TO RUN OR WALK UPHILL: A MATTER OF INCLINATION

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ABSTRACT

People prefer to walk at slow speeds and to run at fast speeds. In between, there is a speed at which people choose to transition between gaits, the Preferred Transition Speed (PTS). At slow speeds, it is metabolically cheaper to walk and at faster speeds, it is cheaper to run. Thus, there is an intermediate speed, the Energetically Optimal Transition Speed (EOTS). My goals were to determine: 1) how PTS and EOTS compare at inclines relevant to trail and mountain runners and 2) if the heart rate optimal transition speed (HROTS) can predict either the EOTS or PTS. Ten healthy, high-caliber, male trail and mountain runners participated. On day 1, data for 0° and 15° were collected and on day 2, 5° and 10°. PTS was determined by averaging the run-to-walk transition speed (RWTS) and walk-to-run transition speed (WRTS) using an incremental protocol. EOTS was determined from metabolic cost data for walking and running at three or four speeds per incline near the expected EOTS. The intersection of the walking and running linear regression equations defined EOTS. HROTS was determined using the same linear regression procedure. PTS, EOTS, and HROTS all were slower on steeper inclines. PTS was slower than EOTS at 0°, 5°, and 10°, but the two converged at 15°. PTS and EOTS were moderately correlated at best. Although EOTS correlated with HROTS, heart rate is not an accurate tool for predicting EOTS.

INTRODUCTION

People prefer to walk at slow speeds and to run at fast speeds. In between, there is a speed at which people choose to transition between gaits, the Preferred Transition Speed (PTS). At slow speeds, it is metabolically cheaper to walk and at faster speeds, it is cheaper to run. Thus, there is an intermediate speed, the Energetically Optimal Transition Speed (EOTS). The prevailing scientific thinking into the 1980s was that people transition between gaits to minimize energy expenditure [10], i.e. that PTS = EOTS. But more recent research indicates that the PTS occurs at a speed slightly slower than the EOTS [8] [21] [30]. In 1993, a leading researcher on the topic of the walk-run gait transition, Alan Hreljac, found that on level terrain, the average PTS was 2.06 m/s and the EOTS was 2.24 m/s [8]. Minetti et al. [21] and Rotstein et. al. [30] found very similar results. If energetics do not trigger the walk-run transition, perhaps biomechanics do.

As a framework for identifying a biomechanical trigger, in 1995, Hreljac [10] proposed that four criteria should be met. Criterion 1 is that, at the PTS, an abrupt change in the proposed causal variable (PCV) must take place, so that the value in walking is much greater than in running at the PTS or *vice versa*. Criterion 2 is that the lower value of the PCV in one gait at the PTS must reach similar values in the other gait at a speed either slower or faster than the PTS. The first two criteria usually occur together. Criterion 3 is that neural proprioceptors must be able to detect the change in the PCV. This criterion is rarely tested, due to the invasive procedures necessary. Criterion 3 is usually just assumed to be true if there is a biologically plausible explanation for the PCV satisfying this criterion. Criterion 4 is that the PCV must reach a critical value that the person avoids, choosing to transition between gaits rather than exceeding the critical value. Originally, Hreljac proposed that all four criteria need to be met.

However, in 2008, Hreljac was less stringent and considered a variable to be a determinant of the PTS if only two of the criteria were met [14].

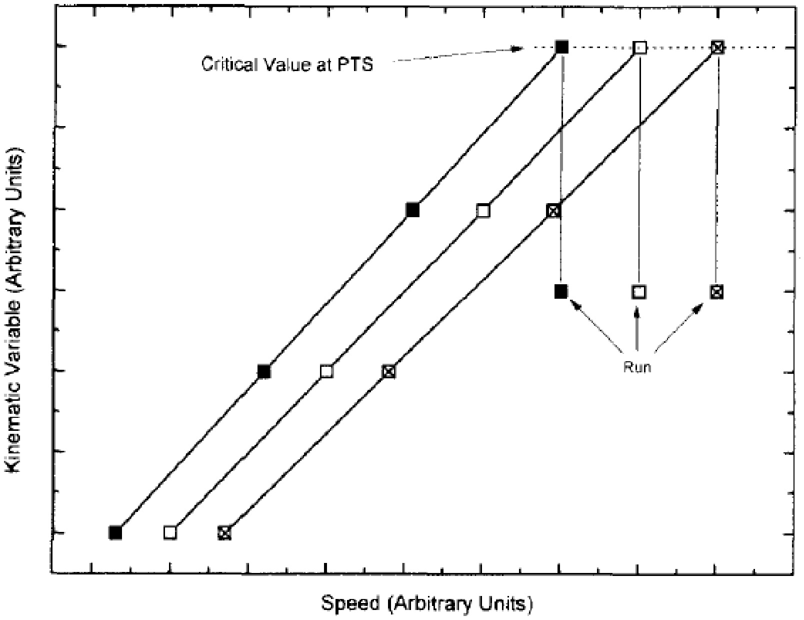

Figure 1: This diagram, from Hreljac [10], is a visual representation of criteria 1, 2, and 4 being satisfied for an arbitrary kinematic value in three different conditions.

