AGE-RELATED DETERMINANTS OF THE WALK-TO-RUN TRANSITION IN YOUTH

A thesis presented in partial fulfilment of the requirements for the degree of

Doctor of Philosophy
in Sport and Exercise Science

Massey University
Wellington, New Zealand

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2020

ABSTRACT

There is a lack of consensus regarding when mature or adult-like gait is achieved in youth. The ability to adjust gait during the walk-to-run transition (WRT) may be a good indicator of whether gait has matured. Specifically, age-related differences in the preferred transition speed (PTS) and determinants of WRT can provide insight into self-organising behaviours and how effectively gait patterns are regulated in youth. This thesis therefore assessed WRT in 49 youth (10-17-year-olds) and 13 young adults (19-29-year-olds) to: 1) investigate how effectively youth can adjust to increasing gait speed; and 2) explore age-related differences in determinants of PTS. Participants completed a WRT treadmill protocol that started at a self-selected walking speed and increased by 0.06 $m \cdot s^{-1}$ every 30 s to determine PTS. Participants also walked and ran on a treadmill at speeds near PTS (PTS, PTS±0.14 $m \cdot s^{-1}$, PTS±0.28 $m \cdot s^{-1}$). During these tests, muscle activity (rectus femoris, biceps femoris, tibialis anterior, medial gastrocnemius), oxygen consumption, heart rate and perceived exertion were assessed for their role in determining PTS. There were no age-related differences in PTS despite there being anthropometric differences. However, 10-12-year-olds exhibited more exploratory behaviour when determining PTS, while adults and 15-17-year-olds generally used a single transition to determine PTS. Age-related differences in PTS determinants were observed. Specifically, the biceps femoris and medial gastrocnemius were additional weak links among 10-12-year-olds and 10-17-year-olds, respectively, suggesting these muscles continue developing through childhood and adolescence. Because youth transition to minimise the demands of more muscles than adults, they may have more conflicting sources of feedback arising from the musculature when adjusting their gait. The 10-14-year-olds also exhibited greater difficulties distinguishing differences in perceived exertion between walking and running at speeds near PTS. The inability to anticipate increases in effort as gait speed increased could explain the indecisiveness in determining PTS among 10-12-year-olds. Overall, this thesis improves our understanding about rate-limiting factors of gait maturation. It seems that 10-12-year-olds have more conflicting sensory cues involved in regulating gait, which can cause difficulties determining how to optimise their gait. As the musculoskeletal system matures through adolescence, so does the ability to adapt gait effectively.

ACKNOWLEDGEMENTS

The various experiences and learning opportunities I've had throughout this PhD candidacy has emphasised the importance of the journey, rather than the destination – and what a rollercoaster of a journey it has been too! There are many acknowledgements that need to be made, as the completion of this thesis has seemed very much like a team effort.

I first want to acknowledge my amazing team of supervisors: Prof. Sarah Shultz, Dr. Philip Fink, Prof. Stephen Legg and Assoc. Prof. Ajmol Ali. They have all done a great job helping me get across the finish line through the sharing of many wise words, ongoing guidance, advice, encouragement and patience, as well as providing the odd giggle to help me get through the tough grind. I particularly want to thank my primary supervisors, Sarah and Phil, for always making themselves available in times of need, for their invaluable help with devising solutions when things didn't go according to plan, as well as reviewing countless iterations of my work. Furthermore, I want to thank Sarah for nurturing my professional and personal growth leading up to and throughout this degree by always pushing me to realise my full potential, and for sharing her enthusiasm for all things biomechanics – without which I most likely would not have embarked on this journey. She has been there to share the highs of this PhD with, but more importantly to help deal with the lows and always provided the best pep talks to keep me trucking along. I also want to thank the rest of the amazing Shultz-Payne family (Gus-inclusive) for being such generous and accommodating hosts in Seattle and more importantly, for putting up with me taking so much of Sarah's time over the years.

I also want to acknowledge and thank all the research assistants who helped me with the substantial amount of data collection involved in this research and my brother Nathan, for his help with data processing. Without the help from each and every one of these amazing people I would not have been able to collect all of my data. A special mention goes to Anja Fricke, who spent many hours in the lab with me during the early stages of testing and helped keep these sessions running smoothly while I was still finding my feet. The lab managers, Brooke Price and Caitlin Robinson must also be acknowledged for ensuring I always had the equipment needed for my research – especially regarding the dreaded task of trying to get our hands on the high in demand Cosmed unit. I also want to thank Dr Blake Perry for his technical assistance and advice for using and analysing the data collected with the Cosmed K4b2. A big thank you also goes to my amazing participants and the families of my younger participants for giving up their time to take part in this research – without them, this research would not have been possible!

The demands of the PhD life not only test you academically, but also mentally and emotionally, so I want to thank my fellow PhD students for being there to share war stories and help blow off steam with – they have been the most amazing support group, both on and off campus. Putting together a doctoral thesis is by no means an easy task, so having this great group of peers to go on this journey with made this experience more enjoyable. I particularly want to thank Victoria Chinn and Tina Nie for their support as I went through the dark tunnel and for showing me that there is light at the other end. Additionally, I would like to thank my family for their support, encouragement and patience, and my friends who were always up for an adventure when I needed to head for the hills (both literally and figuratively).

Finally, I would like to thank Massey University for awarding me a doctoral scholarship to complete this degree, funding this project, providing me with valuable teaching and mentoring work experience and for the additional financial support to help fund my travels to attend international conferences and to work on my thesis in Seattle during the later stages of my PhD journey.

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List of Abbreviations

AIC	Akaike Information Criterion
ANOVA	Analysis of variance
$b \cdot min^{-1}$	Beats per minute
BF	Biceps femoris
COM	Centre of mass
CV	Coefficient of variation
EMG	Electromyography
EOTS	Energetically optimal transition speed
F	Females
GRF	Ground reaction force
HR	Heart rate
Hz	Hertz
kg	Kilogram
PTS	Preferred transition speed
m	Metres
M	Males
$m \cdot s^{-1}$	Metres per second
MG	Medial gastrocnemius
OMNI-RPE	OMNI perceived exertion scale
RF	Rectus femoris
RMS	Root mean square
RPE	Ratings of perceived exertion
RWT	Run-to-walk transition
s	Seconds
SD	Standard deviation
SENIAM	Surface Electromyography for the Non-Invasive Assessment of Muscles
SSW	Self-selected walking speed
TA	Tibialis anterior
TOTS	Theoretically optimal transition speed
$\dot{V}O_2$	Volume of consumed oxygen
$\dot{V}O_2peak$	Peak oxygen consumption
WRT	Walk-to-run transition
yo	-year-olds

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Supplementary Figures [1]

[1] Supplementary figures present the potential nonlinearities in the relationships between the muscular and physiological responses to gait speed for walking and running during the walk-to-run transition protocol across the age range (10-29-year-olds).

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Supplementary Tables [1]

[1] Supplementary tables present the preliminary results from Chapter 3. These data were analysed for the eight paediatric groups (i.e. 10-, 11-, 12-, 13-, 14-, 15-, 16- and 17-year-olds) prior to combining the age groups for further analysis throughout the thesis.

CHAPTER 1

Why study gait transitions in youth?

1.1. Importance of bipedal locomotion

Bipedal locomotion is an essential part of our lives that is critical for independent living (Cech & Martin, 2002). Humans walk and run as an economical means of transport, as well as to participate in various physical activities that contribute to their health and wellbeing. Gait abnormalities can adversely affect an individual's quality of life (Forhan & Gill, 2013; Keawutan et al., 2018; Pelosin et al., 2009; Schmid et al., 2007; Wurdeman, Stevens, & Campbell, 2017). It is important for clinicians and researchers to have a good understanding of healthy gait, including its normal development and maturation, as well as the control mechanisms used to regulate gait patterns. This information can then be used to help tailor appropriate treatment and management plans for individuals with gait abnormalities.

1.2. Self-organising behaviours that regulate gait patterns

Adults prefer to adopt gait patterns that minimise the metabolic cost of locomotion. Specifically, the most economical combinations of stride length and stride frequency while walking and running are often selected (Cavanagh & Williams, 1982; Hogberg, 1952; Holt, Hamill, & Andres, 1991; Zarrugh, Todd, & Ralston, 1974). Adults also optimise their gait by swiftly adjusting their strides to avoid incurring unnecessarily high metabolic costs (Selinger, O'Connor, Wong, & Donelan, 2015). Furthermore, walking is generally preferred at slower locomotive speeds, when kinetic and gravitational-potential energy exchanges are highly conservative (Diedrich & Warren, 1995; Farley & Ferris, 1998). Conversely, running is preferred at faster speeds when elastic energy can be more effectively exploited (Farley & Ferris, 1998). These optimising behaviours appear to occur in a seemingly effortless manner, as locomotion generally requires low amounts of cognitive attention (Abernethy, Hanna, & Plooy, 2002; Schaefer, Jagenow, Verrel, & Lindenberger, 2015). To further demonstrate gait optimisation and the presence of self-organising behaviours, humans exhibit spontaneous transitions between walking and running as the speed of locomotion changes.

1.2.1. Gait transitions

Gait transitions have consistently been reported to naturally occur at a preferred transition speed (PTS) of approximately 2 $m \cdot s^{-1}$ in adults (Brisswalter & Mottet, 1996; Diedrich & Warren, 1995; Hreljac, 1993b, 1995b; Neptune & Sasaki, 2005; Prilutsky & Gregor, 2001; Rotstein, Inbar, Berginsky, & Meckel, 2005; Ziv & Rotstein, 2009). Dynamic systems theory and self-organising behaviours have been used to investigate why gait transitions tend to occur at this common PTS and to identify determining factors of PTS. Self-organising behaviours would require mechanisms to detect changes in the locomotive demands and trigger the necessary adjustments to maintain gait optimisation. These mechanisms have been suggested to optimise the metabolic and mechanical economy of gait and to minimise the mechanical load during locomotion (Diedrich & Warren, 1995; Mohler, Thompson, Creem-Regehr, Pick, & Warren, 2007).

Gait transitions identify a specific moment when locomotive demands have been thought to exceed a critical threshold, resulting in a transition between walking and running (Hreljac, 1993a; Malcolm, Fiers, et al., 2009). The factor(s) that reach their respective critical values first have been suggested to represent ‘weak links,’ which ultimately drive the transition between walking and running (Malcolm, Fiers, et al., 2009). Researchers have studied gait transitions and the factors that drive them to gain insight into the underlying control mechanisms of gait in adults (Bartlett & Kram, 2008; Brisswalter & Mottet, 1996; Diedrich & Warren, 1995; Hreljac, 1993a; Hreljac, 1993b, 1995b; Malcolm, Segers, Van Caekenberghe, & De Clercq, 2009; Mohler et al., 2007; Monteiro, Farinatti, de Oliveira, & Araújo, 2011; Neptune & Sasaki, 2005; Prilutsky & Gregor, 2001; Sasaki & Neptune, 2006; Seay, Haddad, van Emmerik, & Hamill, 2006; Segers, Lenoir, Aerts, & De Clercq, 2007). However, paediatric gait transitions have not had the same amount of attention (Tseh, Bennett, Caputo, & Morgan, 2002). Investigating differences in these weak links between youth (i.e. individuals younger than 18 years of age) and adults may provide useful information about how paediatric gait is regulated and could thus reveal rate-limiting factors of gait maturation.

1.2.2. Factors that could affect gait transitions in youth

Young adults and youth would be expected to transition differently for a number of reasons. Children and adolescents are still developing, as are their gait patterns. However, there lacks a clear consensus regarding the age at which mature or adult-like gait is achieved (Chester, Tingley, & Biden, 2006; Froehle, Nahhas, Sherwood, & Duren, 2013; Hausdorff, Zemany, Peng,

& Goldberger, 1999; Sutherland, 1997; Van de Walle et al., 2010). Walking has been suggested to mature as early as 7-8 years old (Dusing & Thorpe, 2007; Sutherland, Olshen, Cooper, & Woo, 1980). However, more evidence suggests gait continues maturing until late childhood or early-to-mid adolescence because children and adolescents have exhibited diminished joint kinetics (Chester et al., 2006; Ganley & Powers, 2005; Van de Walle et al., 2010) and more variability in their muscle activity patterns (Tirosh, Sangeux, Wong, Thomason, & Graham, 2013) and spatiotemporal parameters (Bisi & Stagni, 2016; Gouelle, Leroux, Bredin, & Megrot, 2016; Hausdorff et al., 1999; Muller, Muller, Baur, & Mayer, 2013).

Anthropometric scaling alone does not account for differences in children's spatiotemporal parameters prior to 3.5-4 years old (Sutherland, 1997). Thelen's research with infants suggested that development of muscular strength and changes in body size and composition are rate-limiting factors during the initial years of gait development (Thelen, 1986; Thelen & Cooke, 1987). Differences in early walking patterns have also been suggested to be attributed to central nervous system development (Sutherland, 1997). While the exact mechanisms limiting this initial gait development is unclear, it appears that gait patterns are adapted to help minimise the risk of falling (Vaughan, 2003). As strength and postural control rate-limiting factors improve, gait patterns shift more toward adult-like gait and there is a greater emphasis on improving gait economy (Dusing & Thorpe, 2007; Frost, Dowling, Dyson, & Bar-Or, 1997; Lythgo, Wilson, & Galea, 2009; Okamoto, Okamoto, & Andrew, 2003; Sutherland et al., 1980). Thereafter, leg length can account for the majority of differences in step lengths and walking speed between adults and children up to the age of 10 years (Dusing & Thorpe, 2007; Sutherland et al., 1980). Thus, it would be expected that gait transitions, particularly children's PTS, would be scaled to their smaller body size and leg lengths when compared to adults. However, changes in cadence, durations of single and double support, base of support and step length continue into adolescence along with ongoing growth of the legs, while walking speed seems to plateau after the age of 8 years (Froehle et al., 2013). Therefore, additional factors besides growth must also influence the rate of gait maturation.

Muscle strength and motor control may also affect gait transitions and the ability to optimise locomotion. As gait regulation shifts towards improving the economy of locomotion during childhood, muscle activity durations (Sutherland et al., 1980) and muscle co-activation (Frost et al., 1997) progressively decrease in children until approximately 15-16 years of age. Children's hip and knee kinetics mature as early as 5 years old (Chester et al., 2006; Ganley &

Powers, 2005). However, mature control of the ankle joint is not achieved until later because 7-9-year-olds (yo) continue to exhibit diminished ankle plantarflexor moments and ankle power while walking compared to adults (Chester et al., 2006; Cupp, Oeffinger, Tylkowski, & Augsburger, 1999; Ganley & Powers, 2005). Ground reaction forces (GRF) during running have also indicated that 4- and 6-yo possess immature ankle control, exhibiting larger impact forces in the vertical direction and more erratic braking forces in the anterior-posterior GRF (Fortney, 1983). Children may therefore experience difficulties dissipating force during weight acceptance. A limited ability to perform negative joint work and recover mechanical energy until 9- and 11-years of age, respectively (Van de Walle et al., 2010), would contribute to these difficulties at weight acceptance. Moreover, immature muscle-tendon units and their limited capacity to store and release elastic energy (Waugh, Korff, & Blazevich, 2017) may contribute to the limited amounts of mechanical energy recovery in children. If gait transitions are regulated by mechanisms to optimise mechanical aspects of locomotion, the behaviour of these mechanisms may differ in children due to differences in their muscle function. Furthermore, as energy expenditure is associated with muscle activity (Frost et al., 1997), the higher amounts of muscle activity among children may also affect the ability to optimise the metabolic economy during children's gait transitions.

Variability of gait patterns can also provide information about the maturity of paediatric gait. Greater amounts of variability within a gait pattern can reflect a lack of skill proficiency, or adaptability of a skill. However, it is difficult differentiating between which of these factors are causing gait to be more variable. The variability that could hinder performance presumably reflects a lack of skill proficiency and would thus be considered as 'bad' variability. From this perspective, greater amounts of variability would reflect immature gait or ongoing development of neuromuscular control during locomotion. As such, gait may only be considered to be mature once there are adult-like amounts of variability in various gait parameters. Accordingly, children's gait becomes progressively more mature with age, alongside decreasing variability in the muscle activity patterns (Granata, Padua, & Abel, 2005) and spatiotemporal parameters (Gouelle et al., 2016; Hausdorff et al., 1999; Muller et al., 2013). In particular, muscle activity patterns do not appear to mature until at least 10 years old (Granata et al., 2005). Spatiotemporal variability predominantly decreases prior to 8 years old (Hausdorff et al., 1999; Muller et al., 2013), but the amount of variability continues to decrease through adolescence (Gouelle et al., 2016; Muller et al., 2013).

Variability within a skill could also be considered to be functional as it enables adaptability of the motor task (Komar, Seifert, & Thouvarecq, 2015; Vereijken, 2010). Functional variability could also be associated with learning and would assist with adapting gait to changing anthropometric characteristics during periods of growth. After a growth spurt, adolescents have exhibited more gait variability when compared to adolescents who had not just experienced a sudden increase in height (Bisi & Stagni, 2016). Therefore, as body dimensions continue to change, greater amounts of variability may be used to help recalibrate gait to changing individual constraints. This fine-tuning of gait would presumably continue into adolescence, as the lower limbs continue lengthening until approximately 13-15 years of age along with various spatiotemporal parameters (Froehle et al., 2013; Lythgo et al., 2009). Since gait continues to be adjusted to ongoing growth, the ability to optimise locomotion may be limited until an individual stops growing. Moreover, children only develop the ability to optimise walking patterns to minimise the metabolic cost by 7-12 years of age (Jeng, Liao, Lai, & Hou, 1997). Prior to this age, 3-4 yo were often unable to modulate stride frequency, whereas 5-6yo could regulate their stride frequencies, but their gait was not constrained to minimising metabolic cost (Jeng et al., 1997). Therefore, continuous fine-tuning of gait due to growth, as well as a limited ability to optimise gait would presumably be detrimental to children's gait transitions. Consequently, children may be less successful at minimising the metabolic and mechanical demands of locomotion until growth has completed.

In summary, numerous factors could affect paediatric gait transitions and the ability to effectively optimise gait in youth. Greater amounts of muscle activity among children could affect how successfully gait transitions minimise the mechanical load and optimise gait economy during locomotion. Ongoing fine-tuning of gait due to growth may affect the ability to effectively regulate locomotion and thus determine PTS during late childhood and/or adolescence. Therefore, investigating differences in the mechanisms that trigger gait transitions in a paediatric population could help to gain insight into the factors influencing gait maturity. If the critical thresholds of the determinants differ between youth and adults due to growth and development, it could be expected that: a) PTS would also differ; and/or b) the determinants of PTS may differ, suggesting youth have different weak links. The ability to effectively adapt a skill to various environmental and task constraints has been suggested to be a good indicator of whether or not a skill has been mastered (Komar et al., 2015). Therefore, exploring age-related differences in the determinants of PTS and understanding how these factors influence the ability to adjust gait during the walk-to-run transition (WRT) may provide new information about gait maturation and the associated rate-limiting factors.

1.3. Aims

The overarching aims of this thesis are to:

1) Investigate how effectively youth can adjust their gait to changing locomotive demands (i.e. increasing gait speed) compared to young adults.
2) Explore age-related differences in the determinants of the preferred transition speed (PTS) between youth and young adults during the walk-to-run transition (WRT).

1.4. Structure of the thesis

Following this introductory chapter (*Chapter 1*), the next four chapters of this thesis have been prepared as a collection of manuscripts that have been submitted or are already published in refereed journals. They consist of a review article (*Chapter 2*) and three original research studies that address the overarching aims of the thesis (*Chapters 3-5*). *Chapter 3* addresses the first aim, while *Chapters 4 and 5* address the second aim. The prepared manuscripts have been reformatted from their original form for consistency of style throughout the thesis, but the content generally remains the same unless otherwise specified in the footnote following the abstract at the beginning of each chapter. *Chapters 2 and 3* have been published in *Human Movement Science*. *Chapter 4* has been submitted to the *Journal of Biomechanics* and *Chapter 5* has been submitted to *Pediatric Exercise Science*; both of these manuscripts are currently under review. Since these chapters have been prepared as manuscripts suitable for publication in peer-reviewed journals, there may be some repetition throughout the thesis. The statements of contribution for *Chapters 2-5* can be found in *Appendix K*.

Chapter 2 presents a review of PTS determinants in humans. The review starts by setting the rationale for the presence of self-organising behaviours in humans and how these behaviours can be applied to gait transitions. The next section of the review presents individual constraints of PTS and identifies factors contributing to four potential triggers of gait transitions (i.e. *metabolic economy*, *mechanical economy*, *mechanical load* and *cognitive and perceptual* triggers). The final section of the review then critiques and revises four previously proposed criteria that were used to assess whether variables could be considered as determining factors of PTS (Hreljac, 1995a). The revised criteria will then be used to assess whether the proposed triggers could be used to initiate gait transitions.

To address the overarching aims of the thesis, a single comprehensive project was completed, from which *Chapters 3, 4 and 5* are derived. The project consisted of three testing sessions that were used to assess the WRT of 49 youth (10-17 yo), as well as their walking and running patterns at a range of speeds near PTS. Participants completed the testing sessions at least 48 hours apart, but within a week of each other. Preliminary analyses of stride duration variability during the WRT protocol in 10-13 yo revealed an increase in variability following the transition (Appendix M), which contrasted what was previously seen in adults (Brisswalter & Mottet, 1996). To ensure WRT differences were age-related rather than protocol-related, 13 young adults (19-29 yo) were also assessed, which enabled the paediatric gait to be directly compared to presumably typical mature gait under the same testing conditions. Using data from the preliminary analysis (Appendix M) and Brisswalter and Mottet (1996), an *a priori* calculation was performed to determine a sample size of n=12 per group would provide 80% power to detect differences at a significance level of 5%. At least six participants were recruited at each age between 10-17 years, under the assumption that the paediatric participants could be grouped with an age range of at least two years.

Although four potential gait transition triggers were identified in *Chapter 2*, the thesis focuses on exploring age-related differences in the transition process (*Chapter 3*), the metabolic economy and mechanical load determinants (*Chapter 4*), and the cognitive and perceptual determinants (*Chapter 5*). The mechanical economy determinants were not addressed in this thesis because an instrumented treadmill was not available to measure the necessary kinetic data. More specifically, *Chapter 3* investigates whether there are age-related differences in gait maturity through the analysis of spatiotemporal variability and comparisons of PTS and how PTS is determined between youth and adults. Three age-related levels of gait maturity were observed in *Chapter 3*, which highlighted differences in gait variability and how well gait is regulated among children and adolescents compared to adults. There were a lack of age-related PTS differences, but the process of determining PTS did differ across the levels of gait maturity. As PTS did not scale to body size, it was hypothesised that there were age-related differences in the PTS determinants. The aims of *Chapters 4 and 5* build on from the observations made in *Chapter 3* to test this hypothesis. Specifically, *Chapter 4* aims to identify metabolic and mechanical load factors that may explain why the younger participants did not transition at a slower speed than the older participants. To address this aim, the criteria outlined in *Chapter 2* were used to identify age-specific physiological and muscular weak links across the different levels of gait maturity identified in *Chapter 3*. The physiological and muscular weak links were considered to have a potential role in determining the PTS, acting through the metabolic economy and mechanical load triggers, respectively. *Chapter 5* then investigates age-related differences in the influence perceived exertion has on PTS across the different levels of gait maturity to identify why children exhibited a more variable WRT process than the adults as seen in *Chapter 3*.

The final chapter (*Chapter 6*) provides a general discussion that integrates the findings from the research chapters, thus providing an overview of how youth's WRT differ from those of adults and the factors that contribute to these age-related differences. It also considers the limitations of the thesis and provides suggestions for future research. The chapter finishes with the conclusions of this thesis.

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CHAPTER 2

What factors determine the preferred gait transition speed in humans? A review of the triggering mechanisms*

2.0. Abstract

Human locomotion is a fundamental skill that is required for daily living, yet it is not completely known how human gait is regulated in a manner that seems so effortless. Gait transitions have been analysed to gain insight into the control mechanisms of human locomotion since there is a known change that occurs as the speed of locomotion changes. Specifically, as gait speed changes, there is a spontaneous transition between walking and running that occurs at a particular speed. Despite the growing body of research on the determinants of this preferred transition speed and thus the triggering mechanisms of human gait transitions, a clear consensus regarding the control mechanisms of gait is still lacking. Therefore, this article reviews the determinants of the preferred transition speed using concepts of the dynamic systems theory and how these determinants contribute to four proposed triggers (i.e. *metabolic economy*, *mechanical economy*, *mechanical load* and *cognitive and perceptual*) of human gait transitions. While individual anthropometric and strength characteristics influence the preferred transition speed, they do not act to trigger a gait transition. The research has more strongly supported the mechanical economy and mechanical load determinants as triggering mechanisms of human gait transitions. These mechanical factors acting through proprioceptive feedback, combined with cognitive and perceptual processes may thus be used to regulate human gait patterns as the speed of locomotion changes.

Keywords: Biomechanics, energetics, perceptions, triggers

* Published manuscript:

SM Kung, PW Fink, SJ Legg, A Ali & SP Shultz (2018). What factors determine the preferred gait transition speed in humans? A review of the triggering mechanisms. *Human Movement Science*, 57, 1-12.

Notes:
This chapter has been adapted from the original review article published in *Human Movement Science* and has reproduced the original figures and tables from this publication (Kung, Fink, Legg, Ali, & Shultz, 2018). Revisions in the text have been made to clarify the terminology used in this chapter and throughout the rest of the thesis, particularly regarding the use of 'economy' (i.e. energy cost of transport per unit distance) versus 'efficiency' (i.e. amount of work done relative to the energy expended). As the triggers help reduce the metabolic and mechanical costs of transport, the use of 'economy' was preferred in this chapter and throughout the thesis as it more accurately reflects the outcomes of the energetic (metabolic and mechanical) triggers.

Available at: https://doi.org/10.1016/j.humov.2017.10.023

2.1. Introduction

Human locomotion is a fundamental skill that is integrated into various activities of daily living. Following the acquisition of bipedal locomotion, healthy adult gait requires little cognitive input (Abernethy, Hanna, & Plooy, 2002). However, the complexity of human locomotion may be overlooked due to the frequency and ease of its use. The ability to constantly adapt gait to various individual and task constraints requires mechanisms to provide continuous feedback about the adopted gait pattern. Gait transitions offer a unique insight into possible underlying mechanisms that shape human locomotion, as there is a change in the mode of gait as the speed of locomotion changes.

Humans generally either walk or run depending on the locomotive speed; walking is preferred at slower speeds of locomotion whereas running is preferred at faster speeds. As the speed of locomotion changes, there is a spontaneous transition between the walking and running modes of gait. That is, gait transitions are not premeditated or pre-planned actions, but may occur naturally without conscious thought. A walk-to-run transition (WRT) occurs with increasing locomotive speeds, while a run-to-walk transition (RWT) occurs as the speed decreases. Gait transitions have been shown to occur over a number of steps, including the steps directly before and after the transition step (Hagio, Fukuda, & Kouzaki, 2015; Li & Hamill, 2002; Li & Ogden, 2012; Segers, De Smet, Van Caekenberghe, Aerts, & De Clercq, 2013; Van Caekenberghe, Segers, De Smet, Aerts, & De Clercq, 2010). While the transition step more closely resembles the post-transition mode of gait, there are still numerous kinematic and kinetic differences (Segers et al., 2013). This set of ordered behaviours does not necessarily reflect a lack of spontaneity when transitioning. Rather, gait transitions occur over a number of steps to maintain balance and upright posture and to prepare the system for the transition between these two mechanically different modes of gait.

There are a number of theories about why humans transition between walking and running, particularly as the preferred transition speed (PTS) in young adults has consistently been reported to occur within a narrow range of speeds around 2 $m{\cdot}s^{-1}$ (Brisswalter & Mottet, 1996; Diedrich & Warren, 1995; Hreljac, 1993b; Hreljac, Imamura, Escamilla, & Edwards, 2007b; Prilutsky & Gregor, 2001; Thorstensson & Roberthson, 1987; Tseh, Bennett, Caputo, & Morgan, 2002; Ziv & Rotstein, 2009). These theories include anthropometric characteristics (Alexander, 1984) and energy conserving or protective mechanisms (Cavagna & Kaneko, 1977; Farley & Taylor, 1991; Hreljac, 1993b; Prilutsky & Gregor, 2001). Previous studies have demonstrated that humans tend to use the most metabolically economical gait pattern, especially in terms of adopting the optimal combination of stride length and stride frequency (Cavanagh & Williams, 1982; Hogberg, 1952; Holt, Hamill, & Andres, 1991; Zarrugh, Todd, & Ralston, 1974). Deviations from this preferred combination of stride length and stride frequency have increased oxygen consumption during both walking (Zarrugh et al., 1974) and running (Cavanagh & Williams, 1982; Hogberg, 1952), thus reducing the economy of the gait pattern. Therefore, the transition may be a response to the change in the combination of stride length and stride frequency rather than locomotive speed itself, as the speed of locomotion is the product of these spatiotemporal variables. Altering spatiotemporal parameters may have important implications on the energy cost of transport and effort required at the cellular and musculoskeletal levels, especially when considering the differences in the mechanics of walking and running (i.e. inverted pendulum model of walking versus the spring-mass model of running (Farley & Ferris, 1998)). At the PTS, it would seem that the body experiences either unfavourable or unstable patterns of coordination that are difficult to maintain. This instability is demonstrated by greater variability in gait patterns (Brisswalter & Mottet, 1996; Diedrich & Warren, 1995), as well as greater muscle activity (Li & Ogden, 2012; Prilutsky & Gregor, 2001) and energy expenditure (Mercier et al., 1994). Thus, a single gait determinant, or a combination of determinants, may reach a critical value at the PTS, thereby triggering the transition between the modes of gait.

Numerous determinants of the PTS have been investigated, but there is not a clear consensus regarding the triggering mechanisms of gait transitions and thus the underlying control mechanisms of gait. The previously proposed energy conserving and protective mechanisms that trigger gait transitions are thought to help conserve metabolic (Hreljac, 1993b) and mechanical (Cavagna & Kaneko, 1977; Minetti, Ardigo, & Saibene, 1994) energy and to reduce musculoskeletal stress and minimise the risk of injury (Farley & Taylor, 1991; Hreljac, 1993a; Prilutsky & Gregor, 2001). Accordingly, the determinants that reflect energy conserving and protective mechanisms have been used to form hypotheses about the triggering mechanisms of human gait transitions (Diedrich & Warren, 1995; Mohler, Thompson, Creem-Regehr, Pick, & Warren, 2007). Specifically, these proposed triggers of gait transitions have included energetic (i.e. *metabolic and mechanical economy)* and mechanical (i.e. *mechanical load*) triggers, respectively. These triggers presumably work through proprioceptive feedback that may act at the spinal level; however, cognitive or perceptual processes must also be considered. Therefore, there may also be a *cognitive* or *perceptual* trigger that would assist the mechanical load trigger in reducing musculoskeletal stress and the risk of injury through cognitive and perceptual processes. The proposed triggers and their accompanying determinants are presented in Figure 2.1.

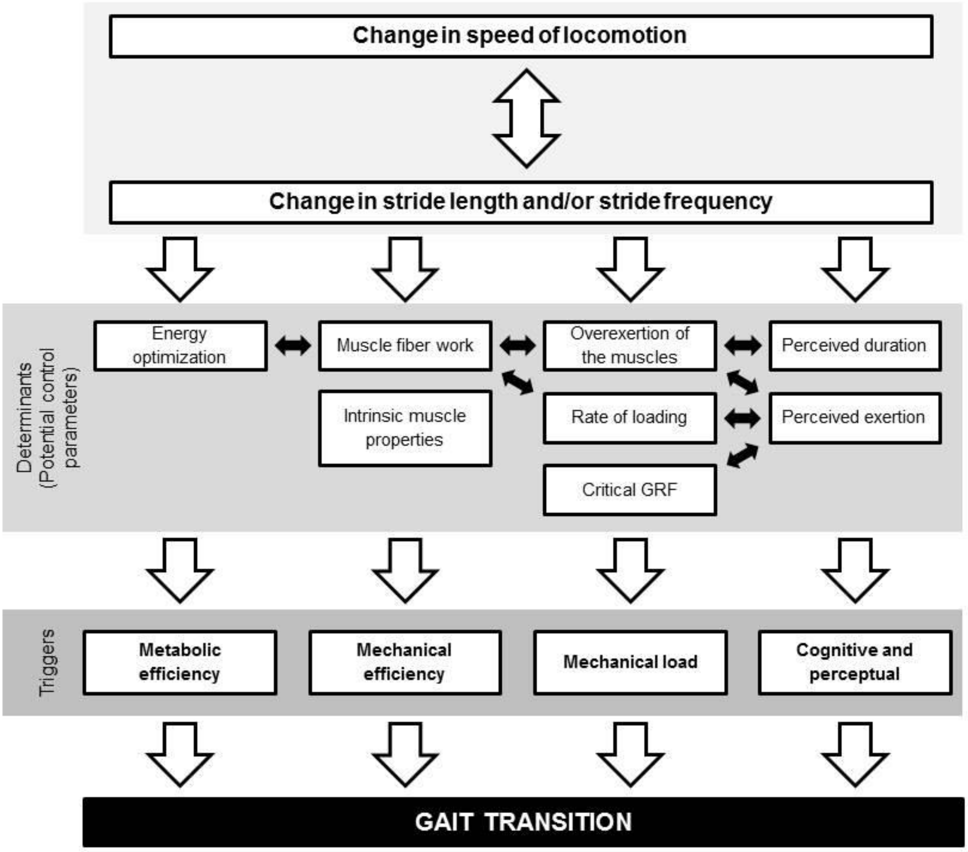

Figure 2.1. The proposed triggers of human gait transitions and the determinants of the speed at which individuals prefer to transition between gaits. As the speed of locomotion and thus the combination of stride length and stride frequency change, the values of the determinants also change; when they reach a critical value it is hypothesised that a gait transition is triggered. The black arrows indicate possible interactions between the determinants.
Please note that the metabolic efficiency and mechanical efficiency triggers (referred to as 'metabolic economy' and 'mechanical economy' in the text) presented in this figure would act to improve gait economy (i.e. the metabolic and mechanical cost of transport per unit distance) rather than its efficiency.

While the aim of each of the proposed triggers are different, the determinants that fall within each trigger are highly correlated, thus presenting a challenge when identifying which determinants drive the transition between walking and running as task constraints change. The *dynamic systems theory* provides a foundation from which the determinants of the PTS can be analysed, particularly regarding their role in triggering gait transitions (Diedrich & Warren, 1995; Kelso, 1984; Kelso & Schöner, 1988). The dynamic systems theory was initially used to identify transitional behaviour during hand and finger coordination activities (Kelso, 1984; Kelso & Schöner, 1988). When applied to gait transitions, walking and running are considered as two separate organisational states of the system, or 'attractors,' while gait transitions resemble phase transitions. As the task constraints change, accompanying changes in the determinants of the PTS would trigger a gait transition. The purpose of this chapter is to review (a) the dynamic systems theory as a basis from which gait transitions are analysed; and (b) the determinants of the PTS and their role in triggering gait transitions in humans.

2.2. How does the dynamic systems theory apply to human gait transitions?

Dynamic systems theory applies principles of self-organisation to understand how low dimensional (i.e. ordered) behaviour arises in human coordination (Kelso, 1997). In particular, it proposes that orderly behaviour arises out of the nonlinear interaction between different components (e.g. limbs, perceptual variables, neurons in the brain) without reliance on a centrally controlled or stored pattern. Using this theory, coordination between effectors can be captured by a collective variable, which undergoes a qualitative shift (i.e. a phase transition) as a control parameter is varied. In the classic example of bimanual finger coordination (Kelso, 1984), both in-phase (where both index fingers perform the same action at the same time) and anti-phase (where when one finger abducts, the other adducts, and vice versa) coordination is possible at slow movement frequencies. As the control parameter of movement frequency is increased, anti-phase coordination becomes more difficult, and at a critical value of the control parameter a shift from anti- to in-phase coordination is observed (Kelso, 1997).

