



## Age-dependent variability in spatiotemporal gait parameters and the walk-to-run transition

Stacey M. Kung<sup>a,\*</sup>, Philip W. Fink<sup>b</sup>, Stephen J. Legg<sup>c</sup>, Ajmol Ali<sup>d</sup>, Sarah P. Shultz<sup>a,e</sup>

<sup>a</sup> School of Sport, Exercise & Nutrition, Massey University, 63 Wallace Street, Mt Cook, Wellington 6021, New Zealand

<sup>b</sup> School of Sport, Exercise & Nutrition, Massey University, Tennent Drive, Palmerston North 4474, New Zealand

<sup>c</sup> Centre for Ergonomics and Occupational Health and Safety, School of Public Health, Massey University, Tennent Drive, Palmerston North 4474, New Zealand

<sup>d</sup> School of Sport, Exercise & Nutrition, Massey University, Albany Highway, Albany 0632, New Zealand

<sup>e</sup> Department of Kinesiology, Seattle University, 901 12th Avenue, Seattle, WA 98122, USA

### ARTICLE INFO

#### Keywords:

Gait maturation  
Spatiotemporal parameters  
Locomotion  
Variability

### ABSTRACT

Adolescents tend to exhibit more variability in their gait patterns than adults, suggesting a lack of gait maturity during this period of ongoing musculoskeletal growth and development. However, there is a lack of consensus over the age at which mature gait patterns are achieved and the factors contributing to gait maturation. Therefore, the purpose of this study was to investigate gait control and maturity in adolescents by determining if differences existed between adolescents and adults in a) the amount of spatiotemporal variability of walking and running patterns across a range of speeds, and b) how swiftly gait patterns are adapted to increasing gait speed during the walk-to-run transition. Forty-six adolescents (10–12-year-olds,  $n = 17$ ; 13–14-year-olds,  $n = 12$ ; and 15–17-year-olds,  $n = 17$ ) and 12 young adults completed an incrementally ramped treadmill test ( $+0.2 \text{ km}\cdot\text{h}^{-1}$  every 30 s) to determine the preferred transition speed (PTS) during a walk-to-run transition. Age-related differences in the variability of stride lengths and stride durations were assessed across 4 speeds (self-selected walking speed,  $\text{PTS} - 0.06 \text{ m}\cdot\text{s}^{-1}$ ,  $\text{PTS} + 0.06 \text{ m}\cdot\text{s}^{-1}$ ,  $\text{PTS} + 0.83 \text{ m}\cdot\text{s}^{-1}$ ). Repeated measures ANOVAs ( $p < 0.05$ ) compared coefficients of variation for these spatiotemporal parameters, while a one-way ANOVA compared the numbers of gait transitions and speed increments used to identify PTS between the adolescent groups and young adults. Compared to adults, 10–12yo exhibited more spatiotemporal variability during all gait conditions, while 13–17yo only exhibited more variability at  $\text{PTS} + 0.06 \text{ m}\cdot\text{s}^{-1}$ . No age-dependent pattern was observed in PTS values, but 10–12yo completed more gait transitions over more speed increments than 15–17yo and adults. The development of mature gait patterns is thus a progressive process, with walking maturing at an earlier age than running. As 10–12yo were unable to swiftly adapt gait patterns to the changing task demands, their control mechanisms of gait may not have fully matured yet.

### 1. Introduction

Healthy gait and normal gait development have been widely investigated due to the importance of locomotion for independent daily living. Walking and running not only provide a means of transport, but also enables participation in various physical activities for health and wellbeing. Gait abnormalities can thus have adverse effects on an individual's quality of life if not managed properly.

\* Corresponding author.

E-mail addresses: [s.kung@massey.ac.nz](mailto:s.kung@massey.ac.nz) (S.M. Kung), [p.fink@massey.ac.nz](mailto:p.fink@massey.ac.nz) (P.W. Fink), [a.ali@massey.ac.nz](mailto:a.ali@massey.ac.nz) (A. Ali), [shultzsarah@seattleu.edu](mailto:shultzsarah@seattleu.edu) (S.P. Shultz).

<https://doi.org/10.1016/j.humov.2019.06.012>

Received 14 February 2019; Received in revised form 19 June 2019; Accepted 20 June 2019

Available online 02 July 2019

0167-9457/ © 2019 Elsevier B.V. All rights reserved.

To effectively identify, manage or treat gait abnormalities, clinicians and researchers require a robust understanding of how and when mature, or adult-like, gait patterns normally develop and the factors that contribute to its development (Sutherland, 1997).

