WALK-RUN TRANSITION SPEED AND THE RELEVANCE OF LOADING, MUSCULAR FATIGUE, AND HUMAN KINEMATICS: A COMPARISON OF HUMAN GAIT PATTERNS

By

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ABSTRACT

Walk-Run Transition Speed and the Relevance of Loading, Muscular Fatigue, and Human Kinematics: A Comparison of Human Gait Patterns

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INTRODUCTION: The walk-to-run transition (WRT) typically occurs at a preferred transition speed (PTS) of 1.9-2.1ms^{-1}. Previous research has focused on potential triggers for this transition such as leg length, muscular fatigue, loading rates (LR), and vertical ground reaction forces (VGRFs). Rather than focus on mechanisms responsible for the transition, the purpose of the current study was to determine if basic anthropometrics or gait characteristics are predictive of the WRT. **METHODS**: Thirty participants were recruited for the current study (*n* = 13 male, 17 female; *n* = 11 normal weight, *n* = 10 overweight, *n* = 9 obese; age *M* = 26.3, *SD* = 5.5 years; height *M* = 68.8 *SD* = 3.8 inches; weight *M* = 182.6, *SD* = 41.0 lbs; BMI = 27 kg/m^s). Participants' passive hip and ankle range of motion (ROM) was measured. Next, participants performed a minimum of three overground walking trials at their preferred walking speed (PWS), followed by three WRT trials and four tibialis anterior (TA) strength and endurance tests on a Biodex Isokinetic Machine (Biodex Medical Systems Inc, Shirley NY). TA Strength was the

peak torque derived from three maximum voluntary contractions. TA endurance was defined as the graphical value that dropped below 60% of the peak torque for three consecutive trials. Kinematic data were collected with eight Vicon MX series cameras (VICON, Denver, CO, USA), and VGRFs were collected with four force platforms (Kistler, Amherst, MA, USA & Advanced Mechanical Technology, Inc., Watertown, MA, USA). The following variables were calculated from the overground trials: active ankle/hip ROM, foot progression, vertical LRs, stride length, stride frequency, VGRFs, and PWS. The PTS was assessed using a motorized treadmill with a velocity increasing by 0.10 mph every 10 s. **STATISTICAL ANALYSIS:** A Classification and Regression Tree (CART) analysis was used in MATLAB (Mathworks, Natick, MA, USA) to identify and assess variables' predictive ability of PTS. A series of *t* tests were also run on results from the CART. **RESULTS & CONCLUSION**: The CART analysis resulted in a tree with two splits and three terminal nodes. PWS was the primary splitter, creating a division at 1.61 ms^{-1}. A PWS above 1.61 ms^{-1} resulted in a PTS of 2.28 +/- 0.21 ms^{-1} for three participants, creating the first terminal node. The second splitter was BMI, subdividing participants at 27 kg/m^2, with 27 participants below 27 kg/m^2 transitioning at 1.97 +/- 0.17 ms^{-1} and creating the second terminal node. Twelve participants were categorized above 27 kg/m^2 and transitioned at 1.8 +/- 0.13 ms^{-1}, creating the third terminal node. A cross-validation technique generated mean square errors of 0.0734, 0.0565, and 0.0456 for the first, second, and third terminal nodes, respectively. Independent *t* tests were run on the two BMI groups (< 27 kg/m^2 and > 27 kg/m^2) from the secondary split. Passive hip ROM was statistically significant between the participants above and below 27 kg/m^2 ($p = 0.009 < 0.05$), at 136 +/- 13° degrees and 161 +/- 27°, respectively. Also, TA endurance ($p = 0.043 < 0.05$) and step width ($p = 0.05$) were statistically significant, with participants above 27 kg/m^2 at TA endurance values of 32 +/- 2.48 repetitions and participants below 27 kg/m^2 at 24 +/- 0.71 repetitions. Step width values were 0.14 +/- 0.02 m and 0.11 +/- 0.01 for participants above and below 27 kg/m^2, respectively. According to the CART analysis, PWS and BMI were identified as the best predictors for PTS compared to the other measure variables. In general, it is likely that there are differences across multiple variables between these groups, and it is the collective nature of these differences that influence the PTS. Future research on PTS must examine diverse populations in order to gain further insight on transition speed.

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CHAPTER 1: INTRODUCTION

Interest in the area of transition speed first evolved from research in quadruped animals, with specific emphasis on horses and their walk-to-trot and trot-to-gallop transitions. Transition speed from the locomotion of walking to the locomotion of running is highly studied in gait-related research (Alexander, 1977; Hreljac, 1995a; Hreljac, 1995b; Hreljac Imamura, Escamilla, & Edwards, 2007; Farley & Taylor, 1991; Neptune & Sasaki, 2005; Raynor, Yi, Abernethy, & Jong, 2002; Segers, Lenoir, Aerts, & De Clercq, 2007b; Thorstensson & Roberthson, 1987). The point of transition from a walk to a run is referred to as the walk-to-run transition (WRT) and is highly dependent on movement speed (Rotstein, Inbar, Berginsky, & Meckel, 2005). This speed is know as the preferred transition speed (PTS) and typically occurs at a rate of about 1.9-2.1ms^{-1} (Rotstein et al., 2005). In general, the presence or absence of a flight phase also indicates the change in the mode of locomotion, with walking considered to include double support phases. Despite what researchers may have hoped to find, the transition of quadruped animals has proved to be very different from that of bipedal species, such as humans (Hreljac, 1995a).

There are several protocols used to measure the walk-to-run transition. The most commonly used protocols are termed “continuous” and “incremental.” The incremental protocol involves the manual control of speed in increments by the researchers (Raynor et al., 2002). At each given speed, participants are given a decision period to determine whether walking or running is the preferred gait. However, some researchers propose that this protocol does not exhibit a true spontaneous transition or the steps leading up to the transition (Li & Hamill, 2002). Conversely, a continuous protocol can be used, where the treadmill is constantly accelerating without interference from researchers. Although this method has also shown to be reliable, some argue that the true point of transition is not always obvious under these circumstances. Because of the difficulty in pinpointing the exact moment of transition, recent research has illustrated that the transition itself is not just a singular event. Rather, the transition is a sequence of events with pre-transition steps that precede the WRT (Hreljac et al., 2007). The identification of the pre-transition phase has highlighted the complexity of the PTS and has led to further research that explores the trigger or cause of the WRT.

Many theories have been developed to explain the cause of the WRT, however, none of the variables stemming from these theories have been defined as primary contributing factors. Many of the leading hypotheses include metabolic, physiological, and biomechanical factors, with varying intrinsic and extrinsic potential determinants (Malcolm, Fiers, Segers, Van Caekenberghe, Lenoir, & De Clercq, 2009a).

The WRT may be related to the minimization of metabolic cost (Mercier, Legallais, Durand, Goudal, Micallef, & Prefaut, 1994). The transition from walking to running has been viewed as an energy saving mechanism, in which the body transitions as an order of efficiency. However, research conducted by Raynor et al. (2002) suggests that energy cost is not minimized or even reduced during the WRT for humans. Although oxygen consumption and transport cost have been ruled out as potential triggers of the transition, the gait transition did result in a more efficient mode of locomotion than if the speed of walking had been maintained (Raynor et al., 2002). In a study that compared PTS to energetically optimal transition speed (EOTS), Sentija and Markovic (2009) investigated how energy expenditure and gas exchange relate to gait patterns. Twenty-two untrained but physically active males performed four tests which revealed VO_{2max}, walking/running gas exchange thresholds, walk-to-run/run-to-walk PTS, and EOTS. Significant positive correlations between WRT and PTS were found, suggesting that aerobic threshold in running could be an important predictor of PTS (Sentija & Markovic, 2009).

Additional studies exploring correlations between oxygen consumption and the WRT have specifically examined the theoretical transition speed (TTS). TTS is defined as the speed where oxygen consumption while walking becomes greater than the consumption during running (Beaupied, Multon, & Delamarche, 2003). Previous studies that have measured TTS among sprinters, endurance runners, and untrained subjects have revealed significant differences in TTS values between the groups, indicating transition speed may be closely linked to the subject's type of training and fitness level (Beaupied et al., 2003). More recent investigations contradict this conclusion, using PTS values rather than TTS. Rotstein et al. (2005) compared PTS between runners and non-runners, but no significant differences were found. Thus, PTS was concluded to be independent of aerobic capacity and training status (Rotstein et al., 2005).

Aside from training status, size and anthropometric measures have also been investigated in regard to transition speed. Much of the early research on quadruped gait and transition has confirmed the relevance of size on time of transition, claiming that smaller animals transition sooner than large animals (Heglund & Taylor, 1988). Hreljac (1995b) investigated this principle in humans, attempting to make associations between leg length and transition speed. However, it was found that there was no single length variable that highly correlated with PTS (Hreljac, 1995b).

Although anthropometric values may not influence PTS in humans, musculoskeletal fatigue may be a trigger for PTS for animals and humans. Much of the research among quadrupeds suggests that the WRT occurs when musculoskeletal effort reaches a critical level to avoid injuries (Farley & Taylor, 1991; Shung, de Oliveira, & Nadal, 2009). This was evident in horses during the trot-gallop transition in which energetic demands increased greatly while ground reaction forces decreased (Farley & Taylor, 1991). Given this positive correlation in animals, the role of musculoskeletal stress in human transitions has been examined as well. It has been hypothesized that the WRT is influenced by dorsiflexor muscle fatigue, where the dorsiflexors reach a state of fatigue in which changing gaits significantly reduces localized stress (Hreljac, Imamura, Escamilla, Edwards, & MacLeod, 2008). Specifically, research has shown that tibialis anterior fatigue can greatly reduce the WRT speed, thus proving its significant role in determining the WRT (Bartlett & Kram, 2008; Segers, Aerts, Lenoir, & De Clercq, 2006). Conversely, Neptune and Sasaki (2005) concluded that the plantar flexor muscles trigger the WRT because of their reduced force-generating capacity during fast walking. Additional “trigger muscles” such as the soleus, rectus femoris, and the medial/lateral gastrocnemius have also been shown to affect the WRT, especially in response to fatiguing/assistive protocols (Bartlett & Kram, 2008). By overloading the proposed trigger muscles, PTS has been shown to decrease significantly. Conversely, when demand decreases for the trigger muscles, PTS may increase. Therefore, the role of certain groups of muscles such as the plantar flexors or dorsiflexors appear to be vital components to the initiation of WRT (Prilutsky & Gregor, 2001).

The current state of research in this area has two main shortcomings: the discrepancy in proposed triggers of the WRT, and the narrow populations used in these studies. Many studies have used recreationally active college students as participants (Bartlett & Kram, 2008), or healthy adults who are free of injury and disease (Hreljac et al., 2007; Malcolm et al., 2009a; Rotstein et al., 2005) Because of the similar subject population used in most transition speed research, it is not surprising that there is a proposed general or standardized transition speed across the human species. However, considering the amount of research conducted on animals with varying sizes and characteristics (Heglund & Taylor, 1988), it is puzzling that more diverse populations among humans have not been investigated. As mentioned above, the research conducted by Hreljac (1995b) claimed that humans do not share the same size-transition correlation as animals. However, it should be noted that the subject population used in their study did not deviate from any “normal” anthropometric measures or body compositions. The highest body fat percentage was 25%, and was that of a female participant. According to health standards, this composition is not even considered overweight and should not be considered unique or unusual.

Based on the homogenous participant population seen in previous studies, the next step in transition research should be directed towards a more diverse selection of subjects. For example, it is well known that overweight and obese individuals tend to adopt a different gait pattern while walking, such as greater step width, greater hip circumduction, and decreased knee flexion (Browning & Kram, 2009). By including a more diverse subject population, there is the potential to take greater strides in the area of transition speed. There is no sole contributing factor to PTS that has been agreed upon. Some of the main supported causes or triggers of the PTS include loading rates, musculoskeletal fatigue, and kinematic variables such as ankle angular velocity. Due to the discrepancy of previous findings, the current study investigated PTS and its associated variables from a difference approach. As opposed to examining potential causes or triggers of the WRT, the current study examined a cohort of variables presented within the literature from a broader perspective.

