.

We hypothesized that locomotor constraints including the constant average speed requirement (Dingwell, Cusumano, Cavanagh, & Sternad, 2001) and static visual flow (Prokop, Schubert, & Berger, 1997) imposed by treadmill walking, would diminish the strength of statistical persistence observed in pediatric stride interval time series. We further expected that implementation of handrail support would enhance sensory feedback, providing additional cues to facilitate locomotor control (Dickstein & Laufer, 2004), and thus compensate for the reduced visual input. Therefore, we expected the handrail-supported treadmill walking condition to restore the strength of statistical persistence observed in stride interval time series toward values measured during overground walking.

2. Methodology

2.1. Data acquisition

2.1.1. Participants

A total of 31 children were recruited through the staff and community programs at Bloorview Kids Rehab (located in Toronto, Ontario, Canada). Data from one subject were discarded due to technical difficulties with gas exchange measurement, which is part of a secondary investigation reported elsewhere (Fairley, Sejdić, & Chau, 2010). Of the remaining 30 children (11 male) forming the sample for this analysis, mean age was 7.1 ± 1.6 years (range: 4–10 years), height was 1.249 ± 0.115 m, and body mass was 24.1 ± 4.9 kg. Participants were asymptomatic, with normal or corrected-to-normal vision and no history of orthopedic, neurological, respiratory, or cardiovascular illness. The study was approved by the institutional research ethics board and all subjects and their care-givers provided informed, written assent and consent, respectively.

2.1.2. Experimental protocol

Each subject participated in one study session, completing a minimum of three, 10-min walking trials, under the following conditions: (i) overground walking (OW), (ii) unsupported (hands-free) treadmill walking (UTW), and (iii) supported treadmill walking (STW). Condition sequences were pseudo-randomized, ensuring that each of the six possible sequences was completed every six participants. A random subset of subjects repeated at least one of the walking trials (immediately following the same study session), while wearing only a portion of the measurement equipment. These repeat trials were carried out to determine if the additional metabolic equipment donned by subjects had an effect on the primary outcome measure (stride interval persistence). The three initial walking trials completed by all 30 subjects are herein referred to as the primary walking trials, while additional trials are referred to as the repeat walking trials.

At the outset of a study session, the subject was introduced to the protocol and outfitted with the measurement equipment. Pre-exercise resting heart rate was then recorded at 1-min intervals, with the subject resting in a seated position, long enough to obtain steady-state readings for at least three minutes. Steady-state heart rates were identified when consecutive (1 min apart) readings differed by less than 5 beats/min (Siconolfi, Cullinane, Carleton, & Thompson, 1982).

After this initial rest period, the subject was given at least 5 min to become familiar with treadmill walking and the measurement equipment. Handrail height was adjusted such that the base of the cylindrical side-rails was located at the level of the subject's radial styloid process, while he or she stood on the treadmill with arms relaxed at his or her sides. The subject walked until the investigator visually identified gait to appear natural and until the subject reported feeling comfortable with the setup. Following the equipment familiarization period and between each walking trial, to mitigate the effects of fatigue, subjects rested for at least 7 min and long enough to ensure that heart rate had returned to within the pre-exercise resting range.

Prior to handrail-supported treadmill walking trials, subject's were instructed to "keep [his or her] hands on the rails for the entire 10 min of walking". If the subject lost hand contact with either rail during the trial, he or she was reminded to "please put [his or her] hand(s) back on the rail(s)". For all trials, subjects were instructed to walk at their comfortable speed as if "walking to school" or "going for a walk in the park". Comfortable treadmill speeds were determined immediately prior to each treadmill walking trial. Initially, the subject walked on the treadmill (GK200T, Mobility Research, USA) at a relatively slow speed. The speed was then increased in 0.1 mph increments until the subject reported that his or her comfortable speed had been reached. Subsequently, the speed was increased by at least 0.5 mph and to the extent that the subject was pressed to maintain a walk. The speed was then decreased in 0.1 mph increments until the subject once again reported that his or her comfortable walking speed had been reached. This procedure was repeated and the mean of the four reported walking speeds was taken as the comfortable speed for that particular treadmill walking trial. For overground walking trials, subjects completed a single lap warm-up immediately prior to the trial, to ensure that he or she was familiar with the route and thus facilitate maintenance of a comfortable pace. The overground route consisted of a rectangular circuit (total length = 84.4 m), through a level, linoleum-floored hallway (width = 2.43 m). Lap times were recorded using a stopwatch to allow for subsequent calculation of the subject's comfortable overground walking speed. This speed was taken as the average of completed lap speeds, where lap speed was estimated by dividing lap distance by the time required for lap completion.

