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CADENCE AS AN INDICATOR OF THE WALK-TO-RUN TRANSITION

A Thesis Presented

by

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ABSTRACT

CADENCE AS AN INDICATOR OF THE WALK-TO-RUN TRANSITION

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Humans naturally select a point at which to transition from walking to running when gradually increasing locomotor speed. This point is known as the walk-to-run transition (WRT). The WRT is traditionally expressed in terms of speed and is known to occur within a close range of 2.1 m/s, which is an accepted heuristic (i.e., empirically based, rounded) threshold value. Very little research exists defining the WRT in terms of cadence (steps/min) despite the fact that spatial temporal aspects of gait underlying the WRT include this parameter. Preliminary evidence suggests that the WRT may be associated with a cadence of 140 steps/min in adults. This overlooked approach to identifying the WRT may be better than speed because of the simplicity and accessibility of recording cadence in both lab- and free-living settings. Wearable technologies can be used to determine cadence in real-time in a variety of settings, and could be used in the future to expand our current knowledge of the WRT. In turn, this knowledge could be used to inform training practices and/or rehabilitation of gait disorders. The purposes of this secondary analysis of an existing treadmill-based data set were to: (1) identify the

optimal WRT cadence threshold, and (2) compare the accuracy of the cadence cutpoint to the previous WRT indicators identified in literature (i.e., speed and Froude number). This secondary analysis focused only on the data collected from the 28 participants (20 men, 8 women) whose protocol was terminated due to selecting to run during the treadmill portion of the larger CADENCE-Adults study. The CADENCE-Adults protocol consisted of a series of five-minute bouts beginning at 0.2 m/s and increasing in 0.2 m/s increments, with each bout followed by two minutes of standing rest. Participants could choose to walk or run each bout. The cadence of the bout during which the participants chose to run was considered the WTR cadence, and ROC analyses were performed to determine the optimal cadence cutpoint. Sensitivity, specificity and overall accuracy were calculated to compare the accuracy of the speed and Froude values from literature to the calculated cadence cutpoint. In addition, these analyses were expanded *post hoc* to also examine the accuracy of the previously proposed cadence cutpoint from the literature and the speed and Froude cutpoint identified from the dataset. Following analyses, three cadence cutpoints (134, 139, or 141 steps/min) were identified that shared equal overall accuracy (92.9%); therefore, there was no single optimal cutpoint. This also occurred for the speed cutpoints, where both 1.9 and 2.0 m/s shared overall accuracies of 78.6%. The optimal Froude cutpoint identified was 0.46 (82.0% overall accuracy). The rank-order overall accuracy of previously identified cutpoints were: a cadence of 140 steps/min (91.1%), Froude number of 0.5 (76.8%) and speed of 2.1 m/s (66.1%). Based on the identified optimal cadence cutpoints, a heuristic range of running cutpoints was recommended anchored on specificity vs. sensitivity preferences. For researchers interested in identifying episodes more likely to be running behavior (with the preference

that very few episodes of walking behavior are mistakenly identified), it would be best to use 140 steps/min. However, if they want to be as inclusive as possible in identifying episodes of running behavior (and can tolerate more mistakenly identified episodes walking behavior), they could use 135 steps/min. When applied to this dataset, 96.0% (24/25) of the individuals who were ≥ 140 steps/min were running, but this decreased to 92.5% (25/27) with ≥ 135 steps/min. In conclusion, cadence clearly performed much better in terms of overall accuracy when compared to traditionally used WRT indicators of speed and Froude numbers. The recommended heuristics cadence cutpoint range can be used by researchers who want to evaluate the locomotor patterns of individuals when analyzing free-living step-defined data collected using wearable device.

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LIST OF ABBREVIATIONS

WRT – Walk-to-Run Transition

BMI – Body Mass Index

RPE – Rate of Perceived Exertion

Steps/min – Steps per Minute

m/s – Meters per Second

kg – Kilogram

ROC – Receiver Operating Characteristics

MET – Metabolic Equivalent

CHAPTER 1

INTRODUCTION

Bipedal human locomotion can be classified as either walking or running. Walking is generally performed at lower speeds (0.0 – 2.1m/s) and running at higher speeds (≥ 2.1 m/s).^{1,2} Walking speed is a function of step length and cadence (steps/min). As individuals take longer step lengths and perform at higher cadences they naturally select to transition from walking to running. This point is known as the walk-to-run transition (WRT). The WRT is traditionally measured in terms of speed (m/s) and occurs at approximately 2.1 m/s.^{1,2} An alternative form of measurement is converting the WRT speed to a dimensionless Froude number, which is calculated using the following equation: $Fr = v/(gd)^{1/2}$, where v = walking velocity, g =gravity, and d =leg length. The Froude number is used to take into consideration leg length. The accepted WRT Froude number is 0.5.

The WRT is not yet fully understood, and furthering the current knowledge of this important aspect of human gait could inform training strategies and/or rehabilitation of human locomotive function. Furthering this knowledge of human locomotion can occur through studying gait and stepping patterns including the WRT. The recent widespread explosion of wearable technologies focused on step counting, and more particularly, cadence (steps/min) tracking,³ opens the door for researchers and practitioners to consider cadence as an alternative and potentially improved metric for defining the WRT.

Step counting has a storied history as a useful measurement approach. Early use of step counting is evident from ancient Romans' desire to quantify distance, especially for military purposes.^{4,5} This strategy made natural sense at a time when walking was the

most common mode of transportation and body parts were commonly used as lengths of measure.⁵ In fact, the word ‘mile’ has Latin origins in the phrase *milia passuum*, meaning ‘one thousand paces’.⁵ Subsequently, Leonardo da Vinci invented the first mechanical step counter during the late 1400s, Thomas Jefferson commissioned a step counter to measure the steps between famous Paris landmarks (and sent one to James Madison in the U.S.) during the late 1700s, and in 1820 the Tsar of Russia had a pedometer designed by a Swiss watch-maker.⁵ In the 1960s Japanese researchers began to use step counting devices to assess physical activity, and in 1965 the ‘10,000 steps a day’ motto was associated with a specific pedometer brand developed in Japan.⁴ At the time, the popular recommendation for 10,000 steps/day was believed to be the dose of walking necessary to reduce risk of coronary heart disease.⁵ The first English-language scientific article advocating 10,000 steps/day was published in 1995.⁶ Objective physical activity assessment and self-tracking using various types of pedometers and accelerometers subsequently took off in the mid-1990s, cemented in part by a landmark original research article published in 2000 and led by Dr. David Bassett that focused on the validity of pedometers and popularized the use of the Japanese-manufactured Yamax brands.⁴

In 2001 Tudor-Locke and Myers⁷ published a review article discussing opportunities and challenges for measuring physical activity in sedentary adults. The article explored how accelerometers and pedometers did not have the same potential for bias (i.e., misreporting values due to the desire to appear more active) and recall error (i.e., misreporting values due to inaccurate memory) as associated with the traditional method of self-reporting physical activity. Researchers began exploring the potential for using step counting as a novel approach to physical activity intervention.⁷⁻⁹ Such physical

activity interventions aim to change (i.e., increase) current deficient behavior, sometimes targeting specific populations (e.g., children, older adults, etc.) or locations (e.g., schools, the workplace, etc.). Step counting is popular in contemporary physical activity interventions because it is simple to incorporate using wearable technologies and the metric itself is intuitive to understand. Specifically, wearable technologies intended for consumers, including pedometers or fitness watches, are often used to track steps because they are designed to sense small changes in force with ambulation (i.e., a step). This makes the step an easy unit of measurement for assessing physical activity levels, and interventions can use daily 'step goals' to motivate increased physical activity.³

One example of a pioneer pedometer-based physical activity intervention was the First Step program published by Tudor-Locke¹⁰ in the early 2000s. The First Step program was an intervention which consisted of a 4-week adoption phase followed by a 12-week adherence phase. During the adoption phase, the intervention participants used a pedometer to record their number of steps each day. During this phase, they also had weekly group meetings to discuss their behaviors, success strategies, goals and relapse prevention, as well as walk as a group. During the adherence phase, individuals continued with their self-recording without the support from the program or meetings. This intervention was effective at increasing physical activity (+3700 steps/day) and became one of many pedometer-based physical activity interventions that emerged in the early 2000s.^{8,9,11}

As interest in step-based research continued to expand, Tudor-Locke et al.¹² asserted that achieving a minimum of 7,000 – 8,000 steps/day might be sufficient to meet the public-health guidelines for 30-minutes of moderate-to-vigorous physical activity per

day.¹² Additionally, <5,000 steps/day was suggested as a sedentary lifestyle index and linked to negative body composition and cardiometabolic risk.¹³ For example, a review of studies examining a step-defined sedentary index reported that reducing the daily physical activity of healthy active young adults from >10,000 steps/day to <5,000 steps/day demonstrated acute effects on adiposity, insulin sensitivity, and glycemic control.¹³ As other steps/day indices emerged, several studies examined the relationship between steps/day and various health outcomes, including body mass index (BMI), weight, blood pressure, and cardiometabolic risk factors.^{5,9} For example, a systematic literature review by Bravata et. al⁹ identified 26 articles with a total of 2767 participants that described how multiple controlled pedometer-based interventions demonstrated decreased BMI (-0.4, 95% CI, 0.05 – 0.72, P = .03), decreased systolic blood pressure (-3.8 mmHG, 95% CI, 1.7 – 5.9 mmHG, P < 0.001), and increased physical activity levels (+2183 (+26.9%) steps/day, 95% CI, 1571 – 2796 steps per day, P < 0.0001). Another review by Kang et al.¹¹ examined 32 studies and reported that use of pedometers had a moderate and positive effect on increasing physical activity levels in pedometer intervention studies (+2000 steps/day). A third review by Richardson et al.⁸ examined 9 studies (total participants = 307) and determined that pedometer-based interventions led to weight loss (0.05 kg/week), and that the longer interventions were associated with greater weight loss. These three early reviews sent a clear message that pedometer-based interventions could produce quantifiable increases in step-defined physical activity and a wide variety of associated health benefits.