Purpose

The purpose of this study was to determine whether physical characteristics such as anthropometrics or kinematics are predictive of PTS through the use of a participant population with a wide range of body mass index (BMI) values. Rather, normal weight, overweight, and obese individuals were examined to determine if unique physical characteristics were predictive of the WRT. These physical characteristics were examined during participants' normal walking gait in order to determine the predictive nature of certain variables rather than their classification as triggers or causes.

Significance

This study has significance in several areas of human movement science. By studying the WRT from a predictive standpoint, there is the potential to reveal novel information regarding PTS during the WRT. Also, the use of a diverse group of participants ranging from normal weight to obese may lead to a better understanding of how anthropometrics and gait characteristics influence the PTS. Finally, studies examining gait and walking kinematics within the obese population are becoming increasingly prominent. With the current study, there is the potential to add to the base of obesity-related research and perhaps provide novel information within this area.

Methods

Participants

30 participants (*n* = 13 male; *n* = 11 normal weight, *n* = 10 overweight, *n* = 9 obese; age *M* = 26.3, *SD* = 5.5 years; height *M* = 68.8 *SD* = 3.8 inches; weight *M* = 182.6, *SD* = 41.0 lbs; BMI = 27 kg/m^s) free of lower body musculoskeletal injury and previous joint surgeries were recruited for the study. Written informed consent, approved by Boise State University Institutional Review Board, was obtained from all participants prior to involvement.

Data Acquisition

Passive range of motion tests were performed on the participant on the hip and ankle by the primary investigator. Participants then performed multiple overground walking trials over two force plates mounted in the floor. Participants were instructed to walk at a comfortable pace from point A to point B (approximately 7 meters), traveling over the force plates.

Participants then performed a warm-up on a motorized treadmill. Participants walked at 2.0 mph for 6-minutes at a 0% incline. The treadmill was programmed to automatically accelerate and function through the use of National Instruments Labview Software 8.6 (National Instruments, Austin, TX, USA), enabling researchers to manually start and stop the treadmill from the computer. Following the warm-up period, participants then participated in a WRT familiarization trial on the treadmill. Treadmill velocity began at 1.5 mph and increased at .10 mph every 10 seconds. Participants were informed that the treadmill would gradually accelerate at a constant pace and eventually bring them to a speed where they would transition to a run.

Following the familiarization trial, three additional WRT trials were conducted to find the participants' PTS. The WRT trials were identical to the familiarization trial in protocol and treadmill acceleration. A 3-minute rest was given to the participants following the familiarization trial, and in between each WRT trial thereafter. After completion of the WRT trials, all reflective markers were removed. Participants then rested for 15-minutes.

Participants then participated in Tibialis Anterior (TA) Strength/Endurance testing trials. Participants were seated on a Biodex isokinetic machine (Biodex, Shirley, NY) with the test leg at a 60° angle of knee flexion and 90° (or neutral) for the ankle. The speed was set at 210°/s for dorsiflexion and 400°/s for plantar flexion. The participant first completed three isokinetic dorsiflexion maximal voluntary contractions (MVCs), beginning plantar flexed and initiating movement into dorsiflexion. This set of three qualified as the warm-up as well as provided a baseline value MVC to be evaluated later (Parijat & Lockhart, 2008). Following a 3-minute rest, participants then performed a fatiguing test on the Biodex machine. Participants performed isokinetic repetitions until they could no longer move through the full range of motion.

Data Analysis

All data from the overground trials were averaged from three successful trials for each limb. The purpose of these trials was to collect data on active ROM at the ankle and hip, foot progression, vertical loading rates, stride length, stride frequency, the first peak of vertical ground reaction forces (VGRFs), and preferred walking speed (PWS). The WRT was defined as the first evident flight phase following toe-off of the opposite limb (Segers et al., 2006). PTS was then defined as the speed at which this event occurred.

The peak value from the three maximal repetitions on the Biodex machine was drawn from graphical data and indentified as the TA strength variable. Data graphs from the endurance portion of the trial were analyzed according to 60% of the peak torque value acquired during the strength trial. Specifically, when the torque value fell below 60% of the peak strength value for at least three consecutive repetitions, the endurance value was identified as that specific number of repetitions (Parijat & Lockhart, 2008).

All data were collected and processed in Vicon Nexus software (VICON, Denver, CO, USA). Data were then further processed and analyzed in Visual 3D (C-motion Inc, Germantown, MD, USA). All data was filtered with a lowpass butterworth filter with a cut-off frequency of 6 Hz. VGRFs were measured using two Kistler force plates (Kistler, Amherst, MA, USA) and two AMTI force plates (Advanced Mechanical Technology, Inc., Watertown, MA, USA) mounted in the floor and were filtered at 40 Hz.

Statistical Analysis

A Classification and Regression Tree (CART) analysis was run in MATLAB (Mathworks, Natick, MA, USA) to identify and assess different contributing factors to transition speed. Specifically, the CART analysis subdivided the subjects on the basis of measurements that detected binary, ordinal or continuous covariates that maximized split criterion. Mean square error was used to determine the predictive ability variables displayed in the tree. The generated tree was cross-validated in order to apply trends within the tree to its own data. The tree with the lowest of mean square error across splitters was selected and then minimized or “pruned” to eliminate less applicable variables. Such subdivisions allow for more generalized data to successfully predict outcomes of alternative data sets. A minimum leaf value (N value) of three participants was implemented.

As an additional exploratory measure, an Independent *t* Test was run on the results generated in the CART analysis. Specifically, the *t* test was used to determine if significant differences existed between the classification groups revealed by the CART tree. This method of analysis was a secondary approach to testing the significance of variables that contribute to the predictor variables themselves.

Limitations

Because the study was conducted on a college campus, many of the participants were college-aged. Although participant recruitment was also conducted off campus, many of the individuals who responded were students. Therefore, the average age of participants was M = 26.3 years old (SD = 5.5). Although there is no documented research on the relationship between age and PTS, the results of the study display a small range in age and lack of diversity in that respect. Also, race and gender were not controlled in the current study. Although neither has been shown to affect WRT or PTS values, the current study's results include more females. Overall, race or ethnicity was not observed or required information in order to participate.

Delimitations

BMI was held constant in the current study, excluding individuals with a BMI over 40 kg/m^2 for experimental reliability purposes. Also, individuals who had lower extremity joint surgery, lower extremity injuries, or had trained for race walking were also excluded. Also, overground walking trials were only deemed reliable if one full foot landed on an entire force plate.

Summary

By studying a physically diverse subject population from a biomechanical perspective, much of the disagreement surrounding the WRT and the associated variables may be resolved. Overall, the current study will positively influence many areas of human movement research and greater insight that further progress transition research.

CHAPTER 2: LITERATURE REVIEW

Introduction

The transition from walking to running occurs spontaneously in both humans and animals. When a person begins walking and gradually increases their speed, they prefer to switch to a run at one particular speed. This gait transition occurs because it instinctively feels easier to run than to walk, even though it is possible to walk faster than the preferred transition speed (PTS) (Kram, Domingo, & Ferris, 1997). The walk-to-run transition (WRT) and the run-to-walk transition (RWT) are initiated when the speed of travel reaches a critical value (Raynor et al., 2002). The WRT in particular is characterized by a discrete and relatively abrupt change dependent on movement speed (Rotstein et al., 2005). The WRT has been defined as “the slowest speed at which people prefer to run, or the moment in which a double support phase is no longer present in the mode of locomotion” (Thorstensson & Roberthson, 1987).

The speed at which transition occurs is referred to as the preferred transition speed, a generalized term used for both the WRT and RWT. This point of transition, or PTS, commonly occurs at approximately 2.0 ms^{-1} when transitioning from walking to running.

(Hreljac, 1995a; Hreljac et al., 2008; Raynor et al., 2002; Thorstensson & Roberthson, 1987).

WRT Overview

Origins of Transition Research

To better understand the WRT, the mechanics of walking itself must be understood. Two interrelated models are commonly used to describe walking gait transitions: the inverted pendulum mechanism and the Froude number. Both models interpret the roles of gravity, mass, leg length, and forward speed in locomotion.

The inverted pendulum is a mechanical model that perhaps best describes walking for bipedal species (Alexander, 1977). This model considers walking to be a series of vaults over rigid legs (Cavagna, Heglund, & Taylor, 1977). In humans, the pendulum-like mechanism conserves approximately 70% of the mechanical energy from step to step at the PTS (Cavagna et al., 1977). Pendulum-like exchange eventually disappears at faster walking speeds due to a disparity in the magnitudes and phases of the fluctuations of the two forms of mechanical energy, gravitational potential energy and kinetic energy. Therefore, at non-optimal speeds, the muscles must provide additional mechanical power (Kram et al., 1997).

The Froude number provides a simple explanation for both bipedal and quadruped transition (Alexander, 1977). The Froude number represents the ratio between centripetal force and gravitation force ($F = v^2/gl$, $(mv^2/l)/mg = v^2/gl$) (Kram et al., 1997). There is evidence that the moment of transition occurs at one particular Froude number for all animals, of which is governed by speed, acceleration, and leg length. Humans and other bipedal animals switch from a walk to a run at a Froude number of approximately 0.5 (Alexander, 1977; Hreljac, 1995b ; Thorstensson & Roberthson, 1987). At a Froude number above 1.0, walking is impossible for the simple inverted-pendulum model described above (Kram et al., 1997).

The association between biomechanically based models and locomotion initially led researchers to begin observing changes or transitions to other forms of locomotion. Through the observation of a variety of quadruped animals, researchers formed general hypotheses regarding gait transition as a highly dynamical process.

Specifically, gait transitions displayed by animals are related to a spring mass model to describe the mechanics of bouncing gaits (Farley, Glasheen, & McMahon, 1993). It was determined that in the context of the spring mass model, dynamic similarity between a large and small animal predicts that while moving at similar Froude numbers, equal compression, equal angle, and equal ratio of peak force will be present (Farley et al., 1993). This finding not only confirms the relevance of the Froude number across a variety of quadrupeds but it also reveals that animals experience similar muscular stress prior to transition.

Levels of peak ankle extensor muscular stress during movement are also highly studied. Researchers have shown two different species of rats (Kangaroo and white rats) developed nearly identical levels of peak stress in the ankle extensors at their preferred speeds, using only 1/3 of their peak isometric force (Perry, Blickhan, Biewener, Heglund, & Taylor, 1988). This finding suggests that animals prefer to travel at speeds that are the most energetically inexpensive and with a reduced amount of stress. Accordingly, it has been hypothesized that at increased speeds, terrestrial vertebrates in general are forced to alter their gait in order to reduce mechanical forces and muscular stress (Perry et al., 1988).

Using the Froude number and the inverted pendulum model, researchers continue to investigate the relevance of animal size to PTS. Additional research on animals has focused on the anthropometric attributes that may cause gait transition to occur, such as leg length and general size (Heglund & Taylor, 1988).

As predicted by researchers (Heglund & Taylor, 1988), there is a high correlation between animal size and transition speed. Such conclusions have been formed through the study of speed and stride frequency among a multitude of species of animals, ranging from rodents to horses. Through this research, a high correlation between body mass and speed was revealed. Based on these results, it has been concluded that minimum, preferred, and maximum speeds with a trot or gallop change are predictable dependent upon body size (Heglund & Taylor, 1988).

It has also been suggested that quadruped gait transition is triggered by joint kinetic factors. Research on larger quadrupeds such as horses has shown extensive amounts of musculoskeletal stress on the limbs prior to transition (Farley & Taylor, 1991). Based on this finding, it is hypothesized that quadrupeds change gaits to prevent musculoskeletal stress from reaching a critical stage thereby reducing the risk of injury.

<u>Quadruped versus Human Terrestrial Locomotion</u>

As a result of advanced research in quadrupedal gait, the topic of locomotion has increasingly evolved. Alexander (1977) first proposed that humans and quadrupeds share several gait characteristics, most importantly, the transition occurring at the same Froude number. Based on this information, many researchers have assumed that animals and humans perhaps share similar transition characteristics.