There is no clear consensus on what mechanism triggers the walk-run gait transition on level terrain [19], but there are six popular hypotheses: local fatigue, kinetic variables, muscle force-length relationship, kinematic variables, inverted pendular mechanics and metabolic substrate conservation.

The local fatigue hypothesis posits that the gait transition is triggered to avoid overexertion of a specific muscle (or muscles). There is a greater totality of evidence for this hypothesis, but no overwhelming consensus as to which muscle/muscle group is critical. Hreljac has concluded in three studies that overexertion of the ankle dorsiflexor muscles triggers the walk-to-run transition [10] [12] [14]. Abe et. al. [1] concur, but also found that soleus muscle activity decreases when switching to running at the PTS. Consistent with those studies, Bartlett and Kram [3] showed that an external elastic device, that provides dorsiflexion and relieves the tibialis anterior, extends the PTS to a slightly faster speed. However, Bartlett and Kram also showed that an external elastic device, that provides hip flexion and relieves the rectus femoris, also extends the PTS to a slightly faster speed. More generally, Prilusky and Gregor [27] showed that when walking speed is increased towards the PTS, hip flexor, knee flexor, and dorsiflexor muscles are overexerted and are relieved by switching to running. Conversely, as running speed is decreased towards the PTS, Prilutsky and Gregor found that the knee extensor and plantar flexor muscles are overexerted and are relieved by switching to a walking gait. Overall, while the scientific consensus on which muscles trigger the gait transition is not unanimous, the strongest evidence for one specific muscle triggering the PTS points to the tibialis anterior.

It has also been hypothesized that kinetic variables such as ground reaction forces (GRF) are triggers for the walk-run transition. In 1993, Hreljac [9] tested five kinetic variables (maximum vertical loading rate, braking and propulsive impulse, and braking and propulsive force peaks) but found that none met the four criteria for being a PTS trigger. However, in 2002, Raynor et. al. [28] found that the increased time to the first GRF peak and the decreased vertical loading rate in walking were likely determinants of the PTS. In 2008, Hreljac [14] determined that the maximum dorsiflexor moment increased with walking speed and that switching to running reduced the dorsiflexor moment.

Force insufficiency due to the muscle force-length relationship is another proposed gait transition trigger. Neptune and Sasaki [23] found that, when walking at the PTS, the plantar flexor muscle force production was severely impaired during walking at/near the PTS, despite an increase in EMG muscle activation. They concluded that plantar flexor muscles were operating away from the optimal point on their force-length relationship as walking speed approached the

PTS. Neptune and Sasaki further noted that the force generating ability of those muscles returns immediately when the person changes to a running gait which suggests that the plantar flexor muscles were not fatigued.

Kinematic variables may also trigger gait transition. For example, Hreljac [10] found that maximum ankle dorsiflexion angular velocity ($\omega_{max\text{-}dorsi}$) was a trigger for the gait transition, since $\omega_{max\text{-}dorsi}$ was lower in running than in walking at the PTS (criteria 1 and 2). A critical value for this variable was not exceeded despite altering the PTS by varying incline (criterion #4), and the effect size between incline and $\omega_{max\text{-}dorsi}$ was negligible. Hreljac [10] also found that the maximum ankle dorsiflexion angular acceleration ($\alpha_{max\text{-}dorsi}$) nearly qualified as a trigger for a gait transition (via all four criteria). At the PTS, the $\alpha_{max\text{-}dorsi}$ was lower in running than in walking (meeting criteria 1 and 2), a critical value for this variable was not exceeded despite altering the PTS by varying incline (meeting criterion 4), and the effect size between incline and $\alpha_{max\text{-}dorsi}$ was small. Hreljac concluded that the relationships between $\omega_{max\text{-}dorsi}$, $\alpha_{max\text{-}dorsi}$ and PTS support the view that dorsiflexor local fatigue is the trigger for the walk-to-run transition.

The physics of the motion of the body's center of mass inform another hypothetical gait transition trigger. Walking is usually modelled as an inverted pendulum with a point mass at the center of mass (COM) and two massless, rigid legs [5]. Inspired by such simple models, Kram et al. [18] utilized simulated reduced gravity and observed how the PTS was altered. They found that simulating reduced gravity slowed the PTS in a systematic way such that the dimensionless Froude number (the ratio of the centripetal force and the gravitational force) stayed nearly constant despite the change in gravity. The authors concluded that the mechanics of an inverted pendulum model for a human walking are the trigger for the walk-to-run gait transition.