While evidence accumulated on the positive health outcomes related to increasing volume of steps/day, little attention was paid to understanding the effect of intensity of

the steps taken. It is important to understand physical activity intensity because the national guidelines for adults recommend achieving a minimum of 150 minutes/week of *moderate intensity* physical activity.¹⁴ Absolutely defined moderate intensity physical activity is that which is performed at 3 METs (metabolic equivalents).¹⁵ A single MET is equivalent to the amount of oxygen consumed per kilogram of body weight per minute (ml/kg/min). A single MET is the oxygen cost of sitting still, and is approximately equivalent to 3.5 ml/kg/min. Exercising at 3 METs is 3 times the intensity of sitting still, or approximately 10.5 ml/kg/min.

Recently, researchers have sought to develop a reasonable heuristic cadence value corresponding to absolutely defined moderate intensity physical activity.¹⁶⁻¹⁸ A heuristic value is a 'rule of thumb' value which is determined from empirical research but rounded to allow for easier communication and education. A heuristic cadence value can be supported because it is easily measured using a criterion standard (i.e., most accurate method), specifically, manually hand-counting observed steps. Several studies have demonstrated that the heuristic threshold value for cadence that corresponds to absolutely defined moderate intensity physical activity (or 3 METs) is 100 steps/min.¹⁶⁻¹⁸ In one such study, Tudor-Locke et al.¹⁶ asked 76 healthy adult participants (male = 50%, ages = 30.4 ± 5.8 years) to complete incrementally-accelerating treadmill walking bouts. Participants' metabolic data (METs) were collected using an Oxycon (a portable device that measures oxygen or metabolic cost of exercise) and cadence was directly observed and hand-counted. The optimal cadence threshold for moderate-intensity physical activity (100 steps/min) was identified using a segmented regression model with random coefficients, as well as Receiver Operating Characteristic (ROC) models. Since cadence

has a strong correlation with intensity,¹⁶ there is a potential for using cadence to also indicate the WRT.

1.1 Purpose of Study

The purpose of this secondary analyses is to: (1) identify the optimal WRT cadence cutpoint value from a dataset of healthy adults (average age 36.6 ± 12.8 years, range 21 – 60 years old) who completed a WRT treadmill protocol, and (2) examine whether the identified cadence cutpoint value has higher specificity, sensitivity and overall accuracy for predicting the WRT compared with a speed of 2.1m/sec or a Froude number of 0.5.

1.2 Aims and Hypotheses

Aim 1: Identify the optimal WRT cadence cutpoint value from a dataset of young, healthy adults who completed a WRT treadmill protocol.

H₁: As per previous research,¹⁹ the identified cadence WRT cutpoint value will be 140 steps/min.

Aim 2: To examine whether the identified WRT cadence cutpoint value is a similar indicator (i.e., similar sensitivity, specificity and overall accuracy) of the WRT than a speed of 2.1m/sec^{1,2} or a Froude number of 0.5^{2,20,21} calculated from the same data. These alternative metrics will be discussed in more detail below.

H₁: The identified WRT cadence cutpoint will have a similar specificity, sensitivity and overall accuracy for predicting the WRT than a speed of 2.1m/sec^{1,2} or a Froude number of 0.5^{2,20,21}.

CHAPTER 2

LITERATURE REVIEW

A systematic review of the original research directly relevant to the WRT is presented below. The dual purposes of the systematic literature review were to: (1) provide a general overview of the WRT by summarizing previous original research studies that have examined the WRT, and (2) review the proposed causes of the WRT. This section discusses the methods and findings of a systematic review of literature specifically surrounding the WRT. The findings include a general overview of the WRT and currently used WRT indicators (i.e., speed and the Froude number).

2.1 Methods for Systematic Literature Review

The online review software Covidence (Cochrane, Melbourne, Australia) was used to complete this literature review. Covidence is a software that aids in streamlining the systematic review process by aggregating potential source articles into a single digital location and thereby facilitating annotation and data abstraction. The reviewer completes an electronic search, uploads the articles into Covidence, and then completes the abstract and full-text screening within the software. The database search was updated on December 17th, 2019 with a Boolean string search of PubMed, a commonly used biomedical search database. Boolean strings were piloted with various combinations of words reflecting WRT in order to identify the specific search strategy that yielded the highest number of studies. The Boolean string that was ultimately employed was: (“walk to run transition” OR “walk transition” OR “run transition”). The search filters of timespan (inception or earliest PubMed records-present), species (human), and language

(English) were applied. This initial search strategy yielded 83 articles. Following abstract screening for irrelevant articles (i.e., articles related to fitness testing, human gait in outer space, and cycling), 38 articles were selected for full-text review. Of these culled articles, 25 more were excluded because 24 were focused on variables unrelated to the review (for example, articles related to animal WRT instead of human) and one was not an original research study (i.e., a systematic literature review). The reference sections of the individual articles were also reviewed in an effort to identify any additional relevant studies. One additional study was located. Ultimately, 14 independent original research studies were confirmed for this literature review.

Details of the source articles' sample characteristics, treadmill protocols (bouts and speeds), purposes and findings are presented in Table 1. All of the identified studies included some form of a standardized WRT treadmill protocol. This was defined as a protocol during which participants were asked to locomote on a treadmill that was incrementally increased in speed (the exact speeds and durations of each increment varied between studies). Participants were asked to select whichever mode of locomotion (walking or running) felt most natural and comfortable at the time. The WRT speed was defined as the speed obtained when participants naturally selected to transition to running, and the protocol was generally terminated following the end of the segment during which the participant selected to run. All reported measures were converted to metric units (m/s) (and rounded to 1 decimal place) in Table 1 as needed to allow for more direct comparisons. Other apparent variations in reported elements between studies are due to actual differences that could not otherwise be reconciled.

2.2 The Walk-to-Run Transition (WRT)

The WRT consists of a single gait transition step which occurs when accelerating from walking to running. From a spatiotemporal perspective, this transitional step cannot be considered walking or running since its characteristics do not easily fall under either of their accepted discrepant definitions.²² To be clear, since the transitional step enters into a flight phase, it could be classified as running based on the motion of the body. However, the transitional step varies significantly more in duty factor (the amount of time the foot spends on the ground), cadence and stride (i.e., a complete gait cycle; two steps) length than the subsequent running step that occurs following the transition.²³ In actual fact, the process of transitioning between walking and running is not limited to a single gait transitional step. Segers et al.²³ conducted a study with 20 healthy adults (0.0% men, aged 24.5 ± 2.8 years) who completed 25 treadmill bouts divided into five blocks which were characterized by constant accelerations (+0.1 m/s, + 0.05 m/s, + 0.07m/s, -0.1m/s, and - 0.05 m/s). Segers et al.²³ determined that the WRT had an identifiable “pre-transitional period” prior to the transition step. This “pre-transitional period” was characterized by exponential increases in cadence and stride length. Since steps are easily observed and counted, the pre-transitional period can be characterized in terms of the specific number of steps leading up to WRT. The researchers of this specific study reported that during pre-transitional steps 15 through 8, cadence and stride length increased linearly, but then an exponential increase was observed from approximately 8 steps prior to the transitional step and up until the transitional step.²³ Additionally, during the last step prior to WRT, the landing placement of the foot more closely resembled running as lower limbs prepared for the upcoming flight phase.²³ Regardless, the ultimate transitional step is a

feature of the WRT that is observed consistently across various transitional speeds and individuals, making it an identifiable event for measurement purposes.

As mentioned above, the most common means of predicting when the WRT will occur is by measuring speed, and the WRT speed appears to average ~ 2.1 m/s^{1,2} with little variation observed across uncompromised individuals and populations (refer to section 2.2). Also mentioned was how the speed at which the WRT occurs can also be converted to a dimensionless number known as the Froude number. A dimensionless number is a one without any units, and therefore a product of other pure numbers. As mentioned above, the Froude number is calculated using the following equation: $Fr = v/(gd)^{1/2}$, where v = walking velocity, g =gravity, and d =leg length. This equation is used to adjust speed for leg length, which has been shown to have an effect on the Froude number.²¹ The Froude number for maximum possible walking speed is set at a dimensionless value of 1, and studies have demonstrated that the WRT occurs at a Froude number of ~ 0.5 .^{20,21} Participants completed a standard treadmill protocol to identify their WRT speed, and then the participants' leg length and speeds at transition were used to calculate the Froude number. This means that the participants naturally transitioned from walking to running well before their biomechanical limit of walking.

In addition to leg length, there are other factors to consider that could potentially influence the WRT speed including sex, age, training status, intellectual disorder, and cognitive load. Ganley et al.²⁴ examined the influence of sex on the WRT speed by studying ten healthy adults (40% male, age = 26.6 ± 5.7 years, mass = 66.8 ± 3.9 kg). In their study the treadmill speed began at 1.6 m/s and was increased by 0.1 m/s every 10

minutes. The mean WRT speed was 2.1 ± 0.03 m/s, and no sex differences were observed.

Another potential factor that could influence WRT speed is age. Farinatti and Monteiro²⁵ compared the WRT speeds of younger ($n = 13$, age = 24 ± 3 years) versus older ($n = 13$, age = 64 ± 6 years) adults (sex not reported). The WRT speeds were established using a standard WRT treadmill protocol which began at a speed of 1.5 m/s and increased by 0.1 m/s every 15 seconds. The WRT was identified as the speed at which video footage showed the first flight phase (i.e., both feet off the ground at the same instant) in the participant's gait. There was no significant difference ($p = 0.62$) between the WRT speeds of the younger (1.97 ± 0.2 m/s) versus the older (1.9 ± 0.2 m/s) group.

Additionally, there are mixed findings on whether training status impacts WRT speed. Evidence that the speed at which the WRT occurs is independent of training status in runners for this assertion comes from a study conducted by Diedrich and Warren²⁰ who determined the WRT speeds of eight adults (50% male, 18-34 years of age) using a standard WRT treadmill protocol. Participants also self-reported their training status ranging, in terms of km/week, from 0 km/wk to 60 km/wk (24.6 km/wk \pm 21.1 km/wk). WRT was 2.1 ± 0.2 m/s. No association was found between training status and WRT speed.