One of the most prominent contributors in quadruped gait transition is the relationship between an animal's size and preferred transition speed. Allometric equations developed for quadrupeds relating body segment mass and length to gait parameters have been shown to apply to bipedal species (Holt, Hamill, & Andres, 1990). Others have proposed that quadrupeds and humans both display similar relationships between temporal gait parameters and speed (Vilensky & Gehlsen, 1984).

Despite the number of proposed associations made between human and animal locomotion, there are many underlying factors that present obstacles. First, it should be considered that animals and humans still exhibit different modes of locomotion. Quadrupeds generally exhibit three modes of locomotion (walking, trotting, or galloping) while bipedal species exhibit two (walking and running). Therefore, two gait transitions exist for quadrupeds (walk-trot and trot-gallop) while only one exists for humans (walk-run) (Hreljac, 1995b). Because of this, certain information has not been considered applicable to human locomotion, such as the mass-transition relationship (Heglund & Taylor, 1988). Such research has revealed a strong relationship between mass and the trot-gallop transition in quadrupeds, but only within an animal group possessing a wide range of length and mass characteristics.

Additionally, many of the procedures used in studies conducted on animals do not provide for reliability or ethical reproducibility for human-based research due to invasive techniques used in previously cited animal studies (Hreljac, Arata, Ferber, Mercer, & Row, 2001). Additionally, inconsistencies exist between the walk-trot and trot-gallop transitions in horses, as joint stress was not reduced during the walk-trot transition. Varying results present the issue of whether quadrupedal gait can truly be applied to that of bipedal species. Can associations be made between animals and humans although the walk-trot or trot-gallop transitions are not present in human gait?

Researchers have approached these questions by studying the adaptations to changing speed in human locomotion and the role of leg length in gait transition (Thorstensson & Roberthson, 1987). Studies comparing acceleration and deceleration have shown that individuals with shorter legs have lower transition speeds. However, no difference in PTS has been evident among individuals with medium or long legs (Thorstensson & Roberthson, 1987). Such results only display a weak tendency for the case of leg length and transition speed in humans.

Despite low correlations, Thorstensson and Roberthson (1987) hypothesized that the inverted pendulum mechanism may still be applicable to size-dependent quadrupedal gait. In order to keep the same high horizontal speed (i.e.. speed walking), a shorter pendulum is forced to exceed its natural frequency more than a long pendulum, provided that the dorsiflexion angle is kept the same in both cases (Thorstensson and Roberthson, 1987). Thus, it is expected that a shorter-legged person would change mode of locomotion at a lower speed.

Similarly, Hreljac (1995b) conducted a study with the purpose of determining whether body size is related to human terrestrial locomotion as shown to be true with quadrupeds. The study investigated the extent to which anthropometric variables (primary length variables) affect the PTS. Additionally, allometric equations (i.e., the Froude number) relevant to quadrupedal locomotion were compared to the bipedal locomotion of humans (Alexander, 1977). A supplementary equation was derived by Hreljac (1995b), which included thigh length to sitting height ratio and lateral malleolus in order to identify anthropometric values. Weak correlations between body mass and PTS were found but it was determined that the Froude number at PTS was highly correlated due to the relationship between Froude number and speed (Hreljac, 1995b). More importantly, no single length variable was significantly more correlated to PTS than others.

Despite these findings, the correlations between body size and PTS in humans are not as significant as those found in studies on quadrupeds (Hreljac, 1995b). Possible explanations may include the small range of length and speed variables within a single species such as humans. Unlike humans, the size of animals can vary greatly, providing the assumption that larger animals have skeletal structures that are larger and stronger. Because of this, larger animals would possibly transition at proportionally greater speeds (Hreljac, 1995a).

In general, animals tend to represent a more diverse selection of size, speed, and strength. Although humans are perhaps less unique, it is clear that each human still displays unique locomotion characteristics. Thus, weak correlations between humans' size and PTS are likely related to the differences in gait kinematics between subjects rather than their anthropometric values (Hreljac, 1995b).

Human Gait Transition: a League of its Own

Human terrestrial locomotion and the associated transitions have been determined to be unique and different than that of animals. Humans not only vary in size and mass but also in their chosen gait patterns (Hreljac, 1995b). The study of gait kinematics among humans requires a foundational understanding of gait itself but also knowledge of the basic elements of transitioning speeds. Thus, the discussion of the occurrence of transition is key to understanding the PTS and WRT literature.

Some researchers have proposed that the WRT is actually a sequence of events rather than an abrupt change in gait, with a “pre” preparation step of the WRT that adapts landing configuration (Segers et al., 2007b). This alternative proposition suggests that the WRT is not quite as spontaneous as it may appear and may include a transition process. To test this theory, several studies have examined the steps prior to and following a transition step (Hreljac et al., 2007; Segers et al., 2007b; Segers, Aerts, Lenoir, & De Clercq, 2008). The transition step (TS) is typically defined as the first step with a flight phase when speed was increased (Segers et al., 2007b). Research has shown that at the start of the TS, the limb already has an altered landing configuration similar to the running configuration. This preparation is likely starting as early as the swing phase of the last walking stride (Segers et al., 2007b). Based on these results, it is possible that transition is realized in one discrete step. This event is termed the “pre” preparation period, occurring during the last stride that adapted the landing configuration of the foot.

Additional research on ground reaction forces (GRF) during the transition phase also supports the preparation theory (Li & Hamill, 2002; Segers et al., 2008). Reported changes in the vertical ground reaction forces (VGRFs) in the steps prior to the WRT may indicate a preparation mechanism. Similarly, the transition process has been studied with a specific emphasis on GRFs and center of mass (COM), indicating that kinetic adaptations were found in the last step before transition (Segers et al., 2008).

Transition Speed Protocols

Examination of preparatory steps or phases tends to be more or less successful depending on the protocol used. Treadmill protocol and overground protocols are the two most general methods used to examine WRT and PTS. . In some cases, one protocol may be more useful than the other, as both techniques have various advantages and disadvantages.

The use a treadmill protocol for analyzing gait offers a number of benefits, such as reduced physical space and number of motion capture cameras. However, treadmill walking may not exactly mimic overground walking mechanics (Van Ingen Schenau, 1980). Slightly significant differences in temporal, kinematic, and kinetic components exist between overground and treadmill walking. (Van Ingen Schenau, 1980; White, Yack, Tucker, & Lin, 1998). In contrast, more recent research has determined that differences between the two protocols were small and within a range of reproducibility (Riley, Paolini, Della Croce, & Kerrigan, 2007). It has been proposed that a familiarization period of a minimum of 4 minutes is required to allow a participant to adjust to treadmill walking. Following such a familiarization period, overground and treadmill gait kinematics are very similar (Matsas, Taylor, & McBurney, 2000).

With specific regards to WRT, treadmill protocols are most commonly used in research settings. By using treadmills to analyze gait transition, researchers have the ability to observe the moment of transition in a more controlled setting.

Conversely, an overground WRT protocol allows a participant to utilize gait patterns most similar to normal walking mechanics when transitioning. This also includes a more spontaneous and less controlled transition. Few documented studies have used overground protocols to examine the WRT, with the exception of more recent research examining spatiotemporal parameters (Segers et al., 2008). Given this, there is currently no literature confirming or denying the accuracy of treadmill versus overground protocols for PTS.

When using the treadmill method to examine PTS, two protocols termed “incremental” and “continuous” are typically used. The most commonly used method in measuring WRT and PTS is the “incremental” protocol (Raynor et al., 2002), in which researchers manually control the treadmill speed or incline in a set incremental manner. During this type of protocol, participants have 30 seconds at each speed increment to determine whether it is most comfortable to walk or run at the given speed. The speed at which the participant decides that running is the most appropriate gait is termed the PTS. Although this method provides an accurate and easy form of measurement, some argue that an actual spontaneous transition does not occur. Because of this, an analysis of the steps leading up to the transition is impossible, such as the “pre” preparation step defined by Segers and colleagues (2007b) (Li and Hamill, 2002).

In contrast, the “continuous” protocol can be used, which utilizes a constantly accelerating treadmill to determine PTS. As opposed to the incremental protocol, the continuous protocol elicits a spontaneous gait transition, but the determination of the exact instant of the transition is not always obvious (Hreljac et al., 2007). Hreljac and colleagues (2007) compared the incremental and continuous protocols in different grade conditions. The overall PTS between both protocols was 1.89 m s^{-1} at 0% grade, with similar WRT and PTS between both incremental and continuous trials. However, at 10% and 15% grade, PTS was greater during the continuous protocol than the incremental protocol. It was proposed that the slower PTS during the incremental protocol may have been due to increased sensitivity to dorsiflexor stress, allowing the subjects to perceive this stress differently due to the long decision period (Hreljac et al., 2007).

Despite the many advancements in gait and transition related research, the primary cause or trigger that initiates the WRT is still debated. Some researchers have stated that any variable can be considered a trigger for the WRT if it becomes larger during walking than during running, and is reduced following transition (Prilutsky & Gregor, 2001). There are several aspects of PTS that appear to meet the criteria of the above-mentioned definition. Energetic/metabolic variables, muscular activity, fatigue, ankle kinematics, and loading rates have been identified as potential contributing factors (Bartlett & Kram, 2008; Hreljac, 1995b; McGowan et al., 2008; Raynor et al., 2002; Sasaki & Neptune, 2006).

WRT Variables

<u>Energy Efficiency</u>

Many studies have concluded that the gait transition occurs due to energetic/efficiency determinants, with the system attempting to optimize or reduce the effect of certain energetic variables (Raynor et al., 2002). There is a basic understanding that the recruitment of muscles involves generating a unit of force per unit of time (Heglund & Taylor, 1988). This leads to the notion of energy efficiency or perhaps the idea of how much work is necessary to produce a certain mode of locomotion. With efficiency, the question of demand or effort for a task is addressed. In terms of traveling from one point to the next, is it more efficient to use a mode of locomotion that is faster and more energetically costly, or a mode of locomotion that is somewhat slower and requires less energy?

With regards to PTS between walking and running, muscle fiber mechanical work before, during, and after transition may be a likely trigger of the WRT. In order to address this question, researchers have investigated the storage and return of elastic energy as a type of energy saving mechanism in the human body (Sasaki & Neptune, 2006). Total muscle fiber work throughout the gait cycle in running below the PTS can be as much as 20% greater than walking at the same speed (Sasaki & Neptune, 2006). This is attributed to the increase in fiber work during the stance phase. As expected, walking above the PTS has been shown to require higher muscle fiber work than in running. Based on this information, it is reasonable to conclude that walking below the PTS requires less fiber work than running above the PTS (Sasaki & Neptune, 2006).

This information is strongly related to elastic energy utilization while running. It has been suggested that effective utilization of elastic energy is an important determinant of PTS (Kram et al., 1997). Similarly, it is presumed that conservation of mechanical energy would potentially reduce the metabolic cost of locomotion. In order for there to be a metabolic trigger involved in gait transition, the PTS must correspond to the speed that surpasses where it would be metabolically cheaper to use a different gait (Kram et al., 1997). From an energetic perspective, there is a speed where it is advantageous to transition from walking to running. This particular speed is termed the energetically optimal transition speed (EOTS) (Rotstein et al., 2005). In an EOTS study, weight-specific oxygen consumption is typically measured as a form of energetic expenditure. Using a participant base with a range of training levels, it has been shown that PTS occurs at a velocity significantly lower than the EOTS (Rotstein et al., 2005). Such research has shown that despite the higher energy demand of running, PTS occurs on its own accord.

The low correlation between EOTS and PTS may indicate that selection of transition speed is independent from optimization of energy expenditure. Several researchers have also questioned how well humans perceive small changes in energy expenditure (Raynor et al., 2002; Rotstein et al., 2005). These conclusions contradict findings reported by Hanna, Abernethy, Neal, and Burgess-Limerick (2002), who found evidence that EOTS and PTS were nearly identical. Oxygen consumption rate was found to be 99.6 % of the PTS while energy cost of locomotion was 100.5% (Hanna et al., 2000). However the results of Hanna et al should be viewed with caution because metabolic steady states cannot be reached in the time required for the WRT to be based on information perceived by the body (Minetti, Ardego, & Saibene, 1994).