Neuromuscular development and muscular strength are likely to be rate-limiters of gait maturation in adolescents (Cupp, Oeffinger, Tylkowski, & Augsburger, 1999; Ganley & Powers, 2005; Van de Walle et al., 2010), due to physical growth and development occurring within the musculoskeletal system. Ongoing musculoskeletal development during adolescence would also have an effect on motor behaviour and consequently how gait patterns are regulated. Specifically, the system would need to adjust gait patterns to altered leg length and muscular strength. Thus, measures of gait variability can provide valuable insight into motor behaviour during gait and the development of mature gait patterns. Intra-individual variability of movement patterns reflects how consistently a motor task is executed (Hausdorff, Zeman, Peng, & Goldberger, 1999; Komar, Seifert, & Thouvarecq, 2015; Maruyama & Nagasaki, 1992). Decreasing levels of variability in a movement pattern tends to reflect motor learning and thus improvement in motor skill proficiency (Komar et al., 2015). Therefore, assessing spatiotemporal variability can be informative when investigating the development of mature gait.

Spatiotemporal variability decreases as a child gets older (Gouelle, Leroux, Bredin, & Megrot, 2016; Hausdorff et al., 1999; Muller, Muller, Baur, & Mayer, 2013). Although the amount of spatiotemporal variability in the walking patterns of 10–14-year-olds (yo) (Hausdorff et al., 1999) and 14–17yo (Gouelle et al., 2016) approached values seen in adults, their gait patterns still exhibited more variability. Spatiotemporal parameters during running also appear to be more variable in 7–9yo compared to adults (Rogers, Turley, Kujawa, Harper, & Wilmore, 1994). These differences in variability during walking and running suggest that gait patterns have not fully matured by early-to-mid-adolescence. It is not known when spatiotemporal variability of gait patterns becomes similar to what is seen among healthy adults. These studies only assessed variability during comfortable self-selected walking speeds (Gouelle et al., 2016; Hausdorff et al., 1999), or a couple of predetermined running speeds (Rogers et al., 1994). However, walking and running are highly dynamic, requiring speed changes to meet the demands of daily life and various external factors. Therefore, more research is required to better understand the development of mature gait and ability to effectively adapt gait patterns to changing task demands.

The control mechanisms of gait have been investigated during gait transitions, as they must react to a change in the task demands (i.e. gait speed) to trigger a transition between walking and running. Individual constraints such as anthropometric and strength characteristics can influence an individual's preferred transition speed (PTS) (Kung, Fink, Legg, Ali, & Shultz, 2018). As the muscular, skeletal and neural systems continue to develop through adolescence (Cech & Martin, 2002), the feedback mechanisms would be required to continue calibrating to the changes in the neuromusculoskeletal system. A lower PTS seen among 11yo compared to 13yo and 15yo (Tseh, Bennett, Caputo, & Morgan, 2002) reflects this possible effect of ongoing neural and musculoskeletal development on the ability to regulate gait patterns, which could influence the determinants of PTS.

The first purpose of this study was to determine if adolescents exhibit more spatiotemporal variability in their gait patterns across a range of walking and running speeds compared to healthy young adults. As adult-like levels of spatiotemporal variability have previously been used as an indicator of gait maturity, more spatiotemporal variability in adolescent gait would suggest that gait patterns are not yet mature. However, it has been argued that the emphasis of mastering a skill should be on the ability to swiftly adapt a skill or motor task to changing task demands (Komar et al., 2015). Therefore, the second aim was to investigate gait maturity through the ability to adjust gait patterns to changing task demands by comparing PTS during a walk-to-run transition and how effectively PTS was identified between adolescents and young adults.

## 2. Methods

### 2.1. Participants

Forty-six adolescents (10–17 years) participated in the study and were initially categorised by chronological age into 10-, 11-, 12-, 13-, 14-, 15-, 16-, and 17yo groups (see [Supplementary data; Table S1](#)). Twelve healthy young adults (19–29 years) were recruited for comparison. Exclusion criteria consisted of any lower extremity injuries or surgeries that occurred within the six months prior to testing, as well as a diagnosis of any neuromusculoskeletal condition, cardiovascular disease, diabetes, or asthma. For participants aged 10–16 years, informed written participant assent and parental consent were obtained. The 17–29yo provided their own informed written consent. The study was approved by the institutional human ethics committee.

### 2.2. Protocol

Participants visited the laboratory on two occasions. During the first session, participants became familiar with treadmill locomotion by first walking and then running on a treadmill for at least 15 min at self-selected speeds. As children vary in the amount of time to accommodate to treadmill gait (Frost, Bar-Or, Dowling, & White, 1995), participants who still exhibited difficulties after the initial trial were given extra time for familiarisation. Following the walking and running trials, participants completed at least three practice walk-to-run transition trials, which started at their self-selected walking speed and the treadmill speed was increased by  $+0.06 \text{ m}\cdot\text{s}^{-1}$  every 10 s until the participant started running and remained in a running pattern.