Despite the strong evidence for a biomechanical trigger for the PTS, there is a recent hypothesis proposed that supports a metabolic trigger. In 2011, Ganley et. al. [6] found that the respiratory exchange ratio (RER, ratio of CO_2 production to O_2 consumption) when running and walking at or near the PTS hardly changed at faster running speeds but increased with speed in walking. A higher RER reflects an increased relative reliance on carbohydrate as a metabolic substrate, relative to fat. The RER differences were not accompanied by significant changes in blood lactate, leading researchers to conclude that the RER differences between gaits were the result of metabolic substrate utilization differences. Upon further investigation, they found that carbohydrate oxidation rates were equal between running and walking at the PTS. The reason that overall energy expenditure was higher when running at the PTS was solely due to increased fat oxidation while running. When locomoting slightly faster than the PTS, walking utilized more carbohydrate, while running did not. When locomoting slightly slower than the PTS, walking utilized less carbohydrate, meaning that the carbohydrate sparing optimal transition speed (CARBOTS) occurred at the PTS. Fat oxidation was always higher in running near the PTS.

It is now clear that metabolic cost is not the trigger of PTS [8] [21] [30] on flat terrain. This may be because the gluteus maximus, rectus femoris, vastus medialis, and vastus lateralis, all large leg muscles, are slightly more active when running than when walking at speeds near the PTS [24]. These larger muscles have a greater overall effect on metabolic cost than smaller muscles such as the tibialis anterior. It is plausible that at the PTS, large differences between gaits in tibialis anterior activity (or other smaller muscles) have a substantial effect on the PTS, despite not significantly altering metabolic cost. Conversely, small differences between gaits in larger leg muscles activity (gluteus maximus, rectus femoris, etc) may not have a large effect on the PTS, despite significantly altering metabolic cost.

Body dimensions and perceptual effects are not the primary PTS triggers, but they can explain some of the variation in PTS among individuals. Anthropometric variables such as leg length [31] (which increases PTS) can account for some variation among individuals, but the relationship in humans between various leg length measurements and PTS is not as strong as in quadrupeds [11]. Visual effects that distort a person's perception of speed while on a treadmill can also affect PTS [22]. Finally, different protocols can change the PTS [13]. PTS determinations often reveal a hysteresis effect, in which the walk-to-run transition speed (WRTS) is usually greater than the run-to-walk transition speed (RWTS). When locomoting at speeds between the RWTS and the WRTS, subjects will run during RWTS determination but walk during WRTS determination.

Compared to all of the gait transition research on level ground (or treadmills), research focused on the walk-run transition on inclines is quite sparse. That being said, it is already well-documented that the PTS is slower on inclines [8] [21] [30]. But only one published scientific study has compared PTS and EOTS on inclines. Minetti et al [21] found that: the PTS and EOTS were slower uphill compared to level ground and the PTS was slower than the EOTS on all inclines measured (up to 8.5°). They also found that the difference in speed between the two transition speeds remained constant (at about 0.2 m/s) on those moderate grades.

Although gait transition on inclines has been little studied, the topic is of great interest to trail and mountain runners who often ponder whether they should walk or run uphill. Everchanging factors such as the steepness of the incline, speed of the participant, length of the climb, ground surface, and the overall duration of the race all affect an individual's gait selection process. Many trail and mountain runners use devices such as GPS watches and heart rate monitors to guide them in training and racing. Determining how these devices may help athletes determine optimal gait selection is of practical importance.

The purpose of this study was to determine how the PTS and EOTS change over the range of inclines that trail and mountain runners commonly experience. Specifically, I wanted to investigate how incline affects the PTS, EOTS and the relationship between the two. I also wanted to determine how heart rate is influenced by gait selection.

My first hypothesis was that PTS and EOTS would both be slower on steeper inclines. I also hypothesized that PTS would be slower than EOTS but the difference in speed between the PTS and EOTS would converge at steeper inclines. I thought this would occur because both walking and running are more metabolically demanding at steeper inclines and thus there would be greater drive to minimize energetic cost. Finally, I hypothesized that heart rate optimal transition speed (HROTS) and EOTS would be equal at each incline. I thought this would occur because heart rate generally correlates with energetic cost during steady state endurance exercise [2].

Investigating how incline affects optimal gait selection is important to me because many trail and mountain running coaches and athletes believe that deciding whether to walk or run uphill is solely determined by speed or solely determined by incline [29]. I sought to inform practitioners of the nuance and complexity of gait selection in the context of their sport. I also feel that researching and comparing PTS and EOTS are important, because many trail and mountain running coaches and athletes utilize a cardiovascular or energetic model of training [17], and I wanted to learn if determining gait selection through this lens was appropriate. Furthermore, since coaches and athletes often utilize heart rate monitors to approximate cardiovascular stress or energetic cost [16], I also wanted to learn if this was a useful tool for approximating EOTS.

METHODS

Subjects

Ten healthy, high-caliber, male trail and mountain runners (28.7 ± 5.7 yr, 1.79 ± 0.06 m, 67.6 ± 4.9 kg) volunteered and provided informed consent as per the University of Colorado Institutional Review Board. All subjects were high-level athletes, who had all run up Green Mountain (a popular trail in Boulder, Colorado, USA that ascends 713 m) in less than 40 minutes via the standard route (https://www.strava.com/segments/843314) or had placed in the top 10% in a trail or mountain running competition within the previous two years.