However, contrasting evidence that training status does have an influence comes from a study conducted by Beaupied²⁶ who determined the WRT speeds of 15 male adults (ages not reported). These 15 males were divided into either an untrained, sprint or endurance group as defined by self-reported training of a minimum of 12-hrs/week in

their respective category. These individuals completed two separate testing sessions consisting of 5-minute treadmill bouts. During session 1, they were asked to walk at speeds of 0.1, 1.5, 2.1, 2.4, and 2.6 m/s. During session 2, they were asked to run at speeds of 1.5, 2.1, 2.4, 3.9 and 4.4 m/s. Energy consumption was measured using a breath by breath metabolic system. Two different transition speeds were calculated: energetic (St_1), which was transition speed relative to consideration energy consumption, and mechanical (St_2), which was transition speed relative to energy consumption when taking into consideration mass. Energy consumption was plotted for the individual's walking and running speeds, and St_1 was defined as the point at which these walking and running energy consumptions crossed over. St_2 was defined as the speed relative to the calculated energy consumption rate (energy consumption in joules/weight in kg). The St_1 and St_2 transition speeds were reported respectively as 2.3 ± 0.0 m/s and 2.7 ± 0.1 m/s for the untrained group, 2.4 ± 0.1 m/s and 2.2 ± 0.1 m/s for the sprint group, and 2.3 ± 0.1 m/s and 2.3 ± 0.0 m/s for the endurance group. Sprinters had a significantly lower St_2 than St_1 , whereas the untrained group had a significantly lower St_1 than St_2 ($a < 0.0001$). Therefore, these results suggest that training type (specifically sprint-type training) has an influence on transition speed. Specifically, individual engaging in sprint-type training may transition to running at slower speeds than untrained individuals.

Although no significant WRT speed differences have been associated with sex and age, and the influence of training status is still unclear, intellectual disorder and cognitive load do appear to influence it. Agiovlasitis, Yun, Pavol, McCubbin and Kim²⁷ completed a study with nine adults with an unspecified intellectual disorder (88.8 % men, 18 – 43 years of age) and ten adults without an intellectual disorder (60% men, 20 – 34

years of age). These individuals completed a standard WRT treadmill protocol which began at 1.1 m/s and increased in 0.09 m/s intervals every seven seconds. Individuals with intellectual disorders demonstrated WRT speeds that were slower than those without intellectual disorders (1.8 ± 0.1 m/s vs. 2.1 ± 0.2 m/s, respectively, $p = .001$).

Situational mental capacity (i.e., transient differences in cognitive load) within individuals also appears to be related to the WRT. By way of explanation, cognitive load is a measure of working memory resources used during an activity.²⁸ Working memory resources within the cognitive system are responsible for retaining and processing short-term memory information, and these are also referred to as attentional resources.²⁸ Transiently increasing cognitive load (and thereby increasing working memory resources) impacts the WRT due to the need for greater attentional resources. Individuals will delay their WRT when dealing with increased cognitive load. Daniels and Newell²⁸ completed a study with twelve male participants (21.8 ± 2.4 years of age) who performed either no math problems, or easy (e.g., addition and subtraction of two single digit numbers) or hard (e.g., addition and subtraction of single digit numbers from double digit numbers) math problems that were asked verbally while completing a standard WRT protocol. The treadmill began at a speed of 1.7 m/s and increased in 0.1 m/s increments every 2 minutes. When completing the hard math problems, the participants delayed their WRT to a significantly faster speed (no math = 2.1 ± 0.1 m/s, easy math = 2.1 ± 0.1 m/s, hard math = 2.2 ± 0.1 m/s, $p < 0.05$).

However, it is important to note that the studies on these confounding variables have limitations. The contrasting evidence on training status from the Diedrich and Warren²⁰ and Beaupied²⁶ studies may be due to the small sample sizes ($n = 8$ and 15 ,

respectively), the definition of training status (i.e., whether self-reported training is indicative of fitness), lack of reported walking behavior, and lack of knowledge of how body composition could impact the WRT. In the Ganley et al.²⁴ study on sex, there is a lack of exploration on gender-specific differences (i.e., height, leg length) that may contribute to the results. In addition, this study had a small sample size ($n = 10$). Future studies on the effect of sex on the WRT should use a larger sample size and control for other variables affected by gender such as height and leg length. In the Farinatti and Monteiro²⁵ study on age, the sample size is once again quite small ($n = 13$), and the results could potentially be impacted by other aging effects such as fitness, functional capacity and balance. However, regardless of the additional potential cofounders, neither of these studies noted an effect of sex or age on the WRT transition. Finally, a majority of these studies examining potential cofounder factors used group means as their determining factor, which have the potential to be variable and swayed by outliers.

The current literature, with the above limitations noted, shows that the WRT occurs consistently at a speed of ~ 2.1 m/s or a Froude number of 0.5 in adults. It is not influenced by more stable individual traits including sex or age, and the influence of training status is still uncertain. However, intellectual disorders and situational or transient increases in cognitive load do influence the speed at which the WRT occurs.

2.3 Proposed Causes of the WRT

The exact cause of what prompts the WRT is still unknown, although there are many suggested explanations. The two most commonly proposed and debated explanations are: (1) an energetic trigger, which means that the transition occurs to minimize total metabolic cost, or (2) a mechanical trigger, which means that the

transition occurs to prevent excess muscular effort and reduce musculoskeletal loads. These two triggers are discussed in further detail below. Other less commonly suggested explanations (not further discussed) of what causes the WRT include changes in perceived exertion^{29,30} or metabolic fuel selection (i.e., the body's utilization of carbohydrates, protein and fat storages),²⁴ as well as minimizing biomechanical constraints (i.e., improving efficiency of joints and biomechanical movements).³¹

2.3.1 Energetic Trigger

As mentioned above the energetic trigger explains that the WRT occurs to minimize total metabolic cost.³² To be clear, this postulated mechanism underlying the WRT suggests that an individual walking vigorously at a fast speed may select to start running because this locomotor mode will use less energy. This theory is built upon the finding that the maximum walking speed for humans is 3.0 m/s.³³ However, humans transition from walking to running well before this maximum speed, as demonstrated by the 2.1 m/s WRT speed commonly reported.^{1,2} Therefore, this suggests that humans potentially transition to running well before their maximum walking speed in order to achieve a reduced energy expenditure.

Research findings have discounted this energetics trigger theory, however, by demonstrating that individuals actually select to transition from walking to running at a speed when it would still be more metabolically efficient to walk. For example, a study by Hreljac¹ included twenty adults (50% male, age = 24.2 ± 4.4 years) who completed a standard WRT treadmill protocol with five bouts of speeds set at 70%, 80%, 90%, 100% and 110% of the expected WRT speed of 2.1 m/s. The actual average WRT speed was

2.1 m/s \pm 0.1 m/s. The participants then repeated a similar treadmill protocol, but this time they were instructed to only run (not walk at all) for five bouts at speeds of 90%, 100%, 110%, 120% and 130% of the WRT speed of 2.1 m/s. Metabolic information (the rate of oxygen consumption) was collected during all of the standard and running-only treadmill bouts. The researchers also determined the energetically optimal transition speed (EOTS). By way of explanation, the metabolic cost of walking increases curvilinearly as walking speed increases, whereas the metabolic cost of running remains constant and increases linearly with increasing speed.¹ If these lines were plotted for various speeds, the EOTS is the point at which these lines would intersect. In this specific study, the metabolic information from the walking and running treadmill bouts were plotted to determine the EOTS point of intersection. The EOTS was 2.2 \pm 0.1 m/s, which was higher than the sample's average WRT speed of 2.1 m/s \pm 0.1 m/s. This indicated that participants chose to begin running slightly before the point of optimal metabolic efficiency.

Brisswalter and Mottet³⁴ concurred with this conclusion when they applied a similar study protocol that compared the WRT speed to the EOTS. Ten male participants (22.1 \pm 1.6 years of age) completed twenty treadmill bouts beginning at 1.7 m/s and with each bout increasing in speed by 0.1 m/s to establish their WRT speeds. Participants also completed twelve additional treadmill bouts during which metabolic data were collected. During these subsequent twelve bouts, the participants completed the following six bouts twice: their previously established WRT speed - 0.3 m/s, - 0.1 m/s, + 0.0 m/s, + 0.1 m/s, + 0.3 m/s. During the first set of these repeated six bouts, the participants were instructed to walk for every bout. During the second set they were instructed to run for every bout.

The metabolic data from these repeated six bouts were used to plot and determine the EOTS. EOTS was 2.2 ± 0.1 m/s, whereas the WRT speed was 2.1 ± 0.2 m/s. Similar to the Hreljac¹ study, the higher EOTS relative to the WRT speed indicated that participants selected to run at a speed before it was more metabolically efficient to walk.

If reducing metabolic cost is not what triggers the WRT, an alternate theory suggests that the WRT is instead prompted by a mechanical trigger, as discussed in the following section.