Transitions between gait patterns appear to act in a similar manner to previous experiments of dynamic systems theory (Kelso & Schöner, 1988). For example, an early study of gait transitions in a decerebrate cat (Shik, Severin, & Orlovskii, 1966) provided evidence that coordination can naturally emerge without a centrally controlled plan (i.e. a motor program). Shik et al (1966) severed the spinal cord and brain stem from the higher control regions of the cat's brain. The decerebrate cat was suspended over a treadmill with its feet in contact with the treadmill belt. As the treadmill belt continuously accelerated, thus eliciting faster backwards movement of the legs, a spontaneous transition from trotting to galloping was produced. This study provided evidence suggestive of self-organised behaviours that do not require input from the higher control centres of the brain. Rather, movement patterns were presumably produced and regulated at the spinal cord level in response to the change in the control parameter, which in this case was the speed of locomotion produced by the movement of the treadmill belt.

Humans have also exhibited self-organising properties during gait transitions, including pattern formation, bifurcations, multi-stability, hysteresis, critical slowing down and critical fluctuations (Diedrich & Warren, 1998b; Kelso & Schöner, 1988). Specifically, each mode of gait has its own pattern of coordination (Diedrich & Warren, 1995) and at the PTS there is a somewhat abrupt transition between walking and running (i.e. a bifurcation) (Diedrich & Warren, 1995; Li & Hamill, 2002; Segers, Aerts, Lenoir, & De Clercq, 2006). At speeds above and below the PTS, it is possible to both walk and run (i.e. multi-stability), although for each speed there appears to be a preferred mode of gait. When analysing the WRT and RWT separately, the PTS for each of these transitions are different, whereby the WRT speed tends to be slightly faster than the RWT speed (i.e. hysteresis) (Diedrich & Warren, 1995; Hreljac, 1995b; Mohler et al., 2007; Segers et al., 2006; Thorstensson & Roberthson, 1987). At speeds near the PTS, there is greater variability in the gait pattern (i.e. stride duration, stride length and stride frequency) and critical fluctuations have been observed, suggesting a loss of stability (Brisswalter & Mottet, 1996; Diedrich & Warren, 1998a, 1995; Segers et al., 2006). Additionally, a jump in the speed of locomotion has often been identified near the PTS during the WRT, both overground (De Smet, Segers, Lenoir, & De Clercq, 2009; Minetti et al., 1994; Segers et al., 2013) and on a treadmill (Van Caekenberghe et al., 2010), suggesting that individuals attempt to avoid walking or running at a small range of speeds that may be considered as unstable.

To further support the presence of self-organising behaviour, humans have exhibited nine muscle synergies that are used for both walking and running (Hagio et al., 2015). Differences in the activity patterns of these muscle synergies when completing gait transitions with and without the intention to transition suggest there are two pathways through which gait may be controlled. Specifically, when individuals were instructed when to transition between walking and running while the treadmill speed was held constant at the PTS, the activation patterns of the muscle synergies abruptly changed (Hagio et al., 2015). This abrupt change highlights intentionality and demonstrates how the cognitive component of the system has the ability to override the dynamics of the system. However, when transitioning between walking and running as the speed of locomotion gradually changed, the activation patterns of these synergies gradually shifted until a new gait pattern emerged. The latter example suggests humans may be capable of triggering gait transitions at the spinal level in a similar manner to the decerebrate cat (Shik et al., 1966).

The challenge of describing gait patterns and changes in stability of those patterns within the dynamic systems theory is to correctly identify the control parameter(s) and collective variable(s) governing gait. A number of variables have been proposed as either the control parameter that drives the transition between gait modes or the collective variables that are used to describe the attractors (i.e. walking or running patterns of coordination). However, the proposed collective variables and control parameters are highly correlated and often difficult to differentiate. For example, the combination of stride length and stride frequency and the speed of locomotion have previously been treated as the control parameters for analysing gait transitions (Diedrich & Warren, 1995; Schöner, Jiang, & Kelso, 1990). However, when an additional task constraint was introduced (i.e. change in gradient level, increased magnitude of acceleration/decelerations in treadmill speed), a shift in PTS has resulted (Diedrich & Warren, 1998a; Li, 2000; Van Caekenberghe et al., 2010). Therefore, the control parameter may be represented not as a single gait variable but as a combination of determinants that vary with task demands; the PTS would correspond to a boundary in this higher-dimensional space. Figure 2.2 provides a visual representation of how the control parameter and collective variables determine the pattern of coordination (i.e. mode of gait) of the system (Diedrich & Warren, 1995).

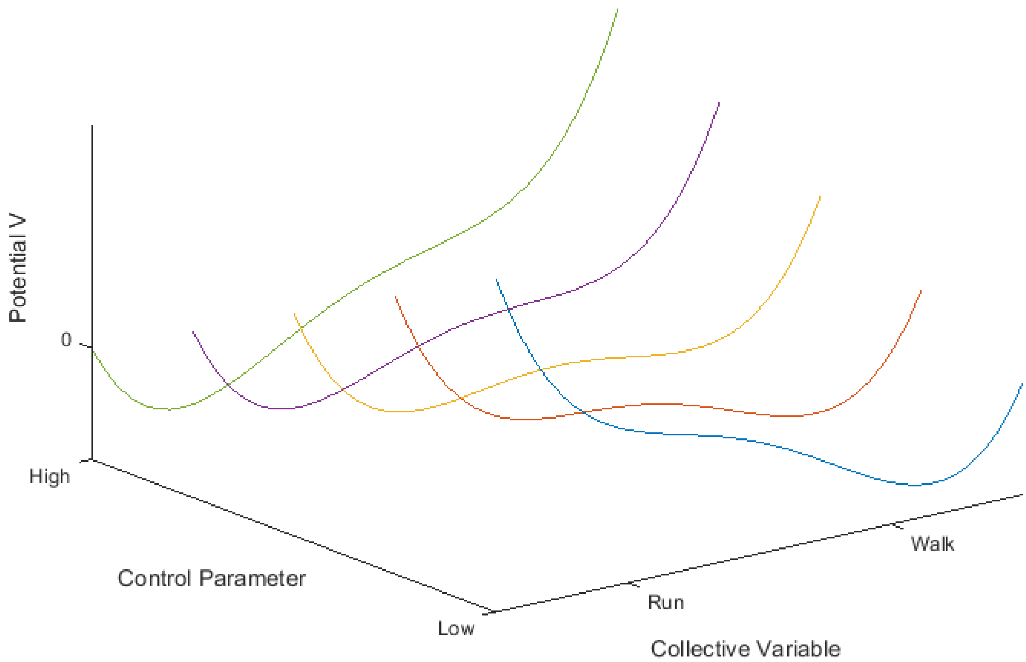

Figure 2.2. A hypothetical schematic of how a potential function (Potential V) changes with a change in the control parameter (Diedrich & Warren, 1995). In this hypothetical, the system is represented as a ball rolling along the potential functions (i.e. each of the different curves), so the system would theoretically settle in the local minimum for a given function. The more defined that the local minimum is, the more stable a given pattern will be. Hence, these functions represent what organisational state the system would be in as the speed changes. At low values of the control parameter, walking is the more stable pattern. As the control parameter increases, the minimum becomes less well defined and a second minimum appears, suggesting that walking becomes less stable and running is possible. As the control parameter is increased further, walking becomes unstable and the system shifts to running.

Using concepts from the dynamic systems theory and the properties of the self-organising system, Hreljac (1995a) proposed a set of criteria to determine whether specific determinants may be considered as triggers of the gait transition. Assuming determinants reach a critical threshold before initiating a gait transition, the first criterion proposed was that the potential determinant must exhibit an abrupt change when the mode of gait is changed. An abrupt change would suggest the stress or instability of the system caused by the critical determinant was relieved following the transition. As a follow-on criterion, the value of the determinant at the PTS was required to return to a magnitude observed at slower walking speeds or faster running speeds for the WRT and RWT, respectively. In order for an individual to recognise the need to transition between the modes of gait, the third criterion was that proprioceptors must be able to detect a change in the potential determinant. Finally, the potential determinant was required to exhibit a critical value at which the gait transition occurs. The remainder of this chapter will review the current knowledge about the determinants of the PTS and how these determinants contribute to the proposed triggers to help clarify which determinants have an influential role in triggering human gait transitions.

2.3. What are the individual constraints of the transition speed?

Anthropometric and strength characteristics pose a limitation on the maximum walking speed and have also been shown to influence the WRT (Diedrich & Warren, 1995; Hanna, Abernethy, Neal, & Burgess-Limerick, 2000; Ranisavljev, Ilic, Markovic, et al., 2014; Ranisavljev, Ilic, Soldatovic, & Stefanovic, 2014; Sentija, Rakovac, & Babic, 2012). Individual anthropometric and strength characteristics may therefore act as constraints of PTS, which could help to explain slight differences in reported PTS values across studies. However, individual constraints are somewhat fixed and would not immediately respond to changes in the task constraints. Therefore, these determinants will be discussed in terms of individual constraints of PTS, as opposed to a trigger of human gait transitions as such.

2.3.1. Anthropometric constraints

Spatiotemporal parameters of gait are influenced by anthropometric characteristics, particularly length characteristics of the lower extremities (Bohannon, 1997; Scrutton, 1969; Sutherland, 1997). Positive correlations between the PTS with various segment lengths (i.e. body height, leg, thigh, shank) and ratios of these lengths have been observed (Hanna et al., 2000; Hreljac, 1995b; Ranisavljev, Ilic, Soldatovic, et al., 2014; Sentija et al., 2012; Thorstensson & Roberthson, 1987; Tseh et al., 2002). Length characteristics of the lower extremities would influence the stride length used and may act as a limiting factor of the PTS, particularly for the

WRT as the locomotive speed increases. The maximum angle between the thighs was also linked to the PTS (Minetti et al., 1994), which would reflect the stride length used and further supports the anthropometric limitation on the PTS. To further analyse the influence of leg length on the PTS, the Froude number (*Fr*) has been used to scale walking speed to leg length (Alexander, 1984). This dimensionless value is calculated as:

$$Fr = v^2/g \cdot l$$

where *v* is the velocity, *g* is the acceleration due to gravity and *l* is the individual's leg length. The PTS tends to occur at a Froude number of approximately 0.5 (Diedrich & Warren, 1998b, 1995; Hreljac, 1995b; Kram, Domingo, & Ferris, 1997). When manipulating the gravity component, the WRT still tended to occur when the Froude number was approximately 0.5, except in extremely low gravity conditions (Kram et al., 1997). Conversely, leg girth and measures of body fat have produced negative correlations with the PTS (Ranisavljev, Ilic, Soldatovic, et al., 2014). These factors would affect the inertial properties of the lower extremity segments. Hence, more muscular effort would presumably be required during gait, which would decrease the PTS. However, the correlations between the PTS and anthropometric characteristics were only of weak-to-moderate strength (Hanna et al., 2000; Hreljac, 1995b; Ranisavljev, Ilic, Soldatovic, et al., 2014; Thorstensson & Roberthson, 1987; Tseh et al., 2002). Therefore, factors such as muscular strength and/or the intrinsic muscle properties may also contribute to the slight individual differences in the PTS.

2.3.2. Strength constraints

Although no significant correlations were found between measures of muscle mass and the PTS (Ranisavljev, Ilic, Soldatovic, et al., 2014), significant correlations have been identified between the PTS and various strength measures of the hip and ankle flexors and extensors (Ranisavljev, Ilic, Markovic, et al., 2014). Ankle dorsiflexor strength was found to be the best predictor of the WRT speed, whereas hip extensor and ankle plantarflexor strength exhibited stronger correlations with the RWT speed (Ranisavljev, Ilic, Markovic, et al., 2014). These correlations corroborate the observations of Prilutsky and Gregor (2001), who suggested that the mechanical load determinants are direction-dependent with respect to the change in the speed of locomotion (i.e. swing-related muscles trigger the WRT and stance-related muscles trigger the RWT). While weak-to-moderate correlations were found for various strength measurements, there was an overall positive effect on the WRT and RWT speeds (Ranisavljev, Ilic, Markovic, et al., 2014). Additionally, a group of obese and overweight women significantly increased their PTS from 1.70 $m \cdot s^{-1}$ to approximately 2.10 $m \cdot s^{-1}$ after a four-month intervention involving various lower extremity and core muscle strengthening and stretching exercises (Ilic, Ilic, Mrdakovic, & Filipovic, 2012). Therefore, muscular strength could also be an important contributing factor to determining the PTS.

2.4. What potential determinants contribute to the proposed triggers?

While anthropometric and strength characteristics would seem to have an important influence on an individual's PTS, they present more of a physical limitation to the preferred walking and preferred running speeds rather than specifically triggering a gait transition. As continuous feedback would be required to be able to adapt gait patterns to changing task constraints, the determinants of the PTS that contribute to the metabolic economy, mechanical economy, mechanical load and cognitive or perceptual triggers are more likely to initiate gait transitions.

2.4.1. Metabolic economy determinants

The metabolic economy trigger was proposed as humans tend to self-optimise their gait patterns with respect to energy expenditure (Hreljac, 1993b). It has been hypothesised that bipedal gait developed in humans as an evolutionary response to minimise the energy cost of locomotion (Alexander, 1989; Vaughan, 2003), which has often been supported by research (Cavanagh & Williams, 1982; Hogberg, 1952; Holt et al., 1991; Zarrugh et al., 1974). While the metabolic energy cost per unit distance remains fairly stable across speeds for running, the energy cost of walking when expressed as a function of speed is curvilinear (Figure 2.3) (Hreljac, 1993b; Margaria, Cerretelli, Aghemo, & Sassi, 1963). In young adults, the lowest point of this energy cost curve for walking occurs at approximately 1.20 – 1.40 $m \cdot s^{-1}$, which also happens to coincide with the preferred walking speed (Hreljac, 1993b; Margaria et al., 1963; Thorstensson & Roberthson, 1987).

As humans naturally walk at speeds that are optimal in terms of metabolic energy cost, it is logical to assume that gait transitions would also occur when it is energetically optimal to do so. To test this assumption, the energetically optimal transition speed has been compared with the PTS. The energetically optimal transition speed is defined as the speed at which the energy cost-speed of locomotion curves for walking and running intercept (Figure 2.3)(Hreljac, 1993b). If a metabolic economy trigger did exist, the PTS and the energetically optimal transition speed would theoretically be the same; however, this hypothesis has not been strongly supported in the research. While one study identified very similar PTS and energetically optimal transition speed values (Hanna et al., 2000), other studies have more frequently reported that humans prefer to transition at speeds slower than what is energetically optimal (Brisswalter & Mottet, 1996; Hreljac, 1993b; Rotstein, Inbar, Berginsky, & Meckel, 2005; Tseh et al., 2002; Ziv & Rotstein, 2009). The PTS may rather be influenced by lactate accumulation (Sentija & Markovic, 2009); however, the PTS was only correlated with the lactate threshold of running and not walking.

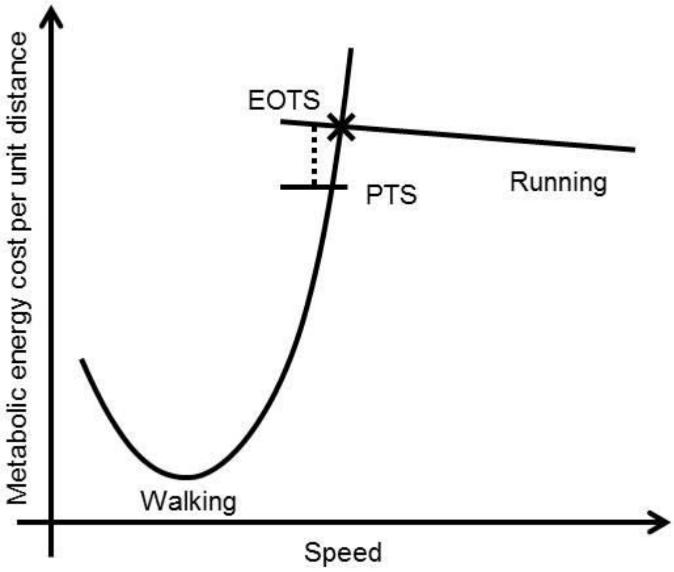

Figure 2.3. Simplified energetic cost-speed curves for walking and running, adapted from Hreljac (1993b) and Minetti et al (1994). The dotted line indicates the margin of error often observed between the preferred transition speed (PTS) and the theoretical energetically optimal transition speed (EOTS).

2.4.2. Mechanical economy determinants

The mechanical economy trigger is assumed to help minimise the mechanical cost of locomotion (Diedrich & Warren, 1995; Farley & Ferris, 1998; Minetti et al., 1994), which would subsequently minimise the metabolic cost. As the current gait pattern becomes less mechanically economical, the mechanical economy trigger presumably initiates a gait transition. The mechanical energy of the body's centre of mass (COM) during walking and running has been analysed using different models, due to the different methods of mechanical energy exchange used between the kinetic and gravitational-potential energies (Farley & Ferris, 1998). Walking is frequently modelled as an inverted pendulum, whereby the trajectory of the COM follows an arc-like motion over a stiff limb (Farley & Ferris, 1998). Step-to-step transitions are then used to maintain forward progression, which requires redirecting the body's COM and overcoming the collisions at each foot strike event (Donelan, Kram, & Kuo, 2002; Kuo, 2007). The mechanical cost of walking increases exponentially with longer stride lengths, which has been attributed to step-to-step transitions (Donelan et al., 2002). While raising the body's COM has been identified as the most costly task during walking (Orendurff et al., 2004), this vertical displacement of the body's COM may actually be the result of longer stride lengths, which in turn have been associated with more costly step-to-step transitions. Therefore, the minimal vertical displacement of the body's COM seen when walking at a self-selected pace may reflect the mechanically optimal balance of stride length and frequency. Conversely, running has been analysed using a spring-mass model (Farley & Ferris, 1998), which exploits the vertical displacement of the body's COM to utilise elastic energy. Therefore, walking is most mechanically economical when the vertical displacement of the COM is minimal, whereas running is more mechanically economical as the vertical displacement of the COM increases.

Simulations of walking and running have revealed that a greater amount of active muscle fibre work is required at non-preferred speeds than at the preferred speeds for each mode of gait (Sasaki & Neptune, 2006), which is less mechanically economical. As walking speed increases, the amount of muscle activity also increases to achieve the longer stride lengths associated with faster walking speeds (Neptune, Sasaki, & Kautz, 2008). In particular, increased muscle activation of the gastrocnemius and soleus muscles have been observed along with no changes in the vertical and anterior-posterior components of the propulsive ground reaction forces (GRF) with faster walking speeds (Neptune & Sasaki, 2005). Additionally, at walking speeds faster than the PTS, there was no increase in the peak ankle plantarflexor moment, which was accompanied by an increase in the hip power generation and extensor moment (Pires, Lay, & Rubenson, 2014). It has been suggested that the reduced force output generated by the ankle plantarflexors is due to unfavourable contractile conditions, regarding the force-velocity relationship (Farris & Sawicki, 2012; Neptune & Sasaki, 2005). Therefore, the greater contribution from the hip may be used to compensate for the lower relative contribution to propulsion from the ankle.

When an individual runs at their preferred running speeds, there is a much higher contribution of positive work completed by the series elastic element of the muscle during stance compared to walking (Sasaki & Neptune, 2006). This is largely due to the ability to store and utilise elastic energy during running, which makes running more mechanically economical at fast speeds of locomotion. In particular, there is a lower rate of increased muscle activation following the WRT, despite increasing running speeds (Monteiro, Farinatti, de Oliveira, & Araújo, 2011). However, when running at the preferred walking speed, there is a significant decrease in the proportion of elastic energy contributing to the positive muscle fibre work

(Sasaki & Neptune, 2006). This suggests a larger proportion of positive muscle fibre work must be completed by the contractile element, which would consequently incur a greater energy cost. Furthermore, the amount of negative work completed by the vastii muscle group significantly increases when running at the preferred walking speed (Sasaki & Neptune, 2006). These factors would significantly reduce the economy of running mechanics at slow speeds; hence the transition from running to walking with decreasing speeds of locomotion resulting in the use of a more economical gait.

The mechanically optimal transition speed has also been assessed (Beaupied, Multon, & Delamarche, 2003). Similar to the energetically optimal transition speed, the internal work was plotted against the speed of locomotion for walking and running and the mechanically optimal transition speed was identified as the speed at which these two lines intercepted. This theoretically optimal transition speed was different between sprinters, endurance runners and untrained individuals. For sprinters and endurance-trained runners, it was mechanically optimal to transition to running earlier than untrained individuals. Thus, sprinters and endurance-trained runners may be able to more effectively utilise elastic energy while running compared to walking and therefore prefer transitioning to running at a slower speed. However, the ability to utilise elastic energy and intrinsic muscle properties were not specifically analysed.

2.4.3. Mechanical load determinants

The mechanical load trigger has been suggested to act as a protective mechanism by reducing musculoskeletal stress and the risk of injury (Farley & Taylor, 1991; Hreljac, 1993a). The adaptive nature of gait patterns to reduce joint loading and minimise impact forces has previously been seen during barefoot running (Lieberman et al., 2010; Squadrone & Gallozzi, 2009) and walking (Kung, Fink, Hume, & Shultz, 2015) compared to the corresponding shod conditions. Gait transitions may similarly be used as a method of protecting the musculoskeletal system as the task constraints change. This protective mechanism was first observed in horses (Farley & Taylor, 1991), whereby a critical value of the vertical GRF relative to body weight was reported in horses of various sizes at the trot-gallop transition. The same critical vertical GRF value was also observed in these horses with the addition of a carried load, resulting in a slower transition speed. The extra load may affect the mechanical economy of the gait pattern and thus influence the gait transition through that triggering mechanism. However, this evidence of a critical vertical GRF value, with and without a carried load, suggests that there is potentially a protective mechanism in horses that acts to avoid larger joint forces. Subsequent research has investigated whether a similar protective mechanism is present in humans. Studies observed a similar decrease in the PTS with various loads carried (Hreljac, 1993a; Raynor, Yi, Abernethy, & Jong, 2002), while the time to reach the peak vertical GRF value and the rate of loading were also suggested to be determinants of the PTS (Li & Hamill, 2002; Raynor et al., 2002). However, it is unknown whether the carriage of an extra load may have instead initiated the WRT at a slower PTS to reduce the amount of work required to maintain the gait pattern, or to prevent excess joint loading specifically.

The mechanical load trigger may also act to prevent muscular fatigue. When walking and running at speeds near the PTS, muscle activation patterns have revealed that the WRT and RWT may be triggered by different mechanisms (Prilutsky & Gregor, 2001). Specifically, the WRT appears to be triggered by the muscles that largely contribute to the swing phase, including the tibialis anterior, biceps femoris and rectus femoris (Hreljac, Arata, Ferber, Mercer, & Row, 2001; Prilutsky & Gregor, 2001; Shih, Chen, Lee, Chan, & Shiang, 2016), whereas the RWT tends to be triggered by the stance-related muscles, including the vastii muscle group, soleus and gastrocnemius (Prilutsky & Gregor, 2001). The differences between the inverted pendulum and spring-mass mechanics may explain why different mechanisms trigger each of the transitions. Assuming the exchanges between gravitational-potential and kinetic energy become less economical near the PTS, the inverted pendulum mechanics would require a greater active contribution to maintain forward progression of the leg, particularly as this energy exchange during walking is more of an active process than previously predicted (Neptune, Zajac, & Kautz, 2004). Interestingly, the research has consistently supported that the swing-related tasks trigger the WRT rather than stance-related tasks, despite the exponential increase in the mechanical cost of the step-to-step transitions with increasing walking speeds (i.e. a stance-related task) (Donelan et al., 2002). Therefore, it may be speculated that the effort required for the swing phase may also increase exponentially with walking speed to increase both the velocity and range of motion of the leg swing to achieve a longer stride length. For the spring-mass mechanics of running, a greater active contribution may be required to support the limb during the loading response and propulsion, particularly at slower running speeds. Therefore, while collectively acting to reduce the muscular effort required during gait, the mechanical load determinants are likely to be dependent on the direction of change of the speed of locomotion.

Studies have manipulated the muscular demand placed upon various muscle groups to further assess the specific muscles, or muscle groups, that trigger gait transitions (Bartlett & Kram, 2008; MacLeod, Hreljac, & Imamura, 2014; Malcolm, Fiers, et al., 2009; Malcolm, Segers, Van Caekenberghe, & De Clercq, 2009; Segers, Lenoir, Aerts, & De Clercq, 2007). When resisting the actions of the ankle dorsiflexors (MacLeod et al., 2014; Malcolm, Segers, et al., 2009) and plantarflexors (Bartlett & Kram, 2008; Malcolm, Fiers, et al., 2009), there were generally significant decreases seen in the PTS. In addition to increasing the demand placed upon specific muscle groups, a significant decrease in the PTS has also been reported when adding weights around the ankles (Diedrich & Warren, 1998a) and increasing the gradient of the treadmill (Diedrich & Warren, 1998a; Hreljac, 1995b; Hreljac, Imamura, Escamilla, & Edwards, 2007a; Minetti et al., 1994). Furthermore, when reducing the muscular effort required by the hip flexors and ankle plantarflexors and dorsiflexors by means of assistive devices, significantly faster WRT speeds were reported (Bartlett & Kram, 2008). These assistive devices helped progress the swinging limb forward, progress the body forward and dorsiflex the ankle, respectively, using rubber tubing. However, when multiple assistive devices were used together, no additive effects were seen to further increase the PTS, compared to using only one assistive device (Bartlett & Kram, 2008). Similarly, when using an ankle-foot exoskeleton to assist ankle dorsiflexion (Malcolm, Segers, et al., 2009) and plantarflexion (Malcolm, Fiers, et al., 2009) actions, no significant changes in the PTS were reported. From the lack of change in the PTS when assisting muscle actions, a 'weakest link' hypothesis was proposed, which suggests there may be other factors that have already reached their critical thresholds (Malcolm, Fiers, et al., 2009). Therefore, despite reducing the muscular demand required by the ankle dorsiflexors and plantarflexors, individual constraints such as anthropometric or strength characteristics may have prevented a change in the PTS.

2.4.4. Cognitive and perceptual determinants

The metabolic economy, mechanical economy and mechanical load triggers are likely able to initiate a transition at the spinal level. However, cognitive and perceptual processes must also be considered when assessing human gait transitions. Cognitive processes can play a role in human gait transitions, for example cognitively deciding to walk and run at non-preferred speeds of locomotion. Humans also have the ability to consciously determine whether a particular gait pattern becomes increasingly difficult with changes in the task constraints. For example, higher ratings of perceived exertion (RPE) are reported when walking at speeds that are equal to or faster than the PTS, compared to running at the corresponding speeds (Ganley, Stock, Herman, Santello, & Willis, 2011; Hanna et al., 2000; Hreljac, 1993b; Minetti et al., 1994; Monteiro et al., 2011; Rotstein et al., 2005). Therefore, cognitive processes regarding the task difficulty (e.g. intensity and duration) may help regulate gait patterns with the aim of reducing undue stress placed upon the musculoskeletal system. The perceptions about the sustainability of a given gait pattern under various task constraints would have presumably been shaped from previous experiences. Therefore, the perceived difficulty of gait patterns would be individualised depending on the individual constraints, such as anthropometric or strength characteristics. Accordingly, long distance runners (Rotstein et al., 2005) and racewalkers (Ziv & Rotstein, 2009) reported different absolute RPE values when walking and running at the PTS than recreationally active individuals (Rotstein et al., 2005; Ziv & Rotstein, 2009). However, similar differences in RPE values were reported between these modes of gait at the PTS regardless of an individual's training history (Rotstein et al., 2005; Ziv & Rotstein, 2009). When both peripheral (i.e. exertion of the legs) and central (i.e. cardiorespiratory exertion) RPE values were assessed at various speeds of locomotion, the central RPE continued increasing after the WRT, whereas the peripheral RPE somewhat plateaued (Daniels & Newell, 2003). Interestingly, as the speed of locomotion became faster than the preferred walking speeds, the peripheral RPE values were consistently greater than the central RPE values (Monteiro et al., 2011). There may thus be a greater emphasis on the exertion of the muscles compared to the overall exertion when determining the PTS, which may aim to reduce muscular fatigue.

Although there is a cognitive influence over gait transitions, in most cases perceptual feedback tends to have a greater influence over spontaneous gait transitions. Visual feedback is one means of perceptual feedback that is used to help regulate gait patterns (Patla, 1997). As well as assisting with stability and providing instantaneous feedback about the environment, visual feedback may be used to help form perceptions about the intensity, or speed of locomotion. In studies that manipulated the perceived speed of locomotion via the rate of optic flow, individuals exhibited a slower PTS when they thought they were moving at a speed of locomotion that was faster than reality (De Smet et al., 2009; Mohler et al., 2007), whereas the PTS increased when they perceived to be moving at a slower speed (Mohler et al., 2007). Similarly, when moving on a treadmill held constant at the PTS, a slower rate of optic flow often resulted in a walking gait pattern, whereas running tended to be the preferred mode of gait when the optic flow was faster than the actual treadmill speed (Guerin & Bardy, 2008). Therefore, perceptual feedback has a highly integrated and influential role in regulating gait patterns. However, when provided with the concurrent cognitive task of counting backwards during gait on a treadmill, the PTS for the RWT was slower (Abdolvahab, 2015). It was suggested that the additional cognitive load due to the concurrent counting task provided a distraction from the physical and physiological exertion, hence the delay in the RWT.

Therefore, while cognitive or perceptual functions have been shown to be integrated processes in regulating gait patterns, it must be a combination of feedback sources that provide information to help adjust gait patterns to changes in the task constraints**.**

2.5. Could the proposed triggers initiate gait transitions as task constraints change?

Conclusions can be formed about the potential of the proposed triggers and the role that the determinants of the PTS have in triggering human gait transitions by using stringent criteria. As a brief summary, it has been suggested that a variable may be considered as an important determinant of the PTS if there is an abrupt change in its value following a transition (criterion 1) once it reaches a critical value (criterion 4), after which its value should return to a magnitude similar to that observed prior to the PTS (criterion 2). The variable must also be able to act upon proprioceptors to provide feedback at the spinal level (criterion 3). These criteria arise from dynamic systems theory, but in themselves are not sufficient to describe WRT or RWT in humans. In particular, the ability to cognitively override or delay gait transitions (i.e. walking at speeds faster than the PTS and running as speeds slower than the PTS) suggests that additional factors play a role in determining transitions. These additional factors are not necessarily inconsistent with dynamic systems theory (Schöner & Kelso, 1988), but it is clear that the criteria suggested by Hreljac (1995a) needs to be augmented by other factors to describe transitional behaviour in human gait.

As walking and running are two separate modes of locomotion, we can assume the first criterion is somewhat valid. Although gait transitions tend to be more of a gradual process than an instantaneous event (Li & Hamill, 2002; Li & Ogden, 2012; Segers et al., 2013), abrupt changes in the GRFs and joint angular velocities and powers were observed during overground WRTs (Segers et al., 2013). The fourth criterion also has merit as the PTS is consistently reported to occur around 2 $m \cdot s^{-1}$. However, it must be highlighted that the critical value may be shaped from previous experience and may thus be adjusted, or 'calibrated' as various individual constraints change, rather than remaining at a fixed predetermined value. Such calibrations would account for slight differences in PTS values between studies. However, calibrations may only occur after exploring how certain gait adaptations affect the determinants (Selinger, O'Connor, Wong, & Donelan, 2015). Once individuals are familiar with how task constraints affect their gait and thus the determinants, they are able to swiftly adjust their gait within seconds to optimise their gait patterns (Selinger et al., 2015). The studies that manipulated optic flow (De Smet et al., 2009; Guerin & Bardy, 2008; Mohler et al., 2007) and perceived duration (Daniels & Newell, 2002) to investigate their effects on PTS also provide support of this calibration of a critical threshold of difficulty. Thus, while humans aim to self-optimise gait patterns, there may be a significant learning influence.

While only proprioceptive feedback was mentioned in Hreljac's criteria (1995a), there may have been a lack of other feedback mechanisms because the criteria were originally developed for analysing potential kinematic determinants. However, other sources of feedback also need to be considered when analysing the various determinants of PTS. As previously mentioned, there is a convincing contribution from cognitive processes and perceptions about the task demands that are likely to help trigger gait transitions. Therefore, the third criterion needs to be expanded to reflect other sources of feedback. An additional consideration that needs to be made is that the feedback should be available almost instantaneously, as individuals are able to adjust gait patterns within seconds of changes occurring to the task constraints (Selinger et al., 2015). The second criterion may also need to be revised to reflect more of a conservative approach to optimising gait patterns. While it would be advantageous to be able to transition at the most optimal speed, such as the theorised energetically optimal transition speed, it would also be beneficial to transition if it would act to prevent further increases in the task demands. The energetically optimal transition speed is an example where the WRT may not decrease the metabolic energy expenditure, but it does prevent the exponential increase in the metabolic cost of locomotion that would have been incurred had an individual remained walking at speeds above the PTS. Thus, the second criterion would be that a gait transition would need to result in a more favourable value for a given determinant. These revised criteria can now be used to assess the potential influence that various determinants of the PTS have over the triggering of human gait transitions (Table 2.1).

The determinants of the metabolic economy trigger satisfies the first criterion, if the determinant is expressed as the metabolic cost of transport per unit distance (Figure 2.3), rather than just the absolute volume of consumed oxygen ($\dot{V}O_2$). The second criterion would also be satisfied, as gait transitions would contribute to minimising the metabolic cost of transport for both the WRT and RWT. Specifically, the WRT corresponds with a decreased energy cost of locomotion and cardiorespiratory responses (i.e. heart rate, $\dot{V}O_2$ and minute ventilation) (Mercier et al., 1994), while the RWT would reduce the energy expenditure following the transition as gait speed changed (Figure 2.3)**.** However, it is unlikely that a critical value (criterion 4) exists for the metabolic economy trigger. There has been no convincing evidence to suggest that the PTS is determined by a relative metabolic workload among individuals with different aerobic capacities or ventilatory thresholds (Mercier et al., 1994;

Rotstein et al., 2005; Ziv & Rotstein, 2009). Additionally, while the PTS was highly correlated with the lactate threshold of running (Sentija & Markovic, 2009), which chemoreceptors could potentially provide sensory feedback about, this mechanism may be questioned as the lactate threshold of walking did not correlate with the PTS. The closest candidate would be the energetically optimal transition speed; however, it is only similar to the PTS and thus would only loosely satisfy the fourth criterion. Furthermore, there is no known method through which to receive feedback fast enough regarding changes in energy expenditure that would elicit a spontaneous gait transition (criterion 3). Assuming that humans adopt gait patterns that minimise metabolic energy consumption, improving metabolic economy may thus be regarded as one of the ultimate goals that helps govern gait transitions, rather than acting as a proximal cause or trigger of the transition (Hanna et al., 2000; Minetti et al., 1994).