Experimental design

The study consisted of two sessions, each lasting ~3 hours. During both sessions, subjects warmed up on the level treadmill by running for 10 minutes at a speed of their preference. On Day 1, I collected data for walking and running at 0° and then at 15° (26.8% grade). On Day 2, I collected data for walking and running at 5° (8.7% grade) and then 10° (17.6% grade). I chose to not randomize the order of inclines so that both days of testing would be of relatively equal intensity, thus mitigating fatigue. I chose to not randomize the order of the days since there was a chance that some subjects would be unable to complete the 15° condition due to lack of fitness, and I wanted to determine this on Day 1, as opposed to Day 2, so as to not waste the subject's time. However, one subject needed to do 5° and 10° on Day 1 (and 0° and 15° on Day 2) due to constraints in his training program. For each incline, I first determined PTS and then collected metabolic data to calculate EOTS. Due to various technical difficulties with the treadmill and ParvoMedics software, two subjects had to return to the lab for a third visit to repeat one of the inclines. Two more subjects returned to the lab to repeat 15° since their original 15° trials did not capture their EOTS. For each subject, I randomly assigned half the subjects to the “walk first” gait order and half to the “run first” gait order.

Subjects walked and ran on a classic Quinton 18-60 motorized treadmill with a rigid steel deck (Quinton Instrument Company, Bothell, WA). I used a M-D SmartTool™ 24" calibrated digital level (M-D Building Products, Mississauga, Canada) to set the treadmill incline and a Shimpo DT-107A calibrated digital tachometer (Electromatic Equipment Company, Cedarhurst, NY) to measure treadmill speed.

Determination of PTS

The average of the WRTS and RWTS defined the PTS as per Hreljac [13]. I first determined the WRTS in the “walk first” group and then their RWTS and *vice versa*. For WRTS trials, the initial speed was 1.0 m/s at 0°, 0.8 m/s at 5°, 0.6 m/s at 10°, and 0.4 m/s at 15°. For the RWTS trials, the initial speed was 3.0 m/s at 0°, 2.8 m/s at 5°, 2.6 m/s at 10°, and 2.4 m/s at 15°. Based on pilot experiments, I selected those speeds, such that there was no doubt which gait would be preferred at the initial speeds. Once the speed of the treadmill was correctly set, subjects mounted the treadmill and were allowed to choose their gait *ad libitum*. Specifically, I asked the subject: “Do you prefer to walk or run at this speed?”. Once the preferred gait at the particular speed was determined, the subject straddled the treadmill belt while the speed was changed (increased during WRTS trials, decreased during RWTS trials) by 0.1 m/s. The process repeated until a gait transition occurred; this speed was considered the transition speed.

Determination of EOTS

The initial speeds for each subject were 2.2 m/s at 0°, 2.0 m/s at 5°, 1.8 m/s at 10°, and 1.5 m/s at 15° based on pilot experiments indicating that these speeds would be near the EOTS. Subjects in the “walk first” group walked at the incline specific starting speed for 5 minutes, rested for ~5 minutes and then ran at that speed for 5 minutes. Subjects in the “run first” group did the opposite. During the rest periods, I re-weighed the subject and they drank just enough water to compensate for the weight loss due to sweating. Thus, each subject maintained a nearly constant weight throughout all the trials.

To measure the metabolic rates during walking and running, I used an open-circuit, expired gas analysis system (TrueOne 2400; ParvoMedics, Sandy, UT). Subjects were instructed to not eat or ingest caffeine for the 2 hours prior to metabolic testing. Subjects wore a mouthpiece with a one-way breathing valve and a nose clip allowing me to collect their expired air. The ParvoMedics software calculated the rates of oxygen consumption ($\dot{V}O_2$) and carbon dioxide production ($\dot{V}CO_2$) and I averaged the last 2 minutes of each 5-minute trial. I then calculated metabolic rate in W/kg using the Péronnet and Massicotte equation [26], as clarified by Kipp et al. [15]. I only included trials with respiratory exchange ratios (RER) <1.0 which ensured that metabolic energy was predominantly being provided from oxidative pathways. I used an R7 Polar iWL (Polar Electro Oy, Kempele, Finland) to measure heart rate and averaged the data of the last 2 min of each trial.

Immediately after both gaits were completed for the starting speed, I compared the metabolic rates for walking and running. If walking was the more economical gait, the treadmill speed was increased by 0.1 m/s, and the process was repeated. If running was the more economical gait, the treadmill speed was decreased by 0.1 m/s, and the process was repeated.

Each subject performed three or four speeds, both walking and running at each incline, and the three speeds where the differences between metabolic rates between walking and running were smallest were used in linear regression equations for both walking and running.

Data Analysis

Linear regression equations for metabolic cost and heart rate as functions of speed were calculated for each subject and incline. The running and walking equations were then compared to each other, and the speed at which the two equations intersected was considered the EOTS and HROTS, respectively. The linear regression equations were created in Python (code written by Derek Wright) (Python Programming Language, Beaverton, OR), and verified in Microsoft Excel (Microsoft Corporation, Albuquerque, NM).