During the second session, participants underwent an incremental treadmill test to determine PTS. PTS was defined as the first speed where the participant used a running pattern that would be maintained for the rest of the protocol. The protocol started at the participant's self-selected walking speed, which was maintained for 90 s. The first 60 s at this speed were treated as the warm up. The remaining 30 s were treated as the first stage of the testing protocol and incremental changes in treadmill speed of  $+0.06 \text{ m}\cdot\text{s}^{-1}$  occurred every 30 s thereafter, until 5 increments were completed using a consistent running gait pattern. The five speed increments

following PTS ensured that the participant did not transition back to a walking pattern. On the sixth speed increment following PTS, the increments changed to  $+0.14 \text{ m}\cdot\text{s}^{-1}$  every 30 s until peak exertion was reached. Before starting the treadmill protocol, participants were instructed to start running at a speed that felt most comfortable, but were free to transition between walking and running as they pleased. The treadmill speed was hidden from the participants. No verbal cues were given during the protocol to initiate a gait transition so that participants could naturally respond to increases in gait speed.

### 2.3. Data collection

Three-dimensional kinematics were collected at 100 Hz using an 8-camera motion capture system (Bonita 10, Vicon, Oxford, UK). Reflective markers were attached to the trunk, pelvis and lower extremities at specific bony landmarks according to a previously established marker set (Lerner, Board, & Browning, 2014). Markers on the foot were attached to the outer surface of the shoe at the corresponding bony landmarks (Kung, Fink, Hume, & Shultz, 2015). Twenty second samples of kinematic data were collected at each speed increment. The treadmill test was filmed at 30 Hz using a video camera (Exilim EX-F1, Casio, Tokyo, Japan), positioned to capture sagittal plane motion. Video footage was used to count the number of gait transitions completed by the participants throughout the treadmill test. Each walk-to-run transition and run-to-walk transition was counted as separate gait transitions. The number of speed increments used to complete a gait transition was recorded.

### 2.4. Data processing and analysis

To assess spatiotemporal variability, four gait conditions were analysed. The participant's self-selected walking speed and a standardised running speed (i.e.  $\text{PTS} + 0.83 \text{ m}\cdot\text{s}^{-1}$ ) were analysed to assess gait patterns under what were considered familiar gait speeds. Previous research has shown that individuals exhibit a speed jump of approximately  $0.42 \text{ m}\cdot\text{s}^{-1}$  between the transition step and the preceding step to avoid 'unstable gait speeds' (De Smet, Segers, Lenoir, & De Clercq, 2009). Therefore, to assess spatiotemporal variability during walking and running at unstable speeds within this speed jump, walking and running were also assessed at the speeds directly before (i.e.  $\text{PTS} - 0.06 \text{ m}\cdot\text{s}^{-1}$ ) and after (i.e.  $\text{PTS} + 0.06 \text{ m}\cdot\text{s}^{-1}$ ) the PTS respectively.

For each speed, ten strides of the participant's self-reported dominant limb were processed in Nexus (Version 2.6.1; Vicon, Oxford, UK) and analysed in Visual3D (Version 6.01.22; C-Motion, Germantown, MD). Limb dominance was defined as the leg that each participant would prefer to kick a ball (van Melick, Meddeler, Hoogeboom, Nijhuis-van der Sanden, & van Ginkel, 2017). Foot strike events were manually identified in Visual3D by the same researcher. Stride duration was calculated as the time between consecutive foot strike events of the dominant limb. Stride length was calculated as the product of the number of frames between consecutive foot strikes of the dominant limb, the sampling rate (i.e. 100 Hz) and treadmill speed. Anterior-posterior movement of the body in the global reference frame (i.e. relative to the treadmill belt) affects stride length (Van Caekenberghe, Segers, De Smet, Aerts, & De Clercq, 2010); thus, stride length values were adjusted by the change in the global position of the heel at each foot strike event relative to the previous foot strike event. Height and leg length have previously been found to be moderately correlated to PTS (Hreljac, 1995), so to account for anthropometric differences, PTS values were also normalised to height and leg length and expressed as a Froude number (Diedrich & Warren, 1995) for further analysis.

### 2.5. Statistical analysis

Using the 10 processed strides from each speed, coefficients of variation (CV) in stride duration and stride length were calculated for each participant at each speed. An initial  $9 \times 4$  (age  $\times$  speed) ANOVA with repeated measures was performed (SAS version 9.4, Cary, NC) to analyse differences between the adolescent groups and the young adults in the stride duration and stride length CVs at each speed. This initial analysis was performed to determine whether the participants could be grouped into larger age brackets. A progression in the development of mature gait was observed, whereby the 10-12yo exhibited differences in spatiotemporal variability across the walking and running speeds, 13-14yo only exhibited differences at the running speeds and the 15yo and 17yo did not exhibit differences compared to the adults (Supplementary data; Tables S2 and S3). Therefore, the adolescent participants were grouped accordingly into 3 groups: 10–12yo ( $n = 17$ ), 13–14yo ( $n = 12$ ) and 15–17yo ( $n = 17$ ) to be compared with the group of young adults. A subsequent  $4 \times 4$  (age  $\times$  speed) repeated measures ANOVA was performed on the stride duration and stride length CVs. Post-hoc Tukey's tests were used to identify where the significant differences were found. Height, mass, BMI, leg length, PTS values and the counts of the gait transitions completed and speeds at which gait transitions occurred were compared between age groups using a one-way ANOVA with post-hoc Tukey's tests (SPSS version 24, IBM, Armonk, NY). Statistical significance was set at an alpha level of 0.05.