2.1.3. Measurement equipment

Subjects wore an adjustable waist harness which, during treadmill walking trials only, was loosely attached to an overhead bar via safety belts (LGJr200, Mobility Research, USA). The belts did not impede arm swing and subjects remained fully weight-bearing throughout the trials.

During all walking trials, heel strike was recorded bilaterally via two force-sensitive resistors (Model 406, Interlink Electronics, USA). These paper-thin sensors were fastened, one each, to the sole of the subject's shoes underneath the heel and produced a change in voltage upon heel strike. This voltage signal was sampled at 250 Hz and recorded to a data acquisition card (CF-6004, National Instruments, USA), housed in a personal digital assistant (Axim x51v, Dell, USA) that was secured via the waist harness to the subject's abdomen.

A heart rate transmitter (WearLink 31, Polar Electro, Finland) was also worn by subjects throughout the study session and a portable system for pulmonary gas exchange measurement ($K4b^2$, Cosmed, Italy) was donned during the three primary walking trials only. The $K4b^2$ system included a face mask, flow meter, data collection unit, battery, and associated cables. The battery and data collection unit were secured to the waist harness on the subject's back.

To monitor handrail contact during supported treadmill walking trials, each treadmill handrail was instrumented with 14 force-sensitive resistors (Model 408, Interlink Electronics, USA). Sensors were oriented lengthwise and fastened around the cylindrical side-handrails in two layers of seven such that the active area of the sensors did not overlap. Handrails were slightly tapered, with circumferential dead-space reaching a maximum of approximately 2.8 cm at the end of the rail (toward the back of the treadmill) and a minimum of 2.1 cm toward the front. Contact with each force-sensitive resistor was reflected as a change in voltage. These 28 voltage signals were simultaneously sampled at 1 kHz, recorded to a data acquisition card (USB-6210, National Instruments, USA) and stored in a personal computer for subsequent analysis. Measurement of handrail and heel strike contact was commenced simultaneously and recorded in parallel throughout the duration of all treadmill trials.

The total mass of the equipment worn by subjects was 2.5 kg during the primary walking trials and 1.4 kg during repeat walking trials (without the $K4b^2$ system). The experimental setup, showing the equipment worn by subjects during each primary walking trial, is depicted in Fig. 1.

2.2. Data analysis

2.2.1. Stride interval extraction

Prior to the extraction of stride intervals from heel strike data, gait signals were manually trimmed in order to remove the extraneous portions of the recordings, obtained immediately before the initiation and after the termination of gait. The first 10 s of data were then removed in order to ensure the subject had finished accelerating from rest and the subsequent 10 min of walking data were used in the analysis. For stride extraction, the signal was converted into a step function of ones and zeroes denoting possible heel off and heel contact events, respectively.

Stride intervals were extracted based on a stride interval extraction algorithm adapted from Chau and Rizvi (2002). Depending on the cadence of the subject, between 446 and 706 strides comprised each walking trial. In total, 180 stride interval time series were obtained from the three primary trials (30 participants × 3 conditions × 2 sides) and 60 were obtained from the repeat trials (13 from OW, 7 from UTW and 10 for STW for both the right and left foot).