The discussion of energetic expenditure is closely related to that of the muscles involved during human locomotion. As studied by Sasaki and Neptune (2006), muscle fiber activity is directly involved in the transition from the walk to a run in human locomotion. More recent research has studied the role of muscular stress and fatigue as a prime contributor to the WRT, claiming the presence of a stress reduction mechanism (Bartlett & Kram, 2008; Raynor et al., 2002; Segers, Lenoir, Aerts, & De Clercq, 2007a).

Muscular Activity and Fatigue

Within transition literature, overexertion and fatigue are some of the most popular proposed triggers of the WRT. The muscles that are involved in body support during walking are the plantar flexors, mainly the soleus and gastrocnemius (Neptune & Sasaki, 2005). Research involving weight and mass alterations has shown the unique roles of the plantar flexors under stress or load carrying scenarios. A common understanding in weight reduction research is that muscles providing body support (i.e. gastrocnemius) are sensitive to alterations in body weight while muscles providing forward propulsion (i.e. soleus) are sensitive to alterations in body mass (McGowan et al., 2008). Under these premises, differences have been found in the roles of the plantar flexors while walking with added loads. Symmetrical loading to the trunk has shown to effect muscular activity of the plantar flexors, such as the gastrocnemius. Research has shown the gastrocnemius is sensitive to changes in body weight and mostly insensitive to changes in body mass (McGowan et al., 2008). Specifically, gastrocnemius activity tends to increase with added loads and decrease with weight support. Conversely, soleus activity is highly sensitive to not only body weight but also body mass. Based on these results, it is proposed that although both the soleus and gastrocnemius assist in body support, the soleus is the primary contributor to forward trunk propulsion (McGowan et al., 2008). Considering the vital role of the plantar flexor muscles in body support and forward propulsion, the role of plantar flexor activity in the WRT has become a popular entity.

Based on the forward propulsive duty of the soleus, it has been proposed that a reduced force output during fast walking triggers the gait transition (Sasaki & Neptune, 2006). However, plantar flexor fatigue may not initiate the transition due to decreased force production after the point of transition.

Additional studies focusing on plantar flexor activity have resulted in similar conclusions, mainly that plantar flexor activity cannot be a trigger for the WRT due to the consistency of EMG activity during acceleration. More specifically, it has been shown that the plantar flexor activity is amplified as walking speeds increase. Unlike dorsiflexor activity, the plantar flexors continue to increase even following transition (Bartlett & Kram 2008). This function does not coincide with the proposed trigger definition that states muscular activity must change as a result of transition (Hreljac, 1993). Based on these results, research has begun to shy away from plantar flexor activity as a key component in the WRT. However, while the plantar flexor activity does not decrease, there is evidence that the role of the plantar flexor changes after the PTS. Therefore, there is still a debate as to the role the plantar flexors in the WRT.

Conversely, a greater emphasis has been placed on the role of dorsiflexor activity.

Based on the knowledge that ankle angular velocity and acceleration occur at critical levels of dorsiflexion (Hreljac, 1995a), it is feasible to propose that muscular stress in the dorsiflexors would precipitate gait transition (Hreljac, 1995b).

Dorsiflexor Activity

The primary muscle involved in dorsiflexion is the tibialis anterior (TA). Because of the contribution of the TA in dorsiflexion, it is hypothesized that overexertion of the muscle may affect PTS due to fatigue (Bartlett & Kram, 2008; Prilutsky & Gregor, 2001; Segers et al., 2007a). In an effort to compare the TA with other lower extremity muscles, previous studies have utilized EMG analysis on the plantar flexors, quadriceps, hamstrings, and gluteals (Prilutsky & Gregor, 2001).

By comparing swing phases associated with walking and running, certain conclusions can be made from kinematics and joint moments. The speed of ankle flexion is particularly important, as studies have shown that peak velocity of ankle flexion at the PTS is abruptly reduced after switching to running (Hreljac, 1995a). Based on these findings, it can be concluded that mechanical demand of the swing-related muscles (i.e. TA, biceps femurs, and rectus femoris) increases during higher walking speeds and therefore may precede a transition to reduce joint stress (Prilutsky& Gregor, 2001).

Given that the TA generates ankle flexion moments during swing (Prilutsky & Gregor, 2001), there is growing evidence that the TA is the primary contributor to the WRT in humans. In order to single out the role of the TA in the WRT, fatigue protocols have been developed to target the TA itself. The use of a "tib exerciser" (Segers et al., 2007a) in particular has proved to be an accurate method to induce TA fatigue and overexertion. Within such studies, increased EMG activity, decreased PTS, and increased stride length have occurred following TA fatiguing protocols (Bartlett & Kram, 2008; Segers et al, 2007a). Segers et al. (2007a) demonstrated such results with a Tib Exerciser by having subjects perform 15 repetitions at 70% of their maximum load until exhaustion occurred. Following the fatiguing process, subjects then performed a post-fatigue PTS test on a treadmill (the pre-test occurring prior to the fatigue protocol). It was shown that the WRT-speed was significantly lower in all accelerations as compared to the pre-tests (Segers et al., 2007a). Stride length was also found to be significant, as a decrease in WRT-speed due to fatigue was correlated with a decreased stride length.

TA fatigue has also been shown to initiate an increased sense of effort for the performer (Kant-Braun, Ng, Doyle, & Towse, 2002). Because of this detection of overexertion or work, the force generating capacity is reduced and in turn disables the performer to position the foot in a controlled manner (Segers et al., 2007a). Such reactions to fatigue of the TA have also resulted in a lower touch-down angle of the foot, perhaps inferring an inability to achieve toe clearance.

The research on TA fatigue has created a reliable base of knowledge for PTS and WRT literature. Therefore, the role of the TA in PTS is perhaps the most scientifically reliable proposed PTS trigger to date. Such positive associations have led many to hypothesize that *reduced* work or effort on the part of the TA may affect PTS as well.

It has been proposed that a reduction in the demand on trigger muscles would increase transition speed while an increase in demand would slow transition speed (Bartlett & Kram, 2008). However, the trigger muscles have been expanded to more than just the TA for such research. Bartlett & Kram (2008) examined EMG activity of the TA, soleus, rectus femurs, and the medial and lateral gastrocnemius. As opposed to previous research that used only fatiguing devices, Bartlett & Kram (2008) developed and used three assistive devices to test PTS. These included a dorsiflexor assist device (DFA), a leg swing assist device (LSA), and a device that applied a horizontal force (AHF) near the COM to cause positive or negative effects on forward progression by the plantar flexors (Bartlett & Kram, 2008). It was shown that changing the demand of specific muscles altered PTS, including the hip flexors, plantar flexors, and dorsiflexors. Also, the DFA and LSA devices decreased EMG muscle activity, thus increasing transition speed significantly. However, plantar flexor EMG did not display muscular activity changes, limiting is applicability to the WRT. Consistent with previous research, increasing the demand on the dorsiflexors decreased the PTS.

Ankle Kinematics

Due to the growing amount of dorsiflexor and TA research, it is reasonable to conclude that the TA plays an essential role in gait transition. Because the TA is directly related to ankle function, mainly dorsiflexion, ankle kinematics may contribute to transition speed. As previously mentioned, a critical level of dorsiflexion is often reached during ankle acceleration that appears to precede the moment of transition (Hreljac, 1995a). Larger peaks of ankle flexion moment are largely responsible for the contributions of the TA to transition (Prilutsky & Gregor, 2001). Because of this, an abrupt change is thought to occur in ankle flexion as a result of transitioning from a walk to a run. Although previous research has not reported passive ROM of the ankle joint in subject populations, it is possible that ROM of the ankle joint and flexors may affect one's ability to transition. Active ROM in particular has been shown to require at least 10º of dorsiflexion is for walking and 15º dorsiflexion during running for normal gait function (Starkey & Ryan, 2002).

Malcolm et al. (2009a) researched the WRT by examining the moment of ankle push off. An assist condition was developed that targeted the plantar flexor muscles. This assist condition revealed an increased plantar flexion at toe off. However, the resist condition resulted in decreased plantar flexion at toe off, and may be an indicator of decreased effort by the dorsiflexor muscles (Malcolm et al., 2009a). The combination of decreased plantar flexion and decreased muscular effort of the dorsiflexors during the beginning of swing phase may lead to an increase in WRT speed. Thus, the ankle plantar flexion angle can perhaps be considered as strong of a contributor to PTS as dorsiflexion angle.

Loading Rates

As a result of ankle acceleration and critical angles, the loading rates of the ankle joint have also been identified as potential triggers for the WRT (Li & Hamill, 2002; Raynor et al., 2002; Segers et al., 2007a). Consistent with previous ideas that the WRT is an injury prevention mechanism (Hreljac, 1995b), loading rates are considered a stress inducing mechanism. It has previously been shown that increased loading rates significantly decreases PTS during the WRT (Raynor et al., 2002). It is also proposed that loading rates reflect the musculoskeletal system's storage and utilization of elastic energy capabilities. This implies that loading rates are detected by the muscular system, requiring a "response" mechanism rather than an effect mechanism. Essentially, a transition to running from walking allows elastic energy to be used efficiently and effectively (Raynor et al., 2002).

With specific reference to ankle kinematics, TA fatigue has been shown to influence the loading rate of vertical GRF (Segers et al., 2007a). Because increased loading rates are considered "typical" characteristics of the last steps before WRT, there is likely a high correlation between TA fatigue and loading rate levels (Li & Hamill, 2002).

It appears that PTS is closely related to loading rates, ankle velocity, and tibialis anterior fatigue, and can perhaps be considered the trifecta of ankle kinematics. Despite these findings, there are additional factors that should be considered with regards to the WRT. Specifically, an individual's fitness level and size may contribute to the moment of transition, but perhaps may not be considered triggers, per se. These aspects of gait transition research have not been studied as often the thus less is known about how they contribute to PTS.

<u>Fitness Level/Training Status</u>

The EOTS is the point at which it is energetically optimal to transition from a walk to a run (Rotstein et al., 2005; Sentija & Markovic, 2009). When plotted on a graph, $V0_2$ speed curves for walking and running typically intersect at a point that corresponds with the EOTS (Sentija & Markovic, 2009). This similarity is largely correlated to stride frequency and metabolic cost per stride, indicating that the metabolic costs for walking and running should intersect at PTS (Minetti et al., 1994). However, EOTS has continually been shown to occur above PTS, indicating that the moment of transition does not occur due to metabolic cost (Rotstein et al., 2005; Sentija & Markovic, 2009).

In studies comparing aerobic thresholds and gait transition speed, it has been shown that aerobic threshold for walking speeds (AeTw) and aerobic threshold for running speeds (AeTr) did not differ from PTS (Sentija & Markovic, 2009). Because the AeTr and PTS have shown to be highly correlated, aerobic threshold in running could be a proposed trigger of PTS (Sentija & Markovic, 2009).

Despite the high correlations between aerobic thresholds, the subject population of such studies should be considered carefully. Many studies have used untrained or unfit participants for aerobic threshold purposes (Sentija & Markovic, 2009), providing no comparison between individuals of different fitness status. In contrast, the use of athletes is gradually emerging in transition studies (Beaupied et al., 2003; Rotstein et al., 2005). Runners have proved to be reliable subjects in research, in part because of varying training levels (sprinter vs. long distance), and also due to the obvious gap between runners and untrained subjects with respect to oxygen consumption.