As expected, at all inclines, walking generally required less metabolic power at slow speeds and running required less at faster speeds. At a result, regression lines for metabolic power vs. speed in the two gaits intersected. An example for one subject at 15° incline is depicted in Figure 2A. Heart rates also generally showed similar patterns and an example of the heart rate optimal transition speed (HROTS) is shown in Figure 2B. Overall, I analyzed ten subjects at four different inclines, i.e. 40 determinations of EOTS and HROTS. Of those 80 linear regression analyses, the walking vs. running regressions did not converge/intersect at a speed < 3 m/sec for two subjects (one subject for EOTS at 15° and a different subject for HROTS at 10°). Essentially, those regression lines were nearly parallel. I chose to exclude those two conditions from further statistical analysis and aggregate data compilation.

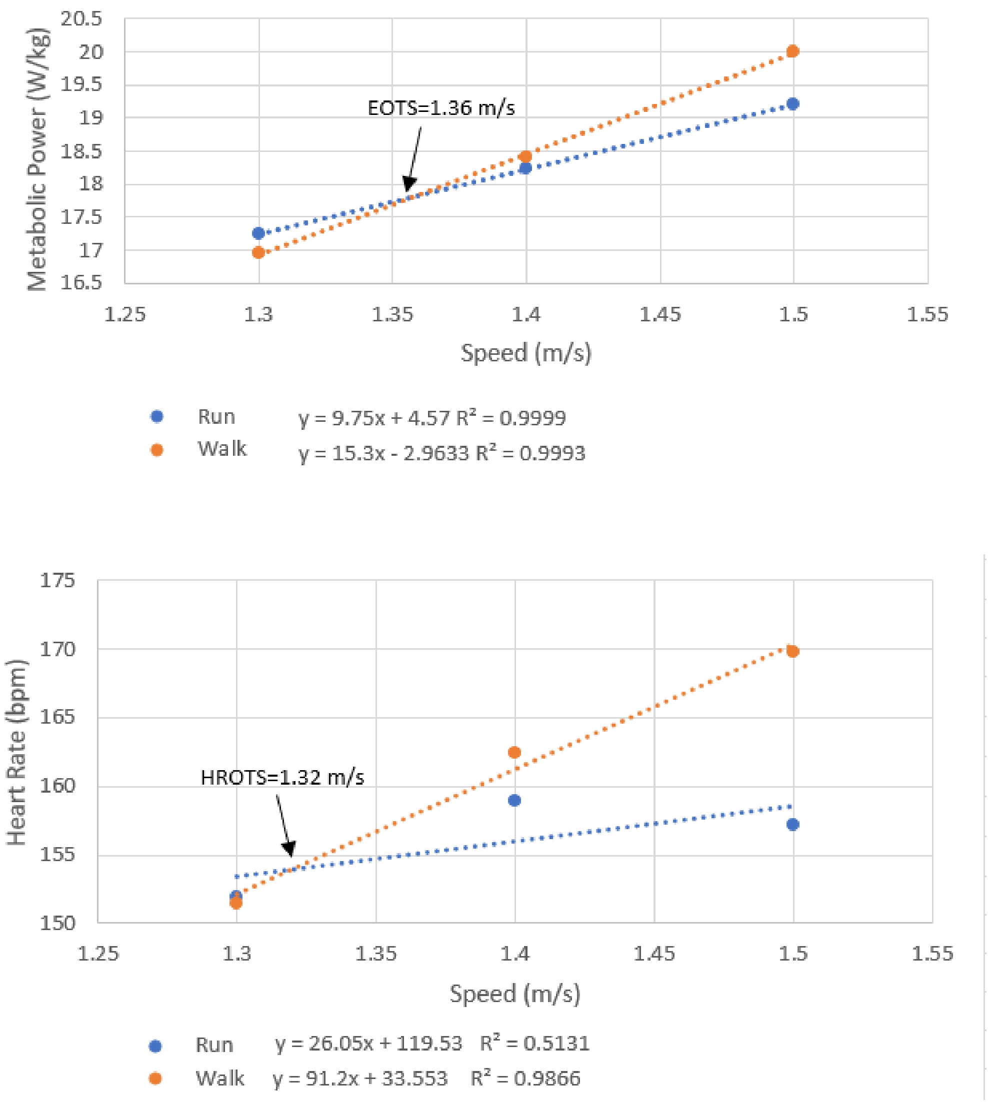

Figure 2A: An example of an EOTS linear regression analysis for one subject on a 15° incline. **B**: An example of an HROTS linear regression analysis for the same subject on a 15° incline.

I analyzed the data using RStudio (RStudio Team, Boston, MA). I performed a linear regression analysis to determine how PTS, EOTS, and HROTS changed with incline. Next, I performed paired t-tests comparing PTS vs. EOTS, PTS vs. HROTS, and EOTS vs. HROTS at each incline.

RESULTS

My major findings are displayed in Table 1.

Table 1: PTS, EOTS, and HROTS averages for each incline. Results presented as mean ± SD.