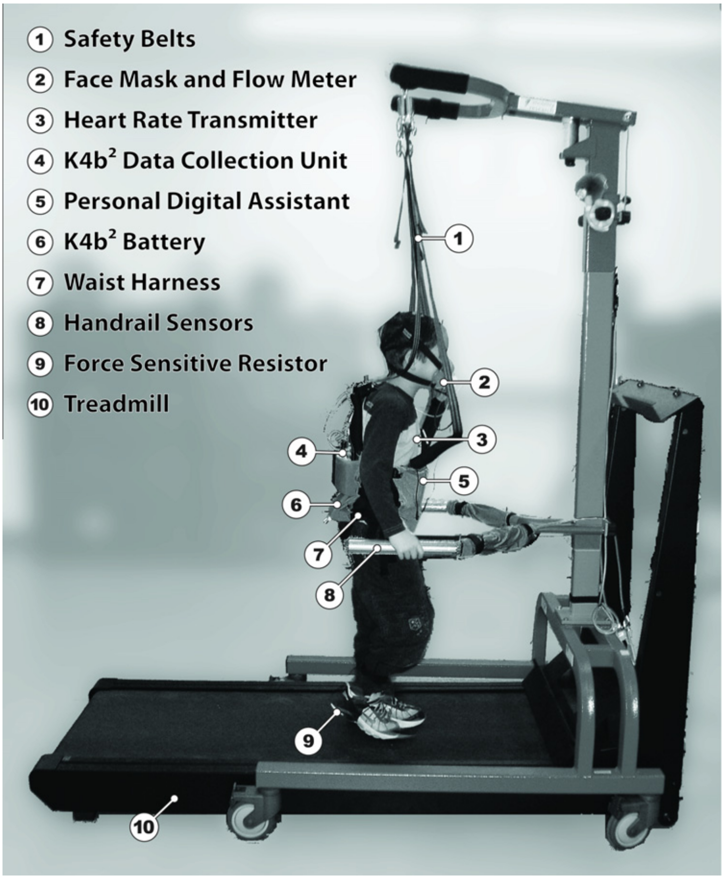

Fig. 1. Subject completing a primary supported treadmill walking trial while wearing study equipment.

For comparison with literature values, number of strides, mean stride interval, and stride interval coefficient of variation (i.e., stride interval standard deviation/stride interval mean × 100) were calculated for both the left and right foot stride interval time series of each participant.

2.2.2. Quantification of stride interval persistence

To estimate the statistical persistence of the stride interval time series, detrended fluctuation analysis (DFA) was implemented as described elsewhere (Peng, Havlin, Stanley, & Goldberger, 1995). This method produces a scaling-estimate, α, for each signal, which is interpreted as follows: $0.5 < \alpha \leqslant 1.0$ indicates that the signal is statistically persistent; $\alpha < 0.5$ means the signal is anti-persistent; $\alpha = 0.5$ indicates random, uncorrelated behavior; and $1.0 < \alpha < 1.5$ indicates a signal between fractional Gaussian noise ($\alpha = 1.0$) and fractional Brownian motion ($\alpha = 1.5$) (Hausdorff et al., 1995). Given that the results of DFA are sensitive to the range of box sizes used, we carried out the analysis proposed by Damouras, Chang, Sejdić, and Chau (2010) for determination of the box size range producing the most stable α-estimates. We began the procedure with a wide box size range of $[n_{min} = 4,\ n_{max} = 128]$, where the upper box size was modified to include at least two boxes in the shortest stride interval time series (446 strides in length). Then, considering the identified left and right foot box size ranges separately, we calculated a single range containing 95% of the individual ranges to use in the DFA analysis. Ultimately, the optimal box size fitting ranges identified for right and left foot series were $[n_{min} = 13,\ n_{max} = 64]$ and $[n_{min} = 16,\ n_{max} = 60]$, respectively.

2.2.3. Handrail contact

To ensure subjects complied with the STW protocol, the duration of handrail contact was quantified using the voltage signals acquired from handrail sensors during both treadmill trials, trimmed to correspond with the same 10-min interval in which stride interval persistence was assessed. Since voltage decreased with increasing force on a sensor, data points recorded during STW that fell below a threshold value were taken to indicate that contact with that respective sensor was in effect. For each sensor, a separate baseline threshold was defined, taken as the lower 95% confidence limit of voltages recorded by the corresponding sensor during the UTW trial (when there was no handrail contact). Handrail contact was computed as the percentage of time, during each 10-min trial, that contact was made with at least one sensor on the right, the left, or both handrail(s).

2.2.4. Statistical analysis

Mixed models regression was used on data obtained from primary walking trials to test the effects of condition (overground walking, unsupported treadmill walking, supported treadmill walking), age group (younger, older), side (left foot, right foot), and trial order (1st walk, 2nd walk, 3rd walk) on our primary outcome measure, stride interval persistence (α), controlling for the random subject effect. This analysis was also repeated for secondary measures including number of strides taken, stride interval and stride interval coefficient of variation (CV). Preferred speed was analyzed without including side in the models since this parameter was measured for the left and right feet combined.