2.3.2 Mechanical Trigger

The primary alternative theory for the cause of the WRT is a mechanical trigger. A mechanical trigger means that the WRT occurs to prevent excess muscular effort (the force needed by the muscles to locomote)²¹ and minimize peak musculoskeletal loads (the force absorbed by the muscles and bones during locomotion).^{35,36} The mechanical limit is defined by muscle-specific fatigue, where a certain known muscle fatigues faster than the surrounding muscles and limits the locomotor potential,^{1,21} or by limits to the muscle force-velocity-length relationship, where a muscle is lengthened past where it can provide the optimal amount of force.³⁷

The mechanical limit may be dictated by peak ankle angular velocity, peak ankle angular acceleration, or a reduction in plantar-flexor force production.³⁷ Peak ankle angular velocity is the maximum rate (rotations/min) of flexion and extension of the ankle (i.e., the highest number of flexes that occur during any given minute). Peak ankle angular acceleration is the maximum rate at which the peak ankle angular velocity changes (rotations/min²; i.e., the greatest change in the number of flexes that occur during

any given minute). Finally, plantar-flexor force production is the amount of force in Newtons produced by the plantar-flexor muscle, a muscle that acts to flex the ankle joint. Neptune and Sasaki³⁷ directed ten participants (50% male, 29.6 ± 6.1 years of age) to complete a treadmill protocol with two stages. The first stage consisted of a standard WRT treadmill protocol with bouts that began at 0.6 m/s and increased in 0.1 m/s intervals every 30 seconds. Using their individually assessed WRT speed (average = 2.0 ± 0.2 m/s) from that initial protocol, the participants then completed a second set of treadmill bouts walking at speeds of 40%, 60%, 80%, 100% and 120% of their WRT speed, and running at 100% of their WRT speed while body segment motion data were collected with motion capture cameras. These researchers then used a musculoskeletal computer model to simulate running and walking. The computer model was made to simulate running and walking at the same speeds as the bouts of the second treadmill protocol that the human participants completed. A musculoskeletal model is a computer simulation designed using acquired knowledge of the movements and limitations of the human bones and muscles, and is used to non-invasively study the movement of individual muscles. The computer simulation analysis showed that the plantar flexor muscle fiber lengths systematically shortened (thereby decreasing contractile force) as the WRT speed approached, indicating a contractile limit. This was in contrast to the other muscles studied (i.e., gluteus maximus, adductor magnus, anterior and posterior portion of gluteus medium, iliac, biceps femoris long head, medial hamstrings, rectus femoris, biceps femoris short head, medial and lateral gastrocnemius, and soleus), which all increased their contractile force in advance of the WRT. Therefore, the contractile limit of the plantar flexor muscles could be a determinant for the WRT.

Pires, Lay and Rubenson³⁸ also supported limited ankle movement as a potential mechanical determinant for triggering the WRT. Similar to Neptune and Sasaki,³⁷ Pires, Lay and Rubenson³⁸ asked eight participants (male = 50%, ages = 24.8 ± 1.8 years) to complete a standard WRT treadmill protocol with speeds ranging from 1.5 to 2.5 m/s and increasing intervals of 0.1 m/s every 30-60 seconds. Video gait analysis of the participants took place during a separate visit where the participants walked at speeds ranging from 30% to 120% of their WRT speed, and ran at speeds ranging from 80% to 170% of their WRT speed. The gait analysis data suggested that as walking speed increased, ankle movement became more limited, and that this limitation could theoretically decrease the amount of push-off power the ankle could produce. This decreased ankle push-off power would cause the hip to compensate by increasing hip push-off power. This increase in hip push-off power would subsequently increase muscular effort and lead to the WRT. All this said, the primary triggering event again appears to be limited ankle movement.

2.4 Cadence as a WRT Indicator

Preliminary research has shown that cadence shows promise as an indicator of the WRT. Hansen, Kristensen, Nielsen, Voight and Madeleine¹⁹ reported that a mean cadence of 140 (± 3.1) steps/min corresponded with the WRT. The nineteen participants in the study (73% male, 26.3 ± 5.4 years of age) completed a standard WRT treadmill protocol which began at 0.3 m/s and increased in 0.1 m/s increments every 30 seconds. The WRT was defined as the moment when the participant selected to run. All treadmill

locomotion was filmed and cadence was subsequently calculated by counting the number of strides in a 20-sec interval and dividing by two to convert from strides to steps.

Another study³⁹ by the same research group agreed with the 140 steps/min WRT cadence and demonstrated that cadence is a reliable WRT indicator by using a test-retest study design. The WRT cadence of twenty-five healthy, active young adults (male = 76%, age = 26.6 ± 4.2 years) was determined using a treadmill protocol during which participants began locomoting at 0.8 m/s and increased in 0.1 m/s increments every 30 seconds until a speed of 2.8 m/s was reached. Participants were instructed to transition from walking to running whenever it felt natural to do so, and the cadence of that bout was considered the WRT cadence. This procedure was repeated on two independent days separated by 4 to 8 days. Day 1 WRT cadence was 142.2 ± 7.4 steps/min, and Day 2 WRT cadence was 141.2 ± 6.2 steps/min. Reliability (i.e., repeatability of the result) was demonstrated (error = 1.6%, smallest real difference = 4.4%).

2.5 Literature Review Summary

In summary, the WRT is an element of human locomotion that is not yet fully understood. Knowledge of what triggers the WRT is important for gaining understanding how humans control their bipedal locomotion. The original WRT theory suggested that that it was caused by an energetic trigger, and occurred in order to select the most metabolically efficient form of locomotion. However, this has been disproven by studies demonstrating that humans transition to running prior to the point of optimal metabolic efficiency.^{1,34} Therefore, the WRT is now thought to be primarily caused by a mechanical trigger, which could potentially be linked to contractile limit of the plantar flexor muscles

and limited ankle movement.^{37,38} The WRT is also accepted to occur at a speed of $\cong 2.1$ m/s.^{1,2} This speed is not affected by sex or age, and the influence of training status²⁶ is still uncertain, but is influenced and slowed by an intellectual disorder or increased cognitive load.^{27,28} While speed is the traditional metric used to predict the WRT, at least two studies have demonstrated that cadence shows promise as a WRT indicator.

The proposed analysis will build upon the findings of these two previous studies by independently identifying the WRT cadence cutpoint and comparing it to the proposed cutpoint of 140 steps/min. This analysis will use ROC curve analyses to determine the WRT cadence cutpoint by considering each individual's cadences, whereas the other studies used group means.^{19,39} In order to determine the most accurate approach to defining the WRT, these proposed analyses will (1) compare the performance of the WRT cadence, speed and Froude number cutpoints and (2) provide a more age-diverse (although still mostly young adults) population compared to previous studies as catalogued in Table 1.

CHAPTER 3

METHODS

3.1 Examination of Cadence as an Indicator of the Walk-to-Run Transition

This thesis is a secondary analysis of data originally collected as part of the NIH/NIA (National Institute of Health/National Institute on Aging) funded R01 (research project grant) CADENCE-Adults study (NCT02650258). Secondary analysis means that this specific analysis was not the original intention of the study. The original purpose of the CADENCE-Adults study was to identify heuristic cadence thresholds associated with different intensities of walking.¹⁶

3.2 Participants

CADENCE-Adults was a sex- and age-balanced laboratory study that included 260 ostensibly healthy and ambulatory men and women ranging between 21-85 years of age. Recruitment and data collection were logistically divided into three Cohorts: Cohort 1 (adults 21-40 years old; $n = 80$), Cohort 2 (adults 41-60 years old; $n = 80$), and Cohort 3 (adults 61-85 years old; $n = 100$). Within each Cohort, 10 men and 10 women were recruited from each 5-year age group. All original procedures were approved by the University of Massachusetts Amherst Institutional Review Board and all participants read and signed an informed consent document. Approval was also granted for this secondary analysis.

Exclusion criteria were as follows: use of an assistive walking device (e.g., wheelchair, cane, walker), impaired ambulation, BMI $<18.5\text{kg/m}^2$ or $>40\text{kg/m}^2$, tobacco use within the past 6 months, stage 2 hypertension (systolic blood pressure > 140 mmHg

or diastolic blood pressure > 90mmHg) history of cardiovascular disease or stroke, conditions or medications that might affect heart rate response to exercise (e.g., metoprolol), implanted medical devices (e.g., pacemaker, metal joint replacements), hospitalization for mental illness within the previous 5 years, or pregnancy.

Data from 28 participants (20 men, 8 women; age = 36.6 ± 12.8 years, range 20 to 60 years of age) who completed the protocol (details below) with a run were used in the present analysis. These 28 participants were all from Cohorts 1 (n = 17, 70.6% male) and 2 (n = 11, 72.7% male) of the CADENCE-Adults study, as Cohort 3 contained no participants who voluntarily ended the protocol running. The size of this dataset is in line with the previous WRT cadence cutpoint studies which included 19¹⁹ or 25³⁹ participants.

3.3 Study Protocol

This secondary data analysis focused only on data collected during the treadmill portion of the larger CADENCE-Adults study. Participants completed a protocol that was comparable to the standard WRT treadmill protocols in the studies catalogued above. Specifically, the CADENCE-Adults protocol consisted of a series of five-minute bouts at 0% grade, with each bout followed by two minutes of standing rest. The treadmill speed began at 0.2 m/s, and the speed for each 5-minute bout was increased incrementally in 0.2 m/s increments. During the standing rest, participants straddled the treadmill belt, and began each treadmill protocol by hopping onto it once it had reached the full speed for the bout. Participants could choose to walk or run each bout, and the protocol was terminated following the first bout during which the participant chose to run, reached a heart rate greater than 75% of their age predicted heart rate maximum ($220 - \text{age}$), reported a rating of perceived exertion (RPE) of greater than 13 on the Borg scale⁴⁰ (i.e., rating of

‘somewhat hard’), or the decision to end the protocol was made by the participant or researcher (e.g., for safety reasons).

3.4 Descriptive Measures

3.4.1 Participant Characteristics

Participants self-reported biological sex and age. Standing height was measured with a wall-mounted stadiometer (ShorrBoard® Portable Height-Length Measuring Board; Weigh and Measure LLC, Olney, Maryland USA). Participants were asked to remove their shoes and stand straight with their back against the board. Measurements were noted to the nearest 0.1 cm, repeated twice, and averaged. If the two measures were not within 3 cm of each other, a third measurement was taken and the nearest two values were averaged. Seated height was also assessed using the same measurement error strategy; participants were asked to sit on a bench with their back and hips against the stadiometer and their legs hanging unweighted, and a slider attached to the stadiometer was brought to the top of their head. Leg length was calculated as the difference between standing and seated height measures. Body mass and percent body fat were measured using a Tanita scale (DC-430U; Tanita Corporation, Tokyo, Japan). Participants were asked to remove their socks and shoes prior to stepping on to the scale. Body mass was recorded to the nearest 0.1 kg, repeated twice, and averaged. If the two measures were not within 0.1 kg of each other, a third measurement was taken and the nearest two values were averaged. Percent body fat was calculated by the Tanita scale and obtained from the scale’s digital output. Measures were repeated twice and averaged.