Runners are also qualified candidates for transition research due to the high influence of form and specific training involved with the activity. Previous research that tested untrained, sprint trained, and endurance-trained men showed PTS to be directly related to a subject's type of training (Beaupied et al., 2003). This conclusion largely considered the running techniques that are typically acquired with experienced runners and differences were partially attributed to these techniques. Such research has also taken a metabolic approach, often times using internal work and metabolic energy expenditure

(MEE) as determinants of PTS. As demonstrated by Beaupied et al. (2003), internal work and MEE were graphically compared in order to find an intersection point corresponding to the theoretical transition speed (TTS). The TTS is slightly different from the PTS in that it represents the point at which “oxygen consumption becomes greater while walking than while running" (Beaupied et al., 2003). Based on this intersection, it was determined that sprinters, endurance trained, and untrained participants varied greatly in terms of both internal work and MEE, therefore altering the intersection point of the TTS.

However, the use of TTS instead of PTS may not accurately reflect the true speed at which transition occurs. In contrast to that of Beaupied et al. (2003), similar research has shown no difference in PTS between long distance runners and non-runners (Rotstein et al., 2005). Such studies have not only shown PTS to be almost equal but have also found no difference in EOTS between distance runners and non-runners. This finding may indicate that oxygen consumption or capacity does not affect PTS and may not determine PTS for participants of any training status level.

In accordance to the assumption that training status may not affect PTS, an individual's size must also be considered. Despite the correlations between size and PTS within animals, anthropometric measurements do not appear to determine PTS in humans (Hreljac, 1995b). Although it has been shown that thigh length to sitting height ratio may be correlated to PTS, it was shown that this measurement does not significantly affect transition time (Hreljac, 1995b). Such findings have provided a basis on which a majority of transition literature has relied on, but it should be mentioned that the variety of subjects in such studies is not wide spread.

Hreljac (1995b) used a subject population including both males and females, with varying body weight, height, and BMI. However, the range in mass only varied by 39.4 kilograms, body fat by 16.3%, and height by 36.7cm. Additionally, the greatest body fat percentage recorded was 25% and was that of a female participant. This indicates that although there was a wide spread in height measurements, the size in relation to body composition of the participants did not appear to vary greatly. Although the premise of this study was not to compare overweight and normal weight subjects' PTS, it is evident that a very narrow selection of participants was used. In fact, it isn't uncommon for many gait transition studies to use a very homogenous base of “healthy” participants (Hreljac, 1995a; Riley et al., 2007; Segers et al., 2007a; Hreljac et al., 2007).

Limitations of Previous Research: Homogenous Subject Populations

A typical subject selection will include healthy adults (Hreljac et al., 2008; Riley et al., 2007; Seay, Haddad, van Emmerik, & Hamill, 2006), but often with no reference to how the term 'healthy' is defined. Active adults are also targeted for transition research, typically free of musculoskeletal injury (Segers et al., 2007b). Also, many studies tend to exclude participants with a BMI greater than 30 or too wide a range of anthropometric variables (Riley et al., 2007). Although such exclusions are necessary to avoid outliers, unique populations outside of healthy or untrained/normal weight groups should be tested. In addition to untrained populations, integration of sedentary, overweight, and obese individuals may provide newly formed hypotheses regarding PTS (Rotstein et al., 2005).

The inclusion of obese populations may be beneficial to transition research on a number of levels. First, previous studies have a tendency to avoid subjects of high BMI or fat percentages. By using individuals who are obese, additional information involving metabolic and fatigue protocols may reveal novel results. Second, individuals who are obese are highly studied within gait research in general, demonstrating unique gait characteristics (Browning, Baker, Herron, & Kram 2006; Browning & Kram, 2007). Investigation of such gait dynamics may indeed reveal more biomechanically related PTS triggers.

Obesity Gait Research

It is well known that obese individuals tend to expend more energy during exercise bouts (Browning et al., 2006, Browning & Kram, 2009). However, it has been shown that obese individuals expend energy at rates only 10% higher than normal weight individuals (Browning et al., 2006). More specifically, percent body fat only explains 45% of the variance in net metabolic rate of walking (Browning et al., 2006); leaving an additional 55% that is not fully understood. These slightly higher metabolic rates in obese individuals may indicate that energy expenditure is a result of adjusted gait dynamics (Browning et al., 2006; Browning & Kram, 2009; Malatesta, Vismara, Menegoni, Galli, Romei, & Capodaglio, 2009).

Individuals who are obese tend to display gait characteristics that differ from normal weight individuals (Browning & Kram, 2007). Walking with a straighter leg and more erect posture are typical adjustments made in order to reduce the cost of supporting increased body weight (Devita & Hortobagyi, 2003). Peak hip extensor, knee extensor, and ankle plantar flexor moments have been shown to be greater in obese populations

(Browning et al., 2007). Also, increased speed while walking coincides with increased joint loads in obese subjects (Browning & Kram, 2009). Other common attributes include a step width as much as 30% greater than normal weight individuals (Malatesta et al., 2009). This use of lateral motion through wider steps is thought to improve recovery of mechanical energy (Browning et al., 2006). This mechanism is likened to the "waddling" pattern utilized by penguins (Griffin & Kram, 2000), which exhibit a similar shifting of weight that causes more lateral movement (Browning, McGowan, & Kram, 2009). However, research has shown that penguin waddling is not wasteful. Their lateral movements actually increase the kinetic energy available to be converted into gravitational potential energy (Griffin & Kram, 2000). This typical lateral movement pattern displayed by obese individuals is unique from an energetic perspective, but also from a biomechanical perspective. The inverted pendulum mechanism is an appropriate biomechanical model that describes bipedal walking for the purpose of this study. However, it is commonly understood that the pendulum model is primarily applied to sagittal plane motion. Considering this, it is evident that the gait exhibited by obese individuals has significant non-sagittal components. In other words, an obese person may not exactly “follow the rules” when it comes to the typical inverted pendulum model. And if an obese individual does not conform to “normal” walking gait patterns, there is the potential for additional gait related variables to deviate from what is considered “normal” as well.

Application to Gait Transition

Because individuals who are obese typically walk with greater step width, it is possible that normal heel-toe walking is not present. And if indeed obese individuals use mechanisms similar to waddling while walking, it is possible that typical plantar flexor or dorsiflexor activity does not occur. There is evidence that obese individuals display greater hip circumduction than normal weight subjects, accompanied by greater lateral leg swing (Browning & Kram, 2009). This mechanism may provide a majority of the work required for locomotion, therefore reducing the work of dorsiflexors such as the TA. Given this, the TA may be underdeveloped in individuals who are obese, and may not be accustomed to the demand required during “normal” walking gait patterns. It has been previously demonstrated that TA fatigue is highly correlated with PTS (Bartlett & Kram, 2008). Given this conclusion, it may be reasonable to propose that the TA is more highly susceptible to fatigue and overexertion among obese individuals. Thus, increased time to fatigue may result in a decreased PTS.

Additionally, it is possible that obese individuals may have decreased passive and active ROM at the ankle joint. Plantar flexion and dorsiflexion have both been shown to play pivotal roles in stability and forward propulsion (Neptune & Sasaki, 2005). However, in alignment with TA function, it is possible that the full range of dorsiflexion or plantar flexion is not present in gait patterns utilized by the obese population. This may be due to less flexion occurring during lateral motion, or perhaps inactivity levels that may be associated with sedentary lifestyles.

Loading rates have been shown to be contributing factors to PTS and WRT

(Hreljac, 1995b) and may also affect PTS for the obese population. Increased loading rates are expected in obese populations due to a greater amount of body mass present. Because of this existing characteristic, it is reasonable to believe that loading rates may increase even more at gait transition.

Based on previous research, it is clear that individuals who are obese tend to adopt unique gait patterns. Gait transition in specific populations such as those who are overweight or obese is not well understood due to a lack in research. However, there is the potential to advance knowledge in PTS by studying special populations. By studying unique gait patterns, underlying mechanical factors may be brought forward as predictive variables to the WRT.

Summary

Research on preferred transition speed in human locomotion has gradually evolved over time. The study of quadruped gait transitions provided a strong base of knowledge, and has given insight to the diverse qualities of a number of species. Like that of quadruped research, greater steps should be taken in human gait analysis to examine more unique subject populations.

CHAPTER 3: METHODS

The purpose of the current study was to determine if basic anthropometrics or gait characteristics are predictive of this transition. Due to the nature of some of the variables of interest, a diverse participant pool with regard to body composition and height were recruited for this study. The participants were required to fill out several questionnaires and a consent form prior to participation as well as attend one informational meeting and one testing session. The sessions included measuring range of motion (ROM) of several joints, a familiarization period with the WRT protocol, performing three walk-to-run transitions, and a tibialis anterior (TA) endurance test. Standard motion capture techniques were used to record the participants' gait patterns. Reflective markers were placed on the participants in order to track and record their gait patterns. All data collection trials took place in the Center for Orthopaedic and Biomechanics Research at Boise State University. The relationships between the variables of interest and WRT were examined using a Classification and Regression Tree (CART) analysis. As an additional exploratory measure, an Independent *t* Test was run on the results generated in the CART analysis. The following is a table (See Table 1.1) of variables that will be identified and analyzed for this study (See Appendix A for variable definitions).

Table 1.1 – WRT Variables Classified as either 'Anthropometric' or 'Gait'

ANTRHOPOMETRIC	GAIT	GAIT
Age	Stride Frequency	Preferred Walking Speed (PWS)
Height	Active Ankle ROM	Preferred Transition Speed (PTS)
Weight	Passive Ankle ROM	Tibialis Anterior Strength
Body Mass Index (BMI)	Active Hip ROM	Tibialis Anterior Fatigue
Leg Length	Passive Hip ROM	Vertical Ground Reaction Forces (VGRFs)
Stride Length	Foot Progression Angle	Loading Rates

Participants

30 Participants (n = 13 male, 17 female; M = 26.3, SD = 5.54 years; height M = 1.75, SD = 0.1 meters; weight M = 83, SD = 28.93 kilograms; normal weight n = 11, overweight = n = 10, obese n = 9) were recruited for the current study. Participants were recruited through mailings, announcements in local fitness centers, flyers, and community centers. Recruitment on Boise State campus occurred by word of mouth and email. The participants were required to fill out a Physical Activity Questionnaire (PAR-Q) and an independently formatted Medical History Questionnaire prior to participating

in the current study. Any individuals who checked ‘no’ for at least one box on the PAR-Q were excluded. Participants were also excluded if they endured a musculoskeletal injury or underwent joint surgery on the lower body in the previous year, arthritis in a lower body joint, any current lower body injuries that impaired locomotion, or if they were currently training for race walking. Participants were also excluded from the study if BMI exceeded 40 due to the experimental difficulty associated with accurate marker placement and motion capturing data.

All information and data collected regarding the participants is strictly confidential. All participants were assigned ID numbers in order to remain anonymous throughout the study. Also, all participants had the right to not participate or cease participation at any time throughout the duration of the study. It was the responsibility of the primary investigator to properly inform the participants of their rights and fully explain the intention and methods of the current study.

To determine if the subjects could safely participate in the study, a Physical Activity Readiness Questionnaire (PAR-Q) and independently formatted Health History Questionnaire were administered. The PAR-Q is an appropriate survey for identifying individuals who can safely participate in physical activity and those who cannot and is considered a reliable questionnaire for identifying high-risk individuals (Kaelin, 2001). The Health History Questionnaire included questions regarding previous injuries, joint surgery, or debilitating diseases (e.g., arthritis) that may have impaired the participant’s ability to perform the walk-to-run transition. Additionally, subjects completed the International Physical Activity Questionnaire (IPAQ) to determine the activity level of the participants. The IPAQ is a commonly used survey to determine activity levels, and is considered an effective form of physical activity assessment (Ainsworth et al, 2006).

Data Collection

Testing Materials

A standard weight scale and tape measure were used to determine the participants' weight, height, and BMI. Such calculations are typically used in physiological and biomechanical studies and are considered an accurate measurement of body composition (Browning et al., 2006; Browning et al., 2009; Malatesta et al., 2009). Also, a standard goniometer was used to measure passive range of motion (ROM) at the ankle and hip. A Biodex isokinetic machine (Biodex, Shirley) was used for the dorsiflexor endurance testing procedures.