Given the age range of our sample, age group was included in the models in order to test for possible maturation effects. Specifically, based on the findings for α reported by Hausdorff et al. (1999), we divided our sample into two groups: younger, 4- to 7-year-old children ($n = 18$), and older, 8- to 10-year-old children ($n = 12$).

Finally, considering the additional weight and potential unfamiliarity imposed by the subject-worn metabolic equipment, we subsequently tested for any effects of this equipment on each outcome measure (α, number of strides, stride interval, stride interval CV, and speed) by including session (primary, repeat) as a variable in the models. Repeat walking trials, performed without wearing the metabolic equipment, were done only after the initial set of primary walking trials were completed. In order to determine if differences observed between each session were due to the change in amount of equipment used or the result of fatigue or a practice effect, trial order was included as a covariate in all of the models to identify any systematic changes in outcome over time.

3. Results

For the gait parameters for which the effect of condition was significant, the least squares means (LSmeans) and their 95% confidence limits (CL) for each of the three conditions are reported in Table 1, along with estimates of the pairwise differences between the different conditions, their 95% confidence limits, and *p*-value. The LSmeans were obtained from primary walking trial data, using models controlling for age group, side (with the exception of models for speed), and trial order. Similarly, Table 2 reports significant results obtained from primary walking trial data when considering the effect of age group, using models controlling for condition, side (with the exception of models for speed) and trial order. Finally, Table 3 depicts the significant findings when considering the effect of session (i.e., considering both primary and repeat walking trial data), using models controlling for condition, age group, side (with the exception of models for speed), and trial order.

A significant condition effect ($p < .0001$) was identified for all outcomes (α, number of strides, stride interval, and speed) except for stride interval CV, which was not significant ($p > .1$). There was a significant age effect for coefficient of variation ($p < .002$) and speed ($p < .0004$), but not for α, number of strides and stride interval ($p > .07$). Neither side nor trial order had a significant effect on any of the outcomes ($p > .1$), the latter of which suggests that any session effect occurred due to the change in equipment and not because of fatigue or practice effects. A significant session effect was identified for number of strides ($p < .02$), stride interval ($p < .008$), and speed ($p < .006$) but not for α and stride interval CV ($p > .3$).

Table 1
Least squares means (LSmean) and their 95% confidence limits (CL) of gait measures for which walking condition was significant. Results for the three walking conditions (OW = overground walking, UTW = unsupported treadmill walking, STW = supported treadmill walking) are reported, followed by estimates of the pairwise differences between each condition, their 95% confidence limits and *p*-value. LSmeans were obtained from models controlling for age group, side (with the exception of models for speed), and trial order.

Measure	Condition	LSmean	(95% CL)	*p*-Value
Alpha (α)	OW	0.86	(0.82; 0.89)	
	UTW	0.72	(0.69; 0.76)	
	STW	0.79	(0.75; 0.83)	
	OW vs UTW	0.13	(0.09; 0.18)	<.0001
	OW vs STW	0.07	(0.02; 0.11)	.006
	UTW vs STW	−0.07	(−0.11; −0.02)	.005
Number of strides	OW	594	(580; 608)	
	UTW	536	(522; 549)	
	STW	492	(479; 506)	
	OW vs UTW	58	(48; 69)	<.0001
	OW vs STW	102	(91; 112)	<.0001
	UTW vs STW	43	(34; 54)	<.0001
Stride interval (s)	OW	1.01	(0.98; 1.03)	
	UTW	1.11	(1.09; 1.14)	
	STW	1.21	(1.18; 1.24)	
	OW vs UTW	−0.11	(−0.13; −0.09)	<.0001
	OW vs STW	−0.20	(−0.22; −0.18)	<.0001
	UTW vs STW	−0.10	(−0.12; −0.08)	<.0001
Preferred speed (m/s)	OW	1.14	(1.09; 1.19)	
	UTW	0.74	(0.69; 0.79)	
	STW	0.77	(0.72; 0.82)	
	OW vs UTW	0.4	(0.34; 0.46)	<.0001
	OW vs STW	0.37	(0.31; 0.43)	<.0001
	UTW vs STW	−0.03	(−0.09; 0.03)	.3

Table 2
Least squares means (LSmeans) and their 95% confidence limits (CL) of gait measures for which age group was significant. Results for the two age groups (older, younger) are reported, followed by the estimate of the pairwise difference between age groups, its 95% confidence limits and *p*-value. LSmeans were obtained from models controlling for condition, side (with the exception of models for speed), and trial order.