## 3. Results

The characteristics of the combined age groups are reported in Table 1, while the characteristics of the individual adolescent age groups and young adults can be found in the Supplementary data (Table S1).

### 3.1. Stride duration and stride length variability

Significant differences were observed in the stride length and stride duration CVs between the adolescents and young adults

**Table 1**  
Participant characteristics for each of the age groups.

	10–12yo	13–14yo	15–17yo	Adults
n (F:M)	17 (12:5)	12 (6:6)	17 (7:10)	12 (6:6)
Height (m)	1.511 ± 0.069	1.634 ± 0.081*	1.698 ± 0.081*	1.706 ± 0.095*
Mass (kg)	42.4 ± 9.3	48.1 ± 8.5	58.4 ± 8.2 <sup>†</sup>	62.6 ± 10.5 <sup>††</sup>
BMI (kg·m <sup>-2</sup> )	18.4 ± 2.6	17.9 ± 1.8	20.2 ± 2.4 <sup>†</sup>	21.4 ± 2.2 <sup>††</sup>
Leg Length (m)	0.807 ± 0.039	0.869 ± 0.051*	0.890 ± 0.044*	0.884 ± 0.063*

Significant differences ( $p < 0.05$ ) are highlighted in the table with the following symbols to indicate that there was a difference compared to the \* 10–12-year-olds; <sup>†</sup> 13–14-year-olds. F: Female. M: Male. yo: year olds.

( $p < 0.05$ ; Tables 2 and 3). The stride duration and stride length CVs for the 10–12yo were consistently greater than the adults for all speeds. Compared to the adults, the 13–14yo and 15–17yo groups exhibited more stride duration variability at  $PTS + 0.06 \text{ m}\cdot\text{s}^{-1}$ , but not at any other gait conditions.

### 3.2. Preferred transition speed and gait transition variability

Significant differences were detected in the absolute PTS values between age groups ( $F(3,54) = 3.240$ ,  $p = 0.029$ ; Table 4). 15–17yo had a significantly higher PTS compared to the 10–12yo. No other significant differences in any of the other absolute or normalised PTS values were observed between the other age groups. The results from the comparisons between the individual adolescent groups and adults can be found in the Supplementary data (Table S4).

Significant differences were observed in the numbers of gait transitions completed ( $F(3,54) = 4.768$ ,  $p = 0.005$ ) and speeds at which gait transitions occurred ( $F(3,54) = 5.537$ ,  $p = 0.002$ ). The 10–12yo completed more gait transitions than the 15–17yo ( $p = 0.003$ ) and the adults ( $p = 0.014$ ) (Tables 5 and S5). The 10–12yo also completed gait transitions across a higher number of speeds during the treadmill test than the 15–17yo ( $p = 0.006$ ) and the adults ( $p = 0.036$ ). Approximately half of the 10–12yo group and about a quarter of the 13–14yo group used more than one gait transition over more than one speed to determine their PTS. Only one participant out of the 15–17yo and adult groups transitioned more than once over more than one speed.

## 4. Discussion

This study investigated spatiotemporal variability during treadmill walking, running, and the walk-to-run transition to better understand gait maturation. The walk-to-run transition was analysed as there is a change from inverted pendulum to spring mass mechanics that occurs in response to increasing locomotive speed at PTS. Analysing walk-to-run transitions can provide insight into how gait is regulated, how swiftly gait patterns can be adapted to external constraints, and thus the level of gait maturity. Since the adolescents exhibited more variable gait patterns than the adults, gait maturation appears to be an ongoing process during adolescence. To subsequently analyse how well adolescents can adapt their gait to changing task demands, the study investigated whether differences existed in PTS and how effectively the adolescents could determine their PTS compared to adults. No systematic age differences in PTS were observed, but the 10–12yo transitioned more frequently and used more speed increments to determine PTS during the treadmill protocol than the older adolescents and adults. These combined results support that gait patterns are not

**Table 2**  
Mean ± SD of the stride duration coefficient of variation (CV) values across the gait conditions for each age group.