A set of reflective markers was placed on the participants in order to track each segment's actions (See Appendix B). For calibration purposes, a set of 24 reflective spherical markers were fixed securely onto the lateral and medial side of the bony anatomical landmarks of the right and left leg. Individual markers included placements on the right and left calcaneous, lateral and medial malleoli, lateral and medial epicondyle of the knee, one marker on each anterior superior iliac spine (ASIS), and one marker on each posterior superior iliac spine (PSIS). The marker set also included several clusters of markers that were placed on specific areas of the legs and feet. A cluster of three markers was placed on the lateral side of each foot, a cluster of four markers on the lateral shank, and a cluster of four markers on the lateral thigh of each leg. The above-mentioned marker placements are typically used to examine lower extremity muscles during transition, providing reliable kinematic data (Seay et al., 2006; Segers et al., 2007).

A treadmill (Model 10Qi, Columbus Image Company) was used for warm-up procedures and the walk-to-run transition trials. The treadmill was manually operated from the computer through National Instruments Labview Software 8.6 (National Instruments, Austin, TX, USA),

Eight cameras were used to capture the movements of the participant as they performed the overground trials and the WRT trials. The cameras used during this study are Vicon MX series cameras (VICON, Denver, CO, USA). Specifically, the cameras collected 3D kinematic data of the limbs and joint movements, all of which is commonly used to assess gait transition (Hreljac et al., 2007; Segers et al., 2007).

Anthropometric Measurements and ROM

Initially, participants' height, weight, and leg length was measured. Leg length was measured from the anterior superior iliac spine (ASIS) to the medial malleolus of the tibia with a standard tape measure with the participant standing (Starkey & Ryan, 2002). An average of two values was computed for leg length. Participants' passive ROM was measured with a goniometer by the primary researcher and a research assistant. Passive ankle dorsiflexion/plantar flexion, knee flexion/extension, hip flexion/extension, and hip adduction/abduction were measured. Participants sat at the end of the examination table with the legs and feet relaxed and hanging over the edge of the table for ankle ROM. Participants laid supine for knee flexion and hip adduction/abduction, and prone for leg extension. Each measurement was taken three times for an average.

Marker Placement and Overground Trials

Following ROM, 16 reflective markers were placed on lower body joint centers and bony landmarks according to standard procedure (Seay et al., 2006; Segers et al., 2007a). Participants then performed active hip and knee ROM trials while being captured by eight Vicon MX series cameras through the use of Nexus Motion Capturing software (VICON, Denver, CO, USA).

Participants then performed multiple overground walking trials at their preferred walking speed (PWS). Participants were instructed to walk at a comfortable pace from point A to point B (approximately 7 meters), traveling over the force plates. Participants were told to alter their starting point based on the primary researcher's observation of valid force plate data. This method assisted in ensuring the participants did not adjust their gait to the plates.

Warm-up and Familiarization

Participants then performed a warm-up on the motorized treadmill. Participants walked at 2.0 mph for 6-minutes at a 0% incline. The treadmill was programmed to automatically accelerate and function through the use of National Instruments Labview Software 8.6 (National Instruments, Austin, TX, USA), enabling researchers to manually start and stop the treadmill from the computer. Following the warm-up period, participants then participated in a WRT familiarization trial on the treadmill. Treadmill velocity began at 1.5 mph and increased by .10 mph every 10 seconds. Participants were informed that the treadmill would gradually accelerate at a constant pace and eventually bring them to a speed where they would transition to a run. Participants were instructed to let the transition occur “naturally” if they asked for further direction or explanation. Very few instructions were given regarding the transition. This was done in an effort to deter participants from approaching the PTS from a mental aspect rather than physical. Participants were unable to see the speed of the treadmill throughout the duration of the locomotion trials. Participants were also informed that they could stop the trial with a verbal command or by grabbing the safety/stabilization handrail if they ever felt unsafe or uncomfortable. The point of transition or WRT was observed as evidence of the first flight phase during locomotion, or an obvious jogging locomotion. The investigators then gave 5-10 seconds following transition to ensure that the participant continued to run rather than revert back to a walking gait. The participants were then given verbal warning that the treadmill would stop.

WRT Trials

Following the familiarization trial, three additional WRT trials were conducted to find the participants’ PTS. The WRT trials were identical to the familiarization trial in protocol and treadmill acceleration. A 3-minute rest was given to the participants following the familiarization trial, and in between each WRT trial thereafter. After completion of the WRT trials, all reflective markers were removed. Participants then rested for 15-minutes.

Tibialis Anterior Muscular Endurance & Strength

Participants then participated in Tibialis Anterior (TA) Strength/Endurance testing trials. Participants were seated on a Biodex isokinetic machine (Biodex, Shirley, NY) with the test leg at a 120° angle of knee flexion and 90° (or neutral) for the ankle. The speed was set at 210°/s for dorsiflexion and 400°/s for plantar flexion. The participant first completed three isokinetic dorsiflexion maximal voluntary contractions (MVCs), beginning plantar flexed and initiating movement into dorsiflexion. This set of three counted as the warm-up as well as provided a baseline value MVC to be evaluated later on (Parijat & Lockhart, 2008). Following a 3-minute rest, participants then performed a fatiguing test on the Biodex machine. Participants performed isokinetic repetitions until they could no longer move through the full range of motion. This required the participant to perform as many repetitions as possible at the same settings as the strength test. The test concluded participants could no longer move through the full range of motion of dorsiflexion and plantar flexion

Data Analysis

The purpose of the overground trials was to collect data on active ROM at the ankle and hip, foot progression, vertical loading rates, stride length, stride frequency, the first peak of vertical ground reaction forces (VGRFs), and preferred walking speed (PWS). The variables derived from the first three successful overground trials were averaged for each limb. During the PTS trials, the WRT was defined as the first evident flight phase following toe-off of the opposite limb (Segers et al., 2006). PTS was defined as the speed at which this event occurred and was the only variable observed during the WRT trials.

The peak value from the three maximal repetitions on the Biodex machine was drawn from graphical data and indentified as the TA strength variable. Data graphs from the fatiguing test, or TA endurance, were be analyzed according to 60% of the peak torque value acquired during the strength trial. Specifically, when the torque value fell below 60% of the peak strength value for at least three consecutive repetitions, the endurance value was identified as that specific number of repetitions.

All data were collected and processed in Vicon Nexus software (VICON, Denver, CO, USA). Data were then further processed and analyzed in Visual 3D (C-motion Inc, Germantown, MD, USA). All data was filtered with a lowpass butterworth filter with a cut-off frequency of 6 Hz. VGRFs were measured using two Kistler force plates (Kistler, Amherst, MA, USA) and two AMTI force plates (Advanced Mechanical Technology, Inc., Watertown, MA, USA) mounted in the floor and were filtered at 40 Hz.

Statistical Analysis

A Classification and Regression Tree (CART) analysis was run in MATLAB (Mathworks, Natick, MA, USA) to identify and assess different contributing factors to transition speed. Specifically, the CART analysis subdivided the subjects on the basis of measurements that detected binary, ordinal or continuous covariates that maximized split criterion. Square error mean was used to determine the power of variables displayed in the tree. The generated tree was cross-validated in order to apply trends within the tree to its own data. The tree with the lowest of mean square error across splitters was selected and then minimized or “pruned” to eliminate less applicable variables. Such subdivisions allow for more generalized data to successfully predict outcomes of alternative data sets. A minimum leaf value (N value) of three participants was implemented.

As an additional exploratory measure, an Independent *t* Test was run on the results generated in the CART analysis. Specifically, the *t* test was used to determine if significant differences existed between the classification groups revealed by the CART tree. This method of analysis was a secondary approach to testing the significance of variables that contribute to the predictor variables themselves.

CHAPTER 4: RESULTS

Results

To avoid overfitting of the data to our specific participant pool, a cross-validation technique was used to determine how well the tree may represent the larger population. As a result of this process the original tree was pruned two levels (Figure 3.1). The CART analysis resulted in a tree with two splits and three terminal nodes. Gait velocity or PWS was identified as the primary splitter, creating a binary division at 1.61 ms^{-1}. A PWS above 1.61 ms^{-1} predicted a transition speed of 2.28 +/- 0.21 ms^{-1} for three participants, creating the first terminal node. The second strongest identified splitter within the tree was BMI, subdividing participants at 27 kg/m^2, with 27 participants below 27 kg/m^2 predicted to transition at 1.97 +/- 0.17 ms^{-1} and creating the second terminal node. Participants categorized above at BMI of 27 kg/m^2were predicted to transition at 1.8 +/- 0.13 ms^{-1} and creating the third and final terminal node for 12 participants Therefore, the primary and secondary splitters were identified as PWS and BMI, while the three terminal nodes represented three PTS values of 2.28 +/- 0.21 ms^{-1}, 1.97 +/- 0.17 ms^{-1}, and 1.8 +/- 0.13 ms^{-1}. The cross-validation technique generated mean square errors of 0.0734, 0.0565, and 0.0456 for the 2.28 +/- .21 ms^{-1}, 1.97 +/- 0.17 ms^{-1}, and 1.8 +/- 0.13 ms^{-1} terminal nodes, respectively. Overall group means are displayed in Figure 3.1.

As an additional exploratory measure, a series of independent t-tests were run on the two BMI groups (< 27 kg/m^2 and > 27 kg/m^2) demonstrated by the split in the CART analysis. Specifically, the t-tests were used to determine if significant differences existed between the two BMI classification groups on specific variables. The difference in passive hip ROM was statistically significant between the participants above and below 27 kg/m^2 ($p = 0.009 > 0.05$), at 136 +/- 13° degrees and 161 +/- 27°, respectively. Also, differences in TA endurance ($p = 0.043 < 0.05$) and step width ($p = 0.05$) were statistically significant, with participants above 27 kg/m^2 at TA endurance values of 32 +/- 2.48 repetitions and participants below 27 kg/m^2 at 24 +/- 0.71 repetitions. Step width values were shown to be 0.14 +/- 0.02 m and 0.11 +/- 0.01 for participants above and below 27 kg/m^2, respectively. This statistical method was investigative in nature and was not the primary form of analysis.

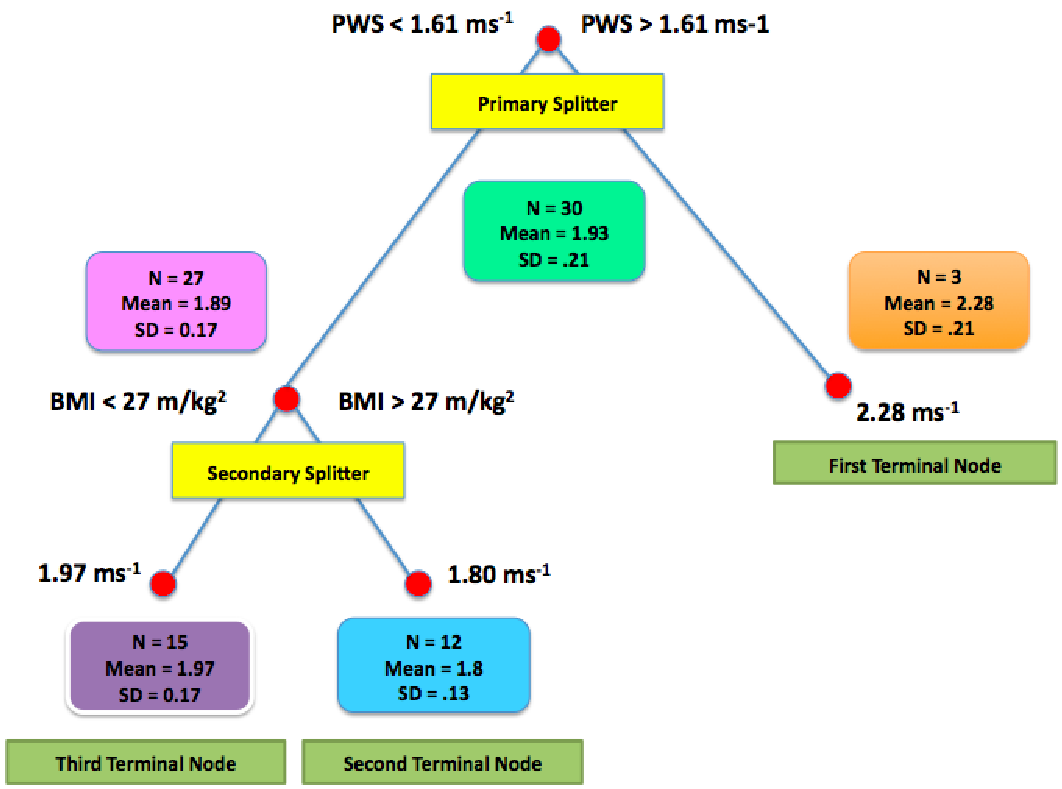

Figure 3.1 – CART Analysis Tree

Table 3.1 – Group Means and Standard Deviations from WRT Variables

VARIABLE	AVERAGE	STANDARD DEVIATION
Age (Years)	26.3	5.54
Height (meters)	1.75	0.1
Weight (kg)	83	28.93
BMI (m/kg^2)	27	9.27
Passive Ankle ROM (degrees)	76	11.39
Active Ankle ROM (degrees)	33	6.25
Passive Hip flex/ext ROM (degrees)	151	4.97
Active Hip flex/ext ROM (degrees)	38	24.02
Passive Hip add/abd ROM (degrees)	51	6.59
Active Hip add/abd ROM (degrees)	12	0.71
Step width (m)	0.13	0.03
Stride Length (m)	1.43	0.24
Cycle Time steps/min	1.02	0.15
TA Strength (ft/lb)	15.63	3.98
TA Endurance (repetitions)	28	9.49
PWS (ms^{-1})	1.41	0.14
PTS (ms-1)	1.93	0.21
VGRFs N/s	1.12	0.065
Loading Rates BW/s	7.13	1.43
Physical Activity (Scale 1-3)	2	1.41