Changes in the mechanical economy determinants are seen for both the WRT and RWT. A plateau in the peak ankle plantarflexor moment becomes apparent as the walking speed increases, which suggests a critical value is reached prior to the WRT (criterion 4). The WRT would thus enable a greater propulsive plantarflexor moment to be produced at speeds faster than the PTS (Pires et al., 2014). Although the actual gait transition was not assessed (Pires et al., 2014), the peak ankle plantarflexor moment was significantly greater for running than walking at speeds faster than the PTS. Therefore, an abrupt change could occur following the WRT, which would satisfy the first criterion and enable a more favourable outcome in terms of the plantarflexor moment produced, thus also satisfying the second criterion. Furthermore, the proprioceptors in the muscles and tendons (i.e. muscle spindles and Golgi tendon organs) can provide feedback regarding the stretch and tension of the muscles and thus the exertion of the muscles, which satisfies the third criterion. Perceived difficulties or inefficiencies may also be sensed at faster walking speeds (Daniels & Newell, 2003), which would also help satisfy the third criterion. For the RWT, the proportion of positive work completed by the series elastic element decreases and more negative work is completed by the vastii muscle group (Sasaki & Neptune, 2006), which would reduce the economy of the running gait mechanics with decreasing running speeds. When considering the overall effect of the mechanical economy trigger, it is assumed that individuals transition when it is mechanically optimal to do so. While the mechanically optimal transition speed has been investigated with regards to the internal mechanical work (Beaupied et al., 2003), this theoretical speed was not compared to an actual PTS and may require further investigation. However, it was reported that it was mechanically optimal to transition at 2.65 $m \cdot s^{-1}$ in untrained individuals (Beaupied et al., 2003), which is higher than what is typically reported for PTS values. Therefore, while speculative, it would appear untrained individuals may also transition before it is mechanically optimal to do so. Regardless of potential differences between this mechanically optimal transition speed and the PTS, the evidence supporting the presence of a mechanical economy trigger is convincing.

The mechanical load determinants are also likely to trigger human gait transitions. Specifically, the peak vertical GRF, rate of loading and amount of muscle activity have been proposed as possible determinants of the mechanical load trigger. When completing the WRT with various carriage loads, no critical vertical GRF value was identified (Hreljac, 1993a). Running also elicits a greater peak vertical GRF value compared to walking (Li & Hamill, 2002; Nilsson & Thorstensson, 1989), which questions whether a critical value of the vertical GRF triggers gait transitions (criterion 4). Alternatively, the time to reach the peak vertical GRF may be a triggering factor as it abruptly increased following the WRT (first and second criteria) (Raynor et al., 2002), which would influence the rate of loading and can be detected by the proprioceptors (criterion 3). However, a critical value has not yet been identified (criterion 4). Interestingly, no difference was observed in the maximum resultant GRF loading rate (Hreljac, 1993a). These loading rate variables would presumably influence the exertion of the muscles, which have also been shown to influence the PTS. Again, the proprioceptors in the muscles can provide feedback about how hard the muscles are working (criterion 3). Daniels and Newell (2003) also demonstrated that following the transition, perceived exertion of the legs plateaued following the transition rather than continuing to increase, which supports that perceptual feedback likely contributes to the triggering of gait transitions via a mechanical load trigger (criterion 3). The rate at which the muscle activity increased with faster speeds of locomotion was lower following the WRT, suggesting an abrupt change (criterion 1) to more favourable conditions (criterion 2); and the greater utilisation of the series elastic element to complete positive work would help to reduce muscular fatigue. The tibialis anterior activity appears to be the most convincing of triggers as it is the only muscle that has consistently satisfied the first three criteria**,** even according to Hreljac's original criteria (1995a)**.** Specifically, there is a significant abrupt decrease in muscle activity following the WRT, to a value similarly experienced during walking. However, when assisting the actions of the ankle dorsiflexors, a significant increase in the PTS was not observed (Malcolm, Segers, et al., 2009). Therefore, it is unlikely that a single muscle, or muscle group, acts to trigger a gait transition, but rather a combination of muscles that influence the PTS as suggested by the weakest link hypothesis. Further investigation into this weakest link hypothesis may be required, which may also provide further insight into the potential critical values at which a gait transition is elicited (criterion 4).

Table 2.1.Summary of whether the proposed triggers satisfied the four criteria proposed by Hreljac (1995a) and updated here.

	Criterion 1	Criterion 2	Criterion 3	Criterion 4
Metabolic Economy	✓	✓	×	✓
Mechanical Economy	✓	✓	✓	✓
Mechanical Load	✓	✓	✓	?
Cognitive and Perceptual	✓	✓	✓	✓

Criterion 1: abrupt change in the variable; Criterion 2: value following the transition would become more favourable during the post-transition gait mode than if one were to remain in the pre-transition gait; Criterion 3: rapid feedback available; Criterion 4: there is a critical value at which the gait transition occurs. ✓ indicates whether the proposed trigger satisfied the criterion; × indicates whether the proposed trigger failed to satisfy the criterion; ? indicates that it is yet to be determined whether the trigger satisfies the criterion.

Although cognitive processes do not operate at the spinal level and would not help to explain the triggering of gait transitions in the decerebrate cat (Shik et al., 1966), they are integrated into human behaviour and must therefore be included in the analysis of human gait transitions. Using the revised criteria, the cognitive determinants are likely to have a contributory role in triggering gait transitions. There was an abrupt decrease in RPE following the WRT (Monteiro et al., 2011), which satisfies the first and second criteria. Perceptual determinants also appear to have an influential role in triggering gait transitions, particularly when triggering a spontaneous transition. Specifically, it has been shown that manipulating the perception of speed via the rate of optic flow affects the PTS (De Smet et al., 2009; Mohler et al., 2007). Therefore, when combining the cognitive and perceptual determinants it may be suggested that there is a critical threshold of perceived task difficulty, which would satisfy the third and fourth criteria. Furthermore, the difference in RPE values between walking and running at the PTS was similar among individuals of different training statuses (Rotstein et al., 2005), which also supports that there is a critical threshold of perceived difficulty (criterion 4). Therefore, it is apparent that cognitive processes and perceptual feedback do play an important role in regulating gait patterns and thus the triggering of gait transitions. To further demonstrate this, when providing a distraction from the gait task, the RWT occurred at a slower PTS (Abdolvahab, 2015). This observation highlights that cognitive processes are calibrated to contribute to the other feedback mechanisms to help trigger gait transitions. However, cognitive processes alone cannot explain what drives gait transitions, as they can occur without cognitive processes (Shik et al., 1966). Furthermore, the question of what drives the cognitive processes would still need to be answered. Instead, cognitive processes and perceptual feedback may be used to modify the other triggers upon receiving feedback regarding the muscular load or mechanical energy cost of the given gait pattern. Cognitive and perceptual determinants may also be particularly important when gait is completed at speeds similar to the PTS, as neither mode of gait is the clearly optimal choice.

2.6. Conclusion

It is clear that a combination of determinants contribute to the triggering of human gait transitions as task constraints change. While individual anthropometric and strength characteristics help determine the PTS, they do not act to trigger a gait transition. Rather, individual characteristics limit the speeds at which walking and running would be comfortable. The evidence more strongly supports the triggering mechanisms acting at the muscular level, through the determinants of the mechanical economy and mechanical load triggers (i.e. the utilisation of the contractile and elastic components of the muscle and thus overall amounts of muscle activity). These triggers have an overall purpose of reducing muscular fatigue by minimising the amount of work completed, which would subsequently minimise the metabolic cost of locomotion. Cognitive processes and perceptual feedback appear to help achieve this goal, particularly as the speed of locomotion approaches the PTS. The shift in the PTS with changes to additional task constraints clearly demonstrates that the system adjusts the mode of gait to one that will minimise the effort required, regardless of whether the change in the task constraints are real (e.g. increasing the gradient of locomotion), or perceived (e.g. manipulating the rate of optic flow). Gait would therefore be regulated by a combination of proprioceptive feedback and cognitive and perceptual processes in adults. These feedback mechanisms have the ability to respond to acute changes in the task constraints and may be optimised from previous experiences to reduce both the mechanical and metabolic energy cost of locomotion. However, it should be stressed that the triggers and determinants of the WRT and RWT need to be considered separately due to the differences in the mechanics used for each mode of gait. That is, the mechanical factors (i.e. muscle activity and mechanical economy) for each mode of gait will respond in a direction-dependent manner to changes in the speed of locomotion.

2.7. References

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CHAPTER 3

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

3.0. Abstract

Youth 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 youth by determining if differences existed between youth 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 youth (10-12-year-olds, n=17; 13-14-year-olds, n=12; and 15-17-year-olds, n=17) and 12 young adults (19-29-year-olds) completed an incrementally ramped treadmill test (+0.06 $m \cdot s^{-1}$ 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 four speeds (self-selected walking speed, PTS-0.06 $m \cdot s^{-1}$, PTS+0.06 $m \cdot s^{-1}$, PTS+0.83 $m \cdot s^{-1}$). Mixed model ANOVAs with repeated measures ($p<0.05$) 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 paediatric groups and young adults. Compared to adults, 10-12-year-olds exhibited more spatiotemporal variability during all gait conditions, while 13-14-year-olds and 15-17-year-olds only exhibited more variability at PTS+0.06$m \cdot s^{-1}$. No age-dependent pattern was observed in PTS values, but 10-12-year-olds completed more gait transitions over more speed increments than 15-17-year-olds and adults. The development of mature gait patterns is thus a progressive process, with walking maturing at an earlier age than running. As 10-12-year-olds were unable to swiftly adapt gait patterns to the changing task demands, their control mechanisms of gait may not have fully matured yet.

Keywords: Gait maturation, spatiotemporal parameters, locomotion, variability

* Published manuscript:

SM Kung, PW Fink, SJ Legg, A Ali & SP Shultz (2019). Age-dependent variability in spatiotemporal gait parameters and the walk-to-run transition. *Human Movement Science*, 66, 600-606.

Notes:

This chapter has been adapted from the original research article published in *Human Movement Science* and has reproduced most of the original tables from this publication (Kung, Fink, Legg, Ali, & Shultz, 2019). However, Tables 3.2 and 3.3 and Supplementary Tables 3.B and 3.C have been reformatted for clarity. The reformatted supplementary tables have been inserted at the end of the chapter, while the original supplementary tables can be found online.

The use of 'adolescents' for all 10-17yo in the original article has been changed in this chapter to maintain the consistency of terminology used throughout the thesis (i.e. youth as anyone <18 years old, children as 10-12yo, adolescents as 13-17yo).

Available at: https://doi.org/10.1016/j.humov.2019.06.012

3.1. 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. 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 youth (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 changing 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, Zemany, Peng, & Goldberger, 1999; Komar, Seifert, & Thouvarecq, 2015; Maruyama & Nagasaki, 1992). Decreasing 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 maturation of 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 14-17 yo (Gouelle et al., 2016) began to approach values seen in adults, their gait patterns still exhibited more variability. Spatiotemporal parameters during running also appear to be more variable in 7-9 yo 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 typically seen among 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 11 yo compared to 13- and 15-yo (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 youth exhibit more spatiotemporal (i.e. stride duration and stride length) variability in their gait patterns across a range of walking and running speeds compared to young adults. As adult-like amounts of spatiotemporal variability has previously been used as an indicator of gait maturity, more spatiotemporal variability in paediatric 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 youth and young adults.

3.2. Methods

3.2.1. Participants

Forty-six youth (10-17 years) participated in the study and were initially categorised by chronological age into 10-, 11-, 12-, 13-, 14-, 15-, 16-, and 17-yo groups (see Supplementary Table 3.A). Twelve young adults (19-29 years) were recruited for comparison. These participants were part of a larger overarching project investigating age-related differences in determinants of the walk-to-run transition among youth and young adults. 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 17-29 yo provided their own informed written consent. The study was approved by the institutional human ethics committee.

3.2.2. 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 minutes 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 treadmill speed was increased by +0.06 $m \cdot s^{-1}$ 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 $m \cdot s^{-1}$ 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 $m \cdot s^{-1}$ every 30 s until the participant indicated they reached volitional exhaustion. 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.

3.2.3. 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.

3.2.4. 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. PTS+0.83 $m \cdot s^{-1}$) were analysed to assess gait patterns during familiar gait speeds. Previous research has shown that individuals exhibit a speed jump of approximately 0.42 $m \cdot s^{-1}$ 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, or unfamiliar speeds within this speed jump, walking and running were also assessed at the speeds directly before (i.e. PTS-0.06 $m \cdot s^{-1}$) and after (i.e. PTS+0.06 $m \cdot s^{-1}$) 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 Cingel, 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.

3.2.5. 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 x 4 (age x speed) mixed model ANOVA with repeated measures and post-hoc Tukey's tests were performed (SAS version 9.4, Cary, NC) to analyse differences between the paediatric 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 10-12 yo exhibited differences in spatiotemporal variability across the walking and running speeds, 13-14 yo only exhibited differences at the running speeds and the 15 yo and 17 yo did not exhibit differences compared to the adults (Supplementary Tables 3.B and 3.C). Therefore, the paediatric participants were grouped accordingly into 3 groups: 10-12 yo (n=17), 13-14 yo (n=12) and 15-17 yo (n=17) to be compared with the group of young adults. A subsequent 4 x 4 (age x speed) mixed model ANOVA with repeated measures 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 of 0.05.

3.3. Results

The characteristics of the combined age groups are reported in Table 3.1, while the characteristics of the individual adolescent age groups and young adults can be found in Supplementary Table 3.A.

Table 3.1. Participant characteristics for each of the age groups.

	10-12 yo	13-14 yo	15-17 yo	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 *†	62.6 ± 10.5 *†
BMI (kg·m^{-2})	18.4 ± 2.6	17.9 ± 1.8	20.2 ± 2.4 †	21.4 ± 2.2 *†
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; † 13-14-year-olds. F: Female. M: Male. yo: -year-olds.

3.3.1. Stride duration and stride length variability

Significant differences were observed in the stride length and stride duration CVs between the youth and young adults ($p<0.05$; Tables 3.2 and 3.3). The stride duration and stride length CVs for the 10-12 yo were consistently greater than the adults for all speeds. Compared to the adults, the 13-14 yo and 15-17 yo groups exhibited more stride duration variability at PTS+0.06 $m \cdot s^{-1}$, but not at any other gait conditions.

3.3.2. Preferred transition speed and gait transition variability

Significant differences were detected in the absolute PTS values between age groups ($p=0.029$; Table 3.4). 15-17 yo had a significantly higher PTS compared to the 10-12 yo. 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 original eight paediatric groups and adults can be found in Supplementary Table 3.D.

Significant differences were observed in the numbers of gait transitions completed ($p=0.005$) and speeds at which gait transitions occurred ($p=0.002$). The 10-12 yo completed more gait transitions than the 15-17 yo ($p=0.003$) and the adults ($p=0.014$) (Table 3.5 and Supplementary Table 3.E). The 10-12 yo also completed gait transitions across a higher number of speeds during the treadmill test than the 15-17 yo ($p=0.006$) and the adults ($p=0.036$). Approximately half of the 10-12 yo group and about a quarter of the 13-14 yo group used more than one gait transition over more than one speed to determine their PTS. Only one participant out of the 15-17 yo and adult groups transitioned more than once over more than one speed.

Table 3.2. Mean ± SD of the stride duration (s) and stride duration variability (coefficient of variation; CV) values across the gait conditions for each age group.

	10-12 yo	13-14 yo	15-17 yo	Adults
Walking				
Familiar walk (SSW)				
Mean (s)	1.08 ± 0.08	1.11 ± 0.07	1.07 ± 0.07	1.06 ± 0.06
CV (%)	1.88 ± 0.66 †	1.53 ± 0.40	1.39 ± 0.70	1.27 ± 0.55
Unfamiliar walk (PTS-0.06 $m{\cdot}s^{-1}$)				
Mean (s)	0.88 ± 0.08	0.90 ± 0.03	0.90 ± 0.06	0.91 ± 0.06
CV (%)	1.99 ± 0.97 †	1.45 ± 0.33	1.35 ± 0.53	1.14 ± 0.49
Running				
Familiar run (PTS+0.83 $m{\cdot}s^{-1}$)				
Mean (s)	0.72 ± 0.04	0.73 ± 0.04	0.72 ± 0.04	0.74 ± 0.03
CV (%)	2.03 ± 0.79 ‡	1.50 ± 0.55	1.41 ± 0.34	1.22 ± 0.44
Unfamiliar run (PTS+0.06 $m{\cdot}s^{-1}$)				
Mean (s)	0.74 ± 0.04	0.77 ± 0.05	0.75 ± 0.04	0.77 ± 0.03
CV (%)	2.19 ± 0.51 ‡	1.82 ± 0.30 †	1.64 ± 0.45 *	1.26 ± 0.34

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 3.3. Mean ± SD of the stride length (m) and stride length variability (coefficient of variation; CV) values across the gait conditions for each age group.

	10-12 yo	13-14 yo	15-17 yo	Adults
Walking				
Familiar walk (SSW)				
Mean (m)	1.18 ± 0.12	1.32 ± 0.09	1.37 ± 0.12	1.37 ± 0.11
CV (%)	2.42 ± 0.77 ‡	1.86 ± 0.40	1.51 ± 0.64	1.37 ± 0.61
Unfamiliar walk (PTS-0.06 $m{\cdot}s^{-1}$)				
Mean (m)	1.56 ± 0.11	1.75 ± 0.15	1.76 ± 0.10	1.75 ± 0.08
CV (%)	2.02 ± 1.07 ‡	1.29 ± 0.28	1.15 ± 0.39	0.90 ± 0.41
Running				
Familiar run (PTS+0.83 $m{\cdot}s^{-1}$)				
Mean (m)	1.91 ± 0.15	2.06 ± 0.23	2.06 ± 0.16	2.08 ± 0.14
CV (%)	2.63 ± 0.68 ‡	1.85 ± 0.40	1.58 ± 0.55	1.36 ± 0.58
Unfamiliar run (PTS+0.06 $m{\cdot}s^{-1}$)				
Mean (m)	1.41 ± 0.13	1.57 ± 0.21	1.57 ± 0.16	1.57 ± 0.14
CV (%)	2.91 ± 0.66 ‡	2.05 ± 0.48	1.92 ± 0.55	1.69 ± 0.40

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 3.4. Absolute and normalised preferred transition speed (PTS) values for each of the age groups.

PTS	10-12 yo	13-14 yo	15-17 yo	Adults
$m \cdot s^{-1}$	1.84 ± 0.17	1.99 ± 0.17	2.01 ± 0.18 *	1.98 ± 0.18
statures$\cdot s^{-1}$	1.22 ± 0.14	1.22 ± 0.09	1.19 ± 0.12	1.16 ± 0.10
leg lengths$\cdot s^{-1}$	2.28 ± 0.25	2.29 ± 0.17	2.25 ± 0.21	2.24 ± 0.24
Froude number	0.43 ± 0.08	0.47 ± 0.07	0.47 ± 0.08	0.46 ± 0.08

Values presented as means ± SDs. * Significantly different (p=0.032) compared to the 10-12-year-olds. PTS: Preferred transition speed. yo: -year-olds.

Table 3.5. Means ± SDs of the counts (n) for the number of gait transitions completed by the participants and the number of speed increments at which gait transitions occurred throughout the walk-to-run transition protocol for each age group.

		10-12 yo	13-14 yo	15-17 yo	Adults
Transitions	n	3.71 ± 3.24	1.83 ± 1.59	1.13 ± 0.50 *	1.33 ± 1.16 *
	(range)	(1-11)	(1-5)	(1-3)	(1-5)
Speeds	n	1.88 ± 0.99	1.25 ± 0.62	1.06 ± 0.25 *	1.17 ± 0.58 *
	(range)	(1-4)	(1-3)	(1-2)	(1-3)

* indicates statistical difference compared to the 10-12-year-olds. yo: -year-olds.

3.4. 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 youth exhibited more variable gait patterns than the adults, gait maturation appears to be an ongoing process during childhood and adolescence. To subsequently analyse how well youth can adapt their gait to changing task demands, the study investigated whether differences existed in PTS and how effectively they could determine their PTS compared to adults. No systematic age differences in PTS were observed, but the 10-12 yo transitioned more frequently and used more speed increments to determine PTS during the treadmill protocol than the older adolescents (15-17 yo) and adults. These combined results support that gait patterns are not 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 10-12 yo did not exhibit mature walking and running patterns due to the greater spatiotemporal variability seen during all of the gait conditions. The 13-17 yo 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 adolescents. While running at the standardised running speed did appear to be mature by 13 years of age, running at the unfamiliar 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 in children up until the age of 3 years (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 unfamiliar 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 determined. PTS observed across the age 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 10-12 yo and 15-17 yo groups, no consistent age-dependent pattern in PTS was observed, despite significant height and leg length differences between the children (10-12 yo) 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 10-12 yo than the adults. These children 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 10-14 yo. These children and younger adolescents may have been exhibiting exploratory behaviour necessary for learning (Ulman, Ranganathan, Queen, & Srinivasan, 2019). Specifically, the 10-14 yo varied their spatiotemporal parameters while attempting to determine the most economical combination of stride length and stride frequency. Conversely, adults often quickly adopt the most economical 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 economy 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 children may therefore indicate that it took longer to determine the most economical spatiotemporal parameters than the adults.

To further demonstrate the adults' superior ability to swiftly adapt gait patterns than the children, the adults often determined their PTS using only one gait transition over a single speed. The 15-17 yo were also able to generally determine their PTS with a single transition. However, the 10-12 yo more frequently used multiple gait transitions over more speed increments before finally settling in a running pattern at their PTS compared to the 15-17 yo and adults. The lack of statistical significance between 13-14 yo and both 10-12 yo and 15-17 yo may suggest that the 13-14 yo 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 mins 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 at speeds near PTS. Although PTS±0.06 $m{\cdot}s^{-1}$ would have been unfamiliar for all groups, the children and adolescents continued to exhibit more variability at the unfamiliar running condition and the 10-12 yo also exhibited more variability at the unfamiliar 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.

3.5. Conclusion

There was a lack of gait maturity among the children and younger adolescents, particularly those between 10 and 12 years of age. Mature walking emerged by 13 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. The 10-14 yo 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 10-14 yo 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.

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Supplementary Table 3.A. Participant characteristics for each of the eight paediatric groups and the young adults.

	10 yo	11 yo	12 yo	13 yo	14 yo	15 yo	16 yo	17 yo	Adults
n (F:M)	6 (4:2)	5 (4:1)	6 (4:2)	6 (2:4)	6 (4:2)	6 (2:4)	5 (2:3)	6 (3:3)	12 (6:6)
Height (m)	1.439 ± 0.021	1.509 ± 0.025	1.584 ± 0.042 *	1.628 ± 0.055 *	1.640 ± 0.107 *	1.734 ± 0.027 *†‡	1.640 ± 0.089 *	1.710 ± 0.094 *†	1.706 ± 0.095 *†‡
Mass (kg)	34.8 ± 4.3	40.9 ± 3.1	51.2 ± 9.2 *	46.8 ± 7.1	49.4 ± 10.2	57.4 ± 4.2 *	54.6 ± 11.3 *	62.6 ± 7.7 *†◊	62.6 ± 10.5 *†◊
Leg length (m)	0.770 ± 0.017	0.804 ± 0.006	0.847 ± 0.029	0.873 ± 0.033 *	0.864 ± 0.067 *	0.914 ± 0.025 *†	0.853 ± 0.047	0.896 ± 0.042 *†	0.884 ± 0.063 *†
BMI ($kg \cdot m^{-2}$)	16.8 ± 1.7	18.0 ± 1.6	20.3 ± 3.0	17.6 ± 1.7	18.2 ± 1.9	19.1 ± 1.5	20.1 ± 2.4	21.5 ± 2.8 *	21.4 ± 2.2 *◊

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-year-olds; † 11-year-olds; ‡ 12-year-olds; and ◊ 13-year-olds. yo: -year-olds. F: Female. M: Male.

Supplementary Table 3.B. Mean ± SD of the stride duration (s) and stride duration variability (coefficient of variation; CV) values across the age range and young adults (19-29 yo).

	10 yo	11 yo	12 yo	13 yo	14 yo	15 yo	16 yo	17 yo	Adults
Walking									
Familiar walk (SSW)									
Mean (s)	1.03 ± 0.07	1.06 ± 0.08	1.14 ± 0.06	1.11 ± 0.09	1.11 ± 0.05	1.06 ± 0.08	1.08 ± 0.06	1.07 ± 0.07	1.06 ± 0.06
CV (%)	1.87 ± 0.18 *	2.15 ± 0.80 †	1.65 ± 0.83	1.45 ± 0.44	1.60 ± 0.38	1.28 ± 0.30	1.86 ± 1.13	1.09 ± 0.28	1.26 ± 0.54
Unfamiliar walk (PTS-0.06 $m \cdot s^{-1}$)									
Mean (s)	0.85 ± 0.04	0.83 ± 0.06	0.95 ± 0.07	0.90 ± 0.03	0.91 ± 0.01	0.87 ± 0.06	0.90 ± 0.03	0.94 ± 0.07	0.91 ± 0.06
CV (%)	2.29 ± 1.04 ‡	1.94 ± 0.56 *	1.73 ± 1.21	1.36 ± 0.38	1.53 ± 0.26	1.41 ± 0.74	1.33 ± 0.44	1.30 ± 0.43	1.14 ± 0.49
Running									
Familiar run (PTS+0.83 $m \cdot s^{-1}$)									
Mean (s)	0.70 ± 0.03	0.69 ± 0.03	0.75 ± 0.04	0.74 ± 0.05	0.72 ± 0.03	0.73 ± 0.03	0.69 ± 0.02	0.73 ± 0.04	0.74 ± 0.03
CV (%)	2.17 ± 0.85 †	2.34 ± 0.99 ‡	1.63 ± 0.37	1.30 ± 0.39	1.68 ± 0.66	1.35 ± 0.30	1.48 ± 0.44	1.40 ± 0.34	1.22 ± 0.44
Unfamiliar run (PTS+0.06 $m \cdot s^{-1}$)									
Mean (s)	0.73 ± 0.03	0.71 ± 0.04	0.79 ± 0.03	0.78 ± 0.07	0.75 ± 0.03	0.75 ± 0.02	0.75 ± 0.06	0.77 ± 0.02	0.77 ± 0.03
CV (%)	2.38 ± 0.68 ‡	2.14 ± 0.52 ‡	2.04 ± 0.28 ‡	1.84 ± 0.34 †	1.79 ± 0.28 *	1.53 ± 0.54	1.77 ± 0.28 *	1.63 ± 0.50	1.25 ± 0.33

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.

Supplementary Table 3.C. Mean ± SD of the stride length (m) and stride length variability (coefficient of variation; CV) values across the age range and young adults (19-29 yo).

	10 yo	11 yo	12 yo	13 yo	14 yo	15 yo	16 yo	17 yo	Adults
Walking									
Familiar walk (SSW)									
Mean (m)	1.21 ± 0.08	1.12 ± 0.20	1.20 ± 0.08	1.36 ± 0.07	1.29 ± 0.10	1.39 ± 0.13	1.35 ± 0.12	1.35 ± 0.14	1.37 ± 0.11
CV (%)	2.44 ± 0.66 †	2.65 ± 1.04 †	2.19 ± 0.69 *	1.69 ± 0.23	2.02 ± 0.48	1.37 ± 0.22	1.96 ± 1.06	1.25 ± 0.21	1.36 ± 0.60
Unfamiliar walk (PTS-0.06 $m \cdot s^{-1}$)									
Mean (m)	1.51 ± 0.11	1.56 ± 0.09	1.61 ± 0.11	1.81 ± 0.11	1.69 ± 0.16	1.82 ± 0.05	1.68 ± 0.12	1.76 ± 0.10	1.75 ± 0.08
CV (%)	2.43 ± 1.59 ‡	1.76 ± 0.42 *	1.81 ± 0.81 †	1.33 ± 0.27	1.25 ± 0.30	1.11 ± 0.41	1.23 ± 0.34	1.11 ± 0.44	0.89 ± 0.41
Running									
Familiar Run (PTS+0.83 $m \cdot s^{-1}$)									
Mean (m)	1.85 ± 0.14	1.91 ± 0.09	1.98 ± 0.18	2.15 ± 0.21	1.96 ± 0.23	2.17 ± 0.12	1.95 ± 0.14	2.04 ± 0.16	2.08 ± 0.14
CV (%)	3.07 ± 0.79 ‡	2.32 ± 0.24 †	2.43 ± 0.63 ‡	1.81 ± 0.48	1.89 ± 0.33	1.52 ± 0.50	1.64 ± 0.62	1.57 ± 0.63	1.36 ± 0.57
Unfamiliar Run (PTS+0.06 $m \cdot s^{-1}$)									
Mean (m)	1.38 ± 0.13	1.41 ± 0.11	1.43 ± 0.17	1.67 ± 0.20	1.48 ± 0.19	1.65 ± 0.14	1.50 ± 0.23	1.54 ± 0.10	1.57 ± 0.14
CV (%)	2.66 ± 0.63 †	2.98 ± 0.41 ‡	3.10 ± 0.86 ‡	2.01 ± 0.44	2.07 ± 0.56	2.00 ± 0.65	1.89 ± 0.47	1.85 ± 0.58	1.68 ± 0.40

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.

Supplementary Table 3.D. Absolute and normalised preferred transition speed (PTS) values across the age range and young adults (19-29 yo).

PTS	10 yo	11 yo	12 yo	13 yo	14 yo	15 yo	16 yo	17 yo	Adults
$m \cdot s^{-1}$	1.84 ± 0.16	1.93 ± 0.11	1.76 ± 0.20	2.07 ± 0.11 ‡	1.90 ± 0.18	2.16 ± 0.18 *‡	1.92 ± 0.16	1.94 ± 0.11	1.98 ± 0.18
statures$\cdot s^{-1}$	1.28 ± 0.13	1.28 ± 0.08	1.11 ± 0.13	1.27 ± 0.06	1.16 ± 0.08	1.24 ± 0.10	1.18 ± 0.14	1.13 ± 0.09	1.16 ± 0.10
leg lengths$\cdot s^{-1}$	2.39 ± 0.21	2.40 ± 0.14	2.08 ± 0.25	2.38 ± 0.12	2.20 ± 0.16	2.36 ± 0.17	2.26 ± 0.27	2.16 ± 0.19	2.24 ± 0.24
Froude number	0.45 ± 0.08	0.48 ± 0.05	0.38 ± 0.08	0.50 ± 0.05	0.43 ± 0.06	0.52 ± 0.08	0.45 ± 0.09	0.43 ± 0.06	0.46 ± 0.08

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-year-olds and the ‡ 12-year-olds. The Froude number is calculated as $v^2/g \cdot l$, where v is gait speed, g is the acceleration due to gravity and l is the individual's leg length. yo: -year-olds.

Supplementary Table 3.E. Means ± SDs (range) of the counts (n) for the number of transitions completed by the participants and the number of speed increments at which gait transitions occurred throughout the walk-to-run transition protocol across the age range and young adults (19-29 yo).

		10 yo	11 yo	12 yo	13 yo	14 yo	15 yo	16 yo	17 yo	Adults
Transitions	n	4.0 ± 3.5	3.8 ± 2.3	3.3 ± 4.1	2.0 ± 1.7	1.7 ± 1.6	1.0 ± 0.0	1.4 ± 0.9	1.0 ± 0.0	1.3 ± 1.2
	(range)	(1-9)	(1-7)	(1-11)	(1-5)	(1-5)	(0-1)	(1-3)	(0-1)	(1-5)
Speeds	n	2.2 ± 1.3	2.0 ± 0.7	1.5 ± 0.8	1.5 ± 0.8	1.0 ± 0.0	1.0 ± 0.0	1.2 ± 0.4	1.0 ± 0.0	1.2 ± 0.6
	(range)	(1-4)	(1-3)	(1-3)	(1-3)	(0-1)	(0-1)	(1-2)	(0-1)	(1-3)

yo: -year-olds.

CHAPTER 4

Age-related differences in muscular and physiological variables during the walk-to-run transition: Application of the weakest link principle*

4.0. Abstract

Determinants of the preferred transition speed (PTS) theoretically initiate walk-to-run transitions when they reach a critical value, thus minimising effort and energy cost. Various factors, known as ‘weak links’, approach these critical values near PTS, whereby the weakest link reaches its critical threshold first. The purpose of this study was to investigate whether age-related differences in specific weak links exist. 10-12-year-olds (n=19), 13-14-year-olds (n=12), 15-17-year-olds (n=16) and adults (19-29-year-olds; n=12) completed an incrementally ramped treadmill protocol and walked and ran at a range of speeds near their PTS while heart rate, oxygen consumption and muscle activity (rectus femoris, biceps femoris, medial gastrocnemius, tibialis anterior) were measured. To be considered a weak link, variables needed to be: 1) significantly lower, or increase at a lower rate while running at PTS than walking; and 2) at lower values while running at speeds faster than PTS compared to walking; PTS also needed to be statistically similar to the theoretically optimal transition speed for the given variable. Physiological variables failed to satisfy the criteria for being considered as potential PTS determinants, thus gait patterns are likely adjusted to minimise muscular effort. Rectus femoris and tibialis anterior were common weak links across all age groups, while the biceps femoris and gastrocnemius were additional weak links for the 10-12-year-olds and 10-17-year-olds, respectively. Therefore, children and adolescents appear to transition to minimise the effort for more muscles, which could result in more conflicting sources of feedback when adjusting their gait. The biceps femoris and medial gastrocnemius thus appear to continue developing through childhood and adolescence.

Keywords: Gait maturation, locomotion, paediatrics, gait

* Manuscript submitted and currently under review:

SM Kung, PW Fink, SJ Legg, A Ali & SP Shultz. Age-related differences in muscular and physiological variables during the walk-to-run transition: Application of the weakest link principle. *Journal of Biomechanics* (*under review*).

4.1. Introduction

Adults transition between walking and running in a predictable way as gait speed changes. The walk-to-run transition (WRT) reduces the mechanical load on the tibialis anterior, rectus femoris and biceps femoris (Hreljac, Arata, Ferber, Mercer, & Row, 2001; Malcolm, Segers, Van Caekenberghe, & De Clercq, 2009; Prilutsky & Gregor, 2001), improves the mechanical efficiency of the ankle plantarflexors (Farris & Sawicki, 2012; Neptune & Sasaki, 2005; Schwartz, Rozumalski, & Trost, 2008), and prevents metabolic cost of locomotion from increasing exponentially (Hreljac, 1993). These self-optimising behaviours suggest individuals respond to continuous feedback about the task demands to effectively and economically adjust their gait, particularly as the preferred transition speed (PTS) is generally close to the theoretically optimal transition speed (TOTS) for minimising metabolic energy expenditure (Hreljac, 1993; Rotstein, Inbar, Berginsky, & Meckel, 2005). Adolescents display similar tendencies, including transitioning before it is energetically optimal (Tseh, Bennett, Caputo, & Morgan, 2002), but the same factors may not necessarily be driving transitions in youth as compared to adults. Particularly, children and adolescents exhibit signs of possessing immature gait through to late adolescence (Chester, Tingley, & Biden, 2006; Kung, Fink, Legg, Ali, & Shultz, 2019; Van de Walle et al., 2010). Continued musculoskeletal development may explain differences in gait variability (Kung et al., 2019) and joint moments (Chester et al., 2006; Ganley & Powers, 2005), but these age-related differences could suggest that youth use different mechanisms to regulate their gait.

When walking speeds are expressed as the dimensionless Froude number, children and adults exhibit similar relationships between stride length and stature at slow walking speeds (Alexander, 1984). This dynamic similarity in gait mechanics between children and adults suggests walking dynamics are scaled to body size and thus PTS would also scale to leg length due to inverted pendulum mechanics constraints. Accordingly, 11-year-olds (yo) have been reported to transition at a slower speed than 13- and 15-yo (Tseh et al., 2002), which was suggested to be influenced by leg length differences. However, when PTS was compared between youth and adults, no age-related differences were revealed, despite children having shorter legs (Kung et al., 2019). Therefore, it is likely leg length alone does not determine PTS and other factors also contribute to the determination of PTS, which may explain why children do not transition at slower speeds than adults. These contributing factors presumably assist with minimising the metabolic and mechanical demands of locomotion.

A ‘weakest link’ concept was proposed to describe how potential determinants influence the PTS (Malcolm, Fiers, et al., 2009). Through manipulations of mechanical load on various muscle groups, increasing mechanical load was shown to decrease PTS (Farley & Taylor, 1991; MacLeod, Hreljac, & Imamura, 2014; Malcolm, Fiers, et al., 2009), while assisting one or more muscle groups did not necessarily increase PTS (Bartlett & Kram, 2008; Malcolm, Segers, et al., 2009). Thus, it was suggested that a number of variables approach critical values at speeds nearing PTS, but PTS would be determined by the factor that reaches its critical value first (i.e. the weakest link). Adopting the theoretical framework of the weakest link, it is assumed that a variable, or combination of variables approach a critical value near PTS, which are then relieved following the WRT. The purpose of this study was to investigate whether there are age-related differences in specific muscular and physiological weak links, which could have a potential role in influencing PTS.