Measure	Age group	LSmean	(95% CL)	*p*-Value
Stride interval coefficient of variation (%)	Younger	6.89	(5.99; 7.78)	
	Older	4.52	(3.42; 5.62)	
	Younger vs older	2.36	(0.95; 3.78)	.001
Preferred speed (m/s)	Younger	0.81	(0.76; 0.86)	
	Older	0.96	(0.90; 1.02)	
	Younger vs older	−0.15	(−0.23; −0.07)	.0004

3.1. Handrail contact

Overall, we found children to be very compliant with the handrail supported treadmill walking task. Children maintained contact with at least one rail for no less than 97.49% of the trial duration, and had simultaneous contact with both rails for at least 82.3% of the trial. Given that α was slightly more variable during handrail STW, albeit not significantly so, we also tested for a possible correlation between stride interval persistence (α) and handrail contact durations (right, left, both, and either). No significant correlations were identified ($p > .06$).

Table 3
Least squares means (LSmeans) and their 95% confidence limits (CL) of gait measures for which session was significant. Results for two sessions (primary, repeat) are reported, followed by the estimate of the pairwise difference between conditions, its 95% confidence limits, and *p*-value. LSmeans were obtained from models controlling for condition, age group, side (with the exception of models for speed), and trial order.

Measure	Session	LSmean	(95% CL)	*p*-Value
Number of strides	Primary	541	(528; 553)	
	Repeat	553	(538; 567)	
	Primary vs repeat	−12	(−22; −2)	.02
Stride interval (s)	Primary	1.11	(1.08; 1.13)	
	Repeat	1.08	(1.05; 1.11)	
	Primary vs repeat	0.03	(0.01; 0.05)	.008
Preferred speed (m/s)	Primary	0.89	(0.84; 0.93)	
	Repeat	0.96	(0.90; 1.01)	
	Primary vs repeat	−0.07	(−0.12; −0.02)	.006

4. Discussion

4.1. Effect of treadmill walking on persistence

This study demonstrates that comfortably-paced treadmill walking, both with and without handrail support, significantly reduces a child's natural (i.e., overground) stride interval persistence. In particular, α-values are most diminished during unsupported treadmill walking, while some stride interval persistence is restored through the implementation of handrail support. A number of differences between overground and treadmill walking may have contributed to this change. The requirement for maintenance of a constant average speed within the spatial limitations imposed by the treadmill belt necessarily restricted gait adjustments to be more instantaneous in nature. Logically, with stride intervals changing on a more moment-to-moment basis as opposed to more gradually over the long-term, it seems reasonable that α would decrease, with less dependence between stride intervals taken further apart in time. In support of this, Delignières and Torre (2009) have identified an even greater change in stride interval behavior, from persistent to anti-persistent, when walking is more tightly constrained; paced on a stride-to-stride basis to the constant beat of a metronome.

The lack of optic flow feedback during treadmill walking may have contributed to the reduction in pediatric stride interval persistence. Human locomotor control relies heavily on vision, and optic flow in particular, to control walking under varying environmental conditions (Warren, Kay, Zosh, Duchon, & Sahuc, 2001). Furthermore, the ability to distinguish between and successfully implement visual cues is thought to improve with increasing age and walking experience, with greater automaticity of control gained with practice (Schmuckler & Gibson, 1989). Interestingly, in an adult population performing an analogous set of walking tasks, α was not affected during UTW compared to overground walking (Chang et al., 2009). Therefore, unlike adults, the children in this study may not have been able to adapt to the static visual feedback during treadmill walking due to their incomplete neuromaturation and more limited opportunity for locomotor practice in varying environments.

The extent of tactile feedback available to subjects during treadmill walking tasks is also interesting to consider alongside the observed changes in α. In particular, it would appear that the additional sensory feedback provided by use of the handrails during STW may have partially compensated for locomotor cues lost during unsupported treadmill walking (e.g., visual feedback), as stride interval persistence was somewhat restored toward the values measured overground. Similarly, handrail support during treadmill walking was found to augment stride interval persistence in an adult population (Chang et al., 2009).