Incline (°)	**0**	**5**	**10**	**15**
PTS (m/s)	1.95 ± 0.12	1.78 ± 0.27	1.62 ± 0.14	1.47 ± 0.21
EOTS (m/s)	2.14 ± 0.10	1.99 ± 0.13	1.78 ± 0.13	1.51 ± 0.20
HROTS (m/s)	2.13 ± 0.14	1.89 ± 0.13	1.69 ± 0.23	1.46 ± 0.24

Preferred Transition Speed

PTS was slower on steeper inclines (Table 1, Figure 3A). The linear regression equation for the PTS vs. incline was:

$$y = -0.0319x + 1.9405 \qquad y = \text{speed (m/s)},\ x = \text{incline } (^\circ) \qquad \text{(Equation 1)}$$

The slope of the regression was significantly less than zero ($p=6.90$ e-7 and $R^2=0.481$). Seven of the subjects' PTS decreased monotonically with incline, and three subjects had slight inconsistencies in this overall pattern between inclines (Figure 3B).

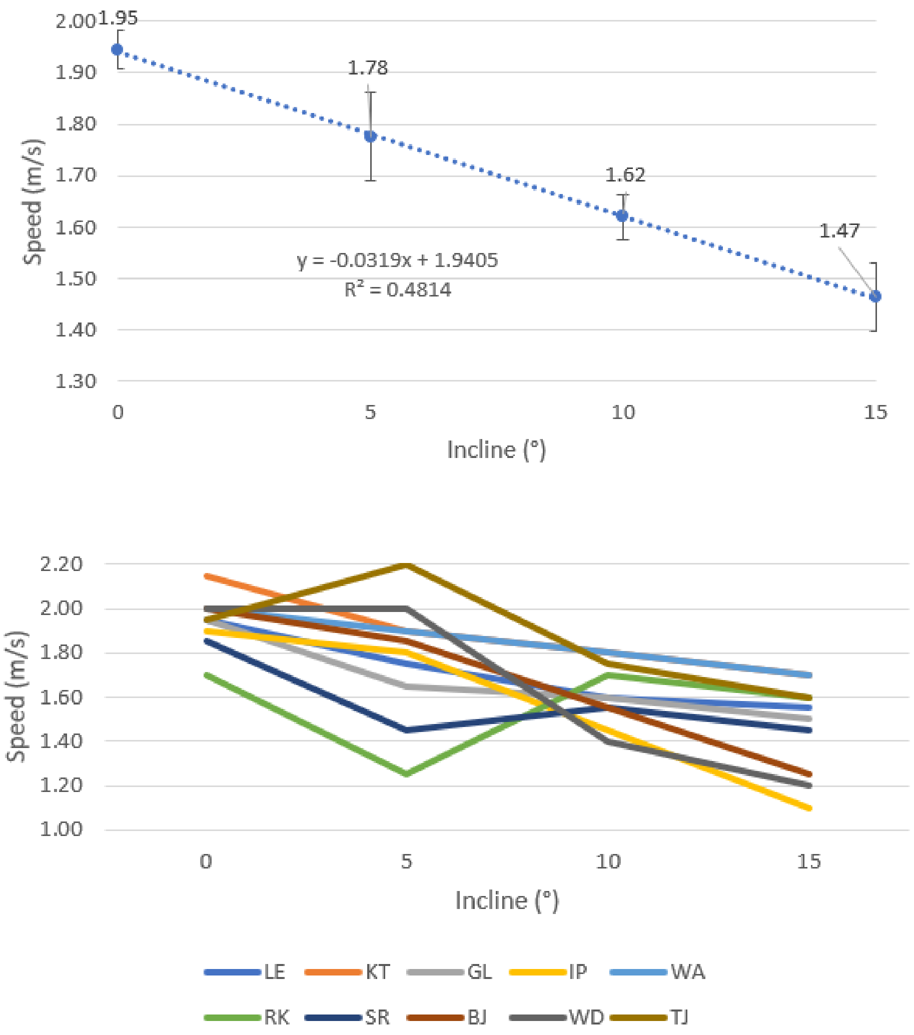

Figure 3A: Average PTS vs. incline, error bars are SEM. The linear regression equation and R^2 value were calculated from 4 inclines and n=10 subjects (40 total data points). **B**: PTS vs. incline for each of the ten subjects plotted individually.

Energetically Optimal Transition Speed

EOTS was slower on steeper inclines (Table 1, Figure 4A). The linear regression of the EOTS vs. incline was:

$y = -0.042x + 2.1689$ y = speed (m/s), x = incline (°) (Equation 2)

The slope of the regression was significantly less than zero ($p=4.22e-12$, $R^2=0.730$). Eight of the subjects' EOTS decreased monotonically with incline, and two subjects had slight inconsistencies in this overall pattern between inclines (Figure 4B).