	10–12yo	13–14yo	15–17yo	Adults
<b>Walking</b>				
SSW				
Mean	1.08 ± 0.08	1.11 ± 0.07	1.07 ± 0.07	1.06 ± 0.06
CV	1.88 ± 0.66 <sup>†</sup>	1.53 ± 0.40	1.39 ± 0.70	1.27 ± 0.55
PTS-0.06 m·s <sup>-1</sup>				
Mean	0.88 ± 0.08	0.90 ± 0.03	0.90 ± 0.06	0.91 ± 0.06
CV	1.99 ± 0.97 <sup>†</sup>	1.45 ± 0.33	1.35 ± 0.53	1.14 ± 0.49
<b>Running</b>				
PTS + 0.06 m·s <sup>-1</sup>				
Mean	0.74 ± 0.04	0.77 ± 0.05	0.75 ± 0.04	0.77 ± 0.03
CV	2.19 ± 0.51 <sup>‡</sup>	1.82 ± 0.30 <sup>†</sup>	1.64 ± 0.45 <sup>†</sup>	1.26 ± 0.34
PTS + 0.83 m·s <sup>-1</sup>				
Mean	0.72 ± 0.04	0.73 ± 0.04	0.72 ± 0.04	0.74 ± 0.03
CV	2.03 ± 0.79 <sup>‡</sup>	1.50 ± 0.55	1.41 ± 0.34	1.22 ± 0.44

Significant differences in the CV values compared to the young adults are indicated in the table: \*  $p < 0.05$ , <sup>†</sup>  $p < 0.01$  and <sup>‡</sup>  $p < 0.001$ . SSW: Self-selected walking speed. PTS: Preferred transition speed. yo: year olds.

**Table 3**Mean  $\pm$  SD of the stride length coefficient of variation (CV) values across the gait conditions for each age group.

	10–12yo	13–14yo	15–17yo	Adults
<b>Walking</b>				
SSW				
Mean	1.18 $\pm$ 0.12	1.32 $\pm$ 0.09	1.37 $\pm$ 0.12	1.37 $\pm$ 0.11
CV	2.42 $\pm$ 0.77 <sup>‡</sup>	1.86 $\pm$ 0.40	1.51 $\pm$ 0.64	1.37 $\pm$ 0.61
PTS-0.06 m·s <sup>-1</sup>				
Mean	1.56 $\pm$ 0.11	1.75 $\pm$ 0.15	1.76 $\pm$ 0.10	1.75 $\pm$ 0.08
CV	2.02 $\pm$ 1.07 <sup>‡</sup>	1.29 $\pm$ 0.28	1.15 $\pm$ 0.39	0.90 $\pm$ 0.41
<b>Running</b>				
PTS + 0.06 m·s <sup>-1</sup>				
Mean	1.41 $\pm$ 0.13	1.57 $\pm$ 0.21	1.57 $\pm$ 0.16	1.57 $\pm$ 0.14
CV	2.91 $\pm$ 0.66 <sup>‡</sup>	2.05 $\pm$ 0.48	1.92 $\pm$ 0.55	1.69 $\pm$ 0.40
PTS + 0.83 m·s <sup>-1</sup>				
Mean	1.91 $\pm$ 0.15	2.06 $\pm$ 0.23	2.06 $\pm$ 0.16	2.08 $\pm$ 0.14
CV	2.63 $\pm$ 0.68 <sup>‡</sup>	1.85 $\pm$ 0.40	1.58 $\pm$ 0.55	1.36 $\pm$ 0.58

Significant differences in the CV values compared to the young adults are indicated in the table: \*p < 0.05, †p < 0.01 and ‡p < 0.001. SSW: Self-selected walking speed. PTS: Preferred transition speed. yo: year olds.

**Table 4**

Absolute and normalised preferred transition speed (PTS) values across the age groups.

PTS	10–12yo	13–14yo	15–17yo	Adults
m·s <sup>-1</sup>	1.84 $\pm$ 0.17	1.99 $\pm$ 0.17	2.01 $\pm$ 0.18 <sup>†</sup>	1.98 $\pm$ 0.18
statures·s <sup>-1</sup>	1.22 $\pm$ 0.14	1.22 $\pm$ 0.09	1.19 $\pm$ 0.12	1.16 $\pm$ 0.10
leg lengths·s <sup>-1</sup>	2.28 $\pm$ 0.25	2.29 $\pm$ 0.17	2.25 $\pm$ 0.21	2.24 $\pm$ 0.24
Froude number	0.43 $\pm$ 0.08	0.47 $\pm$ 0.07	0.47 $\pm$ 0.08	0.46 $\pm$ 0.08

\* Significantly different (p = 0.032) compared to the 10–12-year-olds. PTS: Preferred transition speed. yo: year olds.

**Table 5**

Counts of gait transitions completed and speeds at which gait transitions occurred during the treadmill protocol for each age group.

		10–12yo	13–14yo	15–17yo	Adults
Transitions	n	3.71 $\pm$ 3.24	1.83 $\pm$ 1.59	1.13 $\pm$ 0.50 <sup>*</sup>	1.33 $\pm$ 1.16 <sup>*</sup>
	(range)	(1–11)	(1–5)	(1–3)	(1–5)
Speeds	n	1.88 $\pm$ 0.99	1.25 $\pm$ 0.62	1.06 $\pm$ 0.25 <sup>*</sup>	1.17 $\pm$ 0.58 <sup>*</sup>
	(range)	(1–4)	(1–3)	(1–2)	(1–3)

Values presented as means  $\pm$  SD, while range values are presented in brackets. \* indicates statistical difference compared to the 10–12-year-olds. yo: year olds.

mature by 14 years of age, which agrees with previous research (Hausdorff et al., 1999).