4.1.1. A physiological perspective

Chang et al. (2009) suggested that the cerebellar vermis may play a critical role in the maintenance of stride interval dynamics. To this end, age-dependent neuroplasticity of the cerebellum may in part account for the observed differences in stride interval persistence between children and adults. In a recent investigation of rhythmic tapping performance between early- and late-trained musicians, Watanabe, Savion-Lemieux, and Penhune (2007) attributed greater improvement in early-trained children to a so called 'sensitive' period when stimulated neural systems, in particular the cerebellum, are more susceptible to change. Seemingly then, this cerebellar sensitivity could also be responsible for the observed treadmill-induced change in the stride interval dynamics of children, compared to adults.

On the other hand, the possibility that an entirely different control mechanism may be governing pediatric stride dynamics, perhaps in the lower spinal circuitry, should not be dismissed. This idea may explain the contradictory effect of treadmill walking on stride interval dynamics between children and adults, and also the difference in stride interval complexity previously identified between children and adults when walking overground (Hausdorff et al., 1999). While infant stepping is believed to occur largely under the control of spinal neurocircuitry, adults are thought to have stronger supraspinal connections which contribute to locomotor output (Lamb & Yang, 2000). Furthermore, there is evidence that refinement of corticospinal motor tracts continues into adolescence (Martin, 2005). Conceivably then, stride interval dynamics may be generated by lower spinal mechanisms early in life, with control of dynamics taken over, or greater influence gained, by higher neural centers later in development. This conjecture, paired with the argument that afferent information arising from treadmill walking is first relayed to spinal circuits (Chang et al., 2009), suggests that treadmill walking does not impact the cortically-mediated stride interval persistence of adults but may alter the primarily spinal stride dynamics of children.

Irrespective of the neural circuitry responsible for stride dynamics, the age-sensitivity of these complex patterns would certainly seem to suggest that either: (i) neural feedback being sent to control centers change with age (Berard & Vallis, 2006), or (ii) control centers themselves develop with age and thus differ in their ability to receive, integrate, or process the motor output signals (Martin, 2005; Watanabe et al., 2007). It is well established that human nerve and muscle cells are postmitotic, and therefore present to their greatest extent after early development (Vandervoort, 2002). Subsequently, according to the neuronal group selection theory, a child's neural circuitry adapts and develops with practice, retaining only the most favorable neuromotor networks (Forssberg, 1999). Thus, quantification of stride interval dynamics may provide insight into neural development and efficiency, reflecting the extent of experience-based selection that has occurred within the circuitry. Stride interval dynamics of adults may be robust to subtle gait influences, such as those imposed by treadmill walking, when the locomotor activity sufficiently approximates the activity upon which experienced-based selection of neuromotor networks took place (i.e., overground walking). On the other hand, when presented with a less-familiar task in which experience-based selection may be lacking (e.g., metronomically-paced walking) (Delignières & Torre, 2009; Hausdorff et al., 1996), the selection process is revisited, and stride interval dynamics are altered. In this regard, our findings suggest that where a child has yet to develop advanced neural control, as reflected through diminished stride interval dynamics, sufficient practice may bridge the apparent developmental gap.

4.1.2. Cognitive involvement

The different effect of treadmill walking on the stride interval dynamics of children and adults may be related to the extent of locomotor effort, perhaps cognitive load in particular, required for treadmill locomotion. When going from overground to treadmill walking, a larger change has been identified in children than in adults toward a more protective gait pattern (i.e., a broader step width and greater outward rotation of the foot) (Stolze et al., 1997). Seemingly then, a more cautious or "conscious" gait may lead to a decrease in α. To this end, when an adult population is asked to complete an inherently attentionally demanding task such as metronomically-paced walking, the expression of locomotor complexity is indeed altered (Delignières & Torre, 2009). In addition, other populations that rely significantly on attentional processes to control gait, such as the elderly and individuals with Parkinson's or Huntington's disease (Delval et al., 2008; O'Shea, Morris, & Iansek, 2002; Woollacott & Shumway-Cook, 2002; Yang, Chen, Lee, Cheng, & Wang, 2007), also exhibit reduced stride interval persistence (Hausdorff et al., 1997).