Discussion

The primary purpose of the current study was to determine if basic anthropometrics or gait characteristics are predictive of the WRT and to determine their overall relationship to PTS. The analysis resulted in a primary and secondary split within the CART tree, the first split occurring at a preferred walking speed of 1.61 ms^{-1} and the second split occurring at a BMI of 27 kg/m^2. From these splitters, three terminal nodes formed. The first node included individuals above a PWS of 1.61 ms^{-1} who were predicted to transition at a speed that is considered fast compared to the other participants (2.28 ms^{-1}). Participants below 27 kg/m^2 were predicted to transition at 1.97 +/- 0.17 ms^{-1}, a speed that is considered to be average within the current research and consistent with previous literature. Participants categorized above a BMI of 27 kg/m^2 were predicted to transition at 1.8 +/-0.13 ms^{-1}, a speed that is classified as slow compared to the other participants.

Primary Splitter: Preferred Walking Speed

The CART analysis revealed PWS as the primary splitter, creating a binary division at 1.61 ms^{-1} for preferred walking speed and separating three participants into the upper classification (> 1.61 ms^{-1}) and 27 participants into the lower classification (< 1.61 ms^{-1}). A preferred walking speed of 1.61 ms^{-1} is outside the range of 1.3 – 1.4 ms^{-1}, a commonly accepted PWS mean value within gait related literature (Browning & Kram, 2006; Entin et al., 2010).

Within lower leg mechanics, the role of plantar flexors, dorsiflexors, and ankle angular velocities may relate to PWS. As previously noted by researchers, dorsiflexors and/or plantar flexors may play a significant role in PTS (Bartlett and Kram, 2008; Neptune and Sasaki, 2005; Segers et al., 2006). The role of the plantar flexors specifically applies to stabilization of the leg during stance, an observation that may lend to PTS. However, EMG data has shown plantar flexor activity to continue to increase following transition, an observation that does not classify it as a trigger variable (Bartlett & Kram, 2008; Hreljac, 2003). Conversely, dorsiflexors play a significant role in the WRT. During fast walking, a critical dorsiflexion angle is reached that initiates transition (Hreljac, 1995a). If an individual selects a PWS that is considered faster than other individuals, it is probable that from a musculoskeletal perspective, they are "comfortable" walking at faster speeds. Considering this, it is reasonable to suggest that a faster PWS may be associated to PTS simply due to delayed discomfort in the dorsiflexors during increasing gait velocity. This proposal may be directly related to the strength and endurance capabilities of the TA, as well as ankle ROM. Within the data of the current study, the average TA endurance capabilities of the participants separated into the 2.27 ms^{-1} terminal node was determined to be 28.21 repetitions, approximately .81 repetitions higher than the group average (27.83 +/- 5). Also, the average passive and active ankle ROM values for individuals above 1.61 ms^{-1} (passive = 76 +/- 26°, active = 32 +/- 2°) were similar to that of the individuals below 1.61 ms^{-1} (passive = 81 +/- 14°, active = 30 +/- 1°). Based on this observation, it is difficult to determine if TA endurance capabilities or ROM lent to the selection of PWS among the participants in that terminal node. Also, PWS itself has rarely been studied in relation to PTS. Previous studies have used normal walking gait velocity to identify kinetic variables that contribute to PTS; however, the gait velocities were derived as a percentage of the participants' PTS (Hreljac et al., 2008). Although such research produced valuable results regarding ankle dorsiflexor contribution to PTS, these findings were not reflective of a self-selected walking velocity. Therefore, there is a limited base of research on the relationship between PWS and PTS to draw conclusions from and use as a comparison model.

Secondary Splitter: Body Mass Index

The secondary splitter revealed by the CART analysis was BMI, creating a binary split at 27 kg/m^2. In previous literature, little evidence has been presented to link body size to PTS in humans. In quadrupedal gait, however, size plays a significant role in determining PTS. The Froude number has provided a solid foundational understanding of how animals locomote and transition (Alexander, 1977). Specifically, longer leg length and larger body mass both result in faster PTS within these studies. Theoretically, these same principles might be applicable to human locomotion. However, researchers examining leg length in humans have shown weak tendencies or relationships between PTS and leg length (Hreljac 1995b; Thorstensson & Roberthson, 1987). Body mass has also been examined, but on a smaller scale. However, the presence of BMI as a splitter within the CART is in the current study is inconsistent with previous findings that body size does not affect transition speed (Hreljac, 1995b). Hreljac (1995b) investigated the role of body mass but concluded it was insignificant to PTS values. However, the participant population did not represent a diverse selection of individuals with regards to

BMI or other anthropometric data. Specifically, Hreljac (1995b) used a subject population including both males and females, with varying body weight, height, and BMI. However, the range in mass only varied by 39.4 kilograms, body fat by 16.3%, and height by 36.7cm. Additionally, the greatest body fat percentage recorded was 25% and was that of a female participant. Also, BMI was not accounted for in the given study. This indicates that although there appeared to be a wide spread in height measurements and weight measurements, mass or body composition of the participants did not appear to vary greatly.

Conversely, the present study used a very diverse participant base, recruiting participants that were classified as normal weight, overweight, and obese according to BMI. Considering that BMI was shown to represent the secondary splitter within the CART, associations between gait characteristics and BMI should be examined. However, it should be noted that mass and height were added to the CART separately and were not classified as splitters. Yet, the combination of the two, i.e. BMI, yielded the secondary splitting variable. Therefore, the discussion will proceed by making comparisons to mass-related research while still considering mass alone was not a splitter in the current study.

With regards to animal studies, larger animals tend to transition from a walk-run at a faster speed. This may be due to larger skeletal structure, stronger musculature, and limb length (Hreljac, 1995b). However with humans, increased mass may have an inverse relationship with transition speed. As displayed by the CART, individuals with a BMI below 27 kg/m^2 were predicted to transition at 1.97 ms^{-1}, slightly higher than the group average of 1.93 ms^{-1}. However, BMI above 27 kg/m^2 had a PTS of 1.8 ms^{-1}, a value that is lower than the group average PTS from the current study as well as lower than the reported average of 1.9-2.1 ms^{-1} found in most PTS literature (Bartlett & Kram, 2008; Hreljac, 1995a; Hreljac et al., 2007; Hreljac et al., 2008; Rotstein et al., 2005; Segers et al., 2008; Thorstensson & Roberthson, 1987). This finding indicates that a) BMI may be related to PTS, or b) gait characteristics associated with BMI may be related to PTS. Given the opposing findings compared to quadrupedal research, it is difficult to refer to bodies of literature that are applicable to this result. However, there are several variables that may provide insight regarding this result. First, average passive ROM values for the participants above 27 kg/m^2 was 71 +/- 6° at the ankle and 136 +/- 13° for hip flexion/extension as compared to the overall group averages of 76 +/- 11° at the ankle and 151 +/- 24° for hip flexion/extension. Although ROM has not directly been identified as a contributing factor to PTS, it is possible that limited passive ROM could inhibit active ROM during fast walking. As discussed above, ankle angular velocity is also a strong PTS trigger, as critical angles are reached that initiate the transition (Hreljac, 1995a). Despite the differences in ROM data in the current study, ankle ROM was not identified as a splitter within the CART and therefore not considered to be a strong predictor of the PTS when compared to the current selection of variables. Another variable that was not revealed as a strong predictor within the CART was TA strength and endurance. In previous transition research, dorsiflexor endurance, fatigue, and moments are accepted as the most likely PTS triggers in humans (Bartlett & Kram, 2008). Although these variables were not identified as splitters in the CART analysis, it was noted that individuals in the participant classification group above 27 kg/m^2

demonstrated TA strength and endurance values higher (strength mean = 17.4 +/- 4.59 ft/lbs, endurance mean = 32 +/- 2.48 repetitions) than participants categorized under 27 kg/m^2 (group strength mean = 14.1 +/- 4.28 ft/lbs, group endurance mean = 24 +/- .71 repetitions). This result is intriguing given the observation that dorsiflexor endurance capabilities are likely a trigger of the WRT (Bartlett Kram, 2008; Segers et al., 2007a). The results of the current study show that a) TA strength and endurance was not a primary splitter, and b) the participants with the highest average transition speeds did not demonstrate the highest dorsiflexor testing results (TA strength = 16.8 +/- 3.57 ft/lbs, TA endurance = 28 +/- 2.12 repetitions). Additionally, it was unexpected that obese individuals would actually display the highest TA strength and endurance values. As discussed earlier in the current study, it was proposed that obese individuals may have lower TA fatiguing abilities due to their unique gait patterns. It is possible that obese individuals exhibited higher TA endurance and strength than other participants due to additional muscular demands needed to support greater mass (Hulens et al., 2001).

It should also be noted that the secondary splitter in the CART analysis occurred at a BMI value of 27 kg/m^2, separating participants in the lower range of the overweight classification and normal weight participants from the higher range overweight and obese participants. Because obese participants were included in this split, it is valuable to discuss research relevant to obesity walking mechanics as it applies to variables examined in the current study (i.e., mass, loading rates, VGRFs, and PWS).

A variable that is often studied in current obesity research is loading rate. Although loading rates were not identified as a splitter within the CART analysis, previous research surrounding this topic may shed light on the current study's results.

Grabowski et al. (2005) examined the effect of loading on the center of mass while walking. Adding weight and mass equal to 50% of body weight was shown to double net metabolic cost. However, just adding mass alone only increased net metabolic rate half as much as weight and mass combined. These results demonstrate that load carrying increases the demand on muscles to support a greater weight during stance. This in turn requires additional work to redirect and accelerate a greater mass during step-to-step transitions (Grabowski et al., 2005). Additionally, loading rates have been identified as a stress inducing mechanism within the body (Raynor et al., 2002). This implies that loading rates illicit a response to the mechanical stress being applied at the given joint (Raynor et al., 2002). Griffin et al. (2003) examined the biomechanics and energetics of walking with regard to leg function and loading. By investigating leg swing and force generation during stance, researchers found that the metabolic cost of leg swing was not increased despite increased loads (Griffin et al., 2003). Instead, it was proposed that the metabolic cost of walking is directly proportional to the volume of muscle that is actively generating force against the ground (during stance) and the rate of generating this force. Additionally, obese individuals tend to spend more time in stance while walking and less time in swing (Browning & Kram, 2007). This base of research also supports the theory that obese adults experience a greater rate of joint loading (Browning & Kram, 2007).