Through age comparisons of spatiotemporal variability, different levels of gait maturation were revealed. The 10–12yo did not exhibit mature walking and running patterns due to the greater spatiotemporal variability seen during all of the gait conditions. The 13–17yo exhibited mature walking patterns as there were no differences in spatiotemporal variability during either of the walking conditions. However, running may not have fully matured yet among these older adolescents. While running at the standardised running speed did appear to be mature by 13 years of age, running at the unstable speed was still more variable than the adults. The progression of developing mature, adult-like walking patterns before mature running patterns concurs with previous reports of walking patterns showing signs of maturity earlier than running (Whitall & Getchell, 1995). The present results also show that gait patterns at familiar speeds matured earlier than at the less typical gait speeds near PTS. The latter observation suggests that there is a learning effect, where past experiences help shape the mechanisms modulating gait patterns. Thus, at familiar speeds, especially during running in older adolescents, it was arguably easier to produce consistent gait patterns, than at the less familiar speeds. Furthermore, as the unstable running speed was less variable for the adults compared to all of the adolescents, it appears that adults can more easily adjust their gait parameters than adolescents.

A better understanding of this maturation process was sought through the analysis of PTS and the process through which it is identified. PTS observed in the adolescent and adult groups were comparable to previously reported values (Hreljac, 1993; Prilutsky & Gregor, 2001; Tseh et al., 2002). While there was a difference in PTS between the 10–12yo and 15–17yo groups, no consistent age-dependent pattern in PTS was observed, despite significant height and leg length differences between the 10–12yo and the adults. When PTS was normalised to height and leg length there were no significant age differences. Although the differences in the

normalised PTS values lacked statistical significance, the transition tended to occur at a slightly higher speed relative to height and leg length in the 10–12yo than the adults. These younger adolescents may have thus transitioned at a less than optimal speed.

A lack of neuromuscular maturity may have contributed to greater spatiotemporal variability and poorer ability to optimise gait patterns during the walk-to-run transition among the 10–14yo. These younger adolescents may have been exhibiting exploratory behaviour necessary for learning (Ulman, Ranganathan, Queen, & Srinivasan, 2019). Specifically, the 10–14yo varied their spatiotemporal parameters while attempting to determine the most efficient combination of stride length and stride frequency. Conversely, adults often quickly adopt the most efficient combination of stride length and stride frequency under various task constraints (Hogberg, 1952). After having time to explore how changes in task constraints affect their gait patterns, adults can then optimise metabolic efficiency of walking patterns within seconds (Selinger, O'Connor, Wong, & Donelan, 2015). This self-optimising behaviour is likely to be used during running as well (Cavanagh & Williams, 1982). As all of the participants completed at least 3 practice walk-to-run transition trials during the familiarisation session, participants had time to explore how best to adjust their gait patterns to the given speeds. The increased spatiotemporal variability seen in the younger adolescents may therefore indicate that it took longer to determine the most efficient spatiotemporal parameters than the adults.

To further demonstrate the adults' superior ability to swiftly adapt gait patterns than the younger adolescents, the adults often determined their PTS using only one gait transition over a single speed. The 15–17yo were also able to generally determine their PTS with a single transition. However, the 10–12yo more frequently used multiple gait transitions over more speed increments before finally settling in a running pattern at their PTS compared to the 15–17yo and adults. The lack of statistical significance between 13–14yo and both 10–12yo and 15–17yo may suggest that the 13–14yo were at an intermediary level of gait development before being able to effectively adapt their gait patterns like the older adolescents and adults. As all of the participants completed the same familiarisation protocol, the differences in how quickly PTS was identified likely reflects the degree to which the control mechanisms have been calibrated with age and experience. The control mechanisms of gait may thus require further development before mature gait patterns are obtained.

Limitations existed within this study, particularly in regards to treadmill gait variability and experience. Research has previously indicated that treadmill walking is less variable than overground walking (Hollman et al., 2016). However, this study adjusted stride length to the difference in the position of the heel between foot-strikes, which can better imitate the variability seen during overground locomotion. It is suggested that complete treadmill habituation is achieved across multiple days before day-to-day differences in variability are no longer detected in adults (Schieb, 1986). However, younger individuals tend to vary in how long it takes to habituate to treadmill locomotion (Frost et al., 1995). These studies often examined habituation to a particular speed, but differences in spatiotemporal variability may differ if assessing a range of speeds. Therefore, ensuring individuals were completely habituated to each of the gait speeds used during the protocol was not practical. Prior treadmill experience was not assessed, which is considered a limitation of this study. To minimise the effect of treadmill experience, all participants received at least 45 min of walking, running and transition trials during the familiarisation session and extra time for each task was given if necessary. Additionally, while some participants may have had prior treadmill experience, it is very unlikely that individuals would train on the treadmill while walking and running speeds near PTS. Although  $PTS \pm 0.06 \text{ ms}^{-1}$  would have been unfamiliar for all groups, the adolescents continued to exhibit more variability at the unstable running condition and the 10–12yo also exhibited more variability at the unstable walking speed. Thus, the results from the present study support that adults can more easily adjust their gait parameters, regardless of how experienced they were with treadmill use.