3.4.2 Treadmill-based Variables

During the treadmill protocol (running and walking bouts) steps were assessed via direct observation and recorded using a hand-tally counter. Direct observation is the criterion standard of step counting measurement because taking a step is a behavior that is overtly displayed, highly visible, and easily countable. As backup, a video camera (GoPro HERO4, GoPro Inc., San Mateo, California, USA) recorded the foot movements of participants during each bout for verification purposes. The treadmill's digital speed output (verified using a tachometer) was used to determine locomotor speed in m/s.

3.5 Data Processing

The running bout was defined as the first bout during which participants self-selected to run. The analytical data sample consisted of two bouts for each participant: the running bout and the walking bout immediately preceding the running bout. Speed was defined as the treadmill's digital speed output converted to m/s, and the WRT speed was that recorded during the running bout. Cadence was defined as the average steps/min participants performed during each bout. Cadence for each bout was derived in the original study by dividing the hand-counted steps by the duration of the bout (5 minutes) (see Table 3). Froude numbers for each bout were calculated using the formula presented above.

3.6 Statistical Analyses

Statistical analyses were performed using R-Studio (version 3.0.2, R Foundation for Statistical Computing, Vienna, Austria) and Microsoft Excel. Statistical significance was set at $\alpha \leq 0.05$.

3.6.1 Descriptive Statistics

Categorical data (men/women) were presented as frequencies (%). Distribution of continuous data (age, height, weight, percent body fat, leg length, and treadmill-based variables) was presented as means \pm SD. Sample average speed, Froude number, and cadence were determined for both the walking and running bouts. The values for the running bout were considered the WRT values. The individual and mean differences were calculated, along with a 95% confidence interval (CI) to determine whether there was a significant difference in individual cadences between the walking and running bouts. Specifically, 95% CI for the mean differences between the walking and running bout cadences were examined for overlap with zero. Since zero was not within the range of the 95% CI, this was interpreted as a significant difference.⁴¹

3.6.2 Inferential Analyses

3.6.2.1 WRT Cadence Cutpoint

The optimal WRT cadence cutpoints were identified using receiver operating characteristic (ROC) curve analyses.⁴² While previous WRT studies have used the group mean cadence as the identified cutpoint, ROC curve analyses were selected as the

analytic method for this study to avoid the variability associated with group means, as group means can be swayed by outliers in the dataset.

ROC curve analyses plots the true positive rate against the false positive rate. A grid of all potential cutpoints was laid out using each of the individual participants' actual cadences for both walking and running bouts as the potential cutpoints. The optimal cutpoint was defined as the value that was closest to the ideal classifier, which would consist of a true positive rate = 1 (100% true positives) and false positive rate of 0 (0% false positives). When plotted on the ROC graph, this ideal classifier was visually identified as following along the top and left-hand borders of the ROC graph. The closer the data-driven ROC curve was to those borders, the more accurate the result was considered to be. Findings were also interpreted using the area-under-the-curve (AUC) numerical output. The closer the curve was to those borders, the greater the amount of area that remained underneath the curve; therefore, the greater the AUC and the higher the accuracy.

Individuals who were running at or above the cutpoint were classified as true positives (actual running bouts when running was estimated), whereas individuals who were running below the cutpoint were classified as false positives (actual running bouts when walking was estimated). Individuals who were walking at or below the cutpoint were classified as true negatives (actual walking bouts when walking was estimated), and individuals who were running below the cutpoint were classified as false negatives (running bouts when walking was estimated).

3.6.2.2 Height and Leg Length Analyses

Simple linear regression was performed to determine if there were independent relationships of leg length and height on cadence.

3.6.2.3 Cadence Cutpoint Compared to Speed and Froude Number Cutpoints

Sensitivity was defined as the probability that the observed running bouts were correctly predicted as running based on each of the WRT cutpoints studied (speed = 2.1 m/s; Froude number = 0.5; cadence = optimal value identified from the process described above). Sensitivity was calculated as the number of true positives/(true positives + false negatives)*100 (i.e., correctly predicted running bouts / total running bouts). Specificity was the probability that the observed walking bouts were correctly predicted as walking based on the cutpoint. Specificity was calculated as true negatives/(true negatives + false positives)*100 (i.e., correctly predicted walking bouts / total walking bouts). Overall accuracy was also calculated and refers to the percentage of correctly identified conditions for both running and walking bouts. Overall accuracy was calculated as (true positives + true negatives)/total, which also was the correctly predicted bouts / total bouts.

Once the sensitivity, specificity, and overall accuracy values for the cadence, speed and Froude number were determined, these were compared by simple rank ordering to determine which WRT indicator demonstrated the highest overall accuracy. The computed value for overall accuracy was *a priori* determined to be the deciding factor for comparing the accuracy of the three WRT indicator cutpoints.

3.6.2.4 Post Hoc Analyses

Once the planned data analyses were completed, it became apparent that a number of *post hoc* analyses would be necessary. While the *a priori* analyses consisted of comparing the sensitivity, specificity, and overall accuracy of the optimal speed and Froude number cutpoints from the literature and the optimal cadence cutpoint identified from the dataset, additional analyses were completed in order to also compare the optimal speed and Froude number cutpoints identified from the dataset, as well as the optimal cadence cutpoint identified from previous literature (140 steps/min¹⁹).

Additionally, although an *a priori* decision was made to use overall accuracy to determine the final optimal WRT cadence cutpoint, there was a three-way tie for candidate values and a tie-breaking process became necessary. Positive predictive values were calculated; however, after examining the sensitivity and specificity values in relationship to these, it was determined that the cadence value with the highest PPV may not always identify the locomotion pattern a researcher is looking for, depending on the specific research question. Therefore, *post hoc* analyses were conducted to determine a heuristic (i.e., empirically-based, rounded) cadence cutpoint range for identifying walking and running behaviors and identify the accuracy of the range when applied to this data set. This decision was made to provide a “best use” heuristic cadence cutpoint range after multiple candidate optimal cutpoints of equal overall accuracy were identified. The heuristic cadence cutpoints for the range were determined by rounding to the closest multiple of 5 steps/min from the more precise optimal cadence cutpoints determined from the ROC curves. This approach was based on a similar procedure used by the parent study CADENCE-Adults to determine the heuristic cadence cutpoints for

walking intensities, specifically 100 steps/min for moderate intensity and 130 steps/min for vigorous intensity physical activity.¹⁶

CHAPTER 4

RESULTS

4.1 Descriptive Measures Results

4.1.1 Participant Characteristics

Participant characteristics are reported in Table 2. The analytical sample ($n = 28$) was mostly male (71.4%). While the age range of these two original CADENCE-Adults cohorts ranged between 21 – 60 years of age, the participants who self-selected to run and were ultimately included in this secondary analysis were mostly younger adults (mean 36.6 ± 12.8 years, median= 31.0 years). The mean height, weight and leg length were 175.9 ± 8.0 cm, 81.4 ± 17.0 kg and 82.7 ± 6.1 cm respectively. The average participant BMI was slightly overweight at 26.2 ± 4.7 kg/(m²).⁴³

4.1.2 Treadmill-based Variables

The mean values of the WRT indicators during the walking and running treadmill bouts are reported in Table 3. For the walking bout, the mean speed was 1.8 ± 0.2 m/s, the mean Froude number was 0.4 ± 0.1 , and the mean cadence was 125.9 ± 6.9 steps/min. For the running bout, the mean speed was 2.0 ± 0.2 m/s, the mean Froude number was 0.5 ± 0.1 , and the mean cadence was 148.7 ± 9.7 steps/min. The mean values were all higher for the running bout than for the walking bout. Since 0 did not fall within the 95% confidence interval range for differences (18.9 - 26.0), this difference was interpreted as statistically significant. All of the individual cadence values determined during the walking and running bouts are presented in Table 4.

4.2 Inferential Results

4.2.1 WRT Indicator Cutpoints Determined from the Data Set

Table 5 reports all three WRT indicator values, along with their varying sensitivity (i.e., actual running when running was predicted) and specificity (i.e., actual walking when walking was predicted) results. As determined *a priori*, the optimal cadence cutpoints identified from the data set were those with the highest overall accuracy (i.e., actual walking when walking was predicted and actual running when running was predicted) based on the ROC analyses (AUC > 0.96; 95% CI 0.91 – 1.0) in Figure 1. Three optimal cadence cutpoints (134, 138, and 141 steps/min) shared equal overall accuracy values of 92.9% due to underlying variations in sensitivity and specificity (Table 5). To be clear, these optimal cutpoints worked best for this specific data set.

Confronting these results during *post hoc* analyses, we first attempted calculating positive predictive values to determine whether those would serve as a tie-breaker. The positive predictive values for 134, 138 and 141 steps/min were 92.9%, 89.3%, and 85.7%, respectively. After examining the sensitivity and specificity values in relationship to these positive predictive values, it was determined that the cadence value with the highest PPV may not always identify the locomotion pattern a researcher is looking for. For example, 141 steps/min had the lowest positive predictive value, but that did not take into consideration that 141 steps/min had a specificity value of 100%, meaning it would be ideal for a researcher interested in ensuring no walking behavior was mistakenly identified. Wishing to arrive at a more generalizable heuristic range that could potentially

extend beyond this data set, we determined that the optimal cadence cutpoints identified with the highest sensitivity (134 steps/min) and specificity (141 steps/min) values would be best rounded to the nearest multiple of five (i.e., 135 and 140 steps/min). These two heuristic cadence cutpoints anchor a recommended range for identifying running behavior in a cadence-based data set. When applied to this dataset, 96.0% (24/25) of the individuals who were ≥ 140 steps/min were running, but this decreased to 92.5% (25/27) with ≥ 135 steps/min.