4.2. Effect of metabolic equipment

Of primary importance to the present findings, we found that the additional metabolic equipment worn by subjects during primary walking tasks did not significantly effect α-values. While there were statistical differences between primary and repeat trials in number of strides, stride interval, and preferred speed, the statistics (Table 3) showed that the confidence intervals between primary and repeat sessions overlapped and often the estimated value could belong to either group.

4.3. Other stride parameters

Other gait parameters assessed in this study also showed sensitivity to walking condition. Considering the aggregate, 4- to 10-year-old age group, children walked the fastest during the most familiar overground condition, taking the most strides and having a shorter stride interval. Compared to overground walking, the finding of reduced preferred speed during both treadmill walking conditions is consistent with findings in the literature (Chang et al., 2009; Jeng, Holt, Fetters, & Certo, 1996; Wall & Charteris, 1980) and is likely most responsible for the corresponding decrease in stride number and increase in stride interval. In contrast, when average gait speed is maintained between overground and treadmill walking (Stolze et al., 1997), the closely associated parameters of cadence and stride length typically change in the opposite direction, with an increased cadence and decreased stride length associated with treadmill walking.

To this end, while speed was statistically similar in this study during both treadmill walking tasks, fewer strides and a longer stride interval were identified in the handrail supported condition, suggesting that postural or temporal gait adjustments were made. Although it has been found that grasping the handrails does not alter the sagittal plane kinematics of treadmill walking in adults (Siler et al., 1997), it is unknown if the same is true for children. Furthermore, in a study pertaining to treadmill habituation it was found that stride interval increased with familiarization “as the confidence of the subject grew” (Wall & Charteris, 1980). Thus, some locomotor differences may be attributable to changes in gait due to the level of perceived comfort with the walking task at hand. Considering that even light touch during locomotion provides enhanced spatial orientation and facilitates body stability (Dickstein & Laufer, 2004), subjects may have walked more confidently and comfortably during STW, with a corresponding decrease in stride number and stride interval.

Contrasting between age groups, we found that older children walked significantly faster during all three walking conditions. Not surprisingly given their larger stature, older children typically walk faster than younger children (Beck et al., 1981). These speed differences are suggested to be primarily due to physical and not neuro-developmental maturation (Zijlstra, Prokop, & Berger, 1996). On the other hand, the younger children in our study also had significantly greater stride interval CV across all three conditions compared to the older children. This result is also consistent with other pediatric studies (Hausdorff et al., 1999; Zijlstra et al., 1996) and is suggested to be due to decreased walking speed, decreased postural stability at these slower speeds, and possibly other aspects of motor control development (Hausdorff et al., 1999; Zijlstra et al., 1996).

4.4. Study limitations

Since the gait parameters of children are generally more variable than those of adults (Hausdorff et al., 1999; Stolze et al., 1997), a larger sample size and narrower subject age-ranges may be warrented in future studies to better elucidate the developmental profile of stride interval persistence. Furthermore, although different treadmill familiarization periods have been reported for different gait parameters (Lavcanska, Taylor, & Schache, 2005; Van de Putte, 2006; Wall & Charteris, 1980, 1981; White, Gilchrist, & Christina, 2002), we only implemented a single clinically relevant timeframe of approximately 5 min which may be insufficient for the stabilization of stride dynamics. Future research should investigate the necessary familiarization period, both within-day and between-day, to obtain the most stable α-estimate. Finally, the explanations offered herein for the observed changes in statistical persistence, while plausible, are largely extrapolations from literature. Further studies are required to pinpoint the specific, persistence-altering mechanisms.

5. Conclusions

In a group of 30 neurologically healthy children, we found stride interval persistence to diminish significantly from overground values when walking on a treadmill both with and without handrail support. Preferred speed, number of strides, and stride interval duration also differed between overground and treadmill conditions. Furthermore, older children exhibited lower stride interval variability and increased speed compared to younger children. The observed treadmill and age effects on stride characteristics may be due to a combination of different locomotor constraints between overground and treadmill walking, and developmental differences in sensory processing, corticospinal contributions to locomotor control, and cerebellar plasticity between children and adults. Future research with more children and finer age demarcations is required to further elucidate the developmental profile of stride interval dynamics.

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