## 5. Conclusion

There was a lack of gait maturity among the younger adolescents, particularly those between 10 and 12-years old. Mature walking emerged between 13 and 14-years of age and mature running emerged between 15 and 17 years of age. While PTS did not exhibit an age-dependent pattern, there were notable differences in how PTS was identified. 10–14yo tended to experiment with transitioning between gait modes until they settled on their PTS, while the older participants were able to generally determine their PTS on the first attempt. The inability to effectively determine PTS among the 10–14yo suggests that younger adolescents have not yet developed the ability to swiftly adapt gait patterns to address changing task demands. The present study provides further evidence that gait patterns do not mature before adolescence and that the development of mature walking and running patterns is a gradual process.

## Funding

This work was supported by the School of Sport, Exercise and Nutrition (Massey University, New Zealand), but had no involvement in the study design; collection, analysis or interpretation of the data; or in the writing of the report.

## Declaration of Competing Interest

The authors have no conflicts of interest to declare.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.humov.2019.06.012>.

## References

- Cavanagh, P. R., & Williams, K. R. (1982). The effect of stride length variation on oxygen uptake during distance running. *Medicine and Science in Sports and Exercise*, 14, 30–35.
- Cech, D., & Martin, S. (2002). *Functional movement development across the life span* (2nd ed.). Philadelphia, PA: W.B. Saunders.
- Cupp, T., Oeffinger, D., Tylkowski, C., & Augsburg, S. (1999). Age-related kinetic changes in normal pediatrics. *Journal of Pediatric Orthopedics*, 19, 475–478. [https://doi.org/10.1067/S0161-4754\(00\)90225-2](https://doi.org/10.1067/S0161-4754(00)90225-2).
- De Smet, K., Segers, V., Lenoir, M., & De Clercq, D. (2009). Spatiotemporal characteristics of spontaneous overground walk-to-run transition. *Gait & Posture*, 29, 54–58. <https://doi.org/10.1016/j.gaitpost.2008.06.005>.
- Diedrich, F. J., & Warren, W. H., Jr. (1995). Why change gaits? Dynamics of the walk-run transition. *Journal of Experimental Psychology. Human Perception and Performance*, 21, 183–202. <https://doi.org/10.1037/0096-1523.21.1.183>.
- Frost, G., Bar-Or, O., Dowling, J., & White, C. (1995). Habituation of children to treadmill walking and running: Metabolic and kinematic criteria. *Pediatric Exercise Science*, 7, 162–175. <https://doi.org/10.1123/pes.7.2.162>.
- Ganley, K. J., & Powers, C. M. (2005). Gait kinematics and kinetics of 7-year-old children: A comparison to adults using age-specific anthropometric data. *Gait & Posture*, 21, 141–145. <https://doi.org/10.1016/j.gaitpost.2004.01.007>.
- Gouelle, A., Leroux, J., Bredin, J., & Megrot, F. (2016). Changes in gait variability from first steps to adulthood: Normative data for the gait variability index. *Journal of Motor Behavior*, 48, 249–255. <https://doi.org/10.1080/00222895.2015.1084986>.
- Hausdorff, J. M., Zemany, L., Peng, C., & Goldberger, A. L. (1999). Maturation of gait dynamics: stride-to-stride variability and its temporal organization in children. *Journal of Applied Physiology (Bethesda, MD.:1985)*, 86, 1040–1047. <https://doi.org/10.1152/jappl.1999.86.3.1040>.
- Hogberg, P. (1952). How do stride length and stride frequency influence the energy-output during running? *Arbeitsphysiologie; Internationale Zeitschrift für Angewandte Physiologie*, 14, 437–441. <https://doi.org/10.1007/BF00934423>.
- Hollman, J. H., Watkins, M. K., Imhoff, A. C., Braun, C. E., Akervik, K. A., & Ness, D. K. (2016). A comparison of variability in spatiotemporal gait parameters between treadmill and overground walking conditions. *Gait & Posture*, 43, 204–209. <https://doi.org/10.1016/j.gaitpost.2015.09.024>.
- Hreljac, A. (1993). Preferred and energetically optimal gait transition speeds in human locomotion. *Medicine and Science in Sports and Exercise*, 25, 1158–1162. <https://doi.org/10.1249/00005768-199310000-00012>.