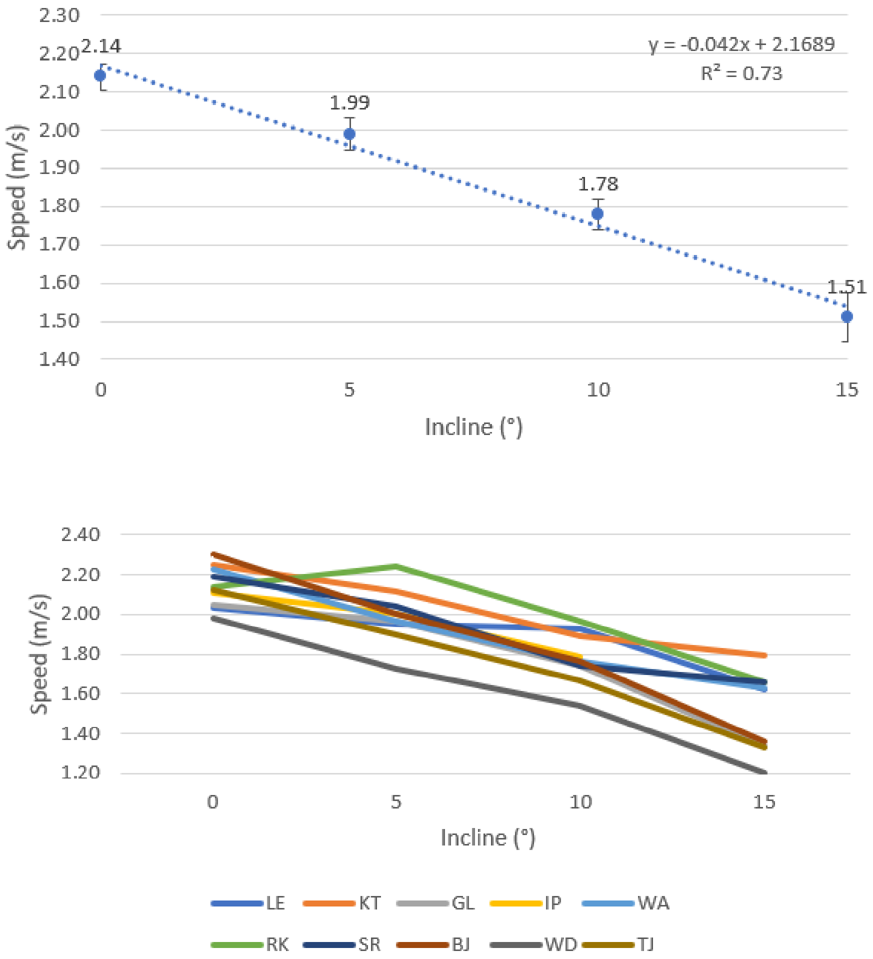

Figure 4A: Average EOTS vs. incline, error bars are SEM. The linear regression equation and R^2 value were calculated from 4 inclines and n=10 subjects at 0°, 5°, and 10°, and n=9 subjects at 15° (39 total data points). **B:** EOTS vs. incline for each of the ten subjects plotted individually.

Heart Rate Optimal Transition Speed

HROTS was slower on steeper inclines (Table 1, Figure 5A). The linear regression of the HROTS vs. incline was:

$y = -0.0445x + 2.1261$ y = speed (m/s), x = incline (°) (Equation 3)

The slope of the regression was significantly less than zero (p= 4.56e-10 and R^2=0.656). Four of the subjects' HROTS decreased monotonically with incline, and six subjects had slight inconsistencies in this overall pattern between inclines (Figure 5B).