As also determined during *post hoc* analyses, the optimal speed and Froude number cutpoints identified from the data set were those with the highest overall accuracy as determined by using ROC analyses (Figure 1). Two optimal speed cutpoints (1.9 and 2.0 m/s) shared equal sensitivity, specificity and overall accuracy values of 83.3%, 75.0%, and 78.6%, respectively. Therefore, there were two optimal speed cutpoints that abutted each other, differing by only 0.1 m/s. The optimal Froude number cutpoint with the highest overall accuracy (82.0%) was 0.46.

4.2.2 WRT Indicator Cutpoints Determined from Previous Literature

As determined *a priori*, the sensitivity, specificity and overall accuracy of the optimal WRT cutpoints identified from previous literature for speed (2.1 m/s) and Froude number (0.5) are displayed in Table 5. As determined during *post hoc* analyses, the sensitivity, specificity and overall accuracy of the optimal cadence cutpoint identified from previous literature (140 steps/min) is also displayed in Table 5. These literature-derived optimal cutpoints all performed at lower overall accuracies than those determined from this data set; however, they were similar in their rank order of overall accuracy.

Cadence (all three optimal cutpoints identified) demonstrated the highest overall accuracy (91.1%) in terms of a WRT indicator, followed by the Froude number (76.8%) and speed (66.1%).

4.2.3 Leg Length and Height Analyses

A simple linear regression indicated a significant relationship between leg length and individual WRT cadences ($p = 0.04$). However, the analyses revealed no significant relationship between height and individual WRT cadences ($p = 0.06$). The associations of leg length and height on individual running cadences are depicted in Figure 2 and 3.

CHAPTER 5

DISCUSSION

5.1 Overall Accuracy of the Optimal Cadence Cutpoint

The ROC analyses (Figure 1) clearly demonstrated that cadence was the most accurate predictor of the WRT. Specifically, cadence was associated with an AUC of 0.962, compared to speed (0.848) and the Froude number (0.807). Cadence also demonstrated higher overall accuracies both when comparing the optimal cutpoints identified from this dataset (cadence = 92.9%, Froude = 82.0%, speed = 78.6%) and those identified from previous literature (cadence = 91.1%, Froude = 76.8%, speed = 66.1%). Therefore, cadence is clearly the most overall accurate WRT optimal cutpoint when compared to the more traditional choices of speed or Froude number.

5.2 Heuristic Cadence Cutpoints

Following *a priori* decision making, this study identified three optimal cadence cutpoints (134, 139, and 141 steps/min) ranked equally in terms of overall accuracy. This was an unexpected challenge to the original plan to determine a single optimal cadence cutpoint from this dataset. To reiterate, there was no clear single optimal cadence cutpoint identified in this specific data set that demonstrated a superior overall accuracy.

As described above, *post hoc* data treatment was completed to determine heuristic cadence cutpoints. To be clear, the optimal cutpoints are specific point estimates emerging from this unique data set whereas heuristic values are purposefully altered to provide more generalized and smoothed cutpoints that are still transferable and defensible. Rounding the identified optimal cutpoints to the nearest multiple of 5

steps/min produced a range anchored by 135 steps/min and 140 steps/min. Researchers' use of this heuristic cadence cutpoint range will be driven by their specific research question, and in particular, their tolerance for errors related to sensitivity vs. specificity of measurement. If they are interested in identifying episodes of running behavior and prefer that very few episodes of walking behavior are mistakenly identified, it would be best to use 140 steps/min. However, if they want to be as inclusive as possible in identifying episodes of running behavior, and can tolerate more mistakenly identified episodes of walking behavior, they could use 135 steps/min. An example of this situation can be seen when applying this range to the dataset. There were less individuals above ≥ 140 steps/min ($n=25$), but a higher accuracy in predicting that those individuals were engaged in running behavior (25/25; 96.0%). There were more individuals ≥ 135 steps/min ($n=27$), but a higher chance of mistakenly identifying walking behavior because of the decreased accuracy in predicting that those individuals were engaged in running behavior (25/27; 92.6%). In summary, the tradeoff is that, when applied to this dataset, one episode of running behavior would have been missed using the 140 steps/min cutpoint, but less mistaken walking behavior would have been identified.

At the upper level of the propose range, the heuristic cadence cutpoint of 140 steps/min corresponds with the findings of previous studies^{19,39} examining the WRT cadence. These studies used a different protocol (i.e., continuous instead of segmented treadmill acceleration) and analytical approach (i.e., group means instead of ROC) than that implemented herein. Therefore, the heuristic WRT cadence value of 140 steps/min appears to be a robust and consistent finding determined across these two different study designs emerging from independent research groups.

5.3 Use of the Heuristic Cadence Cutpoints

The heuristic cadence cutpoints identified in this study have the potential to be applied to wearable technologies and therefore useful for researchers who are examining wearable technology data outputs and wishing to confidently identify instances of running behavior in a standardized manner. It can be challenging to know whether or not an individual is running or walking when analyzing data accessed from wearable technology collected without the benefit of concomitant verification using direct observation. This nascent opportunity is facilitated by the recent widespread explosion of wearable technologies focused on step counting and cadence tracking.³ These types of devices are also being readily adopted into physical activity interventions.⁷⁻⁹ Additionally, it is timely for this exploration of cadence as a WRT indicator as there are now heuristic cadence values with strong associations with absolutely defined moderate and vigorous intensity physical activity.¹⁶⁻¹⁸ The CADENCE-Adults study¹⁶ identified heuristic cadence cutpoints for walking intensities to be 100 steps/min for moderate physical activity and 130 steps/min for vigorous physical activity. Therefore, it is fitting that this secondary analysis proposes a range of heuristic running cadence cutpoints corresponding to the WRT that can be used by researchers to evaluate locomotor patterns of individuals when analyzing free-living data collected using wearable devices. This proposed heuristic cadence cutpoints range fits well into the developing cadence model,³ because the lowest anchor value (i.e., 135 steps/min) suggests that some individuals will select to run soon after reaching vigorous intensity at a walking cadence (i.e., 130 steps/min).

Previous research⁴⁴ suggests that average adults may not spend very much daily time above the 135-140 steps/min heuristic cadence cutpoint range, however. A population-based study⁴⁴ examining the daily cadence patterns of over 3700 adults (> 20 years old) reported that adults in the United States accumulated only $\cong 2$ minutes per day of stepping time above a cadence of 120 steps/min, despite accumulating $\cong 30$ min/day at cadences above 60 steps/min. However, the 135-140 steps/min heuristic range is targeted at identifying running locomotion. Therefore, individuals who frequently engage in vigorous intensity activities such as running may record high quantities of time above 135 steps/min.

5.4 Leg Length and Height Analyses

A simple linear regression indicated a significant relationship between leg length and individual WRT cadences ($p = 0.04$). The analyses revealed no significant relationship between height and individual WRT cadences ($p = 0.06$); however, the significance of this relationship could potentially be influenced by a more variable population. Therefore, it is important that future studies continue to examine the effect of height on cadence. The associations of leg length and height on individual running cadences are depicted in Figures 2 and 3.

The height values in this sample ranged from a minimum of 158.3 cm to a maximum of 188.9 cm, a difference of 30.6 cm, whereas the leg length values ranged from a minimum of 69.6 cm to a maximum of 93.3 cm, a difference of 23.7 cm. It is important to consider that the relatively small differences in leg lengths and heights within this adult group may differ from that apparent in a developing population (i.e., from childhood to adolescence to young adulthood). In the CADENCE-Kids study⁴⁵ (age

range 6 – 20 years old) focused on the relationship between cadence and intensity, no cadence*leg length interactions were observed within age-restricted age groups, specifically in 6 – 8 or 15 – 17 years olds, but they were observed for those 9 – 11 ($p = 0.033$), 12 – 14 ($p = 0.002$) and 18 – 20 years of age ($p = 0.036$). In Cohort 1 of the CADENCE-Adults study¹⁶ (age range 20 – 40 years old), adding leg length into the cadence-intensity model had only marginal effects ($R^2 = 0.85$ vs. $R^2 = 0.84$). These results suggest that the cadence-intensity relationship may be somewhat influenced by an individual's leg length (more so for young people). In summary, it is important to consider the impact that an individual's leg length may have on their cadence, and future studies should consider this when selecting their study population.

5.5 Strengths

The original study protocol, while not initially designed for these specific analyses, has several strengths. The original protocol included direct observation and video backup which increases certainty of recorded cadence values. The original protocol also included a wide range of speeds from very slow walking (0.22 m/s) up to the participant's self-selected run. Furthermore, the study population was more age diverse (age range 21 – 60 years old; mean age 36.6 ± 12.8 years) than previous WRT studies reviewed above (11 studies: age range 20 – 30 years). This secondary analysis was the first study to calculate the optimal cutpoints for all three WRT indicators (speed, Froude and cadence) from the same dataset, using statistical analyses (i.e., ROC) that extended beyond group means to reduce variability. Furthermore, these analyses demonstrated how comparatively well these various WRT indicators (speed, Froude and cadence) performed when applied to the same dataset. Finally, this secondary analysis was the first to suggest

an empirically-based heuristic range of cadence cutpoints for predicting running anchored on specificity vs. sensitivity preferences.

5.6 Limitations

This analysis lacked a developing and older adult populations. A developing population was not included in the original CADENCE-Adults study, and based on the termination criteria implemented, all of the older adult participants in Cohort 3 ended their treadmill protocols prior to running due to meeting some other safety-related termination criteria (i.e., RPE > 13; heart rate > 75% of maximum (220 – age)). Older adults would potentially have higher WRT cadences due to changing locomotion patterns and balance with aging; therefore, studies should examine WRT cadence in older adult populations who are accustomed to running and therefore are not considered to be at high risk of exercise-related complications. Regardless, based on the findings of the literature review,²⁵ age may not be influential in terms of the WRT.