- Hreljac, A. (1995). Effects of physical characteristics on the gait transition speed during human locomotion. *Human Movement Science*, 14, 205–216. [https://doi.org/10.1016/0167-9457\(95\)00017-M](https://doi.org/10.1016/0167-9457(95)00017-M).
- Komar, J., Seifert, L., & Thouwareq, R. (2015). What variability tells us about motor expertise: Measurements and perspectives from a complex system approach. *Movement & Sport Sciences-Science & Motricité*, 65–77. <https://doi.org/10.1051/sm/2015020>.
- Kung, S. M., Fink, P. W., Hume, P., & Shultz, S. P. (2015). Kinematic and kinetic differences between barefoot and shod walking in children. *Footwear Science*, 7, 95–105. <https://doi.org/10.1080/19424280.2015.1014066>.
- Kung, S. M., Fink, P. W., Legg, S. J., Ali, A., & Shultz, S. P. (2018). What factors determine the preferred gait transition speed in humans? A review of the triggering mechanisms. *Human Movement Science*, 57, 1–12. <https://doi.org/10.1016/j.humov.2017.10.023>.
- Lerner, Z. F., Board, W. J., & Browning, R. C. (2014). Effects of an obesity-specific marker set on estimated muscle and joint forces in walking. *Medicine and Science in Sports and Exercise*, 46, 1261–1267. <https://doi.org/10.1249/MSS.0000000000000218>.
- Maruyama, H., & Nagasaki, H. (1992). Temporal variability in the phase durations during treadmill walking. *Human Movement Science*, 11, 335–348. [https://doi.org/10.1016/0167-9457\(92\)90004-U](https://doi.org/10.1016/0167-9457(92)90004-U).
- Muller, J., Muller, S., Baur, H., & Mayer, F. (2013). Intra-individual gait speed variability in healthy children aged 1–15 years. *Gait & Posture*, 38, 631–636. <https://doi.org/10.1016/j.gaitpost.2013.02.011>.
- Prilutsky, B. I., & Gregor, R. J. (2001). Swing- and support-related muscle actions differentially trigger human walk-run and run-walk transitions. *Journal of Experimental Biology*, 204, 2277–2287.
- Rogers, D. M., Turley, K. R., Kujawa, K. I., Harper, K. M., & Wilmore, J. H. (1994). The reliability and variability of running economy in 7-, 8-, and 9-year-old children. *Pediatric Exercise Science*, 6, 287–296. <https://doi.org/10.1123/pes.6.3.287>.
- Schieb, D. A. (1986). Kinematic accommodation of novice treadmill runners. *Research Quarterly for Exercise and Sport*, 57, 1–7.
- Selinger, J. C., O'Connor, S. M., Wong, J. D., & Donelan, J. M. (2015). Humans can continuously optimize energetic cost during walking. *Current Biology*, 25, 2452–2456. <https://doi.org/10.1016/j.cub.2015.08.016>.
- Sutherland, D. (1997). The development of mature gait. *Gait & Posture*, 6, 163–170. [https://doi.org/10.1016/S0966-6362\(97\)00029-5](https://doi.org/10.1016/S0966-6362(97)00029-5).
- Tseh, W., Bennett, J., Caputo, J. L., & Morgan, D. W. (2002). Comparison between preferred and energetically optimal transition speeds in adolescents. *European Journal of Applied Physiology*, 88, 117–121. <https://doi.org/10.1007/s00421-002-0698-x>.
- Ulman, S., Ranganathan, S., Queen, R., & Srinivasan, D. (2019). Using gait variability to predict inter-individual differences in learning rate of a novel obstacle course. *Annals of Biomedical Engineering*, 47, 1191–1202. <https://doi.org/10.1007/s10439-019-02236-x>.
- Van Caekenbergh, I., Segers, V., De Smet, K., Aerts, P., & De Clercq, D. (2010). Influence of treadmill acceleration on actual walk-to-run transition. *Gait & Posture*, 31, 52–56. <https://doi.org/10.1016/j.gaitpost.2009.08.244>.
- Van de Walle, P., Desloovere, K., Truijten, S., Gosselink, R., Aerts, P., & Hallemans, A. (2010). Age-related changes in mechanical and metabolic energy during typical gait. *Gait & Posture*, 31, 495–501. <https://doi.org/10.1016/j.gaitpost.2010.02.008>.
- van Melick, N., Meddeler, B. M., Hoogeboom, T. J., Nijhuis-van der Sanden, M. W. G., & van Cingel, R. E. H. (2017). How to determine leg dominance: The agreement between self-reported and observed performance in healthy adults. *PLoS ONE*, 12, e0189876. <https://doi.org/10.1371/journal.pone.0189876>.
- Whitall, J., & Getchell, N. (1995). From walking to running: Applying a dynamical systems approach to the development of locomotor skills. *Child Development*, 66, 1541–1553. <https://doi.org/10.2307/1131663>.