To assess potential weak links, this study analysed how effectively muscular and physiological demands are optimised during the WRT. Four criteria have previously been proposed to assist with identifying the determinants of PTS (Hreljac, 1995; Kung, Fink, Legg, Ali, & Shultz, 2018) and were used to identify muscular and physiological weak links. Potential weak links must exhibit an abrupt change in either the magnitude or rate of change at PTS (criterion 1). Following the WRT, potential weak links should function at lower values in the post-transition gait mode than the pre-transition gait (criterion 2). To adapt gait to the changing locomotive speed, rapid feedback about the changes in the potential weak links needs to be available (criterion 3). Finally, the WRT should occur at a critical value of the potential weak link (criterion 4). Factors that satisfied these criteria (Table 4.1) were thus considered to be weak links and were identified as good candidates for age-specific PTS determinants. As the presence of feedback systems is largely theoretical, criterion 3 was not specifically tested, but will be addressed in the Discussion.

Table 4.1. Previously published criteria for identifying determinants of the preferred transition speed (PTS).

Criteria	To be satisfied
1) Abrupt change at PTS	a) Magnitude of potential determinant candidates must be lower while running than walking at PTS (i.e. WPTS > RPTS); *and/or* b) Running slope must be lower than the walking slope at PTS.
2) Use most favourable gait mode	a) Walking should be less demanding at pre-transition speeds (i.e. WPTS-2 ≤ RPTS-2, WPTS-1 ≤ RPTS-1); *and* b) Running should be less demanding at post-transition speeds (i.e. RPTS+1 < WPTS+1, RPTS+2 < WPTS+2).
3) Feedback	Rapid feedback about changes in the potential determinant needs to be available.
4) Critical value	Transition occurs when the potential determinant reaches a critical threshold.* If a potential weak link candidate is optimised, the PTS and TOTS would not be statistically different (i.e. p>0.05).

* For the purpose of this study, the critical value is represented by the theoretically optimal transition speed (TOTS) to determine how well the candidate factor was optimised by transitioning from walking to running. These criteria have previously been published (Hreljac, 1995; Kung et al., 2018). WPTS: Walking at PTS. RPTS: Running at PTS.

4.2. Methods

4.2.1. Participants

Forty-seven youth (10-17 yo) and 12 young adults (19-29 yo) participated in this study. These participants were part of a larger overarching project that was investigating age-related differences in the WRT among youth and young adults (Kung et al., 2019). Based on previous assessments of variability (Kung et al., 2019), children and adolescents were grouped into 10-12 yo, 13-14 yo and 15-17 yo (Table 4.2). Exclusion criteria were any lower extremity injuries/surgeries that occurred within the six months prior to testing, and a diagnosis of any neuromusculoskeletal condition, cardiovascular disease, diabetes, or asthma. Informed written parental consent and participant assent were obtained for participants aged 10-16 years, while the 17-29 yo provided their own informed written consent. The institutional human ethics committee approved the study.

Table 4.2. Participant characteristics and preferred transition speeds (PTS).

	10-12 yo	13-14 yo	15-17 yo	Adults
n (F:M)	19 (12:7)	12 (6:6)	16 (7:9)	12 (6:6)
Age (y)	11.0 ± 0.9	13.5 ± 0.5	16.1 ± 0.9	24.9 ± 3.5
Height (m)	1.515 ± 0.066	1.634 ± 0.081*	1.693 ± 0.081*	1.706 ± 0.095*
Mass (kg)	42.3 ± 8.4	48.1 ± 8.5	58.3 ± 8.5*†	62.6 ± 10.5*†
BMI ($kg \cdot m^{-2}$)	18.3 ± 2.4	17.9 ± 1.8	20.3 ± 2.4†	21.4 ± 2.2*†
Leg length (m)	0.808 ± 0.038	0.872 ± 0.049*	0.888 ± 0.043*	0.886 ± 0.047*
$\dot{V}O_2$peak ($mL \cdot kg^{-1} \cdot min^{-1}$)	48.1 ± 4.3	52.8 ± 7.2	53.7 ± 8.7	50.1 ± 7.2
PTS ($m \cdot s^{-1}$)	1.89 ± 0.20	1.99 ± 0.17	2.01 ± 0.19	1.98 ± 0.18

Significant age group differences ($p<0.05$) are highlighted in the table for comparisons with the * 10-12-year-olds (yo) and the † 13-14 yo. $\dot{V}O_2$peak: Peak oxygen consumption. F: Female. M: Male.

4.2.2. Protocol

The testing protocol comprised three sessions that were completed at least 48 hours apart, but no longer than 1 week apart. During session 1, participants were familiarised with walking and running on a treadmill at self-selected speeds for at least 15 min each. Participants then completed at least three practice WRT trials, which started at a self-selected walking speed and treadmill speed was increased by 0.06 $m \cdot s^{-1}$ every 10 s until the participant transitioned to running.

The second session involved an incremental treadmill test to determine PTS (i.e. the speed at which the final transition to running occurred without reverting to walking thereafter). The test began with the participant walking at their self-selected walking speed for 90 s. Treadmill speed was increased by +0.06 $m \cdot s^{-1}$ every 30 s until 5 speed increments after PTS. Subsequent speed increments increased by +0.14 $m \cdot s^{-1}$ every 30 s until participants indicated they reached volitional exhaustion (i.e. peak exertion; $\dot{V}O_2$peak). Participants were instructed to start running at a speed that felt most comfortable and were given no visual or verbal cues about their gait speed.

For session 3, participants walked and ran at five speeds in a randomised order: 1) PTS-0.28 $m \cdot s^{-1}$ (i.e. *WPTS-2, RPTS-2, respectively*); 2) PTS-0.14 $m \cdot s^{-1}$ (i.e. *WPTS-1, RPTS-1, respectively*); 3) PTS (i.e. *WPTS, RPTS, respectively*); 4) PTS+0.14 $m \cdot s^{-1}$ (i.e. *WPTS+1, RPTS+1, respectively*); and 5) PTS+0.28 $m \cdot s^{-1}$ (i.e. *WPTS+2, RPTS+2, respectively*). Each trial lasted 5 min and participants had 5 min rests between trials.

4.2.3. Data collection and processing

Muscle activity of the biceps femoris (BF), rectus femoris (RF), tibialis anterior (TA) and medial gastrocnemius (MG) were assessed during sessions 2 and 3 using surface electromyography (EMG; Telemyo DTS, Noraxon, Scottsdale, AZ). Surface electrodes were placed on the participant's dominant limb according to the SENIAM guidelines (Hermens et al., 1999). EMG data were collected at a sampling frequency of 1500 Hz for 10 s at the end of each speed increment during session 2 and for 30 s at the end of each 5-min gait trial during session 3.

EMG data were processed from full gait cycles completed during the last 10 s of each speed increment in session 2 and the last 30 s from the end of each gait trial in session 3 (Visual3D, v6.01.22, C-Motion, Germantown, MD). EMG signals were band-pass filtered (20-450 Hz) using a fourth-order Butterworth filter and smoothed using a RMS (40 ms window). The EMG data from session 2 were normalised to the muscle-specific peak value from the PTS trial, while the session 3 EMG data were normalised to the muscle-specific peak value from the WPTS trial. An average value was calculated across the gait cycles and expressed as a percentage of the peak value (%PTS_{peak}, %$WPTS_{peak}$ respectively).

Heart rate (HR) was recorded at the end of each speed increment during session 2 and at the end of each 5-min gait trial during session 3 (Polar, Kempele, Finland). Oxygen uptake ($\dot{V}O_2$) was measured over the entire incremental treadmill protocol in session 2, and throughout each 5-min trial in session 3 (K4 b2, Cosmed, Rome, Italy). $\dot{V}O_2$ was averaged over the 30-s period for each speed in session 2 and over the last minute of each gait trial in session 3. All $\dot{V}O_2$ values were normalised to body mass (i.e. $mL \cdot kg^{-1} \cdot min^{-1}$).

Regression models, using a linear mixed model calculated in R (version 3.5.2, R Core Team 2013, Vienna, Austria), were calculated for each variable for walking and running separately on a participant-by-participant basis. To account for potential nonlinearities in the relationship between the variables and speed (see Supplementary Figures 4.A-4.F), both a linear model and a quadratic model as a function of speed were tested for each variable:

$$Linear: y = c_2x + c_1$$

$$Quadratic: y = c_3x^2 + c_2x + c_1$$

where y is the variable in question and x is the speed. The models were assessed using an

Akaike Information Criterion (AIC), and the linear model was used unless the AIC of the quadratic model was less than the AIC of the linear model by at least 2. Examples of the regression models from sessions 2 and 3 are presented in Figures 4.1 and 4.2, respectively.

Slopes of the models from session 2 were calculated from the fitted parameters at PTS. When the linear model was used, the slope was given by c_2; when the quadratic model was used, the slope was calculated as:

$$Slope = 2c_3 x_{pts} + c_2$$

where x_{pts} is the PTS. The slopes were used to test criterion 1.

The TOTS for each variable represented the critical values (criterion 4), which were calculated for each participant as the intersection of the walking and running regression lines from the session 3 data. Where walking and running regression equations did not intersect, the participant's data for that variable were excluded from the analysis. Updated sample sizes are listed in Table 4.3 and reflect these exclusions.

4.2.4. Statistical analysis

A 4 x 2 (age group x gait mode) mixed model ANOVA with repeated measures (SAS version 9.4, Cary, NC) compared the walking and running slopes calculated from session 2 to test Criterion 1b for each age group (i.e. satisfied if running slope < walking slope). A 4 x 10 (age group x gait condition) mixed model ANOVA with repeated measures (SAS) compared each variable during walking and running at each speed completed in session 3 to test the following criteria for each age group: criterion 1a was satisfied if RPTS < WPTS; criterion 2a was satisfied if WPTS-2 ≤ RPTS-2 and WPTS-1 ≤ RPTS-1; and criterion 2b was satisfied if RPTS+1 < WPTS+1 and RPTS+2 < WPTS+2. Post-hoc Tukey tests were used to identify where significant differences were found. Differences were considered statistically significant when $p<0.05$. Paired t-tests compared PTS and each TOTS within each age group to test criterion 4 (SPSS Statistics version 24; IBM Corp, Armonk, NY), which was satisfied if PTS and TOTS were not significantly different ($p>0.05$).

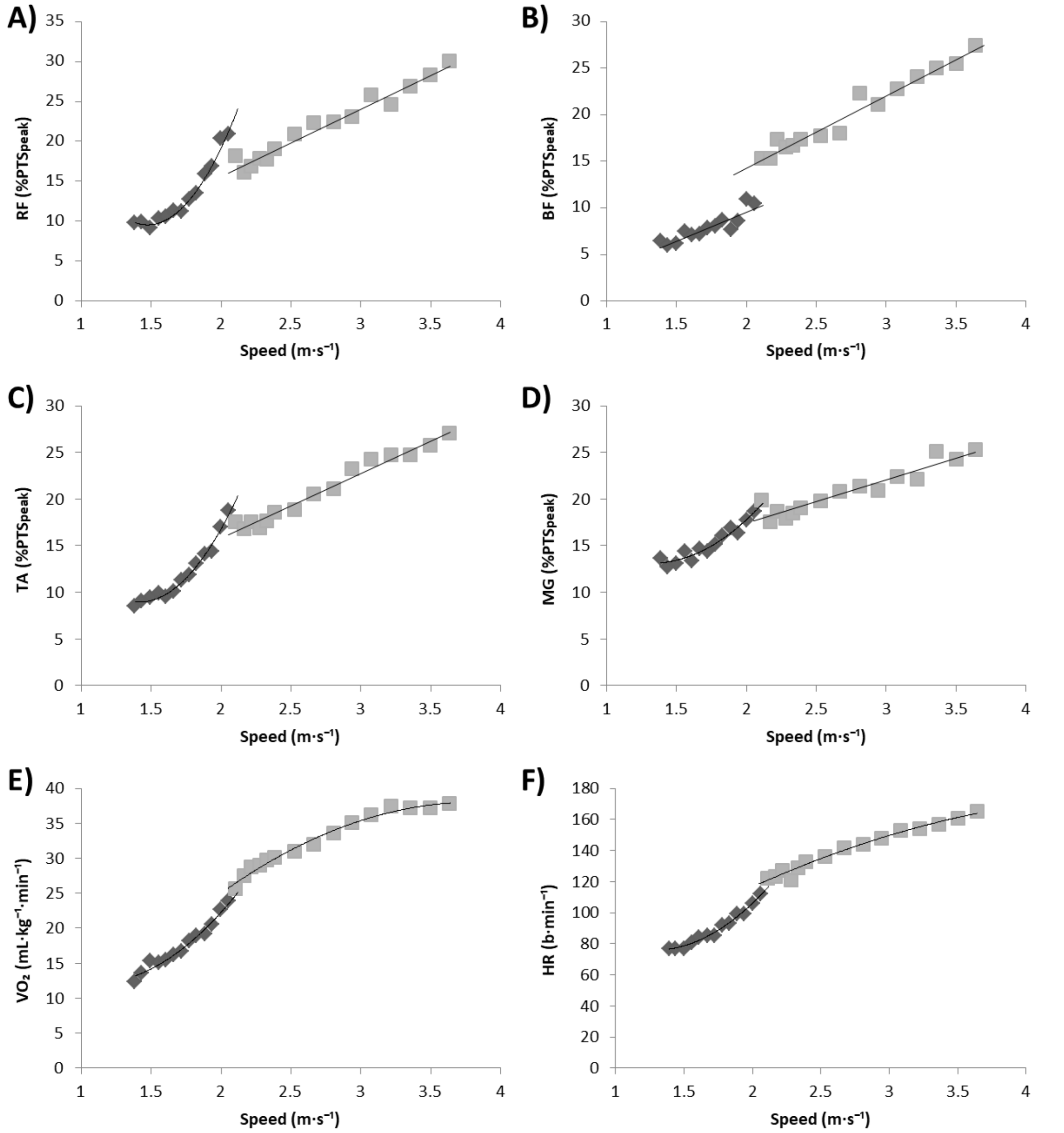

Figure 4.1. Example of the regression models produced for walking (◆) and running (■) from the session 2 data for the (A) rectus femoris, RF; (B) biceps femoris, BF; (C) tibialis anterior, TA; (D) medial gastrocnemius, MG; (E) oxygen consumption, $\dot{V}O_2$; and (F) heart rate, HR.

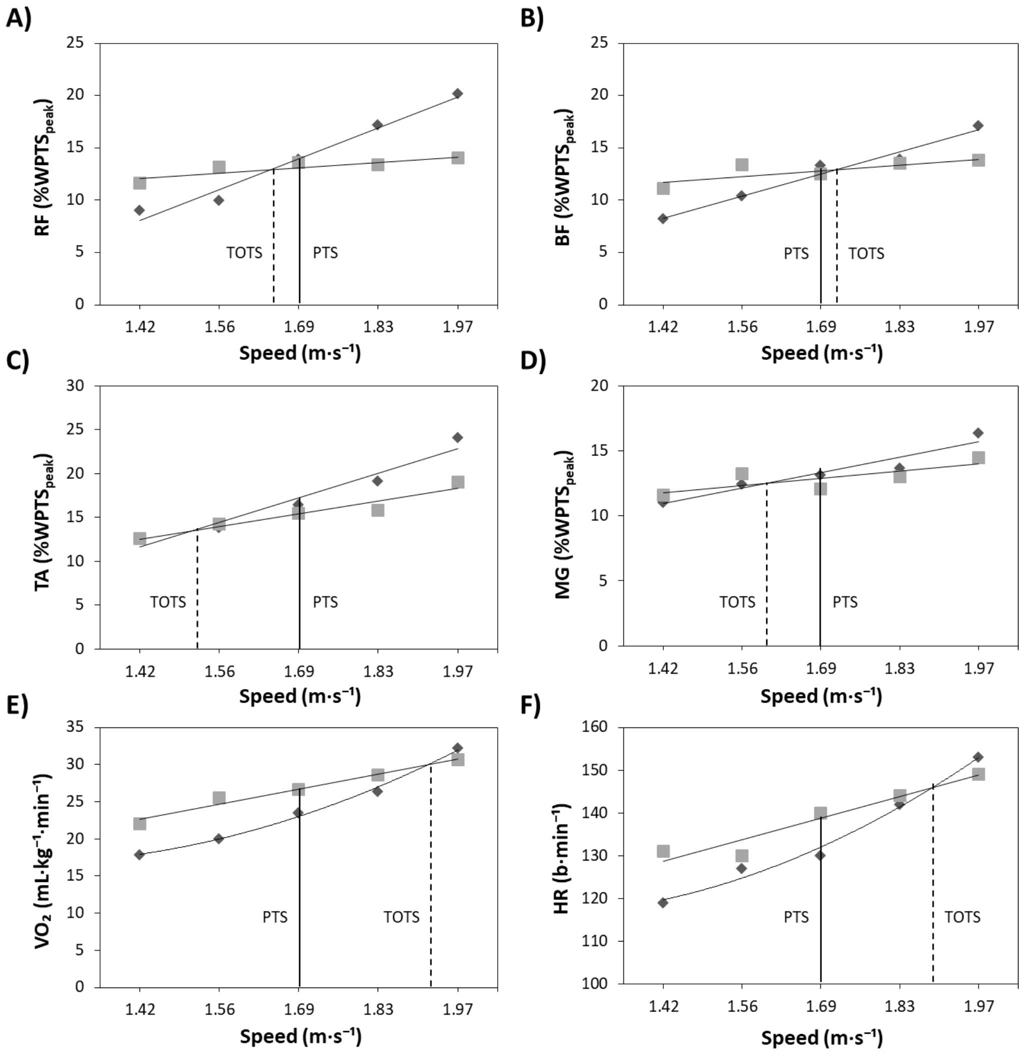

Figure 4.2. Example of the regression models produced for walking (◆) and running (■) from the session 3 data for the (A) rectus femoris, RF; (B) biceps femoris, BF; (C) tibialis anterior, TA; (D) medial gastrocnemius, MG; (E) oxygen consumption, $\dot{V}O_2$; and (F) heart rate, HR. The solid vertical lines indicate the preferred transition speed (PTS), while the dashed vertical lines indicate the theoretically optimal transition speed (TOTS) for each variable.

4.3. Results

4.3.1. Muscular variables

BF satisfied criterion 1 *(running < walking slope, Table 4.4)* and criterion 2 *(walking < running at pre-transition speeds; RPTS+2 < WPTS+2, Table 4.5)*, but not criterion 4 for 10-12 yo. For 13-14 yo, BF satisfied criterion 1 *(running < walking slope, Table 4.4)*; BF did not satisfy any other criteria for 13-14 yo, 15-17 yo or adults.

For 10-12 yo, 15-17 yo and adults, RF satisfied criterion 1 *(running < walking slope, Table 4.4)*, criterion 2 *(walking ≤ running at pre-transition speeds; running < walking at post-transition speeds, Tables 4.5, 4.7, 4.8)* and criterion 4 *(TOTS ≈ PTS, Table 4.3)*. For 13-14 yo, RF satisfied criterion 1 *(RPTS < WPTS, Table 4.4; running < walking slope, Table 4.4)*, criterion 2 *(walking ≈ running at pre-transition speeds; RPTS+2 < WPTS+2; Table 4.6)*, but not criterion 4.

For all paediatric groups, MG satisfied criterion 1 *(running < walking slope, Table 4.4; RPTS < WPTS for 15-17 yo only, Table 4.7)*, criterion 2 *(walking < running at pre-transition speeds; and RPTS+2 < WPTS+2; Tables 4.5-4.7)*, and criterion 4 *(TOTS ≈ PTS, Table 4.3)*. For adults, MG also satisfied criterion 1 *(running < walking slope, Table 4.4)*, criterion 2a *(walking ≤ running at pre-transition speeds, Table 4.8)* and criterion 4 *(TOTS ≈ PTS, Table 4.3)*, but not criterion 2b.

For all groups, TA satisfied criterion 1 *(running < walking slope, Table 4.4; RPTS < WPTS, Tables 4.5-4.8)*, criterion 2 *(walking ≤ running at pre-transition speeds; running < walking at post-transition speeds; Tables 4.5-4.8)*. Criterion 4 was satisfied for 10-12 yo and 13-14 yo *(TOTS ≈ PTS, Table 4.3)*, but not 15-17 yo or adults *(TOTS < PTS, Table 4.3)*.

4.3.2. Physiological variables

For 13-14 yo, $\dot{V}O_2$ satisfied criterion 1 *(running < walking slope, Table 4.4)* and criterion 2 *(walking < running at pre-transition speeds; RPTS+2 < WPTS+2; Table 4.6)*, but not criterion 4. For adults, $\dot{V}O_2$ only satisfied criterion 1 *(running < walking slope, Table 4.4)*. For 10-12 yo and 15-17 yo, $\dot{V}O_2$ did not satisfy any criteria.

For 10-12 yo and 15-17 yo, HR satisfied criterion 1 *(running < walking slope, Table 4.4)*, but not criteria 2 and 4. For 13-14 yo, HR only satisfied criterion 2 *(walking < running at pre-transition speeds; RPTS+2 < WPTS+2; Table 4.6)*. For adults, HR satisfied criterion 1 *(running < walking slope, Table 4.4)* and criterion 2 *(walking < running at pre-transition speeds; RPTS+2 < WPTS+2; Table 4.8)*, but not criterion 4.

Table 4.3. Comparison of the mean ± SD preferred transition speed (PTS; $m \cdot s^{-1}$) and the theoretically optimal transition speeds (TOTS; $m \cdot s^{-1}$) for each variable.

	10-12 yo	p-value	n	13-14 yo	p-value	n	15-17 yo	p-value	n	Adults	p-value	n
PTS	1.88 ± 0.19			1.99 ± 0.18			2.00 ± 0.18			1.98 ± 0.18		
BF	1.99 ± 0.15	0.012	16	2.34 ± 0.36	0.031	8	2.26 ± 0.31	0.005	14	2.25 ± 0.30	0.001	12
RF	**1.86 ± 0.17**	**0.270**	16	1.88 ± 0.14	0.002	8	**1.94 ± 0.14**	**0.128**	16	**2.02 ± 0.23**	**0.266**	11
MG	**1.87 ± 0.61**	**0.953**	17	**2.09 ± 0.22**	**0.167**	10	**2.13 ± 0.52**	**0.395**	16	**2.06 ± 0.31**	**0.257**	12
TA	**1.82 ± 0.23**	**0.375**	18	**2.02 ± 0.75**	**0.910**	10	1.80 ± 0.25	0.001	14	1.82 ± 0.19	0.013	12
$\dot{V}O_2$	2.19 ± 0.17	<0.001	12	2.12 ± 0.19	0.018	8	2.31 ± 0.24	0.005	11	2.24 ± 0.17	0.002	11
HR	2.20 ± 0.45	0.032	15	2.10 ± 0.17	0.009	9	2.19 ± 0.23	0.016	15	2.13 ± 0.15	0.026	11

Criterion 4 required weak links to have similar PTS and TOTS values (i.e. no significant difference between PTS and TOTS; $p>0.05$). Thus, bold text highlights where there are no statistically significant differences between PTS and TOTS for each variable. BF: Biceps femoris. RF: Rectus femoris. MG: Medial gastrocnemius. TA: Tibialis anterior. $\dot{V}O_2$: Volume of oxygen consumption. HR: Heart rate.

Table 4.4. Age group comparisons of the mean ± SD rates of change (slope values) in the muscle activity and physiological responses at the preferred transition speed (PTS) for walking and running.

	10-12 yo	13-14 yo	15-17 yo	Adults
Biceps femoris (%PTS_{peak})				
Walk	13.73 ± 9.97	8.59 ± 5.22	6.55 ± 6.95†	6.66 ± 5.84†
Run	4.75 ± 5.60	5.65 ± 4.80	2.49 ± 4.24	3.71 ± 5.59
p-value	**<0.001**	**0.046**	0.292	0.225
Rectus femoris (%PTS_{peak})				
Walk	13.78 ± 12.63	15.53 ± 12.04	16.16 ± 9.44	17.26 ± 9.96
Run	0.29 ± 4.46	1.62 ± 4.68	2.80 ± 6.59	-0.64 ± 6.68
p-value	**0.007**	**0.019**	**0.0177**	**<0.001**
Gastrocnemius (%PTS_{peak})				
Walk	13.53 ± 8.38	7.94 ± 2.90†	7.80 ± 6.05†	8.32 ± 5.99†
Run	-0.53 ± 4.97	-4.36 ± 7.03	-0.29 ± 2.23	0.52 ± 2.19‡
p-value	**<0.001**	**<0.001**	**<0.001**	**<0.001**
Tibialis anterior (%PTS_{peak})				
Walk	20.41 ± 12.58	17.26 ± 9.51	25.60 ± 19.39	22.89 ± 7.26
Run	3.75 ± 8.90	3.71 ± 8.42	3.52 ± 5.55	1.54 ± 8.53
p-value	**<0.001**	**<0.001**	**<0.001**	**<0.001**
$\dot{V}O_2$ ($mL \cdot kg^{-1} \cdot min^{-1}$)				
Walk	16.54 ± 7.49	19.47 ± 5.23	18.13 ± 11.41	20.60 ± 8.14
Run	14.09 ± 7.80	14.67 ± 8.39	10.99 ± 3.96	13.26 ± 5.19
p-value	0.351	**0.013**	0.156	**0.023**
Heart rate ($b \cdot min^{-1}$)				
Walk	78.22 ± 41.01	53.14 ± 21.80	74.43 ± 27.89	70.87 ± 20.10
Run	52.39 ± 16.69	45.68 ± 22.40	40.88 ± 14.18	36.64 ± 13.46
p-value	**0.011**	0.191	**0.005**	**0.005**

Slope values are derived from the walking and running data collected during session 2 and calculated from the fitted parameters at the preferred transition speed. Significant differences ($p<0.05$) compared to the † 10-12 yo and ‡ 13-14 yo. Bold text indicates significant differences ($p<0.05$) between the walking and running slope values calculated at PTS. yo: year olds. $\dot{V}O_2$: Volume of oxygen consumption.

Table 4.5. Comparisons of the mean ± SD muscle activity and physiological responses between walking and running at speeds near the preferred transition speed (PTS) for the 10-12-year-olds.

	Pre-transition speeds			Post-transition speeds	
	PTS-2	PTS-1	PTS	PTS+1	PTS+2
Biceps femoris (%WPTS$_{peak}$)					
Walk	9.66 ± 0.65	11.08 ± 0.67	12.99 ± 0.79	15.38 ± 0.94	19.00 ± 1.20
Run	13.32 ± 1.06	13.88 ± 0.95	14.70 ± 1.03	14.90 ± 1.07	16.02 ± 1.21
p-value	**<0.001**	**<0.001**	0.053	0.603	**0.002**
Rectus femoris (%WPTS$_{peak}$)					
Walk	8.73 ± 0.86	10.13 ± 1.03	12.20 ± 1.04	14.73 ± 1.39	18.74 ± 1.72
Run	10.86 ± 1.08	11.40 ± 1.13	12.18 ± 1.16	12.23 ± 1.19	13.06 ± 1.22
p-value	**0.003**	0.114	0.976	**0.047**	**0.001**
Gastrocnemius (%WPTS$_{peak}$)					
Walk	11.23 ± 0.77	11.80 ± 0.76	13.12 ± 0.78	14.58 ± 0.86	16.80 ± 1.05
Run	13.56 ± 0.90	14.00 ± 0.92	14.01 ± 0.94	14.07 ± 0.95	14.55 ± 0.97
p-value	**0.001**	**0.002**	0.154	0.508	**0.004**
Tibialis anterior (%WPTS$_{peak}$)					
Walk	12.72 ± 0.83	14.32 ± 0.88	16.64 ± 0.90	18.73 ± 1.09	22.36 ± 1.51
Run	14.09 ± 1.03	14.32 ± 1.13	14.86 ± 1.12	15.27 ± 1.15	15.06 ± 1.11
p-value	**0.024**	0.999	**0.034**	**0.001**	**<0.001**
$\dot{V}O_2$ (mL·kg^{-1}·min^{-1})					
Walk	23.44 ± 1.10	27.01 ± 1.29	30.19 ± 1.54	34.41 ± 1.65	36.68 ± 1.61
Run	31.99 ± 1.32	33.94 ± 1.22	34.93 ± 1.30	36.03 ± 1.24	37.96 ± 1.24
p-value	**<0.001**	**<0.001**	**<0.001**	0.095	0.200
Heart rate (b·min^{-1})					
Walk	134.68 ± 5.72	146.52 ± 6.24	158.47 ± 6.34	162.95 ± 6.83	174.21 ± 6.39
Run	160.37 ± 5.88	160.79 ± 6.26	162.63 ± 6.19	161.84 ± 7.09	173.95 ± 5.81
p-value	**<0.001**	**<0.001**	0.255	0.785	0.919

Bold text indicates significant difference ($p<0.05$) between walking and running.

Table 4.6. Comparisons of the mean ± SD muscle activity and physiological responses between walking and running at speeds near the preferred transition speed (PTS) for the 13-14-year-olds.

	Pre-transition speeds			Post-transition speeds	
	PTS-2	PTS-1	PTS	PTS+1	PTS+2
Biceps femoris (%$WPTS_{peak}$)					
Walk	8.73 ± 0.74	10.87 ± 0.77	13.32 ± 0.95	13.54 ± 1.17	16.76 ± 1.55
Run	12.83 ± 1.34	12.90 ± 1.19	13.80 ± 1.30	14.57 ± 1.35	15.60 ± 1.55
p-value	**0.002**	**0.039**	0.676	0.400	0.338
Rectus femoris (%$WPTS_{peak}$)					
Walk	9.66 ± 1.00	11.43 ± 1.24	14.14 ± 1.27	16.28 ± 1.78	20.37 ± 2.23
Run	10.75 ± 1.32	11.45 ± 1.40	11.37 ± 1.45	13.17 ± 1.48	13.25 ± 1.53
p-value	0.232	0.987	**0.011**	0.064	**0.001**
Gastrocnemius (%$WPTS_{peak}$)					
Walk	9.65 ± 0.91	10.82 ± 0.90	11.98 ± 0.92	13.16 ± 1.05	15.83 ± 1.35
Run	12.87 ± 1.12	13.79 ± 1.14	13.01 ± 1.18	13.60 ± 1.20	13.57 ± 1.23
p-value	**0.001**	**0.002**	0.232	0.678	**0.032**
Tibialis anterior (%$WPTS_{peak}$)					
Walk	12.28 ± 0.99	14.20 ± 1.07	16.62 ± 1.10	18.73 ± 1.39	21.32 ± 2.00
Run	12.23 ± 1.30	13.46 ± 1.44	14.02 ± 1.43	14.79 ± 1.48	15.88 ± 1.42
p-value	0.948	0.490	**0.026**	**0.006**	**0.008**
$\dot{V}O_2$ ($mL \cdot kg^{-1} \cdot min^{-1}$)					
Walk	24.07 ± 1.34	26.60 ± 1.61	30.02 ± 1.96	34.71 ± 2.11	38.78 ± 2.05
Run	31.28 ± 1.65	32.46 ± 1.51	33.94 ± 1.62	34.36 ± 1.54	35.99 ± 1.54
p-value	**<0.001**	**<0.001**	**0.003**	0.785	**0.037**
Heart rate ($b \cdot min^{-1}$)					
Walk	116.30 ± 7.05†	125.63 ± 7.93†	134.07 ± 8.09†	146.07 ± 8.89	156.74 ± 8.17
Run	134.07 ± 7.33†	138.63 ± 7.96†	143.07 ± 7.84	148.30 ± 9.32	146.74 ± 7.20†
p-value	**<0.001**	**0.002**	0.092	0.706	**0.010**

Bold text indicates significant difference (p<0.05) between walking and running. Significant differences (p<0.05) compared to the † 10-12 yo.

Table 4.7. Comparisons of the mean ± SD muscle activity and physiological responses between walking and running at speeds near the preferred transition speed (PTS) for the 15-17-year-olds.

	Pre-transition speeds			Post-transition speeds	
	PTS-2	PTS-1	PTS	PTS+1	PTS+2
Biceps femoris (%WPTS$_{peak}$)					
Walk	6.33 ± 0.58†‡	7.84 ± 0.61†‡	9.20 ± 0.74†‡	11.35 ± 0.91†	13.22 ± 1.20†
Run	11.17 ± 1.04	11.90 ± 0.92	12.67 ± 1.01	13.18 ± 1.05	13.76 ± 1.20
p-value	**<0.001**	**<0.001**	**<0.001**	0.055	0.561
Rectus femoris (%WPTS$_{peak}$)					
Walk	7.71 ± 0.76	9.91 ± 0.94	11.73 ± 0.96	15.91 ± 1.33	19.49 ± 1.67
Run	10.06 ± 1.00	10.32 ± 1.06	11.26 ± 1.09	11.35 ± 1.11	11.21 ± 1.15
p-value	**0.001**	0.609	0.547	**0.001**	**<0.001**
Gastrocnemius (%WPTS$_{peak}$)					
Walk	10.02 ± 0.70	11.01 ± 0.68	11.95 ± 0.70	13.38 ± 0.80	15.34 ± 1.02
Run	12.93 ± 0.85	12.73 ± 0.86	13.55 ± 0.89	13.26 ± 0.91	13.78 ± 0.93
p-value	**<0.001**	**0.014**	**0.015**	0.879	**0.047**
Tibialis anterior (%WPTS$_{peak}$)					
Walk	11.82 ± 0.76	14.35 ± 0.81	16.45 ± 0.83	19.47 ± 1.05	22.64 ± 1.50
Run	11.77 ± 0.98	12.21 ± 1.09	13.47 ± 1.08	13.21 ± 1.12	13.12 ± 1.07
p-value	0.934	**0.009**	**0.001**	**<0.001**	**<0.001**
$\dot{V}O_2$ (mL·kg^{-1}·min^{-1})					
Walk	23.04 ± 1.12	26.78 ± 1.36	29.21 ± 1.66	32.68 ± 1.79	35.79 ± 1.74
Run	31.06 ± 1.39	31.50 ± 1.27	33.22 ± 1.37	34.80 ± 1.30	36.50 ± 1.30
p-value	**<0.001**	**<0.001**	**0.001**	0.055	0.521
Heart rate (b·min^{-1})					
Walk	120.66 ± 5.26	129.95 ± 5.88	137.95 ± 5.99†	149.25 ± 6.56	159.01 ± 6.05
Run	142.48 ± 5.45†	142.60 ± 5.90	146.95 ± 5.81	151.83 ± 6.87	154.42 ± 5.36
p-value	**<0.001**	**<0.001**	**0.022**	0.546	0.099

Bold text indicates significant difference (p<0.05) between walking and running. Significant differences (p<0.05) compared to the † 10-12 yo and ‡ 13-14 yo.

Table 4.8. Comparisons of the mean ± SD muscle activity and physiological responses between walking and running at speeds near the preferred transition speed (PTS) for the young adults.