Additionally, this study protocol had relatively large incremental increases in treadmill speed (0.22 m/s). Due to these jumps, it is possible that an individual would have transitioned at a lower speed (and therefore, potentially a lower cadence) if they had been provided the option. This may contribute to why the group mean running cadence in this study (148 steps/min) was higher than the previously reported group mean cadences previously found in the literature (140 steps/min). Therefore, future studies should consider using smaller incremental increases (i.e., 0.1 m/s).

A further limitation is the need for a separate validation sample. Since these cutpoints were calculated from the same dataset they were tested on, there is the need for future studies to test and validate this cutpoint on independent, separate datasets.

A final limitation is that these treadmill-based WRT findings may differ from overground results and therefore caution should be used when generalizing them to free-living settings. The speed at the start of the WRT transition step has been shown to be higher overground than on a treadmill⁴⁶ (2.3 vs. 2.2 m/s). We know of no overground cadence-based WRT data at this time.

5.7 Conclusion

In summary, the cadence-based WRT optimal cutpoints were clearly more accurate than speed or Froude number counterparts. This was true for both the optimal cutpoints identified from this data set and those derived from previous literature. Based on the optimal cadence cutpoints identified herein, an empirically-based heuristic range of cadence cutpoints for predicting running that was anchored on specificity vs. sensitivity preferences was ultimately recommended. For researchers interested in identifying episodes more likely to be running behavior (with the preference that very few episodes of walking behavior are mistakenly identified), it would be best to use 140 steps/min. However, if they want to be as inclusive as possible in identifying episodes of running behavior (and can tolerate more mistakenly identified episodes walking behavior), they could use 135 steps/min. Although verification in a separate validation sample, as well as in overground and free-living contexts, is required, this heuristic cadence cutpoint range may be used by researchers wishing to identify locomotor mode when analyzing free-living cadence data as detected by wearable technologies.

Additional research is also needed to further validate these heuristic cadence values in larger and more age-diverse populations.

TABLES

1: Samples and Protocols of WRT Studies

Study First Author, Year	Purpose	Sample Characteristics (n, % men, age, height)	Treadmill Protocol	Speeds	Findings
Agioula sitis, 2008	Examine the effect of increased cognitive load on WRT speeds	9 healthy adults with intellectual disorders (ID) (88.9% men; age range 18-43 years); 10 healthy adults without IDs (60.0% men; age range 20 – 34 years).	16-24 bouts evenly split between walk-to- run and run-to- walk	Began at 1.1 – 1.3 m/s and increased in 0.09 m/s increments every 7 seconds	Individuals with intellectual disorders demonstrated WRT speeds that were slower than those without intellectual disorders (1.8 ± 0.1 m/s vs. 2.1 ± 0.2 m/s, respectively, p = .001)
Beaunie d, 2003	To find if the WRT speed is linked to training type	15 healthy adults: 100.0% men; ages not reported	Two separate testing sessions (walking and running) consisting of 5- minute treadmill bouts	During session 1, participants were asked to walk at speeds of 0.1, 1.5, 2.1, 2.4, and 2.6 m/s. During session 2, participants were asked to run at speeds of 1.5, 2.1, 2.4, 3.9 and 4.4 m/s	Sprinters had a significantly lower St_2 than St_1 , whereas the untrained group had a significantly lower St_1 than St_2 ($\alpha < 0.0001$). Therefore, these results suggest that training type (specifically sprint- type training) has an influence on transition speed
Briswa lter, 1996	Examine the relationshi p between the energy cost of locomotio n and stride duration variability in speeds surroundi ng the WRT	10 healthy adults; 100.0% men; aged $22.1 \pm$ 1.6 years, height $= 1.77 \pm 0.04$ m	3 sessions. The first determined WRT speed. The second session (imposed walk) and third session (imposed run) were five randomized 6- minute treadmill bouts in which the treadmill speed was set in pre-determined variations of their WRT speed.	Session 1: 20 trials increasing from 1.6 m/s to 2.78 m/s in increments of 0.056 m/s every minute. Sessions 2 & 3: WRT speed – 0.28 m/s, - 0.14 m/s, - 0.0 m/s, + 0.14 m/s, and + 0.28 m/s.	The EOTS was 2.2 ± 0.1 m/s, whereas the WRT speed was 2.1 ± 0.2 m/s. The higher EOTS relative to the WRT speed indicated that participants selected to run at a speed before it was more metabolically efficient to walk.

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Daniels, 2003	Examine whether cognitive perceptual processes influence the WRT.	12 healthy adults; 100.0% men; aged 21.8 ± 2.4 years, height = 1.76 ± 0.06 m	2 sessions: The first determined WRT speed. The second session added in a psychological aspect of completing easy and hard math problems during the bouts.	Stepped protocol in which speed began at 1.7 m/s and increased 0.1 m/s every 2 minutes with 5-minute rest between trials.	When completing the hard math problems, the participants delayed their WRT to a significantly faster speed (no math = 2.1 ± 0.1 m/s, easy math = 2.1 ± 0.1 m/s, hard math = 2.2 ± 0.1 m/s, $p = 0.0$).
Diedrich, 1995	Examine the shift in human locomotion between walking and running to present a qualitative dynamic theory.	8 healthy adults; 50.0% men; aged 18.0 – 31.0 years, height not reported	Two sessions. During the first session, participants' WRT speeds were determined through 15 incremental treadmill bouts during which participants could naturally select to walk or run. During the second session, participants walked or ran at constant speeds.	Session 2: constant speeds of Froude numbers at 0.1, 0.25, 0.4, 0.5, 0.6 and 0.7 (0.9 – 2.5 m/s) for walking and 0.25, 0.4, 0.5, 0.6, 0.7, 0.85, 1.0, 1.15, 1.3 and 1.45 (1.5 – 3.6 m/s) for running.	No association was found between training status and WRT speed.
Farinatti, 2010	Compare cardio-respiratory responses of older and younger adults locomotion at the WRT speed.	26 healthy adults; equally between the young (aged 24.0 ± 3.0 years, height = 1.71 ± 0.03 m) and older group (aged 64.0 ± 6.0 years, height = 1.69 ± 0.05 m)	Incremental treadmill protocol until participants naturally selected to run.	Began at 1.5 m/s and increased 0.6 m/s every 15 seconds.	There was no significant difference ($p = 0.62$) between the WRT speeds of the younger (1.97 ± 0.2 m/s) versus the older (1.9 ± 0.2 m/s) group.
Ganley, 2010	Assess metabolic fuel	10 healthy adults; 40.0%	3 sessions: session 1 determined WRT	Sessions began at 1.56 m/s and increased in	The mean WRT speed was 2.1 ± 0.03 m/s, and no

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	source in a range of speeds surrounding the WRT.	men, aged 26.6 ± 5.7 years	speed. During sessions 2 and 3 respectively, participants were instructed to walk or run for every bout.	0.11 m/s increments every 10 mins. Session 1 ended when the participant ran; Session 2 ended at 2.46 m/s.	sex differences were observed.
Hansen, 2017	Test whether in spite of the independence of the two different ways of determining the transition stride frequencies, an agreement would be found between the calculated and the predicted walk-to-run transition stride frequencies.	26 healthy adults; 73.0% men, aged 26.3 ± 5.4 years, height = 1.78 ± 0.08 m	3 sessions: session 1 determined WRT speed. Participants rested 5 minutes before sessions 2 and 3, consisting of performing up to 5 minutes of walking and running at self-selected paces.	Began at 0.83 m/s and increased in 0.14 m/s increments every 30 seconds until 2.78 m/s was reached.	Stride frequencies occur spontaneously during unrestricted walking and running.
Hansen, 2018	Determine the test-retest reliability of the WRT predicted cadence.	25 healthy adults; 76.0% men, aged 26.6 ± 4.2 years, height = 1.77 ± 0.08 m kg	2 sessions with three main parts: part 1 determined WRT speed, and participants rested 5 minutes before sessions 2 and 3, consisting of performing up to 5 minutes of walking and running at self-selected paces.	Began at 0.83 m/s and increased in 0.14 m/s increments every 30 seconds.	The freely-chosen velocity, free-chosen stride, WRT velocity and predicted transition cadence showed reliability.

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Hreljac, 1993	determine whether the WRT saves metabolic energy.	20 healthy adults; 50.0% men, aged 24.2 ± 4.4 years, height = 1.7 ± 0.09 m	Stepped protocol until participants selected to run, which determined the WRT speed.	Began at 1.4 m/s, and increased by 0.1 – 0.2 m/s.	1) The actual average WRT speed was $2.1 \text{ m/s} \pm 0.1 \text{ m/s}$ 2) The EOTS was $2.2 \pm 0.1 \text{ m/s}$, which was higher than the study's average WRT speed of $2.1 \text{ m/s} \pm 0.1 \text{ m/s}$. This indicated that participants chose to begin running before the point of optimal metabolic efficiency.
Hreljac, 1995	Determine the relationship between body size and WRT speed.	20 healthy adults; 50.0% men, aged 24.1 ± 4.3 years, height = 1.7 ± 0.1 m	Stepped protocol until participants selected to run, which determined the WRT speed.	Began at 1.4 m/s, and increased by 0.1 – 0.2 m/s.	1) The association between WRT speed and leg length is weak 2) The Froude number for WRT speed was 0.5.
Neptune, 2005	Examine the changes in plantar-flexor force surrounding the WRT.	10 healthy adults; 50.0% men, aged 29.6 ± 6.1 years, height = 1.7 ± 0.1 m	Participants WRT speed was determined using a stepped protocol. The participants then walked at speeds of 40, 60, 80, 100 and 120% of their WRT speed and ran at 100% of the WRT speed on the treadmill.	Began at 0.6 m/s and increased in 0.1 m/s increments every 30 seconds until participants ran for entire 30-second trial.	The computer simulation analysis showed that the plantar flexor muscle fiber lengths systematically shortened (thereby decreasing contractile force) as the WRT speed approached, indicating a contractile limit.
Pires, 2014	Analyze the effect of speed on lower-limb joint parameter	8 healthy adults; 50.0% men, aged 24.8 ± 1.8 years, height = 1.7 ± 0.09 m	Participants walked for 30 – 60 seconds for 10 bouts. WRT speed was determined by	Randomized between 1.5 to 2.5 m/s in 0.1 m/s intervals.	The gait analysis data suggested that as walking speed increased, ankle movement became more limited, and