These findings suggest that obese individuals tend to adopt slower walking paces to reduce these joint loads.

It has also been observed that obese individuals appear to choose slower preferred walking speeds to decrease joint loads (Browning & Kram, 2007). Raynor et al. (2002) demonstrated that loading rates play a vital role in PTS selection, as well as time to first peak in vertical ground reaction forces displayed during transition. Li & Hamill (2002) also observed that loading rates increase as the WRT approached, as well as the first peak of the VGRF. Previous research has shown that obese individuals exhibit higher ground reaction forces in gait related studies (Browning & Kram, 2007). Based on this finding and the results given in the current study, we hypothesized that an individual who is considered obese would produce higher VGRFs, higher loading rates, and therefore slower PTS. However, the current study revealed similar results between VGRF and loading rate values between the two BMI classification groups. VGRF was reported as 1.10 +/- 0.08 N for the upper BMI class while 1.11 +/- 0.02 N was reported for the lower BMI class. Also, loading rate values were reported at 6.9 +/- 0.15 BW/s and 7.2 +/- 0.74 BW/s for the upper and lower BMI classes, respectively.

As stated in the results, a series of independent *t* tests were used to analyze differences in variables between the two BMI classification groups split at 27 kg/m^2. This measurement was used as an exploratory tool to further understand the results displayed in the CART analysis tree. It was shown that differences in passive hip flexion/extension, TA endurance, and step width between the two BMI classification groups were all statistically significant according to the Independent *t* Test. Examination of these variables may provide further insight on the differences between the BMI groups and the contributions of these variables to the PTS.

Overall, the passive hip flexion displayed by the upper BMI group (> 27 kg/m^2) was less than the lower BMI group (< 27 kg/m^2) by approximately 25°. As discussed above, there is evidence within gait transition literature that emphasizes the role of ankle dorsiflexion capacity (Bartlett & Kram, 2008). Although the hip has not been shown to reach critical angles associated with PTS, the contribution of the hip to walking and running may be worth examining. Recently, Riley et al. (2010) proposed that peak hip extension angles and maximal length of single joint hip flexors do not change with increasing speeds. Based on this finding, it is possible that participants demonstrating decreased hip ROM values while walking would display the same ROM values as they approached PTS. Based on the significant results of this data, it is possible that decreased hip ROM may contribute to slower PTS.

With regards to TA endurance, it is surprising that individuals in the upper BMI group demonstrated higher TA endurance values at 32 +/- 2.48 repetitions as opposed to 24 +/- .71 repetitions exhibited by the lower BMI group. As discussed above, TA fatigability is one of the most relevant PTS triggers within transition literature. For the purpose of this study, it seemed plausible to assume that fatigability and strength would be directly related to faster PTS values. However, the results of the current study refute that prediction. Additionally, it was the individuals in the upper BMI group who displayed the highest TA test values. Previous research on leg extension strength differences between normal weight and obese participants has shown obese individuals to be stronger (Hulens et al, 2001). This finding can possibly be explained by the constant increased weight bearing and support capabilities induced by increased body mass (Hulens et al., 2001). Given this, it is possible that increased strength or endurance in the TA may be a result of supporting an increased amount of mass.

Overall, the Independent *t* Test revealed statistical differences between several variables within the BMI classification group, the secondary splitter within the CART. This method of analysis helped further explore the results of the CART and provided an ulterior perspective.

Limitations

There are several limitations within this study that should be addressed. First, BMI classification was a variable used in the present study to categorize participants based on anthropometric data. Due to the majority of size-related PTS studies examining length and mass contributions, BMI is an appropriate variable for the current study. However, it may be useful to integrate body fat measurements into future research as an additional variable relating to size or body mass contributions to PTS.

Additionally, comparisons made between the current study and studies using obese participants should be approached carefully. The split displayed in the CART was at 27 kg/m^2, a value that represents the upper limit of overweight individuals as well as obese individuals above 30 kg/m^2. Comparisons made to research conducted on obese participants is often more specific. For example, Browning et al. (2009) included only obese participants (BMI = 30-40 kg/m^2) and did not include overweight individuals. However, given the positive association between the current study and Browning et al.

(2009), it is reasonable to suggest that future research using heavier participants within the parameters of this study may demonstrate similar if not more applicable results.

Overall, the CART analysis was used in the present study because it provided an appropriate analysis of variables that are most relevant to PTS within the parameters of this study. However, we actively chose the list of variables analyzed based on their relevance to PTS research. Therefore, there is the potential that different results or CART trees could be generated depending on what variables are being evaluated. We believe that this aspect does not weaken the current study; rather, it provides the opportunity to examine alternative variables in relation to the present CART tree generated. Due to the complex nature of the PTS, it is possible that variables that contribute to PTS were not observed in this study and may have played a role in the given outcome.

Conclusion

According to the CART analysis, PWS and BMI were identified as the best predictors for PTS compared to the other measure variables. Previously, preferred walking speed has not been identified as a predictor of PTS. Also, there is limited research available on the relationship between BMI and the WRT. However, it should be mentioned that although previously established predictors such as TA fatigue and ankle velocity were not significant, their importance to PTS research is not disregarded. Instead, the current results only affirm that PTS needs to be investigated within more diverse populations in order to gain further understanding.

Also, the current study differed from previous forms of research by not focusing on causes or triggers of the PTS. Instead, we wanted to investigate if participant characteristics were predictive of PTS. The variables derived from the CART analysis are viewed as predictive contributors to PTS, not causes. Despite this difference, there is still the potential to make associations between variables classified as “triggers” or “predictors”. Further research is required to compare a separate set of participants with similar methods to the current study in order to test the predictive ability of the present CART tree. Also, given the significance of PWS and BMI in the present study, future studies on WRT should include these variables.

As stated above, it was the primary goal of the current study to use a diverse subject population to gain further insight on the PTS. As demonstrated in the results, the use of a heterogeneous population with regards to BMI provides a broader investigation of the diversity seen in human gait and locomotion patterns. However, the contribution of BMI and PWS to PTS have not been investigated in previous studies. Therefore, the present study provides valuable information on these variables, although their relationship to PTS is less understood. Also, it was concluded that participants with a BMI over 27 kg/m^2 transitioned sooner than those with lower BMIs. Although this observation is significant, the reason as to why it was significant is a question requiring further evaluation.

Overall, the relevance of BMI in the current study has opened up a new area for transition research. There are a number of relevant and important PTS trigger variables already established in PTS research, but these findings have been generalized to a very narrow subject population. The current study provides evidence that more variables may exist that play pivotal roles in PTS, especially within participant pools that aren’t typically investigated. In general, the WRT and PTS are likely influenced by multiple factors. This may be one reason that results from previous research that focused on individual variables are somewhat ambiguous. This is consistent with what we found in the current study. No single, specific variable or anthropometric variable was found to be predictive of PTS. Rather, composite variables such as BMI and gait velocity were found to be the most relevant. This may indicate that more work needs to be done to determine the specific nature of the differences between gait patterns of the obese and normal weight individuals as well as normal and fast PWS groups. It is likely that there are differences across multiple variables between these groups and it is the collective nature of these differences that influence the PTS. Therefore, future research on PTS must examine diverse populations in order to gain further insight on transition speed, as well as the specific contributions of BMI and PWS.

CHAPTER 5: SUMMARY

The walk-to-run transition (WRT) and preferred transition speed (PTS) are affected by various kinematic and kinetic variables. However, these triggers or causes of the WRT have been derived from research that has focused on a narrow participant population base. Typically, WRT or PTS research is conducted on normal weight and healthy adults. Although this research has proved valuable, conclusions based on such a homogeneous population may not be applicable to human gait patterns in general. Therefore, it was the purpose of this study to examine a diverse cohort of participants with regards to BMI and approach PTS variables from a broader perspective. Specifically, rather than focus on mechanisms responsible for the transition, the primary goal was to determine if basic anthropometrics or gait characteristics are predictive of this transition. 30 participants (n = 13 male; n = 11 normal weight, n = 10 overweight, n = 9 obese; age M = 26.3, SD = 5.5 years; height M = 68.8 SD = 3.8 inches; weight M = 182.6, SD = 41.0 lbs; BMI = 27 kg/m^s) completed one testing session that involved passive range of motion measurements, overground walking trials, preferred transition speed trials, and tibialis anterior strength and fatigue tests.

Both preferred walking speed and body mass index were identified as the most predictive variables of PTS through the use of a Classification and Regression Tree (CART) analysis. Specifically, the PWS splitter was divided at 1.61 ms^{-1} and BMI was divided at 27 kg/m^2. Also, a series of t tests revealed significant differences between participants for hip range of motion ($p = 0.009 > 0.05$), tibialis anterior endurance ($p = 0.043 > 0.05$), and step width ($p = 0.05 \geq 0.05$).

Conclusions

Previously, preferred walking speed has not been identified as a predictor of PTS. Also, there is limited research available on the relationship between BMI and the WRT. In general, it is likely that there are differences across multiple variables between these groups and it is the collective nature of these differences that influence the PTS. Therefore, the results of this study only affirm that PTS needs to be investigated within more diverse populations in order to gain further understanding.

Also, the current study deviated from previous forms of research by not focusing on causes or triggers of the PTS. Instead, the purpose was to investigate if participant anthropometric and gait characteristics were predictive of PTS. The variables derived from the CART analysis are viewed as predictive contributors to PTS, not causes. Further research is required to compare a separate set of participants with similar methods to the current study in order to test the predictive ability of the present CART analysis. Also, given the significance of PWS and BMI in the present study, future studies on WRT should include these variables. However, the contribution of BMI and PWS to PTS have not been reported in previous studies, let alone investigated. Because of this, the role of both PWS and BMI, although valuable, is less understood. Also, it was concluded that increased BMI caused participants to transition sooner. Although this observation is significant, the reason as to why it was significant is a question requiring further evaluation.

Overall, the relevance of BMI in the current study is valuable to transition research. There are a number of relevant and important PTS trigger variables already established in PTS research, but these findings have been generalized to a very narrow subject population. The current study provides evidence that more variables may exist that play pivotal roles in PTS, especially within participant pools that aren't typically investigated. In general, the WRT and PTS are likely influenced by multiple factors. This may be why the results from previous research using individual variables are somewhat ambiguous. This is consistent with what we found in the current study. No single, specific variable or anthropometric variable was found to be predictive of PTS. Rather, composite variables such as BMI and gait velocity were found to be the most relevant.

Recommendations for Future Research

Based on these conclusions, it is necessary that research on the WRT and PTS targets the specific nature of the differences between gait patterns of the obese and normal weight individuals as well as normal and fast PWS groups. It is likely that there are differences across multiple variables between these groups and it is the collective nature of these differences that influence the PTS. Therefore, future research on PTS must examine diverse populations in order to gain further insight on transition speed, as well as the specific contributions of BMI and PWS.

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APPENDIX A

Variable Definitions

Variable Definitions

Body Mass Index – weight in kilograms divided by height in meters squared (kg/m^2)

End-feel – The specific quality of movement felt by an examiner moving a joint to the end of its range of motion (Starkey & Ryan, 2002).

Foot progression angle – Angle made by foot with plane of progression (Kirtley, 2006)

Initial Transition Limb (ITL) – The limb that comes into contact with the ground prior to the presence of a flight phase

Vertical loading rates – The rate at which a load is applied in the vertical plane

Preferred Transition Speed (PTS) – The speed at which an individual transitions from a walk to run. For the purpose of this study, PTS is defined as the velocity of the center of mass at toe off at the transition step.

Stride frequency – The number of strides per unit of time

Stride length – The distance between two successive contacts of the same foot

Transition step – The first step with a flight phase in WRT (Segers et al., 2007)

Vertical ground reaction forces – The vertical forces exerted by the ground on the body during contact

Walk-to-run transition (WRT) – The point at which a flight phase is evident or the absence of a double support phase (Thorstensson & Roberthson, 1987).

APPENDIX B

Reflective Marker Photos

Reflective Marker Photos