	Pre-transition speeds			Post-transition speeds	
	PTS-2	PTS-1	PTS	PTS+1	PTS+2
Biceps femoris (%$WPTS_{peak}$)					
Walk	7.26 ± 0.69†	8.10 ± 0.72†‡	10.20 ± 0.87†‡	13.69 ± 1.06	16.62 ± 1.38
Run	13.55 ± 1.21	14.40 ± 1.07	15.31 ± 1.17	16.28 ± 1.21	16.80 ± 1.38
p-value	**<0.001**	**<0.001**	**<0.001**	**0.018**	0.867
Rectus femoris (%$WPTS_{peak}$)					
Walk	8.39 ± 0.93	9.77 ± 1.13	12.35 ± 1.15	16.41 ± 1.59	21.22 ± 1.98
Run	11.50 ± 1.20	12.03 ± 1.27	12.26 ± 1.31	12.45 ± 1.33	13.16 ± 1.38
p-value	**<0.001**	**0.019**	0.919	**0.008**	**<0.001**
Gastrocnemius (%$WPTS_{peak}$)					
Walk	9.89 ± 0.85	10.76 ± 0.84	11.40 ± 0.86	13.57 ± 0.97	14.77 ± 1.22
Run	12.50 ± 1.02	12.25 ± 1.04	12.58 ± 1.07	13.17 ± 1.09	13.12 ± 1.11
p-value	**0.001**	0.066	0.121	0.667	0.073
Tibialis anterior (%$WPTS_{peak}$)					
Walk	11.72 ± 0.92	13.25 ± 0.98	14.92 ± 1.01	19.48 ± 1.25	22.57 ± 1.78
Run	12.44 ± 1.18	12.06 ± 1.30	12.63 ± 1.29	13.20 ± 1.33	14.17 ± 1.28
p-value	0.317	0.206	**0.025**	**<0.001**	**<0.001**
$\dot{V}O_2$ ($mL \cdot kg^{-1} \cdot min^{-1}$)					
Walk	21.65 ± 1.22‡	23.70 ± 1.44	26.86 ± 1.72	30.90 ± 1.85	35.43 ± 1.80
Run	27.38 ± 1.47	29.73 ± 1.36†	30.35 ± 1.45	32.12 ± 1.38	33.53 ± 1.38
p-value	**<0.001**	**<0.001**	**0.002**	0.261	0.091
Heart rate ($b \cdot min^{-1}$)					
Walk	112.35 ± 6.65†	119.85 ± 7.36†	129.02 ± 7.48†	141.18 ± 8.13	154.60 ± 7.55
Run	129.27 ± 6.87†	132.43 ± 7.38†	135.52 ± 7.28†	140.52 ± 8.49	146.77 ± 6.77
p-value	**<0.001**	**0.001**	0.158	0.896	**0.020**

Bold text indicates significant difference (p<0.05) between walking and running. Significant differences (p<0.05) compared to the † 10-12 yo and ‡ 13-14 yo.

Table 4.9. Summary of whether each variable satisfied the criteria to be considered as a determinant of the PTS for each age group.

	C1a	C1b	C2a	C2b	C3	C4	Determinant
Biceps femoris							
10-12 yo	✘	✓	✓	✓*	✓	< TOTS*	-
13-14 yo	✘	✓	✓	✘	✓	< TOTS*	✘
15-17 yo	✘	✘	✓	✘	✓	< TOTS*	✘
Adults	✘	✘	✓	✘	✓	< TOTS*	✘
Rectus femoris							
10-12 yo	✘	✓	✓	✓	✓	✓	✓
13-14 yo	✓	✓	✓	✓*	✓	> TOTS	-
15-17 yo	✘	✓	✓	✓	✓	✓	✓
Adults	✘	✓	✓	✓	✓	✓	✓
Medial gastrocnemius							
10-12 yo	✘	✓	✓	✓*	✓	✓	-
13-14 yo	✘	✓	✓	✓*	✓	✓	-
15-17 yo	✘	✓	✓	✓*	✓	✓	-
Adults	✘	✓	✓	✘	✓	✓	✘
Tibialis anterior							
10-12 yo	✓	✓	✓	✓	✓	✓	✓
13-14 yo	✓	✓	✓	✓	✓	✓	✓
15-17 yo	✓	✓	✓	✓	✓	> TOTS	-
Adults	✓	✓	✓	✓	✓	> TOTS	-
Oxygen consumption							
10-12 yo	✘	✘	✓	✘	✘	< TOTS*	✘
13-14 yo	✘	✓	✓	✓*	✘	< TOTS*	✘
15-17 yo	✘	✘	✓	✘	✘	< TOTS*	✘
Adults	✘	✓	✓	✘	✘	< TOTS*	✘
Heart rate							
10-12 yo	✘	✓	✓	✘	✘	< TOTS*	✘
13-14 yo	✘	✘	✓	✓*	✘	< TOTS*	✘
15-17 yo	✘	✓	✓	✘	✘	< TOTS*	✘
Adults	✘	✓	✓	✓*	✘	< TOTS*	✘

Criterion 1a (C1a): An abrupt decrease in magnitude of the variable following the WRT. Criterion 1b (C1b): A significant decrease in the rate of change in the variable following the WRT. Criterion 2a (C2a): Walking was more favourable at the pre-transition speeds. Criterion 2b (C2b): Running was more favourable at the post-transition speeds. ✓* indicates that running was only more favourable at PTS+2 and not at PTS+1. Criterion 3 (C3): Rapid feedback available about changes in the variable; this criterion was not specifically tested in this study. Criterion 4 (C4): PTS and the theoretically optimal transition speed were not different, suggesting the value reached the critical value and thus transitioned at a speed that was optimal to do so. '< TOTS*' indicates the walk-to-run transition occurred earlier than the theoretically optimal transition speed (TOTS), while '> TOTS' indicates the transition occurred after the transition. Variables were considered to be potential determinants of PTS if all criteria were satisfied (✓), while those that satisfied all criteria, except criterion 4 were only considered to be 'weak links' contributing to PTS (-).

4.4. Discussion

To gain insight into factors influencing PTS, this study investigated potential muscular and physiological weak links during the WRT in youth and adults. Leg length differences were observed between the 10-12 yo and both 15-17 yo and adults, which were of similar magnitude to those previously associated with PTS differences (Tseh et al., 2002). Despite these leg length differences, no age-related PTS differences were observed. Therefore, it is argued that PTS is not simply scaled to body size and other factors are likely involved in influencing PTS. Previously established criteria for identifying determinants of PTS (Hreljac, 1995; Kung et al., 2018) were used to investigate age-related differences in factors that are optimised as gait speed increases. Assuming gait is adjusted to minimise effort, age-specific muscular and physiological weak links were identified as potential candidates involved in influencing PTS.

Activity of RF and TA were effectively minimised as a result of the WRT across all age groups (Table 4.9). These results concur with previous research completed in adults (Hreljac et al., 2001; Malcolm, Segers, et al., 2009; Prilutsky & Gregor, 2001). The 13-14 yo transitioned later than optimal to minimise RF activity, while 15-17 yo and adults transitioned later than optimal to minimise TA activity. However, in order to satisfy criterion 1a (i.e. an abrupt decrease in the variable's magnitude at PTS), TOTS for these variables would need to be lower than PTS. Thus, minimising RF and TA activity appears to be an important outcome of the WRT across all age groups. As muscle activity of TA decreased post-transition, it is likely TA reached its critical value first and may thus be considered the weakest link for all age groups. As the 10-14 yo transitioned closer to TOTS to minimise TA activity than the older groups, their critical value may have been lower, whereas 15-17 yo and adults may have a higher load tolerance before needing to transition. Therefore, TA may continue developing until the age of 15 yo.

Age-related differences in the potential weak links were seen for BF and MG. BF only satisfied the criteria to be considered a weak link for 10-12 yo, while MG appeared to be an additional weak link for all paediatric groups. However, walking and running required similar amounts of muscular effort for MG at post-transition speeds for the adults. As such, it is unlikely that the WRT was used to specifically reduce MG activity for the adults, whereas reducing the muscular demands of MG may have been a higher priority for the youth. It is also possible that youth had a lower critical value for MG than the adults, which would explain why youth satisfied criterion 2b (i.e. running < walking at post-transition speeds), whereas the adults did not. The ankle plantarflexors have previously been identified as rate-limiters of gait development, due to diminished joint kinetics at the ankle, particularly during push-off (Cupp, Oeffinger, Tylkowski, & Augsburger, 1999; Ganley & Powers, 2005). Less stable ankle coordination during walking and running has also been observed among children up to the age of 3 years (Whitall & Getchell, 1995). While these studies investigated gait among younger children (i.e. 2-10 yo), the present findings suggest the gastrocnemius continues developing throughout adolescence.

When performing gait tasks within a given time constraint, individuals appear to use a combination of feedforward and feedback mechanisms to adjust their gait strategy (Long III & Srinivasan, 2013). During the relatively unfamiliar task of completing a gait transition on the treadmill, children may have been less able to predict the optimal gait strategy or anticipate when it was ideal to begin running. Thus, different strategies appear to be used to adjust gait. In particular, 10-12 yo were the only group to minimise the effort for all four muscles. As each of the muscles had their own TOTS, the 10-12 yo may have had more conflicting sources of feedback regarding the ideal transition speed making it more difficult to determine PTS. In fact, children aged 10-12 yo transition between walking and running more frequently across a wider range of speeds during WRT protocols than adults (Kung et al., 2019). This exploratory behaviour is presumably used to help identify the speed that minimises muscular demands. As PTS was defined as the final speed at which participants transitioned to running, the more exploratory behaviour of 10-12 yo may help explain why they did not transition at a slower speed than adults. Specifically, children may have needed to ensure running felt more favourable than walking before committing to a running gait. Conversely, older adolescents and adults may be able to better anticipate when a transition was needed in order to reduce the muscular demands of RF and TA. As the number of identified muscular weak links decreased with increasing chronological age, the results reflect a progressive maturation process of the lower extremity muscles.

Adults can adapt their gait patterns within seconds in response to changing task constraints to optimise metabolic economy (Selinger, O'Connor, Wong, & Donelan, 2015). Rapid feedback about physiological and/or muscular demands must be available to enable immediate responses to changing task demands (i.e. criterion 3). Immediate feedback about changes in the muscular effort determinants would be available from various proprioceptors (e.g. muscle spindles, Golgi tendon organs). Therefore, criterion 3 was theoretically satisfied for BF, RF, TA, and MG. However, it is less clear whether immediate feedback is available for changes in metabolic load. Physiological responses to changing demands typically occur too slowly to elicit immediate reactions to sudden changes in gait speed and are arguably too variable to consistently elicit a WRT at the same speed (Monteiro, Farinatti, de Oliveira, & Araújo, 2011). Therefore, it is unlikely that $\dot{V}O_2$ and HR satisfied criterion 3. Furthermore, $\dot{V}O_2$ and HR generally did not satisfy the remaining criteria to be considered as weak links potentially driving the WRT. Although the physiological factors did not generally satisfy the theoretical criteria used in this study, their influence on how gait is adjusted during WRT should not be dismissed entirely. By more effectively reducing the muscular demands of locomotion, adults were better than children and adolescents at minimising physiological demands (as demonstrated by HR meeting the first 2 criteria). Therefore, minimising muscular demands may be a more convincing driving factor of WRT than optimising metabolic economy of locomotion, which is more likely a secondary outcome.

While this study identified age-specific muscular weak links, there are a few limitations to note. Mechanical loads were not actively manipulated to assess the effects on PTS, which has a couple of implications. First, the identification of age-specific weak links in this study does not necessarily correspond directly to differences in the factors driving WRTs, or PTS determinants specifically. Instead, the criteria adopted in this study were used to help identify age-specific weak links, while assessing TOTS helped determine how well-optimised each factor was following the WRT. Secondly, it is difficult to provide conclusions regarding the respective critical thresholds that trigger WRTs without manipulating the mechanical loads. It also became apparent that the TOTS did not necessarily correspond to the critical threshold for a given potential weak link. Further research is needed to confirm if changes in muscular demands trigger WRTs in youth, and if there are age-related differences in the critical transition thresholds through the manipulation of mechanical loads. Such manipulations have not yet been assessed in youth, but would more accurately identify muscle weaknesses or ongoing muscle development during childhood and adolescence. However, this study highlights which muscles warrant further attention when assessing potential PTS determinants among youth and adults. Another limitation of this study was that biological age was not assessed. Instead, the grouping of ages in this study was informed by previous analyses of gait variability (Kung et al., 2019). Further investigation into the influence physical maturity has on the weak links and the ability to effectively adjust gait is warranted, particularly to address some of the peculiarities observed in this study (e.g. criterion 4 not satisfied for RF by the 13-14 yo group).

4.5. Conclusion

This study provides further support that the WRT helps to relieve muscular demands, which may subsequently reduce the metabolic cost of locomotion. Rectus femoris and tibialis anterior were common weak links across all age groups. Children aged 10-12 years tend to transition in a manner that attempts to reduce the effort for all four muscles. As children mature through adolescence, reducing BF activity becomes less of a priority, while reducing muscular demands of MG continues to be an important outcome; however, this was not the case for the adults. Therefore, the BF and MG muscles were additional weak links for the 10-12-year-olds and 10-17-year-olds, respectively, and may thus continue developing through childhood and adolescence. Because children and adolescents transition to minimise the effort for more muscles than adults, they may have more conflicting sources of feedback when adjusting their gait. As such, youth may exhibit difficulties optimising gait as effectively as adults.

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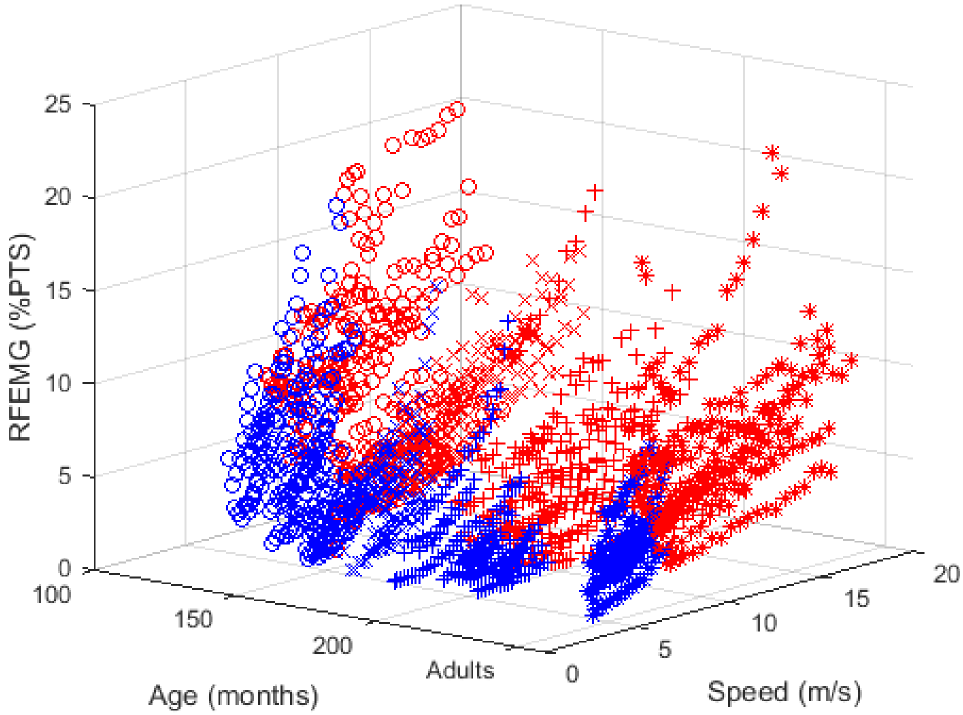
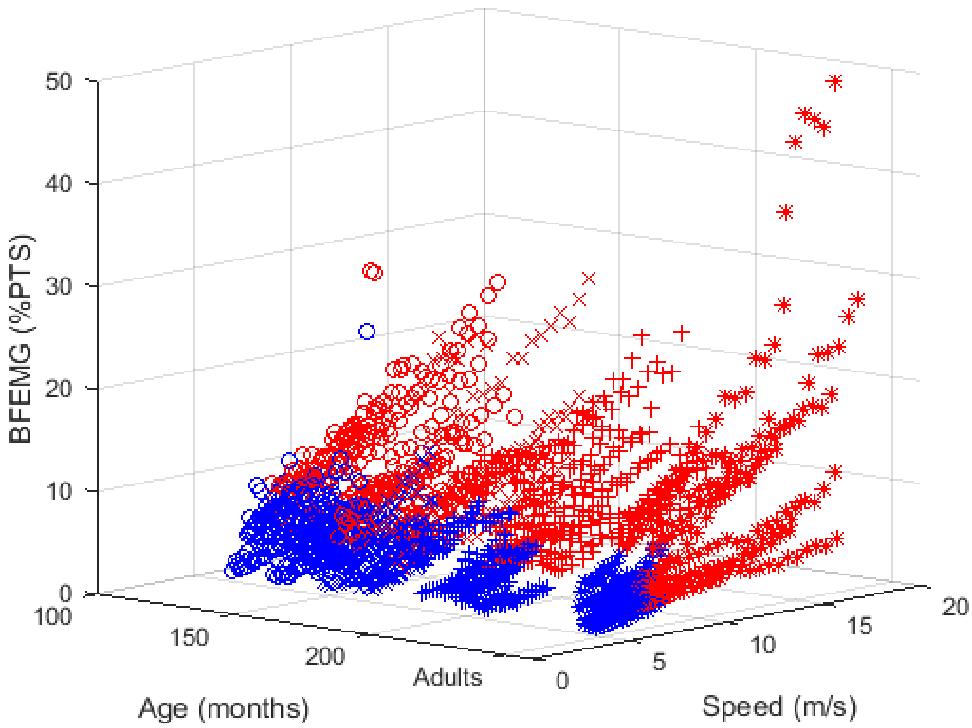
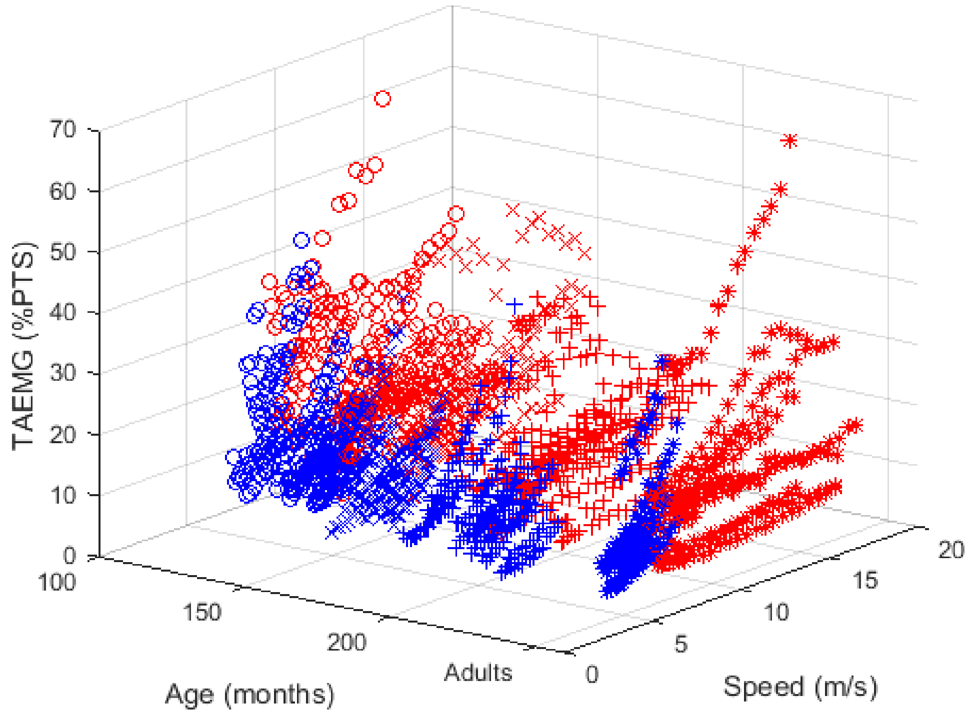


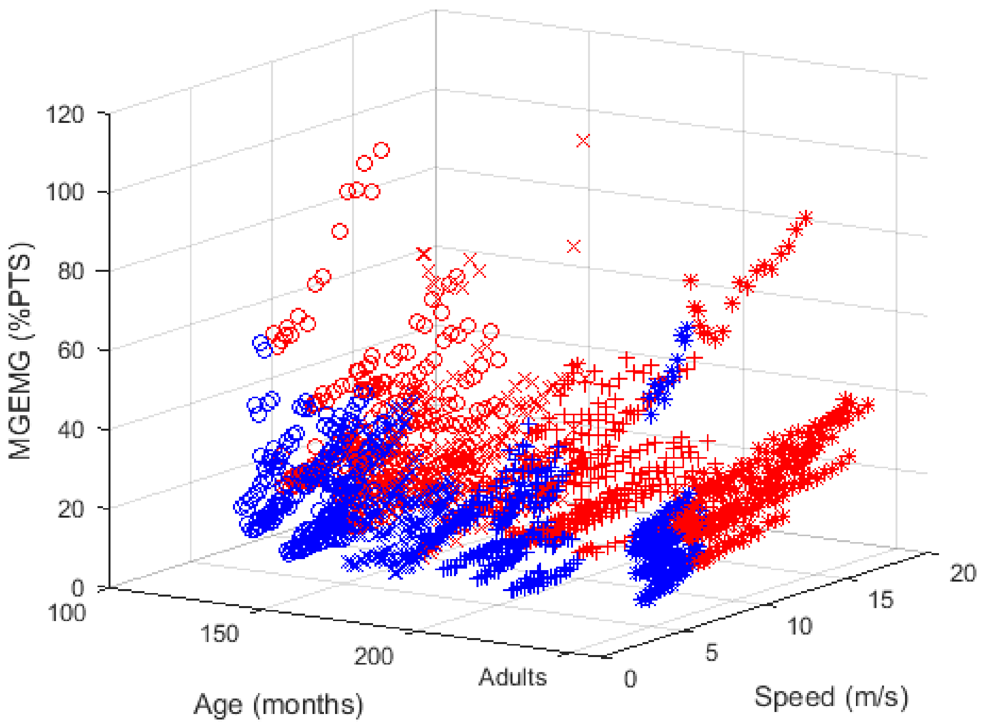
Supplementary Figure 4.A. Muscle activity responses of the rectus femoris (RFEMG) with gait speed (blue: walking, red: running) across the age range (O: 10-12yo; X: 13-14yo; +: 15-17yo; *: Adults).



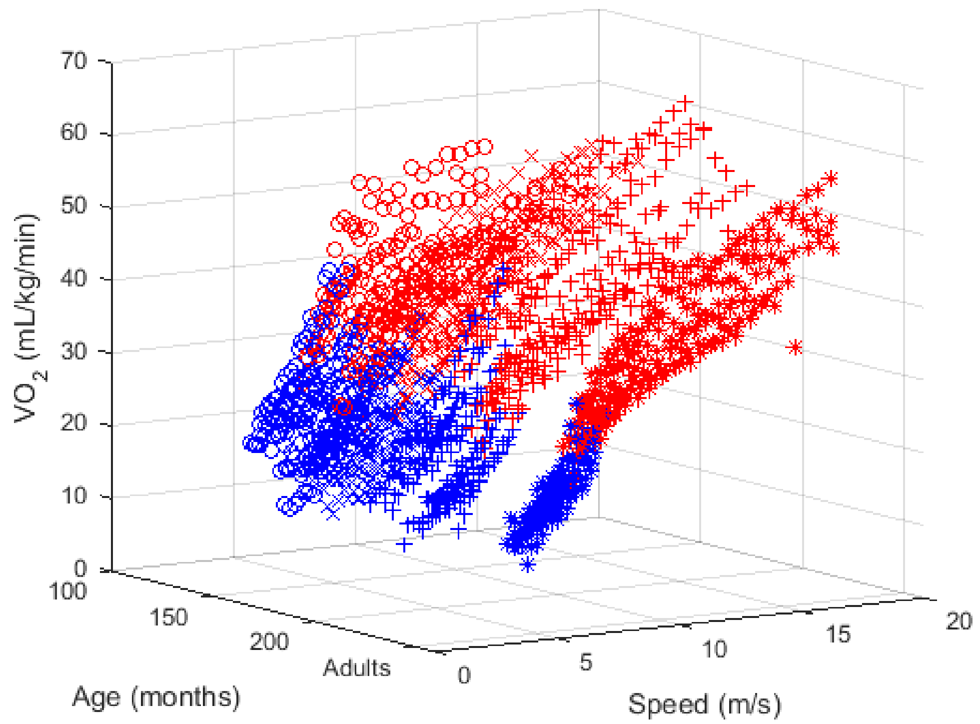
Supplementary Figure 4.B. Muscle activity responses of the biceps femoris (BFEMG) with gait speed (blue: walking, red: running) across the age range (O: 10-12yo; X: 13-14yo; +: 15-17yo; *: Adults).



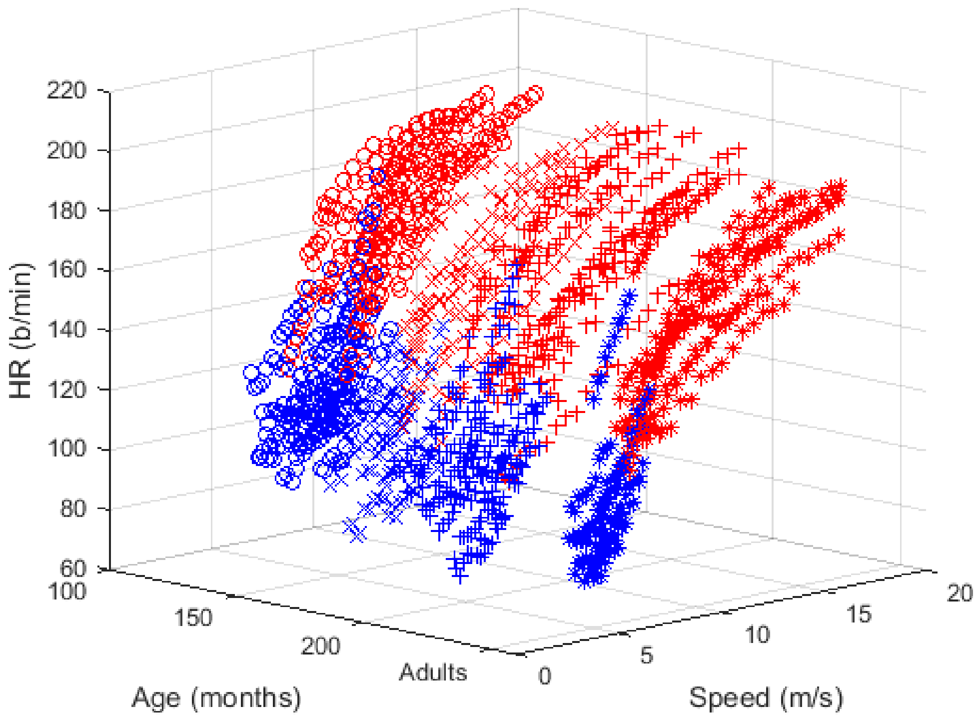
Supplementary Figure 4.C. Muscle activity responses of the tibialis anterior (TAEMG) with gait speed (blue: walking, red: running) across the age range (O: 10-12yo; X: 13-14yo; +: 15-17yo; *: Adults).



Supplementary Figure 4.D. Muscle activity responses of the medial gastrocnemius (MGEMG) with gait speed (blue: walking, red: running) across the age range (O: 10-12yo; X: 13-14yo; +: 15-17yo; *: Adults).



Supplementary Figure 4.E. Oxygen uptake (VO_2) responses to gait speed (blue: walking, red: running) across the age range (O: 10-12yo; X: 13-14yo; +: 15-17yo; *: Adults).



Supplementary Figure 4.F. Heart rate (HR) responses to gait speed (blue: walking, red: running) across ages (O: 10-12yo; X: 13-14yo; +: 15-17yo; *: Adults).

CHAPTER 5

Age-related differences in perceived exertion while walking and running near the preferred transition speed*

5.0. Abstract

The ability to judge whether walking or running requires less effort at any given speed would be necessary in order for walk-to-run transitions (WRT) to effectively minimise sensations of effort. This study investigated whether youth and adults can perceive differences in exertion between walking and running near the preferred transition speed (PTS) and if there are age-related differences in these perceptions. Forty-nine youth (10-12-year-olds, n=21; 13-14-year-olds, n=10; 15-17-year-olds, n=18) and 13 young adults (19-29-year-olds) completed a WRT protocol to determine PTS and peak oxygen uptake. Participants then walked and ran on a treadmill at five speeds (PTS -0.28 $m \cdot s^{-1}$, PTS -0.14 $m \cdot s^{-1}$, PTS, PTS +0.14 $m \cdot s^{-1}$, PTS +0.28 $m \cdot s^{-1}$) and rated their perceived exertion using the OMNI-RPE scale at all speeds. Oxygen consumption was measured during the WRT protocol to obtain the relative intensity (%$\dot{V}O_2$peak) at PTS. OMNI-RPE scores and %$\dot{V}O_2$peak at PTS were compared between age groups. 10-12-year-olds transitioned at a higher %$\dot{V}O_2$peak than adults (64.54±10.18 vs 52.22±11.40, respectively; $p=0.035$). The 10-14-year-olds generally reported higher OMNI-RPE scores than 15-17-year-olds and adults ($p<0.050$). While no groups reported OMNI-RPE differences at PTS and speeds slower than PTS, 10-14-year-olds also failed to distinguish differences in OMNI-RPE between walking and running at PTS+0.14 $m \cdot s^{-1}$. Therefore, children aged 10-14 years are less able to distinguish whether walking or running requires less effort at speeds near PTS compared to adults. The inability to judge which gait mode is less demanding suggests perceived exertion would have a more limited role in regulating gait patterns in youth, which could hinder their ability to minimise locomotive demands.

Keywords: Perceptual feedback, paediatrics, gait, effort, walking, running

* Manuscript submitted and currently under review:

SM Kung, PW Fink, SJ Legg, A Ali & SP Shultz. Age-related differences in perceived exertion while walking and running near the preferred transition speed. *Pediatric Exercise Science* (*under review*).

5.1. Introduction

Perceived exertion has been proposed to help regulate exercise performance through a feedforward and feedback system called teleoanticipation (Hampson, St Clair Gibson, Lambert, & Noakes, 2001; Tucker, 2009). In order to achieve this goal of regulating exercise intensity, individuals would need to anticipate the physiological and mechanical responses to ongoing exercise, which would require knowledge from previous experiences. Research has demonstrated that individuals can successfully adjust their exercise intensity to maintain a given rating of perceived exertion (RPE) (Dunbar et al., 1992; Eston, Davies, & Williams, 1987; Ulmer, 1996). The ability to rate perceived effort and produce exercise intensities that correspond to certain RPE scores is present as early as 5-7 years old (Groslambert & Mahon, 2006). However, the cognitive functions involved in perceiving effort are likely to continue developing through to adolescence (Groslambert & Mahon, 2006). Because the development of cognitive functions and musculoskeletal growth continues through adolescence (Cech & Martin, 2002; Groslambert & Mahon, 2006), the ability to effectively use the perception of effort to help regulate gait may be limited within a paediatric population. Specifically, youth may not be able to adjust their gait to reduce perceived sensations of effort as effectively as adults, which would be detrimental to their ability to anticipate when a change in their gait is required to minimise locomotive demands.

The walk-to run transition (WRT) has been shown to help optimise locomotion as gait speed changes, by reducing the mechanical load (Bartlett & Kram, 2008; Hreljac, Arata, Ferber, Mercer, & Row, 2001; Malcolm, Fiers, et al., 2009; Malcolm, Segers, Van Caekenberghe, & De Clercq, 2009; Prilutsky & Gregor, 2001), improving the efficiency of the ankle plantarflexors (Farris & Sawicki, 2012; Neptune & Sasaki, 2005; Pires, Lay, & Rubenson, 2014) and thus improving gait economy (Ganley, Stock, Herman, Santello, & Willis, 2011; Mercier et al., 1994; Monteiro, Farinatti, de Oliveira, & Araújo, 2011) in adults. It was suggested that changes in mechanical factors could trigger the WRT via feedback from proprioceptors (i.e. muscle spindles and/or Golgi tendon organs) (Hreljac, 1995), which could work at the spinal level (Hagio, Fukuda, & Kouzaki, 2015; Shik, Severin, & Orlovskii, 1966). In addition to these self-optimising tendencies, transitioning from a walk to a run prevents further increases in perceived effort as gait speed increases in adults (Daniels & Newell, 2003; Ganley et al., 2011; Rotstein, Inbar, Berginsky, & Meckel, 2005; Ziv & Rotstein, 2009). However, Children and adolescents transition from walking to running at a preferred transition speed (PTS) that is comparable to that of adults, despite having shorter legs (Kung, Fink, Legg, Ali, & Shultz, 2019; Tseh, Bennett, Caputo, & Morgan, 2002). As such, children may be transitioning at a higher relative workload than adults and thus at a speed that is less than optimal. Differences may exist between youth and adults concerning how sensory cues from the skeletal muscles and physiological functions (e.g. heart rate, respiratory rate) are interpreted and the extent to which this feedback informs perceptions of effort to help regulate gait. However, perceptual factors contributing to the determination of PTS among children and adolescents have not been well-explored.

Proprioceptive feedback may be registered at the cognitive level, particularly as adults have delayed when they perform a gait transition when distracted by a simultaneous cognitive task (Abdolvahab, 2015; Daniels & Newell, 2003). Feedback registered at the cognitive level would allow individuals to regulate gait patterns using subjective RPE. Assessing RPE near PTS determines how responsive subjective perceptions can be to differences in exertion, because neither walking nor running near PTS is clearly more favourable than the other. In particular, when adults are free to choose their preferred gait mode while the average speed is constrained, a combination of walking and running at speeds between 2.0-3.0 $m \cdot s^{-1}$ is observed, rather than committing to either mode (Long III & Srinivasan, 2013). The more variable WRT process seen in children compared to adults (Kung et al., 2019) may reflect a poorer ability to anticipate when completing a WRT would help minimise perceived exertion and locomotive demands. This source of perceptual feedback may thus have a limited role in regulating gait in children. The ability to distinguish whether walking or running requires less effort would be necessary to accurately inform feedforward mechanisms involved in regulating gait at different gait speeds.

Therefore, this study aimed to investigate whether youth and adults can perceive differences in exertion between walking and running at speeds near PTS, and whether there are age-related differences in these perceptions. It was hypothesised that there would be clear differences in RPE for walking and running at speeds near PTS for the adults, but this difference may be less clear among youth. If youth are unable to perceive differences in the sensations of effort, it would be expected that they may have difficulties effectively minimising locomotive demands. To determine if physiological intensity should be considered when comparing perceived effort, the relative workload at PTS was compared across age groups. The relative workload was assessed as the percentage of the peak oxygen uptake ($\dot{V}O_2$peak), as it has been more strongly correlated with RPE than other physiological measures (Utter, Robertson, Nieman, & Kang, 2002).

5.2. Methods

5.2.1. Participants

Forty-nine 10-17-year-olds (yo) and 13 young adults (19-29 yo) were recruited for this study. These participants were part of a larger overarching project that was investigating age-related differences in the WRT among youth and young adults (Kung et al., 2019). The paediatric participants were classified as 10-12 yo (n=21), 13-14 yo (n=10) and 15-17 yo (n= 18; Table 5.1). These age groups were based on previous assessments of gait variability (Kung et al., 2019). Participants were free of any lower extremity injuries or surgeries that occurred within the six months prior to testing, and a diagnosis of any neuromusculoskeletal condition, cardiovascular disease, diabetes, or asthma. Informed written parental consent and participant assent were obtained for participants who were aged 10-16 years. Informed written consent was obtained from the participants aged 17-29 years. The study was approved by the institutional human ethics committee.

5.2.2. Protocol

Participants visited the laboratory for three sessions. During the first session, they were instructed how to mount and dismount the treadmill and a standardised set of instructions for how to use the OMNI Perceived Exertion (OMNI-RPE) scale was read to the participants (Utter et al., 2002). Participants were familiarised to treadmill locomotion by walking and running on the treadmill at self-selected speeds for at least 15 min each. At the end of every 5-min period during these 15-min bouts, participants were asked to rate their perceived exertion using the OMNI-RPE scale, which has been validated for use with children (Utter et al., 2002) and adults (Utter et al., 2004) during treadmill locomotion. Participants then practiced completing a WRT at least three times, using a previously described protocol (Kung et al., 2019). This protocol started at the participant's self-selected walking speed and treadmill speed was increased by 0.06 $m \cdot s^{-1}$ every 10 s. The treadmill speed continued increasing until the participant transitioned to running and did not revert to walking for five consecutive speed increments.