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	s at speeds around the WRT.		participants selecting the slowest speed at which running was their most comfortable gait. This was repeated three times and the average WRT was used.		that this limitation could theoretically decrease the amount of push-off power the ankle could produce.
Segers, 2006	Describe the spatiotemporal patterns of the stride surrounding the WRT.	20 healthy adults; 0.0% men, aged 24.5 ± 2.8 years, height not reported	25 treadmill bouts divided into five blocks with 30 seconds rest between each block.	Each block was characterized by a constant acceleration (+0.1 m/s, +0.05 m/s, +0.07m/s, -0.1m/s, and -0.05 m/s).	<ol style="list-style-type: none"> 1) The WRT has an identifiable “pre-transitional period” prior to the transition step 2) During pre-transition steps 15 through 8, cadence and stride length increased linearly 3) During pre-transition steps 8 to 0, an exponential increase was 4) During the last stride prior to WRT, the landing placement of the foot more closely resembled running

2: Participant Characteristics

Characteristics	Value (mean \pm SD, range)
Sex (M/F)	M = 20 (71.4%), F = 8 (28.6%)
Age (years)	36.6 \pm 12.8, 21 - 60
Height (cm)	175.9 \pm 8.0, 158.3 - 188.9
Weight (kg)	81.4 \pm 17.0, 51.6 - 128.8
BMI (kg/m ²)	26.2 \pm 4.7, 20.2 - 37.6
Percent Body Fat (%)	23.4 \pm 8.1, 8.4 - 40.1
Leg Length (cm)	82.7 \pm 6.1, 69.6 - 93.3

3: Mean Values for Speed, Froude Number, and Cadence

Indicator	Walking bout	Running bout
Speed (m/s)	1.8 ± 0.2	2.0 ± 0.2
Froude number (unitless)	0.4 ± 0.1	0.5 ± 0.1
Cadence (steps/min)	125.9 ± 6.9	148.7 ± 9.7

Notes: Mean values for speed, Froude number and cadence during both the walking and running bouts. Speed (m/s) was calculated from the treadmill speed during the given bout. The Froude number was calculated using the following equation: $v^2/(gd)$, where v =walking velocity, g =gravity, and d =leg length. Cadence was calculated by dividing the manually-counted steps during the observed bout by the 5-minute duration.

4: Individual Cadences

Participant	Walking Cadence (steps/min)	Running Cadence (steps/min)	Difference
1	133	164	31
2	124	159	35
3	132	152	20
4	133	158	25
5	127	148	21
6	138	151	13
7	123	145	22
8	140	152	12
9	115	147	32
10	128	158	20
11	129	139	10
12	131	161	30
13	119	147	28
14	120	141	21
15	124	152	28
16	134	149	15
17	121	145	24
18	119	166	47
19	119	144	25
20	119	147	28
21	130	148	18
22	122	158	36
23	126	147	21
24	131	151	20
25	116	134	18
26	133	148	15
27	122	128	6
28	116	124	8
Mean value \pm SD, min, max	125.9 \pm 6.9; min = 115, max = 140	148.7 \pm 9.7; min = 124, max = 166	22.8 \pm 9.3; min = 6, max = 47

5: Sensitivity, Specificity and Overall Accuracy Values of the WRT Cutpoints

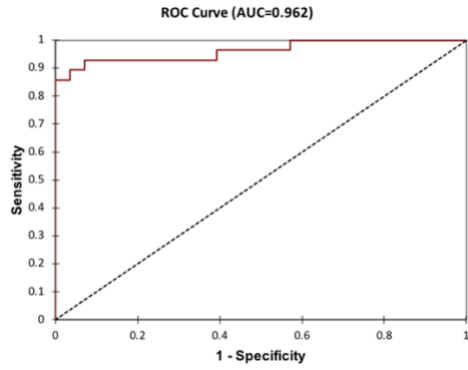
		Optimal Cutpoint(s)	Sensitivity	Specificity	Overall Accuracy
Speed (m/s)	Dataset	1.9	83.3%	75.0%	78.6%
		2.0	83.3%	75.0%	78.6%
	Literature	2.1	80.0%	53.0%	55.0%
Froude number (unitless)	Dataset	0.46	71.0%	93.0%	82.0%
	Literature	0.5	77.8%	75.9%	76.8%
Cadence (steps/min)	Dataset	134	92.2%;	92.2%,	92.9%;
		139	96.4%;	89.3%,	92.9%;
		141	100.0%	85.7%	92.9%
	Literature	140	96.4%	85.7%	91.1%

Notes: Table 5 shows the statistical analyses outputs calculated from both the study dataset (i.e., Dataset) and the previous values from literature (Literature).

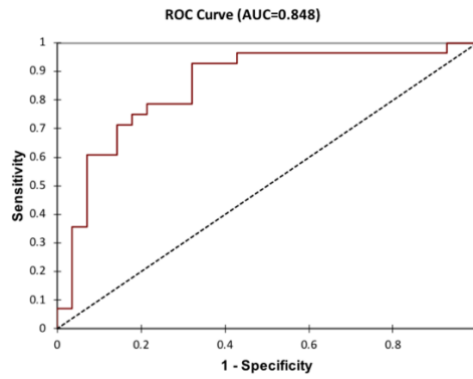
FIGURES

1: Receiver Operating Characteristic Curves for WRT Indicators

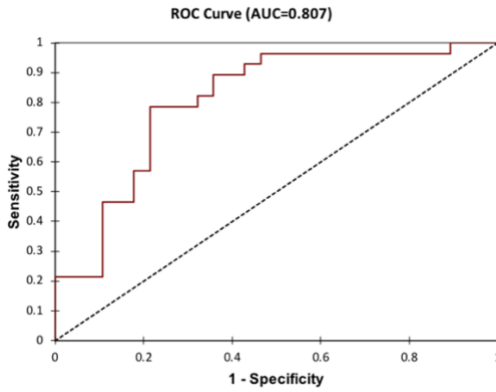
Panel A: Cadence



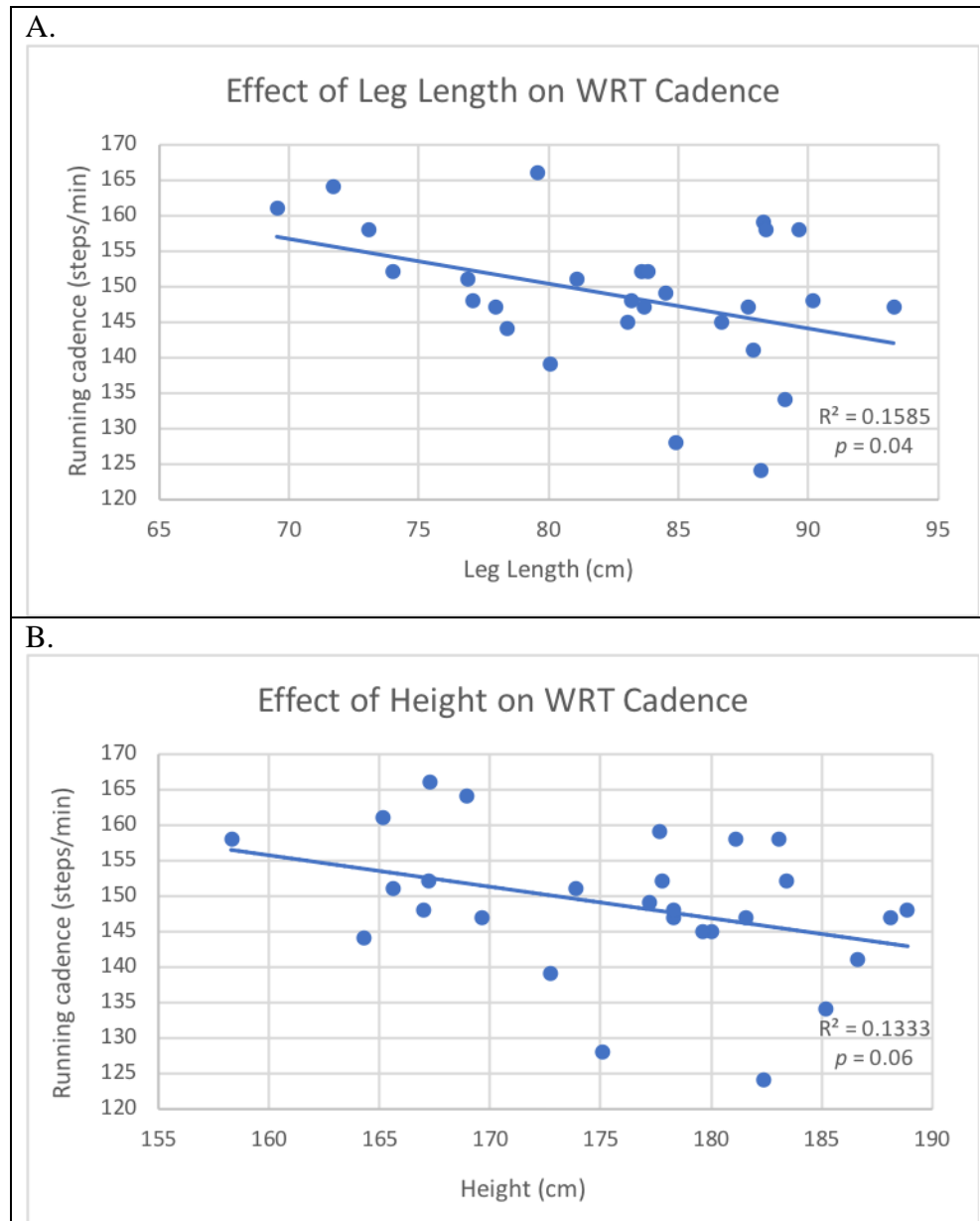
Panel B: Speed



Panel C: Froude number



2: Individual Leg Length and Height vs. Cadence



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