During session 2, participants completed a WRT test to determine their PTS. PTS was defined as the speed at which the final transition to running occurred where the participant did not revert to walking thereafter (Kung et al., 2019). Participants walked at their self-selected speed for 90 s and then the treadmill speed was increased by 0.06 $m \cdot s^{-1}$ every 30 s until five speed increments after the participant's final WRT. Speed increments were then increased by 0.14 $m \cdot s^{-1}$ every 30 s until participants indicated they reached volitional exhaustion (i.e. peak exertion; $\dot{V}O_2peak$). Participants were asked to rate their perceived exertion using the OMNI-

RPE scale at the end of every fifth speed increment. The OMNI-RPE scores from session 2 were used to anchor experiences to each end of the scale, from standing on the treadmill prior to starting the WRT protocol through to peak exertion.

Oxygen uptake ($\dot{V}O_2$) was measured over the entire incremental treadmill protocol in session 2 (K4 b2, Cosmed, Rome, Italy). Due to equipment malfunction, data were only analysed for a subset of the participants (10-12 yo n=14; 13-14 yo n=8; 15-17 yo n=11; adults n=11). $\dot{V}O_2$ was averaged over the 30-s period for each speed increment. The averaged $\dot{V}O_2$ at PTS was then divided by the $\dot{V}O_2$ at peak exertion to obtain the relative intensity at PTS (%$\dot{V}O_2$peak).

During the third session, participants completed 10 gait trials in a randomised order, which consisted of walking and running at five speeds centred around the participant's PTS: 1) PTS-0.28 $m \cdot s^{-1}$ (PTS-2), 2) PTS-0.14 $m \cdot s^{-1}$ (PTS-1), 3) PTS, 4) PTS+0.14 $m \cdot s^{-1}$ (PTS+1) and 5) PTS+0.28 $m \cdot s^{-1}$ (PTS+2). Each gait condition was completed for 5 min and participants were given a 5 min rest between trials. At the end of the fourth minute for each gait condition, participants were asked to rate their perceived exertion using the OMNI-RPE scale.

5.2.3. Statistical analysis

A one-way ANOVA with a post-hoc Tukey's test was used to compare %$\dot{V}O_2$peak at PTS between age groups (SPSS Statistics version 24; IBM Corp, Armonk, NY). A 4 x 10 (age group x gait condition) mixed model ANOVA with repeated measures was performed on the OMNI-RPE scores from session 3. Post-hoc Tukey tests were used to identify where there were significant differences in OMNI-RPE between walking and running at each speed, as well as age group effects on the OMNI-RPE scores (SAS version 9.4, Cary, NC). Differences were considered to be statistically significant when $p<0.050$.

5.3. Results

There were no significant differences in PTS between age groups (Table 5.1). The 10-12 yo transitioned at a higher relative intensity than the adults ($p=0.035$; Table 5.1). No other age group differences were observed in %$\dot{V}O_2$peak at PTS.

5.3.1. Age group comparisons

The 10-12 yo reported significantly higher OMNI-RPE scores than the 15-17 yo at all of the gait conditions ($p<0.025$; Table 5.2), except for the walking conditions at PTS+1 and PTS+2. Higher OMNI-RPE scores were also reported by the 10-12 yo compared to the young adults for the running conditions ($p<0.043$; Table 5.2), except at PTS-2.

The 13-14 yo reported higher OMNI-RPE scores than the 15-17 yo while walking and running at the pre-transition speeds (i.e. speeds slower than PTS), as well as running at PTS+1 (Table 5.2). Compared to the adults, the 13-14 yo also reported higher OMNI-RPE scores while walking at PTS-2 and running at PTS-1 and PTS+1. No age group differences were observed between the 15-17 yo and adults.

5.3.2. Walking versus running

Figure 5.1 presents the comparisons of OMNI-RPE scores for walking and running at each of the gait speeds for each age group. The 10-12 yo only exhibited differences in OMNI-RPE at PTS-2 (walking < running; $p<0.001$) and PTS+2 (running < walking; $p=0.003$). The 13-14 yo did not report differences in OMNI-RPE between walking and running at any of the pre-transition speeds, PTS or PTS+1; however, running at PTS+2 elicited a lower OMNI-RPE than walking ($p=0.001$). The 15-17yo and adults did not report differences in OMNI-RPE between walking and running at the pre-transition speeds and PTS. Running elicited lower OMNI-RPE scores than walking at the post-transition speeds for the 15-17 yo and adults (PTS+1: $p=0.002$ and $p=0.001$, respectively; PTS+2: $p<0.001$ for both groups).

Table 5.1. Comparisons of the anthropometric characteristics and exercise responses at peak exertion ($\dot{V}O_2$peak) and at the preferred transition speed (PTS) across the age groups.

	10-12 yo	13-14 yo	15-17 yo	Adults
Physical characteristics				
n (F:M)	21 (14:7)	10 (4:6)	18 (8:10)	13 (7:6)
Height (m)	1.519 ± 0.068	1.634 ± 0.085*	1.693 ± 0.081*	1.708 ± 0.092*
Leg length (m)	0.813 ± 0.039	0.865 ± 0.052*	0.889 ± 0.043*	0.886 ± 0.060*
Mass (kg)	42.92 ± 8.39	48.17 ± 9.30	58.31 ± 7.97*†	62.87 ± 10.09*†
BMI ($kg{\cdot}m^{-2}$)	18.47 ± 2.37	17.89 ± 1.95	20.33 ± 2.33†	21.46 ± 2.13*†
Exercise responses				
At peak exertion				
$\dot{V}O_2$peak ($mL{\cdot}kg{\cdot}min^{-1}$)	46.96 ± 5.42	53.31 ± 7.33	54.29 ± 8.81*	49.69 ± 7.00
HR_{peak} ($b{\cdot}min^{-1}$)	199.0 ± 8.0	188.7 ± 9.2*	195.4 ± 8.2	190.5 ± 6.7*
RER_{peak}	1.09 ± 0.08	1.11 ± 0.05	1.18 ± 0.06	1.09 ± 0.07
OMNI-RPE_{peak}	9.3 ± 1.0	9.7 ± 0.5	9.5 ± 0.7	9.6 ± 0.5
During the walk-to-run transition				
PTS ($m{\cdot}s^{-1}$)	1.89 ± 0.19	1.99 ± 0.18	2.00 ± 0.18	1.98 ± 0.18
%$\dot{V}O_2$peak at PTS	64.54 ± 10.18	56.54 ± 12.52	55.72 ± 9.69	52.22 ± 11.40*

Significant differences with the * 10-12yo and †13-14yo are highlighted in the table. M: Males. F: Females. $\dot{V}O_2$peak: Peak oxygen consumption. HR_{peak}: Heart rate at peak exertion. RER_{peak}: Respiratory exchange ratio at peak exertion. OMNI-RPE_{peak}: Perceived exertion at peak exertion.

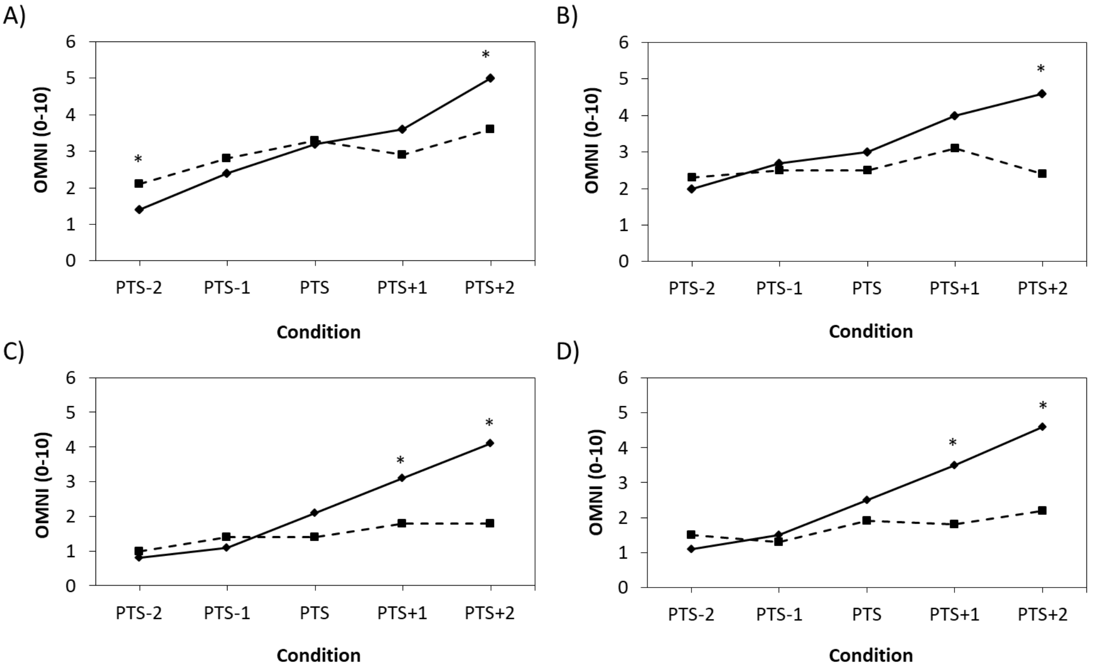


Figure 5.1. Perceived effort (OMNI-RPE scale) while walking (solid line) and running (dashed line) at speeds at and near the preferred transition speed (PTS) for the A) 10-12-year-olds; B) 13-14-year-olds; C) 15-17-year-olds; and D) young adults. * indicates a significant difference ($p<0.05$) between walking and running.

Table 5.2. Age group comparisons of the mean ± SD OMNI scores for walking and running at each of the tested speeds near the preferred transition speed (PTS).

						10-12 yo		13-14 yo	
		10-12 yo	13-14 yo	15-17 yo	Adults	15-17 yo	Adults	15-17 yo	Adults
Walk	PTS-2	1.4 ± 0.2	2.0 ± 0.3	0.7 ± 0.2	1.1 ± 0.3	0.0235		0.0023	0.0463
	PTS-1	2.4 ± 0.3	2.7 ± 0.5	1.0 ± 0.3	1.5 ± 0.4	0.0038		0.005	
	PTS	3.2 ± 0.4	3.0 ± 0.5	1.9 ± 0.4	2.5 ± 0.5	0.0133			
	PTS+1	3.6 ± 0.4	4.0 ± 0.6	2.9 ± 0.4	3.5 ± 0.5				
	PTS+2	5.0 ± 0.4	4.6 ± 0.6	3.8 ± 0.4	4.6 ± 0.5				
Run	PTS-2	2.1 ± 0.2	2.3 ± 0.3	0.9 ± 0.2	1.5 ± 0.3	0.0003		0.0008	
	PTS-1	2.8 ± 0.3	2.5 ± 0.4	1.3 ± 0.3	1.3 ± 0.4	0.0008	0.0026	0.0256	0.0405
	PTS	3.3 ± 0.4	2.5 ± 0.5	1.3 ± 0.4	1.9 ± 0.5	0.0004	0.0222		
	PTS+1	2.9 ± 0.3	3.1 ± 0.5	1.7 ± 0.3	1.8 ± 0.4	0.0136	0.0421	0.0213	0.048
	PTS+2	3.6 ± 0.3	2.4 ± 0.5	1.7 ± 0.4	2.2 ± 0.4	0.0004	0.0152		

p-values for the significant age comparisons ($p<0.05$) are presented on the right. There were no age-related differences between the 15-17 yo and adults. PTS-2: PTS-0.28 $m \cdot s^{-1}$. PTS-1: PTS-0.14 $m \cdot s^{-1}$. PTS+1: PTS+0.14 $m \cdot s^{-1}$. PTS+2: PTS+0.28 $m \cdot s^{-1}$.

5.4. Discussion

This study investigated whether perceived exertion differed between walking and running among youth and young adults. The PTS values observed in the present study are comparable to those previously reported among adults (Hreljac et al., 2001; Neptune & Sasaki, 2005) and adolescents (Kung et al., 2019; Tseh et al., 2002). However, there were no age group differences in PTS despite the 10-12 yo having shorter legs than the older age groups. From the age group comparisons of $\%\dot{V}O_2$peak at PTS, it was revealed that the 10-12 yo transitioned at a higher relative intensity than the adults (i.e. 64.54 ± 10.18 $\%\dot{V}O_2$peak versus 52.22 ± 11.40 $\%\dot{V}O_2$peak, respectively). As such, the range of tested gait conditions presumably corresponded to higher relative intensities among the 10-12 yo than the adults, since the speeds for each participant were based on their PTS. That is, the tested speeds consisted of the participant-specific PTS as well as speeds that were 0.14 $m{\cdot}s^{-1}$ and 0.28 $m{\cdot}s^{-1}$ faster and slower than PTS. Walking and running at speeds corresponding to a higher relative intensity was reflected in higher OMNI-RPE scores reported by the 10-12 yo than the 15-17 yo and young adults, particularly while running. Transitioning at a higher relative physiological workload than the adults also suggests the 10-12 yo were less effective at using the WRT to minimise the physiological effort during locomotion. Furthermore, age-related differences were observed in the OMNI-RPE responses between walking and running near PTS, which suggest the 10-12 yo were less effective than adults and 15-17 yo at using the WRT to minimise perceived effort as well.

The limited ability of the 10-12 yo to minimise effort during locomotion may be influenced by a poorer ability to perceive differences in effort between walking and running at speeds near PTS. As with previous research (Monteiro et al., 2011; Rotstein et al., 2005; Ziv & Rotstein, 2009), the OMNI-RPE for walking increased along with gait speed for all age groups, whereas the rate of change in OMNI-RPE for running was much less steep. At the pre-transition speeds, there were generally no differences in the perceived effort between walking and running for each age group. The only exception was for the 10-12yo at PTS-2, who perceived walking to be easier than running. The general lack of difference in OMNI-RPE scores at these slower speeds may be due to a lack of sensitivity of the RPE scale at lower exercise intensities (Bar-Or, 1989; Robertson & Noble, 1997). While there were no significant differences at PTS, the OMNI-RPE values for walking and running began to diverge at PTS for all age groups, except for the 10-12 yo who did not exhibit this tendency (Figure 1). However, the 15-17 yo and young adults were the only groups to report a lower OMNI-RPE while running at PTS+1, compared to walking. It was only at PTS+2 that all age groups reported that running felt easier than walking. As such, the ability to distinguish differences in effort between walking and running appears to be more established among adults and older adolescents. Conversely, children may lack maturity of the cognitive functions involved in perceiving differences in exertion, which have been suggested to be shaped with age and experience (Groslambert & Mahon, 2006). Perceived effort would also likely be recalibrated alongside the development of the musculoskeletal system throughout childhood and adolescence. Therefore, the results suggest that children may still be learning how to anticipate the mechanical and physiological responses to changing locomotive demands and thus determine how best to adjust their gait to minimise exertion. As the age-related differences in OMNI-RPE scores disappeared by 15-17yo, the ability to use the perceived sensations of effort to regulate gait may continue developing through the age of 14 years. This age typically coincides with the cessation of growth (Froehle, Nahhas, Sherwood, & Duren, 2013), so perceptions of effort would no longer be shaped by ongoing growth and may be less sensitive to physical changes.

As running was generally perceived to elicit lower sensations of effort at the post-transition speeds, the WRT would have helped reduce the perceived effort as gait speed increased. Therefore, the present results support the notion that feedback regarding perceived sensations of effort would help determine PTS during the WRT among youth and adults. However, children exhibit greater difficulties determining which mode of gait would be more favourable at speeds where the optimal mode of gait is somewhat ambiguous (i.e. at speeds near PTS). These results could help explain why children transitioned back and forth more frequently between walking and running when attempting to determine their PTS (Kung et al., 2019). More specifically, children's hesitation to commit to the WRT could have been due to the inability to judge which gait mode would elicit lower sensations of effort without first experiencing each condition. Thus, a lack of experience may limit children's ability to effectively regulate their gait as gait speed changes.

Perceived effort would assist with minimising the mechanical load of locomotion, a previously identified driving factor of the WRT (Hreljac et al., 2001; Neptune & Sasaki, 2005; Prilutsky & Gregor, 2001). In adults, peripheral sensory cues arising from the lower extremity musculature have generally exhibited a more dominant role in determining PTS than cardiorespiratory-metabolic cues (Daniels & Newell, 2003; Monteiro et al., 2011). A similar trend may also be seen among children, as their perceived exertion tends to be dominated by sensory cues arising from the muscular effort within the lower limbs (Mahon, Gay, & Stolen, 1998; Mahon, Stolen, & Gay, 2001; Robertson et al., 2001). However, a limitation of the present study is that a differentiated RPE was not assessed. Instead, an undifferentiated OMNI-RPE was assessed, which represents the integration of various sensory cues without the ability to parse out muscular or cardiorespiratory-metabolic cues. Additionally, this study was largely observational as RPE was not specifically manipulated to assess its effect on the PTS. More work is needed to assess whether there is causality between perceptions of effort and the PTS during the WRT. Further research is required to confirm if age-related differences exist in whether sensory cues arise predominantly from mechanical strain within the muscles or from respiratory factors during the WRT in children and adolescents.

Another limitation of the study was that the validity and reliability of the OMNI-RPE scores were not specifically tested in this study. In particular, there was no correlation analysis completed between physiological measurements, participant's physical activity levels and OMNI-RPE. Such analyses would help determine how accurately perceived effort reflected physiological effort, as well as the influence training history may have on perceptions of effort. However, higher ratings of perceived effort accompanied the higher relative workload at PTS in the 10-12 yo compared to the adults. The reported differences in relative workload and perceptions of effort are likely to reflect true differences, as all age groups were shown to give a similar effort at peak exertion, from which the relative intensity (i.e. $\%\dot{V}O_2$peak) at PTS was derived. In particular, heart rate, respiratory exchange ratio and OMNI-RPE values were generally similar across all groups at volitional exhaustion, except the 10-12 yo reported a higher peak heart rate than the adults (Table 5.1). However, 10-12 yo would be expected to have a higher peak heart rate than adults because the predicted age-related maximum heart rate is calculated as 220 $b \cdot min^{-1}$ minus age. Collectively, these observations suggest the reported OMNI-RPE values in this study reflect actual differences in exercise intensities. Because of the protocol design, there was also a lack of repeated OMNI-RPE measures to assess how consistent the participants were at identifying the exercise intensity. However, the OMNI-RPE scale has been validated for youth and adults (Utter et al., 2004; Utter et al., 2002) and the participants were familiarised with the scale before testing commenced to help improve repeatability of the measure.

5.5. Conclusion

Despite reporting greater perceived effort across the gait conditions than the adults, the 10-12 yo failed to transition earlier with no age-related differences in PTS. Children aged 10-12 years also exhibited difficulties distinguishing whether walking or running is more favourable at speeds near PTS, which may limit their ability to use perceptual feedback to effectively adjust gait to changing gait speeds. The ability to detect and integrate sensory cues regarding the perceived effort during locomotion may continue to develop through to at least 13-14 years of age. As such, the ability to use perceived exertion to regulate gait continues to develop in children, as they learn how to anticipate when changes in gait patterns are required. Moreover, as individuals must learn to use RPE to regulate gait, these results support that gait adjustments are not purely driven by energy minimisation, but also to minimise sensations of effort associated with a combination of biomechanical and physiological demands.

5.6. References

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CHAPTER 6

General Discussion

The gait development literature has reported a number of biomechanical and physiological differences between the gait patterns of youth and adults from the onset of walking through to adolescence (Bisi & Stagni, 2016; Chester, Tingley, & Biden, 2006; Ganley & Powers, 2005; Gouelle, Leroux, Bredin, & Megrot, 2016; Lythgo, Wilson, & Galea, 2009; Muller, Muller, Baur, & Mayer, 2013; Sutherland, 1997; Thelen & Cooke, 1987; Van de Walle et al., 2010). However, the rate-limiting factors of gait maturation are not as well understood. Immature gait has generally been characterised as paediatric gait that deviates from that of young adults. In contrast, the ability to effectively adapt a motor task has more recently been suggested to reflect whether or not a skill has been mastered (Komar, Seifert, & Thouvarecq, 2015). Therefore, this thesis sought to improve the current knowledge of the rate-limiting factors of gait maturation by developing a better understanding of how gait is regulated among youth. To address this aim, the walk-to-run transition (WRT) was used to:

1) Investigate how effectively youth could adjust their gait to increasing gait speed compared to young adults; and
2) Explore age-related differences in the determinants of the preferred transition speed (PTS) between youth and young adults during the walk-to-run transition (WRT).

The first aim was addressed in *Chapter 3*, while also determining whether there were age-related differences in gait maturity among 10-17-year-olds (yo). *Chapters 4* and *5* addressed the second aim by investigating age-related differences in the mechanical load (i.e. muscular effort) and metabolic economy determinants, and the cognitive and perceptual determinants (i.e. perceived exertion) of PTS, respectively.

6.1. Levels of gait maturity

As highlighted in *Chapter 1*, mature gait may not be attainable until growth has finished, which tends to occur during the later stages of adolescence. The results *in Chapter 3* revealed three levels of gait maturity (Table 6.1). Spatiotemporal variability and the ability to effectively adjust gait appeared to progress through similar age-related levels of maturity. Walking patterns matured by 13-14 years of age, while running did not mature until at least 15-17 years old. The 10-12 yo had a limited ability to effectively adjust gait, but adolescents aged 15-

17 years were able to determine their PTS in a manner similar to the young adults. Thus, children (10-12 yo) lacked gait maturity and tended to exhibit more exploratory behaviour when adjusting their gait. The younger adolescents (13-14 yo) appeared to be at an intermediary level of gait maturity. The older adolescents (15-17 yo) exhibited adult-like amounts of spatiotemporal variability and gait adaptability, thus their gait was considered to be mature.

Table 6.1. Summary of age-related levels of gait maturity.

Age range	Gait variability	Method for determining PTS	Developing factors
10-12 yo	- Walking patterns are immature - Running patterns are immature	- Completed more gait transitions per speed increment - Transitioned across more speed increments - Exhibited more variable transition behaviour	- Biceps femoris - Medial gastrocnemius - Perceived exertion
13-14 yo	- Walking patterns are mature - Running patterns at familiar speeds are mature - Running at unfamiliar speeds immature	- Tendency to exhibit a more variable transitioning process	- Medial gastrocnemius - Perceived exertion
15-17 yo	- Walking patterns are mature - Running patterns at familiar speeds are mature - Running at unfamiliar speeds immature	- Generally determined PTS using a single attempt	- Medial gastrocnemius

Note: Maturity of gait patterns indicates that adult-like values were observed (i.e. no significant differences between the paediatric age group and the young adults; $p>0.05$).

6.2. Factors influencing PTS

6.2.1. Anthropometric factors

The review of PTS determinants presented in *Chapter 2* highlighted a number of factors involved in regulating gait. Anthropometric and strength characteristics were argued to act more as physical limits of PTS rather than driving factors of gait transitions. To address the influence of anthropometric characteristics during the WRT in youth, PTS was compared between the 10-12 yo, 13-14 yo, 15-17 yo and young adults in *Chapter 3*. However, no consistent age-related differences in PTS were reported, despite children being significantly shorter and having shorter legs than the adolescent and adult groups. These observations were not consistent with previous research that found moderate correlations between PTS and height or leg length in adults (Hreljac, 1995; Sentija, Rakovac, & Babic, 2012; Thorstensson & Roberthson, 1987). Even still, age-related differences did not exist when PTS was normalised to height, leg length, or expressed as Froude number. Because PTS was not different between groups even when normalised to leg length or height, factors other than growth affect how gait was regulated among children. Therefore, investigating age-related differences in the determinants of PTS was warranted.

6.2.2. Determinants of PTS and the age-specific weak links

The review in *Chapter 2* concluded that gait was regulated by mechanical variables via proprioceptive feedback with assistance from cognitive processes. Using the revised criteria for identifying PTS determinants (*Chapter 2*), age-related differences in the potential determinants related to the mechanical load trigger were revealed in *Chapter 4*. The rectus femoris, biceps femoris, tibialis anterior and medial gastrocnemius were identified as muscular weak links among the children. By adolescence, the biceps femoris was no longer considered a weak link, suggesting it was no longer a potential determinant of PTS. However, the medial gastrocnemius remained as an additional weak link among the adolescent groups, but not for the adults. As such, minimising the muscular demands of the biceps femoris and the medial gastrocnemius progressively becomes less of a priority during locomotion as youth age. The biceps femoris and medial gastrocnemius may thus continue developing through childhood and adolescence, respectively, and could act as rate-limiters of gait maturation. Both of these muscles are bi-articulate, which could take longer to learn how to control, or coordinate their actions as they have more complex actions than muscles that act over a single joint (Van de Walle et al., 2010). However, the rectus femoris is also a bi-articular muscle, but was not identified as a rate limiting factor because it was also identified as a weak link in adults. Greater involvement of the bi-articular muscles in the children could have had an additional role in assisting with joint stability during the WRT. Unfortunately the exact mechanisms driving the additional bi-articular muscle involvement could not be assessed in this thesis. The influence of the roles bi-articular versus uni-articular muscles has on joint stability, coordination and gait maturation could be worth investigating in future research. Further comparisons of the critical values at which WRT occurred for each of these muscles is required to determine the development status of the muscles and their influence on gait maturation.

Chapter 2 also reported that metabolic factors were unlikely drivers of gait transitions because metabolic responses to changing task demands generally act too slowly to elicit rapid gait adjustments. Metabolic factors also lacked a critical value at which gait transitions would occur. Improving the metabolic economy of locomotion has instead been considered a favourable outcome, rather than a driver, of gait transitions (Hreljac, 1993; Monteiro, Farinatti, de Oliveira, & Araújo, 2011; Tseh, Bennett, Caputo, & Morgan, 2002). The results from *Chapter 4* further support this notion because the physiological variables failed to satisfy the criteria to be considered as PTS determinants. Interestingly, heart rate appeared to be more effectively minimised in adults following the WRT compared to the paediatric groups. As such, adults may more effectively minimise the mechanical cost of locomotion and subsequently reduce physiological strain than youth. In contrast, children transitioned at a higher relative intensity than the adults (*Chapter 5*), suggesting they are less effective at minimising the mechanical and/or physiological cost of locomotion.

Although there was a lack of age-related differences in PTS, there were notable differences in how PTS was determined during the WRT treadmill test (*Chapter 3*). Children exhibited more exploratory behaviour when determining PTS, as they more frequently tested transitions across a wider range of locomotive speeds. Conversely, the adults and older adolescents generally determined PTS using a single transition. To address why children used a different method to determine PTS, the influence of perceived exertion was investigated across age groups. In *Chapter 5*, the WRT was suggested to help minimise perceived exertion and may thus have a role in assisting with regulating gait in adolescents and adults. However, children were less capable of distinguishing differences in perceived exertions for walking and running at speeds near PTS. Children's inability to perceive differences in effort may drive the indecisiveness seen when determining PTS. Attempting to minimise the demands of more muscles and thus integrate more sources of potentially conflicting feedback (*Chapter 4*) could be hindering a child's ability to successfully optimise gait patterns. In particular, difficulties anticipating which gait mode would elicit lower sensations of effort may arise from children's uncertainty over what sensory cues to focus on to help regulate gait. Weighting the importance of various sensory cues may also be hindered by ongoing growth and development of the musculoskeletal system, as these individual constraints continue changing through late childhood and early adolescence. By transitioning at multiple speeds, children can instead experience how each gait condition feels so they can subsequently judge which gait mode would be preferable. In contrast, focusing on fewer sources of feedback to inform gait adjustments may allow the self-organising dynamics to naturally shape gait patterns in older adolescents and adults rather than having to cognitively decide when to transition. However, previous experience, which children may be lacking, is required to help shape these self-organising behaviours and identify the necessary sensory cues for effectively regulating gait.

6.3. Limitations of the thesis

As with all research, this thesis had a number of limitations. While study-specific limitations have been outlined in *Chapters 3-5, t*he subsequent sections will present overall limitations of the thesis and then suggest areas of research for future studies.

1) *Chronological age versus biological age*

   Participants were categorised by chronological age, which is the first limitation of this thesis as individuals mature at different rates. Assessments of biological age, such as peak height velocity, could provide further insight into factors influencing gait maturity, as individuals who are still growing have previously exhibited more variability than their non-growing counterparts (Bisi & Stagni, 2016). However, measurements of height across multiple years are required to obtain an accurate peak height velocity value, which was not practical for this thesis or the study's cross-sectional design. Although predictive equations have been formulated to estimate age at peak height velocity, the validity of these predictive methods have been questioned (Malina & Koziel, 2014). Rather than just using arbitrary cut-offs for the age groups, gait maturity levels were observed in *Chapter 3* and were used to inform the age groups for subsequent analyses throughout the thesis. However, further investigation would be required to determine whether the 13-14 yo were actually at an intermediary level of gait maturity, or whether this intermediate status was an artefact of a mixed group of growing and non-growing adolescents.

2) *Ratio of males to females*

   The ratios of males and females in each group were generally quite balanced, but the females were admittedly over-represented among the 10-12 yo group. As females mature at a faster rate than males (Cech & Martin, 2002), their gait also matures at an earlier age (Froehle, Nahhas, Sherwood, & Duren, 2013). However, various spatiotemporal gait parameters have been shown to remain immature prior to the age of 13 years, in both females and males (Froehle et al., 2013). The present results concur with these previous observations as the 10-12 yo group still exhibited less mature gait than the adolescent and adult groups. Therefore, it may be argued that sex differences between 10 and 12 years of age may not have had a large effect on how effectively gait was adapted. Moreover, no sex-related differences in PTS have previously been observed in adults

(Hreljac, 1995; Sentija et al., 2012), so it was not expected to find differences in PTS between the paediatric males and females either.

3) *Treadmill versus overground locomotion*

The present research was completed on a treadmill, which may be seen as a limitation of the study due to slight biomechanical differences between treadmill and overground locomotion (Lee & Hidler, 2008; Murray, Spurr, Sepic, Gardner, & Mollinger, 1985; Riley, Paolini, Della Croce, Paylo, & Kerrigan, 2007). Gait transitions performed on a treadmill also differ from those performed overground, whereby treadmill protocols elicit a lower PTS than those overground (Van Caekenberghe, De Smet, Segers, & De Clercq, 2010). However, the research was more concerned about how various factors respond to different locomotive speeds rather than characterising normal paediatric gait *per se*. To help mitigate some of the differences between treadmill and overground locomotion, all participants were given time to familiarise themselves to treadmill walking and running. Specifically, participants completed at least 45-60 min of treadmill locomotion prior to any data collection, with additional time given to participants who continued to exhibit variable, or unstable gait. It was also expected that overground locomotion would elicit more variability than treadmill locomotion (Hollman et al., 2016), particularly since gait speed cannot be controlled to the same extent overground as it can on a treadmill. To re-introduce some of this natural step-to-step variability during treadmill locomotion, movement of the participant on the treadmill in the global reference frame was calculated and incorporated into the stride lengths in *Chapter 3*. Moreover, treadmill use was considered to be necessary for more precise control over gait speed and was more suitable for the study's design.

4) *Mechanical economy trigger not assessed*

Without having access to an instrumented treadmill for data collection, kinetic variables relating to the mechanical economy trigger (e.g. ratios of positive and negative work completed, utilisation of elastic energy, limb stiffness) were unable to be assessed in this thesis. However, this area of research may benefit from further investigation to better understand what factors contribute to the greater metabolic cost of locomotion in children compared to adults (Van de Walle et al., 2010). As highlighted in *Chapter 1*, children exhibit diminished joint kinetics and are unable to utilise energy conserving mechanisms such as the storage and release of elastic energy as effectively as adults due to an immature musculoskeletal system. It remains to be determined how musculoskeletal development affects these mechanical factors and thus the ability to optimise gait economy. In adults, muscle activity increases with gait speed without increases in propulsive forces (Neptune & Sasaki, 2005; Neptune, Sasaki, & Kautz, 2008). Similar or more exaggerated instances of this plateau in force production may be seen in children with immature ankle plantarflexors, as they already exhibit diminished ankle plantarflexor moments and power generation (Chester et al., 2006; Cupp, Oeffinger, Tylkowski, & Augsburger, 1999; Ganley & Powers, 2005). Comparing the relative contributions towards propulsion from the contractile and series elastic elements within the muscles between adults and children could improve our understanding of muscle development and the ability to utilise energy-saving mechanisms. This information could help explain why the activity of the medial gastrocnemius was a weak link for the paediatric groups, but not the adults.

6.4. Suggestions for future research

As highlighted in the general discussion and limitations of the thesis sections, a number of questions still need to be answered, while further questions have been raised following the observations made throughout this thesis:

1) *How does experience and training affect the critical loads?*

   The influence of training history and physical activity levels on PTS in youth may benefit from further investigation. Awareness of how gait speed affects muscular demands was suggested to shape self-organising behaviours and help with identifying the more important sensory cues needed to effectively optimise gait patterns (*Chapter 5*). As such, it would be interesting to determine whether physical maturity or previous experience is a more dominant contributing factor involved in shaping self-organising behaviours and thus act as rate-limiters of gait maturity.

2) *Do youth rely more heavily on visual feedback to adjust their gait patterns?*

   Treadmill locomotion removes the use of visual flow as a regulatory mechanism of locomotion, because the body is moving but the environment around them is not. PTS is affected by the perceived speed of movement in adults and can be manipulated by changing the visual flow (Mohler, Thompson, Creem-Regehr, Pick, & Warren, 2007). Moreover, youth have a tendency to rely more heavily on visual cues to adapt posture than proprioceptive cues (Assaiante, 1998; Kraan, Tan, & Cornish, 2017; Woollacott & Shumway-Cook, 1990). Therefore, future research may want to investigate whether this dependence on visual feedback for postural control carries over to regulating locomotion in youth and whether manipulating their visual flow affects how well gait is adjusted to perceived locomotive demands. With the absence of visual cues in the present research, there would have been a greater reliance on the mechanical mechanisms to regulate gait. It would be interesting to determine whether the presence of visual cues help children more effectively anticipate increases in effort when approaching PTS and thus improve their ability to optimise gait.

3) *Are there differences in how youth perform a WRT?*

As there were differences in how the children and younger adolescents determined their PTS compared to adults, it could be suggested that they perform the gait transition differently as well. The following questions are raised:

a) *Are there differences in the preparation of the WRT or how long it takes to settle into the post-transition gait in youth?*

In adults, the reorganisation process to naturally transition between walking and running as gait speed gradually changes appears to occur across at least 2-3 steps (Hagio, Fukuda, & Kouzaki, 2015; Li & Hamill, 2002; Segers, Aerts, Lenoir, & De Clercq, 2006; Segers, De Smet, Van Caekenberghe, Aerts, & De Clercq, 2013; Van Caekenberghe et al., 2010). With hesitation in the determination of PTS among children (*Chapter 3*), there may also be a prolonged transitional process for children. In particular, children may require more preparatory steps prior to the transition step, and/or they may take longer to settle into the post-transition mode of locomotion.

b) *How does the combination of stride length and stride frequency play into the triggering of the WRT in youth?*

Gait speed and the combination of stride length and frequency are closely tied to gait economy and have thus been suggested to drive gait transitions in adults (De Smet, Segers, Lenoir, & De Clercq, 2009; Diedrich & Warren, 1995; Segers et al., 2006). Because children transitioned at a similar PTS as adults even though they had shorter legs, it would be expected that they have a different critical combination of stride length and stride frequency that initiates their gait transitions. A step length index has been used to investigate how step lengths and step frequencies contribute to increasing the gait speed during an overground WRT in adults (De Smet et al., 2009). Comparing how this step length index changes with gait speed during the WRT between youth and adults could help reveal age-related differences in the critical combination of stride length and stride frequency.

c) *Do children possess adult-like self-organising behaviours, or have they not developed or matured by the age of 13 years?*

Gait transitions are thought to occur due to a loss of stability in the system, requiring a reorganisation of the system to a more stable pattern of coordination (Diedrich & Warren, 1995). A preliminary analysis of the changes in spatiotemporal variability across the WRT protocol for eleven of the 10-13 yo failed to demonstrate this loss of stability when approaching the PTS (see: *Appendix M* (Kung, Fink, Legg, Ali, & Shultz, 2017)). That is, children failed to exhibit increases in spatiotemporal variability as gait speed approached PTS, when compared to their self-selected walking speed. Furthermore, there was an increase in variability following the WRT, rather than a decrease. As children had immature running patterns including at an unfamiliarly slow running speed (*Chapter 3*), fast walking may have been more stable than slow running, which could explain why children transitioned relatively later than adults. Future research may want to investigate whether children may prioritise optimising gait stability over economy. It would also be interesting to investigate whether spatiotemporal variability accurately represents the control parameters that drive children's gait transitions, or whether the relative phasing of the lower extremity segments (Diedrich & Warren, 1995) more accurately represent these control parameters, particularly in children.

4) *Can gait transitions be analysed in a range of clinical populations to help reveal factors contributing to their gait abnormalities?*

The present research demonstrates that interesting information can be gained from analysing dynamic responses to perturbations (i.e. the WRT). By comparing how youth perform a gait transition to that of adults, differences in the strategies used to adjust gait, a potential learning process involved in shaping these strategies, and the factors that may contribute to this process were revealed. As a result, the thesis was able to identify potential weak links in children and adolescents that limit their ability to effectively adjust their gait to increasing speed. These weak links are thought to represent rate-limiting factors of gait maturation. A similar approach may be used to investigate possible weak links in clinical populations. Identifying the potential weak links, or factors contributing to gait abnormalities, could help tailor more effective physical rehabilitation treatment plans.

6.5. Conclusion

Overall, findings from this thesis contribute knowledge about gait maturation during late childhood and adolescence and the associated rate-limiting factors. Gait maturation continues through to adolescence, whereby walking is mature by 13 years of age and running may continue maturing through to the age of 15-17 years. Children aged 10-12 years were less effective than adults at optimising their gait as the speed of locomotion increased. Specifically, they exhibited more exploratory behaviour when determining their PTS and were less effective at minimising the physiological and perceived effort. Age-related differences in the PTS determinants were also observed, which may have contributed to the differences in how PTS was determined among the children and adults. The biceps femoris and medial gastrocnemius were additional weak links among the 10-12 yo and 10-17 yo, respectively, when compared to those of adults. Thus, the biceps femoris and medial gastrocnemius have been identified as rate-limiting factors of gait maturity that continue to develop through childhood and adolescence, respectively. Due to the presence of additional weak links, children may have more conflicting sources of feedback arising from the lower extremity musculature to regulate their gait. As such, they appear to experience difficulties integrating these sources of feedback, which has proved to be detrimental to their ability to effectively optimise gait. When children mature through to adolescence, there may be fewer conflicting sources of feedback involved in regulating gait and an improved ability to perceive how best to adjust gait is evident. This research further supports the notion that gait maturation is influenced by ongoing development of the musculoskeletal and neuromuscular systems through to adolescence. While growth and development continues, it appears different strategies are used to adjust gait. There is also an important learning component involved in shaping these strategies to thus achieve mature gait and the ability to effectively optimise gait. As the various systems of the body mature through adolescence, so does the ability to adjust gait effectively through the use of self-organising behaviours in an effortless manner.

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List of Appendices

APPENDIX A: Ethics Approval Letters

As mentioned in the introduction, a single study was conducted for this thesis. This appendix presents the ethics approval letters for this research.

Following the initial approval, subsequent changes were made to the study's protocol. Of particular note, the initial sample cohort of 11-13-year-olds was expanded to shift the research focus to exploring age-related differences in the WRT from late childhood through adolescence to better understand the factors influencing gait maturation. Thus, the approval letters reflect the following changes:

1) Initial approval of the study (11-13-year-olds only).
2) A revised recruitment flyer.
3) Inclusion of 10-year-olds, an increase in the koha (gift) for the participants and an updated flyer.
4) Inclusion of 14-17-year-olds and young adults (18-30 years) and appropriate changes across the documents to reflect this change.

Following the inclusion of adults, additional documents were required so that there was separate paperwork for children (<16 years old according to the Massey University Ethics Committee) and their parents, as well as for adults. These documents can be found in the subsequent appendices: health screening forms (*Appendices B and C*); information letters (*Appendices D-F*); consent forms (*Appendices G and H*); and the recruitment flyer aimed at 10-30 yo (*Appendix I*)).

MASSEY UNIVERSITY
TE KUNENGA KI PŪREHUROA

26 January 2016

Stacey Kung
[redacted]

Dear Stacey

Re: HEC: Southern A Application – 15/62
Factors affecting how a child transitions from walking to running

Thank you for your letter dated 21 January 2016.

On behalf of the Massey University Human Ethics Committee: Southern A I am pleased to advise you that the ethics of your application are now approved. Approval is for three years. If this project has not been completed within three years from the date of this letter, reapproval must be requested.

Please note that travel undertaken by students must be approved by the supervisor and the relevant Pro Vice-Chancellor and be in accordance with the Policy and Procedures for Course-Related Student Travel Overseas. In addition, the supervisor must advise the University's Insurance Officer.

If the nature, content, location, procedures or personnel of your approved application change, please advise the Secretary of the Committee.

Yours sincerely

Mr Jeremy Hubbard, Chair
Massey University Human Ethics Committee: Southern A

cc Dr Sarah Shultz
School of Sport & Exercise
WELLINGTON

Dr Philip Fink
School of Sport & Exercise
PN621

Dr Ajmol Ali
School of Sport & Exercise
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Dr Andrew Foskett, Interim HoS
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Massey University Human Ethics Committee
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MASSEY UNIVERSITY
TE KUNENGA KI PŪREHUROA

26 August 2016

Stacey Kung
[redacted]

Dear Stacey

Re: HEC: Southern A Application – 15/62
Factors affecting how a child transitions from walking to running

Thank you for your letter dated 24 August 2016 outlining the change you wish to make to the above application.

The changes to the recruitment flyer have been approved and noted.

If the nature, content, location, procedures or personnel of your approved application change, please advise the Secretary of the Committee. If over time, more than one request to change the application is received, the Chair may request a new application.

Yours sincerely

Mr Jeremy Hubbard, Chair
Massey University Human Ethics Committee: Southern A

cc Dr Sarah Shultz
School of Sport & Exercise
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MASSEY UNIVERSITY
TE KUNENGA KI PŪREHUROA

4 October 2016

Stacey Kung
[redacted]

Dear Stacey

Re: HEC: Southern A Application – 15/62
Factors affecting how a child transitions from walking to running

Thank you for your letter dated 3 October 2016 outlining the changes you wish to make to the above application.

The changes have been approved and noted, as follows:

1. Addition of a small koha in proportion to the time and effort required by the participant;
2. An advertisement to recruit for this study in conjunction with another.

If the nature, content, location, procedures or personnel of your approved application change, please advise the Secretary of the Committee. If over time, more than one request to change the application is received, the Chair may request a new application.

Yours sincerely

Mr Jeremy Hubbard, Chair
Massey University Human Ethics Committee: Southern A

cc Dr Sarah Shultz
School of Sport & Exercise
WELLINGTON

Dr Philip Fink
School of Sport & Exercise
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MASSEY UNIVERSITY
TE KUNENGA KI PŪREHUROA

26 May 2017

Stacey Kung
[redacted]

Dear Stacey

Re: HEC: Southern A Application – 15/62
Factors affecting gait transitions from walking to running

Thank you for your email dated 23 May 2017 outlining the changes you wish to make to the above application.

The changes have been approved and noted, as follows:

- Change in title to reflect the change in participant age groups;
- Broadening of participant pool from 10-13 to 10-17 years, plus a cohort of young adults;
- Increase in the number of participants to ensure adequate numbers for age and weight sub-classifications;
- Revised public documentation to reflect the broadening in the age-range and consent processes required.

If the nature, content, location, procedures or personnel of your approved application change, please advise the Secretary of the Committee. If over time, more than one request to change the application is received, the Chair may request a new application.

Yours sincerely

Dr Lesley Batten, Chair
Massey University Human Ethics Committee: Southern A

cc Dr Sarah Shultz
School of Sport & Exercise
WELLINGTON

Dr Philip Fink
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APPENDIX B: Health and Activity Recruitment Questionnaire (Children and Adolescents)

The following Health and Activity Recruitment Questionnaire was used to screen children and adolescents for eligibility to take part in the study. This form was given to the parents of the children and adolescents (i.e. individuals aged 10-17 years old) to complete.

MASSEY UNIVERSITY
COLLEGE OF HEALTH
TE KURA HAUORA TANGATA

Factors affecting gait transitions from walking to running

Health and Activity Recruitment Questionnaire

Participant Name: ____________________________ DOB:________ Age: ______ Gender:___________

Parent/ Guardian Name: __________________________ Email:___________________________________

Address: ____ Postcode:__________

Contact Phone: (H): _______________ (W): __________________ Mobile:________________________

As your child is to be a participant in this project, would you please complete the following physical activity readiness questionnaire for your child. This form aims to identify any health problems so that we can avoid any risk of illness or injury. The information provided by you on this form will be treated with the strictest confidentiality.

PART A

What is your child's current **height** (preferably without shoes on)?

What is your child's current **weight** (preferably first thing in the morning with minimal clothing)?

What is your child's current shoe size?

Has your child recently (within the last 6 months) had an acute injury to the lower body that required medical attention? (e.g. fracture, sprain, strain)

Yes **No**

- If yes please provide details: ____

Has your child ever been diagnosed with a neuromuscular condition that affects your child's balance and/or the way your child moves?

Yes **No**

- If yes please provide details: ____

Has your child ever had surgery to correct an orthopaedic or neuromuscular condition?

Yes **No**

- If yes please provide details: ____

Does your child have any of the following conditions? (If so, please circle whichever apply)

Cerebral palsy	Muscular dystrophy	Autism
Asthma	Diabetes (Type I or II)	Heart murmur
Dyspraxia	Spina Bifida	Arthritis
Skin allergies/conditions		

Other condition (please specify):____

Does your child have any food allergies/intolerances? ____________________

- **If yes, please specify:** ____________________

____

Is your child on any medications or supplements?: ____________________

- **If yes, what are these for?** ____________________

____

Compared to other people their age, how would you rate your child's physical health at the present?

(please circle one)

Excellent	Very good	Good	Fair	Poor	Don't know
1	2	3	4	5	6

How would you describe your child's present weight? *(please circle one)*

Underweight   Normal Weight   Overweight   Obese

Compared to other people their age, how would you rate your child's physical activity levels at the present? *(please circle one)*

Excellent	Very good	Good	Fair	Poor	Don't know
1	2	3	4	5	6

Please fill out the following table for each physical activity (e.g. Bike riding; Netball; Swimming) that your child currently does in a typical WEEK. Please include biking/walking/skating etc. to school.

Physical Activity	Monday-Friday			Saturday-Sunday		
	How many times?	Minutes per session	Total minutes	How many times?	Minutes per session	Total minutes

Please fill out the following table for each leisure activity (e.g. Homework, Watching TV, Playing video games) that your child currently does in a typical WEEK.

Leisure Activity	Monday-Friday			Saturday-Sunday		
	How many times?	Minutes per session	Total minutes	How many times?	Minutes per session	Total minutes

PART B

Please answer all of the following questions by ticking only one box for each question

1. Does your child have or has she/he ever experienced any of the following:

a.	**Heart condition**	**YES**	☐	**NO**	☐
b.	**High or low blood pressure**	**YES**	☐	**NO**	☐
c.	**Chest Pain**	**YES**	☐	**NO**	☐
d.	**Dizziness or Fainting**	**YES**	☐	**NO**	☐
e.	**A bone, joint or muscular problem**	**YES**	☐	**NO**	☐
f.	**Any sustained injuries or illnesses**	**YES**	☐	**NO**	☐
g.	**Is your child taking any medication**	**YES**	☐	**NO**	☐
h.	**Been hospitalised**	**YES**	☐	**NO**	☐
i.	**Infectious disease that may be transmitted in blood**	**YES**	☐	**NO**	☐

If you have answered 'Yes' to any of the above questions, please provide full details here:

____

____

____

____

I have read, understood and completed this questionnaire.

Signature
(Parent or legal guardian): ________________________________ Date: ______________

Signature ***(Participant):*** ________________________________ Date: ______________

References

1. Thomas S, Reading J and Shephard RJ. Revision of the Physical Activity Readiness Questionnaire (PAR-Q). *Can J Sport Sci* 17(4): 338-345.
2. Cardinal BJ, Esters J and Cardinal MK. Evaluation of the revised physical activity readiness questionnaire in older adults. *Med Sci Sports Exerc* 28(4): 468-472

Thank you for completing this questionnaire. Please return to:

Stacey Kung
School of Sport and Exercise
Massey University
Email: s.kung@massey.ac.nz

APPENDIX C: Health and Activity Recruitment Questionnaire (Adults)

The following Health and Activity Recruitment Questionnaire was used to screen adults (i.e. 19-29 yo) for eligibility to take part in the study.

MASSEY UNIVERSITY
COLLEGE OF HEALTH
TE KURA HAUORA TANGATA

Factors affecting gait transitions from walking to running

Health and Activity Recruitment Questionnaire

Participant Name: ______________________________ DOB:_________ Age: ______ Gender:___________

Email:_____________________________ Contact Phone: (H): ______________ Mobile:________________

Address: ____ Postcode:_____________

This form aims to identify any health problems so that we can avoid any risk of illness or injury. The information provided by you on this form will be treated with the strictest confidentiality.

PART A

What is your current **height** (preferably without shoes on)?

What is your current **weight** (preferably first thing in the morning with minimal clothing)?

What is your current shoe size?

Have you recently (within the last 6 months) had an acute injury to the lower body that required medical attention? (e.g. fracture, sprain, strain)

Yes **No**

- If yes please provide details: ____

Have you ever been diagnosed with a neuromuscular condition that affects your balance and/or the way you move?

Yes **No**

- If yes please provide details: ____

Have you ever had surgery to correct an orthopaedic or neuromuscular condition?

Yes **No**

- If yes please provide details: ____

Do you have any of the following conditions? (If so, please circle whichever apply)

Cerebral palsy	Muscular dystrophy	Autism
Asthma	Diabetes (Type I or II)	Heart murmur
Dyspraxia	Spina Bifida	Arthritis
Skin allergies/conditions		

Other condition (please specify):____

<u>Do you have any food allergies/intolerances?</u> ______________________________

- **<u>If yes, please specify:</u>** ______________________________

  ____

<u>Are you on any medications or supplements?:</u> ______________________________

- **<u>If yes, what are these for?</u>** ______________________________

  ____

<u>How would you rate your physical health at the present?</u> *(please circle one)*

Excellent	Very good	Good	Fair	Poor	Don't know
1	2	3	4	5	6

<u>How would you describe your present weight?</u> *(please circle one)*

Underweight   Normal Weight   Overweight   Obese

<u>How would you rate your physical activity levels at the present?</u> *(please circle one)*

Excellent	Very good	Good	Fair	Poor	Don't know
1	2	3	4	5	6

<u>Please fill out the following table for each physical activity (e.g. Bike riding; Netball; Swimming) that you currently do in a typical WEEK. Please include biking/walking/skating to work etc.</u>

Physical Activity	Monday-Friday			Saturday-Sunday		
	How many times?	Minutes per session	Total minutes	How many times?	Minutes per session	Total minutes

PART B

Please answer all of the following questions by ticking only <u>one</u> box for each question

1. Do you have or have you ever experienced any of the following:

j.	**Heart condition**	**YES**	☐	**NO**	☐
k.	**High or low blood pressure**	**YES**	☐	**NO**	☐
l.	**Chest Pain**	**YES**	☐	**NO**	☐
m.	**Dizziness or Fainting**	**YES**	☐	**NO**	☐
n.	**A bone, joint or muscular problem**	**YES**	☐	**NO**	☐
o.	**Any sustained injuries or illnesses**	**YES**	☐	**NO**	☐
p.	**Is your child taking any medication**	**YES**	☐	**NO**	☐
q.	**Been hospitalised**	**YES**	☐	**NO**	☐
r.	**Infectious disease that may be transmitted in blood**	**YES**	☐	**NO**	☐

If you have answered 'Yes' to any of the above questions, please provide full details here:

____

____

____

____

____

I have read, understood and completed this questionnaire.

Signature

Signature ***(Participant):*** ____________________________________ Date: ________________

References

3. Thomas S, Reading J and Shephard RJ. Revision of the Physical Activity Readiness Questionnaire (PAR-Q). *Can J Sport Sci* 17(4): 338-345.
4. Cardinal BJ, Esters J and Cardinal MK. Evaluation of the revised physical activity readiness questionnaire in older adults. *Med Sci Sports Exerc* 28(4): 468-472

<u>Thank you for completing this questionnaire. Please return to:</u>

Stacey Kung

School of Sport and Exercise

Massey University

Email: s.kung@massey.ac.nz

APPENDIX D: Information sheet for Participants (Children and Adolescents)

The following information sheet was given to the participants aged between 10-17 years old to read prior to volunteering to take part in the study. The information sheet has been reformatted to fit the page.

MASSEY UNIVERSITY
COLLEGE OF HEALTH
TE KURA HAUORA TANGATA

Factors affecting gait transitions from walking to running

INFORMATION SHEET (Child)

Thank you for showing an interest in this study. Please read everything below before deciding if you want to take part. This information sheet will tell you a little more about the study and what we would like you to do. If you decide not to take part it will not change your relationship with the research team or your school.

What is the purpose of this research?
My name is Stacey Kung, and I will be conducting this research project as part of my PhD study within the School of Sport and Exercise at Massey University. My supervisors for the study are Dr Sarah Shultz, Dr Phillip Fink and Prof Stephen Legg. Anja Fricke will also be helping with this project. This study will look at how your joints move, how the muscles in your legs work and how your body uses energy when walking and running on a treadmill. I am also interested to find out whether children with different body sizes move or use energy differently when changing from walking to running.

Who can take part in this study?
We are looking for participants between the ages of 10 and 30 years. Your parents will fill out a form that asks questions about your health. Depending on the answers, you will be told if you can help with the study.

What is involved in taking part in this study?
If you decide that you want to take part in this study, you will need to visit the School of Sport and Exercise at Massey University for three testing sessions. You will receive $30 worth of vouchers as a thank you gift for helping with the study.

<u>Session 1 (approximately 1.5 - 2 hours):</u>

1) We will measure how tall you are, how much you weigh, and also take measurements around your hip and waist.
2) You will lie down for 30 minutes and watch a video. While you are laying down, you will wear a face mask that will go over your nose and mouth; this will tell us how much energy you use when you are not moving around. We will also stick two electrodes to your hand and foot. You will not feel anything from these electrodes, but it will tell us how much water is in your body.
3) You will be asked to walk normally across the laboratory, 5 times so that we know how fast you normally walk.
4) We will give you time to practice walking and running on the treadmill, so that you are comfortable doing exercise in the next two sessions.

<u>Session 2 (approximately 1.5 hours):</u>

1) You will lie down while small areas of skin on your legs are shaved and cleaned. This may cause your skin to go a little red and/or itchy, but this should disappear after a couple of days.
2) Electrodes and shiny markers will be attached to your legs and trunk, which will tell us about how you move while you walk and run (see pictures below). The markers will just feel like having a plaster placed on your leg.

The shiny markers and electrodes will be taped on your legs and trunk, in the same places that you see them in the pictures.

3) You will be asked to do some exercise on a treadmill. During this time, you will need to wear a face mask again, so that we can see how much energy you use when you are moving. You will also wear a strap around your chest, which will tell us how fast your heart is beating.
   - This exercise test will start with you walking on the treadmill.
   - The treadmill speed will slowly get faster. You can start to run whenever the treadmill gets too fast to walk.
   - The speed of the treadmill will continue to get faster until you feel too tired to continue running and we will stop the exercise test immediately. By the end of the exercise test, you may experience very heavy breathing and/or sore or tired legs.

<u>Session 3 (approximately 2.5 - 3 hours):</u>

1) We will give you a muesli bar to eat when you first arrive.
2) You will have to wear the same electrodes and markers in the same places on your legs and trunk. You will also need to wear the face mask and chest strap again.
3) We will select a speed on the treadmill and ask you to run or walk for five minutes. You will do this 10 times (5 for walking, 5 for running), and you will get to rest for 5 minutes after each test. When you are resting, we will ask you to tell us how hard it was to walk or run at that speed.

If you decide at any point in time that you no longer want to be part of the study, then you can stop without any problems.

Preparing for the testing sessions:

For all three testing sessions, we will ask you to make sure not to eat anything before coming in for each session. Testing sessions may take place during the mornings, after school finishes and during the weekends.

You will be asked to wear a swimsuit or compression shorts during sessions 2 and 3. You will be able to get changed in a private room. Only the researchers involved in the study and your parents/guardians and any other family members will be present during the testing sessions. We will provide swimsuits and compression shorts, but you can wear your own if that is more comfortable. We also ask that you bring a pair of clean socks to wear for each testing session. All testing will be completed by female researchers, but if you feel more comfortable, a male researcher can apply the markers and electrodes to your body.

What will happen to this information?

All of the information that the researchers collect will be kept on a computer and your results will only be seen by your parents/guardian and the researchers for this study. We may use the information that we collect, but no one will be able to tell which information is yours.

What is the next step?

If you have any questions, you can ask any member of the research team at any time.
If you have read and understood everything that we will ask you to do and you would like to take part, please write your name on the attached 'Consent Form'.

Participant's Rights

You are under no obligation to accept this invitation. If you decide to participate, you have the right to:

- *decline to answer any particular question;*
- *withdraw from the study at any time (if you choose to withdraw you cannot withdraw the information we collect from you up to that point);*
- *ask any questions about the study at any time during participation;*
- *provide information on the understanding that your name will not be used unless you give permission to the researcher;*
- *be given access to a summary of the project findings when it is concluded.*
- *request a summary of individual results*

Project Contacts

Stacey Kung (PhD student researcher) Email: s.kung@massey.ac.nz
Phone: 04 801 5799 ext 63905

Dr. Sarah Shultz (Primary supervisor) Email: s.p.shultz@massey.ac.nz
Phone: 04 801 5799 ext 63496

<u>MUHEC APPLICATIONS</u>
Committee Approval Statement

This project has been reviewed and approved by the Massey University Human Ethics Committee: Southern A, Application 15/62. If you have any concerns about the conduct of this research, please contact Mr Jeremy Hubbard, Chair, Massey University Human Ethics Committee: Southern A, telephone 04 801 5799 x 63487, email humanethicsoutha@massey.ac.nz.

<u>Compensation for Injury</u>
If physical injury results from your participation in this study, you should visit a treatment provider to make a claim to ACC as soon as possible. ACC cover and entitlements are not automatic and your claim will be assessed by ACC in accordance with the Accident Compensation Act 2001. If your claim is accepted, ACC must inform you of your entitlements, and must help you access those entitlements. Entitlements may include, but not be limited to, treatment costs, travel costs for rehabilitation, loss of earnings, and/or lump sum for permanent impairment. Compensation for mental trauma may also be included, but only if this is incurred as a result of physical injury.

If your ACC claim is not accepted you should immediately contact the researcher. The researcher will initiate processes to ensure you receive compensation equivalent to that to which you would have been entitled had ACC accepted your claim.

APPENDIX E: Information sheet for Participants (Adults)

The following information sheet was given to the young adult participants to read prior to agreeing to take part in the study. The information sheet has been reformatted to fit the page.

MASSEY UNIVERSITY
COLLEGE OF HEALTH
TE KURA HAUORA TANGATA

Factors affecting gait transitions from walking to running

INFORMATION SHEET

Thank you for showing an interest in this study. Please read everything below before deciding if you want to take part. This information sheet will tell you a little more about the study and what we would like you to do.

What is the purpose of this research?
My name is Stacey Kung, and I will be conducting this research project as part of my PhD study within the School of Sport and Exercise at Massey University. My supervisors for the study are Dr Sarah Shultz, Dr Phillip Fink, Prof Stephen Legg and Dr Ajmol Ali. This study aims to identify whether there are factors that may be limiting a child's ability to change from walking to running. Specifically, this research will be investigating how children move, how children's muscles work, how energy is being used when changing from walking to running and how these factors compare to young healthy adults. I will also investigate whether there are differences in how children of varying ages and body sizes change from walking to running. Numerous physical activities and sports involve transitioning between walking and running. Therefore, identifying limiting factors may help to address why some children and adolescents are not meeting the recommended amount of physical activity.

Who can take part in this study?
We aim to recruit 120 participants between the ages of 10 and 30 years. You will not be eligible if you have been injured or had lower limb surgery in the past 6 months, have a skin allergy or other skin condition that may be affected by the application of electrodes, have moderate to severe asthma, have been diagnosed with Type I or Type II diabetes, a neuromuscular disease, or any condition that has changed the way you move, including difficulties with balance. As this study will involve a maximal effort exercise test, you will also be ineligible if you have any heart conditions, as this test may increase your risk of illness or injury. We will provide a muesli bar during Session 3 that is wheat, gluten, dairy and nut free. However, if you have other food allergies, you will not be eligible to participate in this study.

Your participation in this project is voluntary. If you agree to participate, you can withdraw from participation at any time during the project without any adverse consequence. In particular, your choice to either participate, or not, or to withdraw at any stage, will not affect your studies and/or grades.

What is involved in taking part in this study?
If you decide to participate in this study, you will be asked to attend three testing sessions at a laboratory at Massey University (Wellington Campus). You will receive $30 worth of vouchers as a thank you gift for helping with the study.

Time commitment:

- **Session 1:** Approximately 1.5 - 2 hours.
- **Session 2:** Approximately 1.5 hours.
- **Session 3:** Approximately 2.5 - 3 hours.

Sessions will need to be completed at least 48 hours apart. For all of the testing sessions, you will need to be fasted (no food or drink, other than water). This is important as different foods will change the way your body uses energy at rest and during exercise.

- Session 1 will need to be completed in the morning, after an overnight fast.
- For sessions 2 and 3, you will need to be fasted for at least 3 hours. We will provide a muesli bar prior to the exercise activities during session 3.

Tasks:

- **Session 1:** You will lie down for 30 minutes, while we assess body composition (% body fat, muscle and fluids) and how much energy your body uses while resting. You will then have about 30 minutes to learn how to safely get on and off the treadmill and practice walking and running on the treadmill. You will also walk and jog across a 6 metre walkway five times, to determine your normal walking pace.
- **Session 2:** This session will involve a maximal effort exercise test. We will attach surface electrodes and reflective markers to your body (see below for more details). You will initially begin walking on the treadmill at a speed slightly slower than their normal walking pace. The treadmill speed will slowly increase every 30 seconds until you can no longer keep up with the treadmill speed. We will identify your preferred walking to running transition speed.
- **Session 3:** When you first arrive, you will be given a muesli bar to eat. We will attach the markers to your body. You will then be asked to complete 10 different exercise trials on the treadmill; each trial will be completed for 5 minutes. These will include five walking trials and five running trials at speeds that are slightly faster, slightly slower and at the speed at which you prefer to change from walking to running. Between trials, you will have 5 minutes to rest.

Assessments:

- **Anthropometrics:** Height, weight, body composition (% body fat, muscle, fluids), hip circumference and waist circumference will be measured. To assess body composition, two electrodes (small sticky gel pads) will be attached to the hand and foot, while they lie quietly for 10 minutes.
- **Joint movements:** Retro-reflective markers (small silver balls) will be attached to your torso, legs and feet. We will use our 3D motion capture system to collect information about your walking and running gaits.
- **Muscle activity:** You will lie down while small areas of skin on your legs are shaved and cleaned with alcohol swabs. This may make your skin a little red and you may experience mild skin irritation, but this should disappear after a couple of days. We need to do this to be able to collect a clear signal from the muscles. We will then attach surface electrodes over four muscles of the thigh and lower leg. These electrodes are like little sticky gel pads that will be attached to wireless transmitters to collect information about how the muscles are working while walking and running. The electrodes will not cause any type of sensation or stimulation.
- **Ground reaction forces:** We will provide a pair of shoes for you to wear during Sessions 2 and 3. We will insert insoles into these shoes that will tell us about the forces that you are experiencing under your feet as you walk and run on the treadmill.
- **Energy expenditure:** We will assess how your body uses energy while resting (i.e. lying down), and during the walking and running activities by analysing the air that you breathe in and out. This just involves wearing a face mask that will go over your nose and mouth.
- **Heart rate:** Your heart rate will be monitored during each session, using a heart rate monitor that will be worn around your chest.
- **Perceptions of the exercise tasks:** You will be asked to rate how hard you think each exercise trial is and whether you perceive the activity to be pleasurable or not.
- **Video recording:** During testing sessions 2 and 3, we will need to collect video of your performance during the walking and running tasks. This data is not for marketing purposes, but will be used to help to identify when you transition from walking to running and to help explain differences in motion when we are analysing the data. The video will not be displayed publicly and your identity will not be compromised.

<u>Clothing requirements:</u>

You will need to wear a swimsuit or compression shorts during testing for sessions 2 and 3. You will also need to bring a pair of clean socks to wear for each testing session.

- This is important because the reflective markers need to be attached to the skin. Regular clothes that are not skin tight may hide the markers from the view of the cameras.
- Swimsuits and compression shorts will be provided in a range of different sizes, but you can wear your own swimsuit or compression shorts if you would prefer.
- The laboratory will be set up solely for the purpose of this study. The researchers involved in the study will be the only other people present during testing.

What will happen to this information?

All of the information that the researchers collect will be kept on a computer. Your details and results will remain confidential, and your name will not be used at any time during the study. Only the researcher and supervisor will have access to the data. We may use the data that we collect in publications or during presentations, but no one will be able to tell which data is yours. At the end of the project, a summary of findings can be sent at your request.

What is the next step?

If you have any questions, you can ask any member of the research team at any time. If you have read and understood everything and you are happy to take part, please complete the health and activity recruitment questionnaire. Details in the health screening questionnaire will help determine if you are able to participate.

Participant's Rights

You are under no obligation to accept this invitation. If you decide to participate, you have the right to:

- *decline to answer any particular question;*
- *withdraw from the study at any time (if you choose to withdraw you cannot withdraw your data from the analysis after the data collection has been completed);*
- *ask any questions about the study at any time during participation;*
- *provide information on the understanding that your name will not be used unless you give permission to the researcher;*
- *be given access to a summary of the project findings when it is concluded.*
- *request a summary of individual results*

Project Contacts

Stacey Kung (PhD student researcher)	Email:	s.kung@massey.ac.nz
	Phone:	0273840285
Dr. Sarah Shultz (Primary supervisor)	Email:	s.p.shultz@massey.ac.nz
	Phone:	04 801 5799 ext 63496

MUHEC APPLICATIONS

Committee Approval Statement

This project has been reviewed and approved by the Massey University Human Ethics Committee: Southern A, Application 15/62. If you have any concerns about the conduct of this research, please contact Mr Jeremy Hubbard, Chair, Massey University Human Ethics Committee: Southern A, telephone 04 801 5799 x 63487, email humanethicsoutha@massey.ac.nz.

Compensation for Injury

If physical injury results from your participation in this study, you should visit a treatment provider to make a claim to ACC as soon as possible. ACC cover and entitlements are not automatic and your claim will be assessed by ACC in accordance with the Accident Compensation Act 2001. If your claim is accepted, ACC must inform you of your entitlements, and must help you access those entitlements. Entitlements may include, but not be limited to, treatment costs, travel costs for rehabilitation, loss of earnings, and/or lump sum for permanent impairment. Compensation for mental trauma may also be included, but only if this is incurred as a result of physical injury.

If your ACC claim is not accepted you should immediately contact the researcher. The researcher will initiate processes to ensure you receive compensation equivalent to that to which you would have been entitled had ACC accepted your claim.

APPENDIX F: Information sheet for Parents

The following information sheet was given to the parents of the participants aged between 10-17 years old to read prior to their child taking part in the study. The information sheet has been reformatted to fit the page.

MASSEY UNIVERSITY
COLLEGE OF HEALTH
TE KURA HAUORA TANGATA

Factors affecting gait transitions from walking to running

INFORMATION SHEET

Thank you for showing an interest in this study. Please read everything below before deciding if you want your child to take part. This information sheet will tell you a little more about the study and what we would like your child to do. If you decide not to let your child take part it will not affect your relationships with the research team or your child's school.

What is the purpose of this research?

My name is Stacey Kung, and I will be conducting this research project as part of my PhD study within the School of Sport and Exercise at Massey University. My supervisors for the study are Dr Sarah Shultz, Dr Phillip Fink and Prof Stephen Legg; Anja Fricke, completing her postgraduate study, will also be helping with the project. This study aims to identify whether there are factors that may be limiting a child's ability to change from walking to running. Specifically, this research will be investigating how children move, how children's muscles work, how energy is being used when changing from walking to running and how these factors compare to young healthy adults. I will also investigate whether there are differences in how children of varying ages and body sizes change from walking to running. Numerous playground activities and sports involve transitioning between walking and running. Therefore, identifying limiting factors may help to address why some children and adolescents are not meeting the recommended amount of physical activity.

Who can take part in this study?

We aim to recruit 120 participants between the ages of 10 and 30 years. Your child will not be eligible if he/she has been injured or had lower limb surgery in the past 6 months, has a skin allergy or other skin condition that may be affected by the application of electrode pads, has moderate to severe asthma, has been diagnosed with Type I or Type II diabetes, a neuromuscular disease, or any condition that has changed the way your child moves, including difficulties with balance. As this study will involve a maximal effort exercise test, your child will also be ineligible if they have any heart conditions, as this test may increase their risk of illness or injury. We will provide a muesli bar during Session 3 that is wheat, gluten, dairy and nut free. However, if your child has other food allergies, your child will not be eligible to participate in this study.

Your child's participation in this project is voluntary. If he/she does agree to participate, they can withdraw from participation at any time during the project without any adverse consequence.

What is involved in taking part in this study?

If your child decides to participate in this study, he/she will be asked to attend three testing sessions at a laboratory at Massey University (Wellington Campus). Your child will receive $30 worth of activity vouchers as a thank you gift for helping with the study.

Time commitment:

- **Session 1:** Approximately 1.5 - 2 hours.
- **Session 2:** Approximately 1.5 hours.
- **Session 3:** Approximately 2.5 - 3 hours.

For all of the testing sessions, your child will need to be fasted (no food or drink, other than water). This is important as different foods will change the way your child's body uses energy at rest and during exercise.

- Session 1 will need to be completed in the morning, after an overnight fast.
- For session 2, your child will need to be fasted for at least 3 hours.
- For session 3, your child will need to be fasted for at least 3 hours, but we will provide your child with a muesli bar prior to the exercise activities. This session should be completed after school hours or during the weekend.

Tasks:

- **Session 1:** Your child will lie down for 30 minutes, while we assess body composition (% body fat, muscle and fluids) and how much energy your child uses while resting. Your child will then have about 30 minutes to learn how to safely get on and off the treadmill and practice walking and running on the treadmill. Your child will also walk across a 6 metre walkway five times, to determine their normal walking pace.

- **Session 2:** This session will involve a maximal effort exercise test. We will attach surface electrodes and reflective markers to your child's body (see below for more details). Your child will initially begin walking on the treadmill at a speed slightly slower than their normal walking pace. The treadmill speed will slowly increase every 30 seconds until your child can no longer keep up with the treadmill speed. We will identify when your child prefers to change from walking and running.
- **Session 3:** When your child first arrives, he/she will be given a muesli bar to eat. We will attach the markers to your child's body. Your child will then be asked to complete 10 different exercise trials on the treadmill; each trial will be completed for 5 minutes. These will include five walking trials and five running trials at speeds that are slightly faster, slightly slower and at the speed at which your child prefers to change from walking to running. Between trials, your child will have 5 minutes to rest.

Assessments:

- **Anthropometrics:** Height, weight, body composition (% body fat, muscle, fluids), hip circumference and waist circumference will be measured. To assess body composition, two electrodes (small sticky gel pads) will be attached to the hand and foot, while they lie quietly for 10 minutes.
- **Joint movements:** Retro-reflective markers (small silver balls) will be attached to your child's torso, legs and feet. We will use our 3D motion capture system to collect information about how your child moves while walking and running.
- **Muscle activity:** Your child will lie down while small areas of skin on their legs are shaved and cleaned with alcohol swabs. This may make their skin a little red and your child may experience mild skin irritation, but this should disappear after a couple of days. We need to do this to be able to collect a clear signal from the muscles. We will then attach surface electrodes over four muscles of the thigh and lower leg. These electrodes are like little sticky gel pads that will be attached to wireless transmitters to collect information about how the muscles are working while walking and running. The electrodes will not cause any type of sensation or stimulation to your child.
- **Ground reaction forces:** We will provide a pair of shoes for your child to wear during Sessions 2 and 3. We will insert insoles into these shoes that will tell us about the forces that your child is experiencing under their feet as they walk and run on the treadmill.
- **Energy expenditure:** We will assess how your child uses energy while resting (i.e. lying down), and during the walking and running activities by analysing the air that they breathe in and out. This just involves wearing a face mask that will go over your child's nose and mouth.
- **Heart rate:** Your child's heart rate will be monitored during each session, using a heart rate monitor that will be worn around their chest.
- **Perceptions of the exercise tasks:** Your child will be asked to rate how hard they think each exercise trial is and whether they perceive the activity to be pleasurable or not.
- **Video recording:** During testing sessions 2 and 3, we will need to collect video of your child performing the walking and running tasks. This data is not for marketing purposes, but will be used to help to identify when your child changes from walking to running and to help explain differences in motion when we are analysing the data. The video will not be displayed publicly and your child's identity will not be compromised.

<u>Testing sessions:</u>

Sessions will need to be completed at least 48 hours apart. Testing sessions can take place during school hours, which may result in your child missing up to 1.5–2 hours of school (including testing and travel time):

- If this is the case, they will be brought from their school and taken back to their school by an adult researcher involved in the study; transport could include walking or riding in a car.
- The driver will have police clearance, but if you feel uncomfortable having your child ride with a researcher, please note on the consent form that you will provide alternative transportation.
- Testing sessions will also be available after school and on the weekends to avoid missing school.

<u>Clothing requirements:</u>

Your child will need to wear a swimsuit or compression shorts during testing for sessions 2 and 3. Your child will also need to bring a pair of clean socks to wear for each testing session.

- This is important because the reflective markers need to be attached to the skin. Regular clothes that are not skin tight may hide the markers from the view of the cameras.
- Swimsuits and compression shorts will be provided in a range of different sizes, but your child can wear their own swimsuit or compression shorts if they prefer.
- The laboratory will be set up solely for the purpose of this study. There will be space for parents/guardians and other family members to sit during the testing. The researchers involved in the study will be the only other people present during testing. All testing will be completed by female researchers; a male researcher can be present when boys are being fitted with the electrodes and markers if you or your child would prefer.

What will happen to this information?

All of the information that the researchers collect will be kept on a computer. Your child's details and results will remain confidential, and their names will not be used at any time during the study. Only the researcher and supervisor will have access to the data. We may use the data that we collect in publications or during presentations, but no one will be able to tell which data is your child's. At the end of the project, a summary of findings can be sent at your request.

What is the next step?

If you have any questions, you can ask any member of the research team at any time.

If you have read and understood everything and you are happy for us to ask your child to take part, please sign the attached 'Consent Form' and complete the health and activity recruitment questionnaire. Details in the health screening questionnaire will help determine if your child is able to participate. Please ask your child if they would like to take part. If so, they will need to complete the 'Assent Form'.

Participant's Rights

Your child is under no obligation to accept this invitation. If you decide to allow your child to participate, your child has the right to:

- *decline to answer any particular question;*
- *withdraw from the study at any time (if you choose to withdraw you cannot withdraw your data from the analysis after the data collection has been completed);*
- *ask any questions about the study at any time during participation;*
- *provide information on the understanding that your name will not be used unless you give permission to the researcher;*
- *be given access to a summary of the project findings when it is concluded.*
- *request a summary of individual results*

Project Contacts

Stacey Kung (PhD student researcher)	Email:	s.kung@massey.ac.nz	
	Phone:	04 801 5799	ext 63905
Dr. Sarah Shultz (Primary supervisor)	Email:	s.p.shultz@massey.ac.nz	
	Phone:	04 801 5799	ext 63496

MUHEC APPLICATIONS

Committee Approval Statement

This project has been reviewed and approved by the Massey University Human Ethics Committee: Southern A, Application 15/62. If you have any concerns about the conduct of this research, please contact Mr Jeremy Hubbard, Chair, Massey University Human Ethics Committee: Southern A, telephone 04 801 5799 x 63487, email humanethicsoutha@massey.ac.nz.

Compensation for Injury

If physical injury results from your participation in this study, you should visit a treatment provider to make a claim to ACC as soon as possible. ACC cover and entitlements are not automatic and your claim will be assessed by ACC in accordance with the Accident Compensation Act 2001. If your claim is accepted, ACC must inform you of your entitlements, and must help you access those entitlements. Entitlements may include, but not be limited to, treatment costs, travel costs for rehabilitation, loss of earnings, and/or lump sum for permanent impairment. Compensation for mental trauma may also be included, but only if this is incurred as a result of physical injury.

If your ACC claim is not accepted you should immediately contact the researcher. The researcher will initiate processes to ensure you receive compensation equivalent to that to which you would have been entitled had ACC accepted your claim.

APPENDIX G: Consent Form for Children and Adolescents

Individuals aged 16 years and younger are considered to be children according to the Massey University Human Ethics Committee's *Code of Ethical Conduct for Research, Teaching and Evaluations Involving Human Participants*. As such, informed written assent and informed written parental consent were obtained for the participants who were 16 years or younger prior to them taking part in the study.

The following consent form includes both the participant assent and parental consent.

MASSEY UNIVERSITY
COLLEGE OF HEALTH
TE KURA HAUORA TANGATA

Factors affecting gait transitions from walking to running

PARTICIPANT AND PARENT/CAREGIVER CONSENT FORM

Please circle Y or N for your response below:

I have read and I understand the information sheet for volunteers taking part in the study designed to examine the joint movements and muscle activation patterns of the lower limbs and energy expenditure during a variety of walking and running tasks.	Y	N
I understand that it is my and my child's choice to participate in this study and he/she can withdraw at any time without giving any reason.	Y	N
I understand that my child's participation in this study is confidential and that no material that could identify my child will be used in any reports or presentation in this study.	Y	N
I understand that the exercise trials will be video-recorded for the purposes of identifying when my child transitions from walking to running and analysing differences in movement patterns. I also understand that this video will not be displayed publicly.	Y	N
I have had time to consider whether my child will take part in the study.	Y	N
I know who to contact if I have any questions about the study.	Y	N
I wish to have my child's results from the study given to me.	Y	N

- If you would like your child's results, please provide your email address:

  ____

Please choose <u>one</u> transportation option:

☐ I give permission for my child to leave school campus with the university researcher, and I understand that this could involve having my child ride in a car with a Massey University researcher.

☐ I will provide transportation to and from Massey University for my child.

Statement of Child Assent

Your parent or caregiver has allowed you to be part of this research project. By signing your name below, you understand:

- What you will be asked to do during each testing session;
- That you are free to ask any question at any stage during the testing;
- That you can stop being part of the study at any time, without giving any reason.

If you would like to be part of the project, please sign your name on the line below.

Name: ....

Signature: ____________________

Date ________ / ________ / ________

Parent/Caregiver Consent

By signing this form, I give consent for my child to participate in this study

Signature of Parent or Caregiver: ....Date:................................

Full Name (Printed):..

Witnessed by (name printed): ....

Witnessed by (signature): ....

APPENDIX H: Consent Form for Adults

Participants aged 17 years and older provided their own informed written consent prior to participating in the study. The following consent form was used for the participants old enough to provide their own informed consent.

MASSEY UNIVERSITY
COLLEGE OF HEALTH
TE KURA HAUORA TANGATA

Factors affecting gait transitions from walking to running

PARTICIPANT CONSENT FORM

Please circle Y or N for your response below:

I have read and I understand the information sheet for volunteers taking part in the study designed to examine the joint movements and muscle activation patterns of the lower limbs and energy expenditure during a variety of walking and running tasks.	Y	N
I understand that it is my choice to participate in this study and I can withdraw at any time without giving any reason.	Y	N
I understand that my participation in this study is confidential and that no material that could identify me will be used in any reports or presentation in this study.	Y	N
I understand that the exercise trials will be video-recorded for the purposes of identifying when I transition from walking to running and analysing differences in movement patterns. I also understand that this video will not be displayed publicly.	Y	N
I have had time to consider whether I will take part in the study.	Y	N
I know who to contact if I have any questions about the study.	Y	N
I wish to have my results from the study given to me.	Y	N

- If you would like your results, please provide your email address:

  ____

Participant Consent

By signing this form, I give my consent to participate in this study

Signature of Participant:..Date:...............................

Full Name (Printed):..

Witnessed by (name printed): ....

Witnessed by (signature): ....

APPENDIX I: Recruitment Flyer

This appendix presents the final recruitment flyer used to recruit participants across the entire age range assessed for this thesis.

MASSEY UNIVERSITY
TE KUNENGA KI PŪREHUROA
UNIVERSITY OF NEW ZEALAND

Come learn more about your gait!

There's currently an exciting opportunity for you to try 3D motion capture and learn about how your body works during treadmill exercise at Massey University's School of Sport and Exercise!

We're looking for 10 – 30 year olds. The study will be carried out on the Wellington campus and involves 3 visits, each session lasting approximately 2 – 3 hours (up to 7 hours for all 3 sessions).

Participants will receive $30 worth of vouchers for their time!

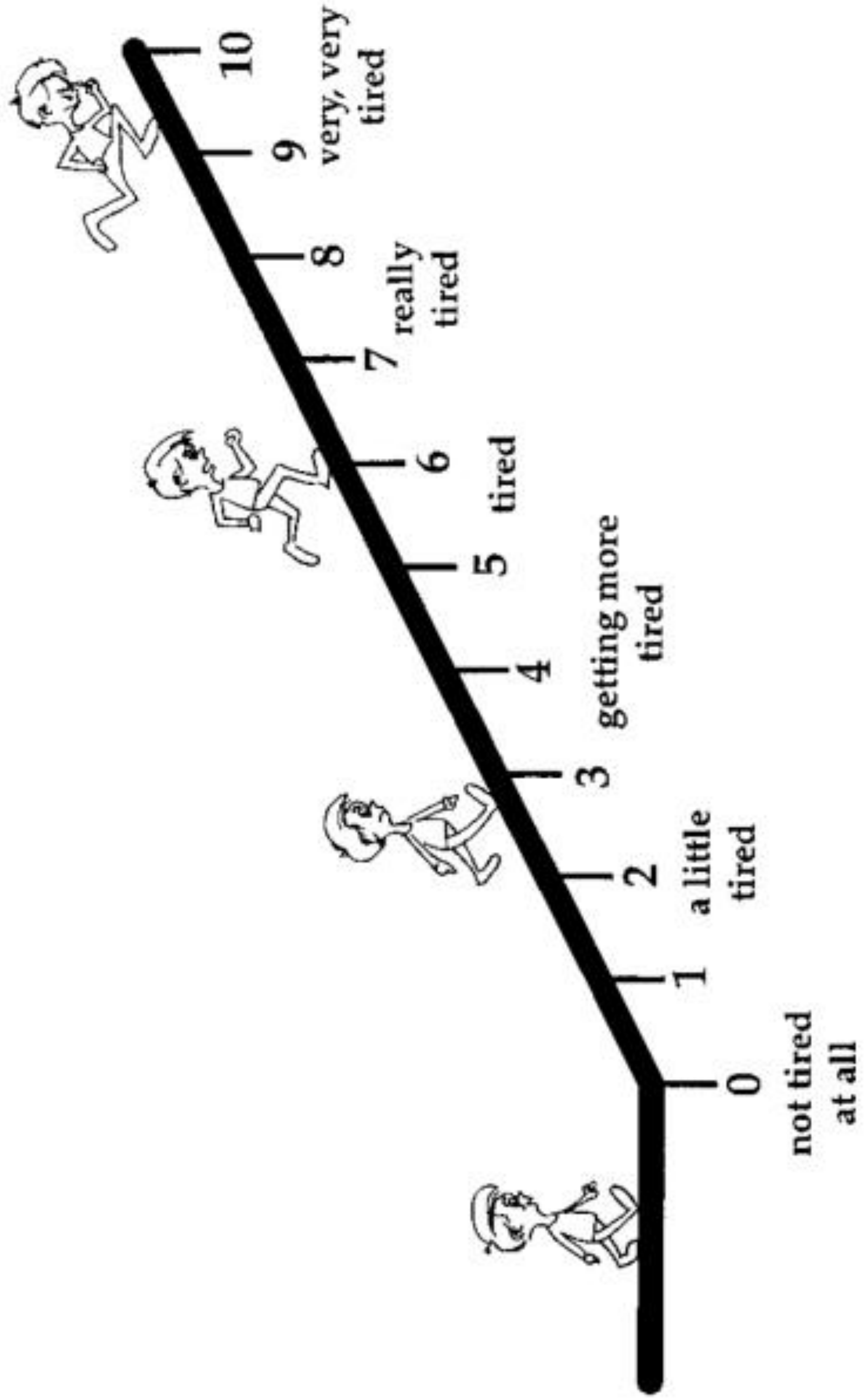
For more information, please contact Stacey Kung and ask about the 'Gait Transition' study.

Email: s.kung@massey.ac.nz

This project has been reviewed and approved by the Massey University Human Ethics Committee: Southern A, Application 15/62. If you have any concerns about the conduct of this research, please contact Mr Jeremy Hubbard, Chair, Massey University Human Ethics Committee: Southern A, telephone 04 801 5799 x 63487, email humanethicsoutha@massey.ac.nz

APPENDIX J: OMNI-RPE Scale

This appendix presents the OMNI-RPE Scale used for the study presented in Chapter 5.



Utter, A. C., Robertson, R. J., Nieman, D. C., & Kang, J. (2002). Children's OMNI scale of perceived exertion: Walking/running evaluation. *Medicine and Science in Sports and Exercise*, *34*(1), 139-144. doi: 10.1097/00005768-200201000-00021

APPENDIX K: Statements of Contribution

This appendix presents the Statements of Contribution (DRC16 form) for each of the chapters that were prepared as manuscripts for publication (i.e. Chapters 2-5).

Chapter 2

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. doi: 10.1016/j.humov.2017.10.02

DRC 16

MASSEY UNIVERSITY
GRADUATE RESEARCH SCHOOL

STATEMENT OF CONTRIBUTION
DOCTORATE WITH PUBLICATIONS/MANUSCRIPTS

We, the candidate and the candidate's Primary Supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the candidate's contribution as indicated below in the *Statement of Originality*.

Name of candidate:	Stacey Kung
Name/title of Primary Supervisor:	Dr Philip Fink
Name of Research Output and full reference:	
Kung SM, Fink PW, Legg SJ, Ali A, Shultz SP. What factors determine the preferred gait transition speed in humans? A review of the triggering mechanisms. Hum Mov Sci. 2018;57:1-12.	
In which Chapter is the Manuscript /Published work:	Chapter 2
Please indicate:	
• The percentage of the manuscript/Published Work that was contributed by the candidate:	80%
and	
• Describe the contribution that the candidate has made to the Manuscript/Published Work:	
Conducted the review of the literature; planning the structure of the review and drafting the manuscript as first/corresponding author	
For manuscripts intended for publication please indicate target journal:	
Human Movement Science (published: 2018; Impact factor: 1.928)	
Candidate's Signature:	Stacey Kung Digitally signed by Stacey Kung Date: 2019.10.25 15:28:57 +13'00'
Date:	25/10/2019
Primary Supervisor's Signature:	Philip Fink Digitally signed by Philip Fink Date: 2019.10.25 13:11:31 +13'00'
Date:	25/10/2019

(This form should appear at the end of each thesis chapter/section/appendix submitted as a manuscript/ publication or collected as an appendix at the end of the thesis)

GRS Version 4– January 2019

Chapter 3

Kung, S. M., Fink, P. W., Legg, S. J., Ali, A., & Shultz, S. P. (2019). Age-dependent variability in spatio-temporal gait parameters and the walk-to-run transition. *Human Movement Science*, *66*, 600-606.
doi: 10.1016/j.humov.2019.06.012

DRC 16

MASSEY UNIVERSITY
GRADUATE RESEARCH SCHOOL

STATEMENT OF CONTRIBUTION
DOCTORATE WITH PUBLICATIONS/MANUSCRIPTS

We, the candidate and the candidate's Primary Supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the candidate's contribution as indicated below in the *Statement of Originality*.

Name of candidate:	Stacey Kung
Name/title of Primary Supervisor:	Dr Philip Fink
Name of Research Output and full reference:	
Kung SM, Fink PW, Legg SJ, Ali A, Shultz SP. Age-dependent variability in spatiotemporal gait parameters and the walk-to-run transition. Hum Mov Sci. 2019;66:600-6.	
In which Chapter is the Manuscript /Published work:	Chapter 3
Please indicate:	
• The percentage of the manuscript/Published Work that was contributed by the candidate:	80%
and	
• Describe the contribution that the candidate has made to the Manuscript/Published Work:	
Involved in designing the study; recruited participants; conducted research; processed and analysed data; statistical analysis; interpretation of results; drafted manuscript as first/corresponding author	
For manuscripts intended for publication please indicate target journal:	
Human Movement Science (published: 2019; Impact factor: 1.928)	
Candidate's Signature:	Stacey Kung Digitally signed by Stacey Kung Date: 2019.10.25 15:29:36 +13'00'
Date:	25/10/2019
Primary Supervisor's Signature:	Philip Fink Digitally signed by Philip Fink Date: 2019.10.25 13:10:59 +13'00'
Date:	25/10/2019

(This form should appear at the end of each thesis chapter/section/appendix submitted as a manuscript/ publication or collected as an appendix at the end of the thesis)

GRS Version 4– January 2019

Chapter 4

Kung, S. M., Fink, P. W., Legg, S. J., Ali, A., & Shultz, S. P. Age-related differences in muscular and physiological variables during the walk-to-run transition: Application of the weakest link principle. *Journal of Biomechanics (under review)*.

DRC 16

MASSEY UNIVERSITY
GRADUATE RESEARCH SCHOOL

STATEMENT OF CONTRIBUTION
DOCTORATE WITH PUBLICATIONS/MANUSCRIPTS

We, the candidate and the candidate's Primary Supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the candidate's contribution as indicated below in the *Statement of Originality*.

Name of candidate:	Stacey Kung
Name/title of Primary Supervisor:	Dr Philip Fink
Name of Research Output and full reference:	
Kung SM, Fink PW, Legg SJ, Ali A, Shultz SP. Age-related differences in muscular and physiological variables during the walk-to-run transition: Application of the weakest link principle. J Biomech (in review)	
In which Chapter is the Manuscript /Published work:	Chapter 4
Please indicate:	
• The percentage of the manuscript/Published Work that was contributed by the candidate:	80%
and	
• Describe the contribution that the candidate has made to the Manuscript/Published Work:	
Involved in designing the study; recruited participants; conducted research; processed and analysed data; statistical analysis; interpretation of results; drafted manuscript as first/corresponding author	
For manuscripts intended for publication please indicate target journal:	
Journal of Biomechanics (Submitted: 2019; Impact factor: 2.576)	
Candidate's Signature:	Stacey Kung Digitally signed by Stacey Kung Date: 2019.10.25 15:30:38 +13'00'
Date:	25/10/2019
Primary Supervisor's Signature:	Philip Fink Digitally signed by Philip Fink Date: 2019.10.25 13:10:19 +13'00'
Date:	25/10/2019

(This form should appear at the end of each thesis chapter/section/appendix submitted as a manuscript/ publication or collected as an appendix at the end of the thesis)

GRS Version 4– January 2019

Chapter 5

Kung, S. M., Fink, P. W., Legg, S. J., Ali, A., & Shultz, S. P. Age-related differences in perceived exertion while walking and running near the preferred transition speed. *Pediatric Exercise Science (under review)*.

DRC 16

MASSEY UNIVERSITY
GRADUATE RESEARCH SCHOOL

STATEMENT OF CONTRIBUTION
DOCTORATE WITH PUBLICATIONS/MANUSCRIPTS

We, the candidate and the candidate's Primary Supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the candidate's contribution as indicated below in the *Statement of Originality*.

Name of candidate:	Stacey Kung
Name/title of Primary Supervisor:	Dr Philip Fink
Name of Research Output and full reference:	
Kung SM, Fink PW, Legg SJ, Ali A, Shultz SP. Age-related differences in perceived exertion while walking and running near the preferred transition speed. Pediatr Exerc Sci (in review)	
In which Chapter is the Manuscript /Published work:	Chapter 5
Please indicate:	
• The percentage of the manuscript/Published Work that was contributed by the candidate:	80%
and	
• Describe the contribution that the candidate has made to the Manuscript/Published Work:	
Involved in designing the study; recruited participants; conducted research; processed and analysed data; statistical analysis; interpretation of results; drafted manuscript as first/corresponding author	
For manuscripts intended for publication please indicate target journal:	
Pediatric Exercise Science (Submitted: 2019; Impact factor: 1.707)	
Candidate's Signature:	Stacey Kung Digitally signed by Stacey Kung Date: 2019.10.25 15:29:53 +13'00'
Date:	25/10/2019
Primary Supervisor's Signature:	Philip Fink Digitally signed by Philip Fink Date: 2019.10.25 13:09:38 +13'00'
Date:	25/10/2019

(This form should appear at the end of each thesis chapter/section/appendix submitted as a manuscript/ publication or collected as an appendix at the end of the thesis)

GRS Version 4– January 2019

APPENDIX L: Publications

Published

Chapter 2:

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.

Available online: https://doi.org/10.1016/j.humov.2017.10.023

Chapter 3:

Kung, S. M., Fink, P. W., Legg, S. J., Ali, A., & Shultz, S. P. (2019). Age-dependent variability in spatiotemporal gait parameters and the walk-to-run transition. *Human Movement Science*, *66*, 600-606.

Available online with supplementary tables: https://doi.org/10.1016/j.humov.2019.06.012

Submitted

Chapter 4:

Kung, S. M., Fink, P. W., Legg, S. J., Ali, A., & Shultz, S. P. Age-related differences in muscular and physiological variables during the walk-to-run transition: Application of the weakest link principle. *Journal of Biomechanics (under review).*

Submitted: September 10, 2019.

Chapter 5:

Kung, S. M., Fink, P. W., Legg, S. J., Ali, A., & Shultz, S. P. Age-related differences in perceived exertion while walking and running near the preferred transition speed. *Pediatric Exercise Science (under review).*

Submitted: November 5, 2019.

APPENDIX M: Conference Abstracts

Conference Abstracts

Kung SM, Fink PW, Legg SJ, Ali A, Shultz SP. (2017). Spatiotemporal variability of children's gait during walk-to-run transitions. 41st Annual Meeting of the American Society of Biomechanics. Boulder, CO, USA. [Poster Presentation].

Kung SM, Fink PW, Legg SJ, Ali A, Shultz SP. (2019). Gait Variability and Control During the Walk-To-Run Transition in Adolescents. XXVII Congress of the International Society of Biomechanics/43rd Annual Meeting of the American Society of Biomechanics. Calgary, AB, Canada. [Oral Presentation].

Kung et al. (2017).

SPATIOTEMPORAL VARIABILITY OF CHILDREN'S GAIT DURING WALK-TO-RUN TRANSITIONS

[1] Stacey Kung, [1] Philip Fink, [1] Stephen Legg, [1] Ajmol Ali, [1] Sarah Shultz

[1] Massey University, Wellington, New Zealand
email: s.kung@massey.ac.nz

INTRODUCTION

Human gait transitions tend to reflect the optimization of gait patterns with changes in task constraints, including the speed of locomotion. As the speed of locomotion changes, adults often choose the more stable and energy efficient gait. Specifically, when walking speeds approach the preferred transition speed (PTS), stride duration variability has previously been shown to increase in adults, which subsequently stabilizes following the walk-to-run transition (WRT) [1]. However, it is unknown whether these self-optimizing tendencies during gait are also present during childhood. Therefore, this study aimed to identify whether children also use the WRT to help stabilize spatiotemporal parameters during gait.

METHODS

Eleven healthy children (8 females, 3 males; Table 1) completed 2 sessions after written informed assent and parental consent was sought. Participants were first familiarized with the treadmill by walking and running at self-selected speeds for 15 minutes each, followed by three practice transition trials. Session 2 involved a stepped treadmill protocol that started at a self-selected walking pace and the treadmill speed increased by 0.2 $km \cdot h^{-1}$ every 30 seconds until the participant reached a treadmill speed that was 1.0 $km \cdot h^{-1}$ faster than the participants' PTS; the speed was then increased by 0.5 $km \cdot h^{-1}$ until volitional exhaustion. Participants were instructed to start running at the speed that felt most comfortable. The PTS was defined as the speed at which the participant stopped transitioning between walking and running.

Three-dimensional kinematic data were collected at each speed during the stepped treadmill protocol. Step frequency (Hz) and step length (m) for the left and right legs were calculated for 10 strides at 10 different treadmill speeds, including the participants' self-selected walking speed, five speeds prior to the PTS (i.e. PTS-1.0 $km \cdot h^{-1}$, PTS-0.8 $km \cdot h^{-1}$, PTS-0.6 $km \cdot h^{-1}$, PTS-0.4 $km \cdot h^{-1}$, PTS-0.2 $km \cdot h^{-1}$), the PTS, two speeds following the PTS (i.e. PTS+0.2 $km \cdot h^{-1}$, PTS+0.4 $km \cdot h^{-1}$) and a standardized running speed that was 3.0 $km \cdot h^{-1}$ faster than the PTS (i.e. PTS+3.0 $km \cdot h^{-1}$).

Table 1: Participants' characteristics and preferred walking (PWS) and transition (PTS) speeds.

	Mean ± SD	Range
Age (years)	11.55 ± 0.93	10 – 13
Height (m)	1.55 ± 0.08	1.45 – 1.69
Weight (kg)	47.12 ± 10.36	32.00 – 67.86
PWS ($km \cdot h^{-1}$)	3.8 ± 0.5	3.0 – 4.8
PTS ($km \cdot h^{-1}$)	6.6 ± 0.7	4.9 – 7.7

Standard deviations (SD) of the left and right step frequencies and step lengths were calculated. One-way analyses of variance with repeated measures for speed were used to analyze the effect of speed on the variability of the step frequencies and step lengths. Where significant effects of speed ($p<0.05$) were found, post-hoc least significant difference (LSD) pairwise comparisons were used to identify the specific relationships ($p<0.05$).

RESULTS AND DISCUSSION

There were significant speed effects on the left step frequency ($F_{(9, 90)}=3.778$, $p<0.001$), right step frequency ($F_{(9, 90)}=5.534$, $p<0.001$), left step length ($F_{(9, 90)}=2.459$, $p=0.015$) and right step length ($F_{(9, 90)}=3.952$, $p<0.001$).

When analyzing the walking and running speeds separately, there were generally no significant differences in the amount of variability of the step frequencies within each mode of gait, irrespective of the speeds, with the exception of walking at PTS-0.8 km·h^{-1}. Yet, there is a clear distinction in the variability of step frequencies between the participants' walking and running gaits (Fig. 1). Specifically, the variability of the step frequencies was significantly different between walking and running, suggesting that each mode of gait was associated with different spatiotemporal characteristics during treadmill locomotion.

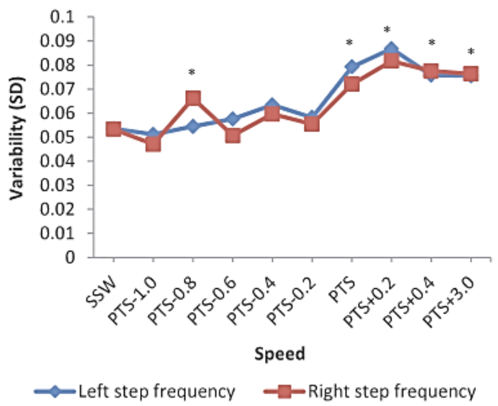


Figure 1: Mean variability (standard deviations, SD) of the left and right step frequencies (Hz). Self-selected walking speed, SSW; Preferred transition speed, PTS. * Significantly different than SSW for step frequency in both limbs.

Interestingly, the participants exhibited a greater amount of spatiotemporal variability following the WRT, which is in contrast to what was observed in adults [1]. Walking may have been the more stable gait pattern in children as it is the more frequently used mode of gait. Additionally, children may have more experience walking at speeds that are faster than preferred if they often walk alongside their parents or other adults, thus contributing to a more stable walking pattern.

Given that there was more spatiotemporal variability during running, the development of a mature, consistent running gait pattern may occur later in children, when compared to walking. Musculoskeletal development during childhood could be an influencing factor, as limb length is not yet fixed. Therefore, the optimal combination of step length and step frequency may still be subject to change during this period of growth and development, hence the greater variability observed during children's gait transitions compared to adults.

Differences between the inverted pendulum mechanics of walking and the spring-mass mechanics of running may have also contributed to the differences observed between the spatiotemporal variability of walking and running. As the center of mass vaults over a somewhat fixed limb length during walking, step length variability is more limited compared to running where the use of a flight phase could increase variability. To this point, the step length variability was the greatest at the standardized running speed, whereas the self-selected walking speed elicited the least amount of step length variability.

It has been previously observed that slow running is less stable than fast walking [2], which would help explain the initial increase in the step frequency variability following the WRT and the subsequent plateau as the running speed continued to increase towards the preferred running speeds.

CONCLUSIONS

A lack of stability in 10–13 year old children's spatiotemporal parameters following the walk-to-run transition suggests their running gait patterns may not yet be mature, which could affect their ability to optimize the efficiency and stability of their gait patterns as the speed of locomotion changes.

REFERENCES

1. Brisswalter J & Mottet D. *Can J Appl Physiol* **21**, 471-480, 1996.
2. Jordan K, et al. *Hum Mov Sci* **28**, 113-128, 2009.

ACKNOWLEDGMENTS

Anja Fricke for her help with data collection.

Kung et al. (2019).

Gait Variability and Control During the Walk-To-Run Transition in Adolescents

Stacey M. Kung[1], Philip W. Fink[1], Stephen J. Legg[1], Ajmol Ali[1], Sarah P. Shultz[2,1]
[1]School of Sport, Exercise & Nutrition, Massey University, Wellington, New Zealand
[2]Department of Kinesiology, Seattle University, Seattle, WA, United States of America
Email: s.kung@massey.ac.nz

Summary

Age-related differences in stride length variability during an incremental walk-to-run transition (WRT) treadmill protocol revealed that walking may only mature by 13 years old and running may not mature until 15 years old. When analysing how gait patterns are regulated in response to increasing gait speed, it was shown that 10-13-year-olds lack the ability to swiftly adapt their gait patterns to changing task demands. Ongoing neuromuscular development and calibration of the control mechanisms of gait may limit the rate of gait maturation. The present results support that gait patterns have not matured before adolescence.

Introduction

Greater variability in children's and adolescent's walking [1] and running [2] patterns compared to adults has suggested that the development of mature gait patterns continues through adolescence. In addition to spatiotemporal variability, the ability to adjust gait patterns to changing task demands, such as gait speed, may also be important for determining whether gait is mature. Therefore, the purpose of this study was to compare stride length variability, preferred transition speed (PTS) and how efficiently PTS was identified during the WRT between adolescents and young adults to determine whether gait patterns and gait control has matured in adolescents.

Methods

Forty-six adolescents (10-17 years; n=5-6; Table 1) and 12 adults completed an incrementally ramped treadmill test (+0.2 km·h⁻¹ every 30 s) to determine PTS. After 5 speed increments following the final speed at which a WRT occurred (i.e. PTS), the increments increased to +0.5 km·h⁻¹ every 30 s until peak exertion. 3D kinematic data were collected at each speed. Stride lengths at a self-selected walking speed, the PTS, PTS±0.2 km·h⁻¹, PTS±0.4 km·h⁻¹, PTS±0.6 km·h⁻¹, PTS±0.8 km·h⁻¹, PTS±1.0 km·h⁻¹, and PTS+3.0 km·h⁻¹ were calculated.

Table 1: Participant characteristics and preferred transition speed.

Age	Height (m)	Mass (kg)	Leg length (m)	PTS (m·s^{-1})
10	1.44±0.02	34.8±4.3	0.77 ± 0.02	1.84±0.16
11	1.51±0.03	40.9±3.1	0.80 ± 0.01	1.93±0.11
12	1.58±0.04*	51.2±9.2*	0.85 ± 0.03	1.76±0.20
13	1.63±0.06*	46.8±7.1	0.87 ± 0.03*	2.07 ± 0.11‡
14	1.64±0.11*	49.4±10.2	0.86 ± 0.07*	1.90 ± 0.18
15	1.73±0.03*†‡	57.4±4.2*	0.91±0.03*†	2.16 ± 0.18*‡
16	1.64±0.09 *	54.6±11.3 *	0.85 ± 0.05	1.92 ± 0.16
17	1.71±0.09*†	62.6±7.7*†◊	0.90±0.04*†	1.94 ± 0.11
19-29	1.71±0.10*†‡	62.6±10.5*†◊	0.88±0.06*†	1.98 ± 0.18

Significant differences compared to the * 10 year olds; † 11 year olds; ‡ 12 year olds; and ◊ 13 year olds ($p<0.05$).

Coefficients of variation were calculated for the stride lengths and compared between the adolescent age groups and adults using a repeated measures ANOVA ($p<0.05$). The numbers of gait transitions observed and speeds at which a gait transition occurred were counted and averaged for each age group.

Results and Discussion

Significant differences were seen in stride length variability between the 10-14-year olds and young adults ($p<0.05$). 10-12-year-olds exhibited more variability across all walking and running speeds. 13-14-year-olds only exhibited differences in variability while running at speeds near PTS, while no differences were seen at PTS+3.0 km·h⁻¹. As the gait patterns at typical walking and running speeds resembled adult-like gait at an earlier age than at less typical speeds near PTS, past experiences may help calibrate the mechanisms controlling gait to improve the consistency of gait patterns.

While PTS did not differ between any of the adolescent groups and the young adults, differences were seen in how PTS was identified (Figure 1). 10-14-year-olds tended to experiment across a larger range of speeds to try identify their PTS, whereas the 15-17-year-olds and young adults were generally able to identify their PTS with one gait transition at a single speed during the treadmill test.

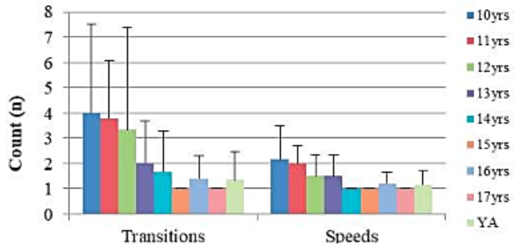


Figure 1: Counts of the gait transitions and speeds at which gait transitions occurred for each age group. YA: young adults.

Conclusions

The development of mature walking and running patterns occurs in progressive stages during adolescence, with walking maturing earlier than running. The ability to efficiently adapt gait patterns to changes in gait speed also continues to develop through to mid-adolescence. Therefore, the control mechanisms of gait are unlikely to have matured until late-adolescence and mature gait patterns may only emerge once neuromusculoskeletal development is complete.

References

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