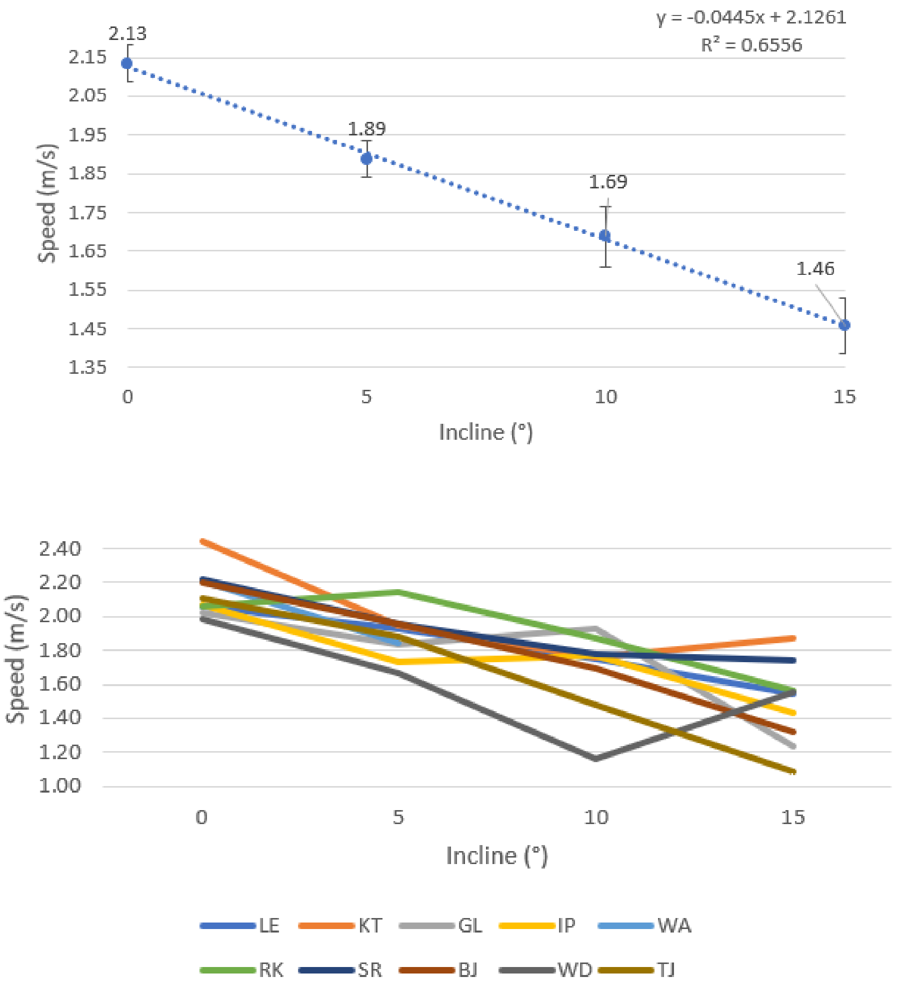

Figure 5A: Average HROTS vs. incline, error bars are SEM. The linear regression equation and R^2 value were calculated from 4 inclines and n=10 subjects at 0°, 5°, and 15°, but n=9 subjects at 10° (39 total data points).
B: HROTS data for each subject presented individually.

Comparisons between PTS, EOTS, and HROTS at each incline

Mean PTS was slower than mean EOTS at 0°, 5°, and 10°, but not at 15° (p-values of 0.002, 0.107, 0.006, and 0.930, respectively). The correlations between PTS and EOTS were weak to moderate at the different inclines (R^2 values of 0.045, 0.478, 0.193, and 0.498 at 0°, 5°, 10°, and 15°, respectively).

Mean PTS was slower than mean HROTS at 0°, 5°, and 10°, but not at 15° (p-values of 0.001, 0.359, 0.267, and 0.958, respectively). The correlations between PTS and HROTS were weak to moderate across each incline (R^2 values of 0.270, 0.371, 0.133, and 0.002 at 0°, 5°, 10°, and 15°, respectively).

Mean EOTS values were not different than mean HROTS values at 0°, were slower than mean HROTS at 5°, 10°, and were not different at 15° (p-values of 0.847, 0.003, 0.118 and 0.511, respectively). The correlations between a subject's EOTS and HROTS were moderate to strong across each incline (R^2 values of 0.658, 0.708, 0.567, and 0.376 at 0°, 5°, 10°, and 15°, respectively).

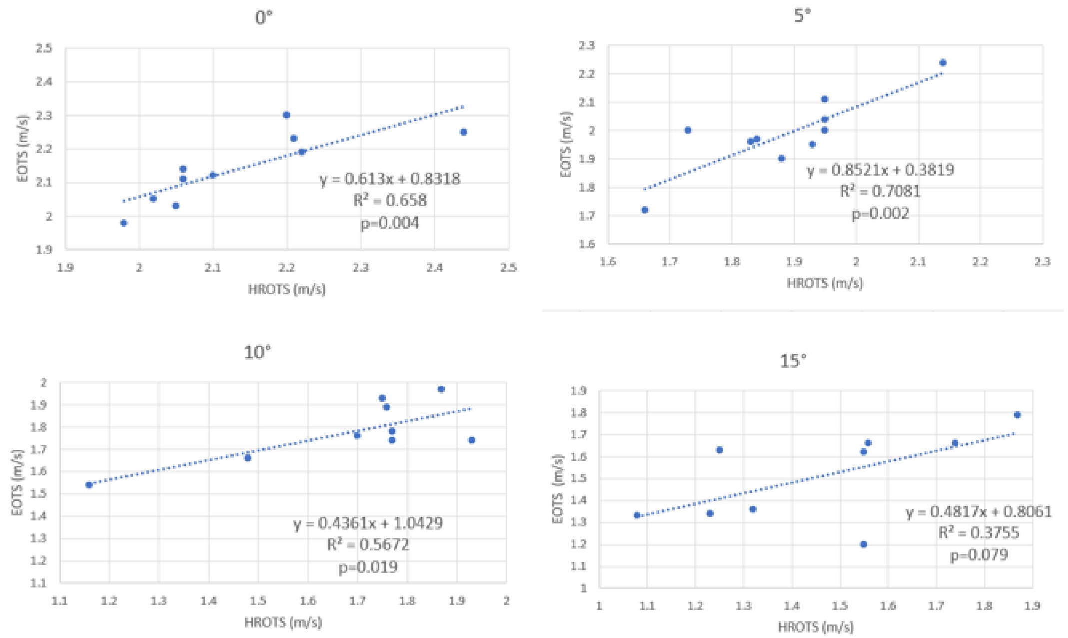

Figure 6: EOTS vs. HROTS data at 0° (n=10), 5° (n=10), 10° (n=9), and 15° (n=9). P-value is comparing the slope of the regression line to zero.

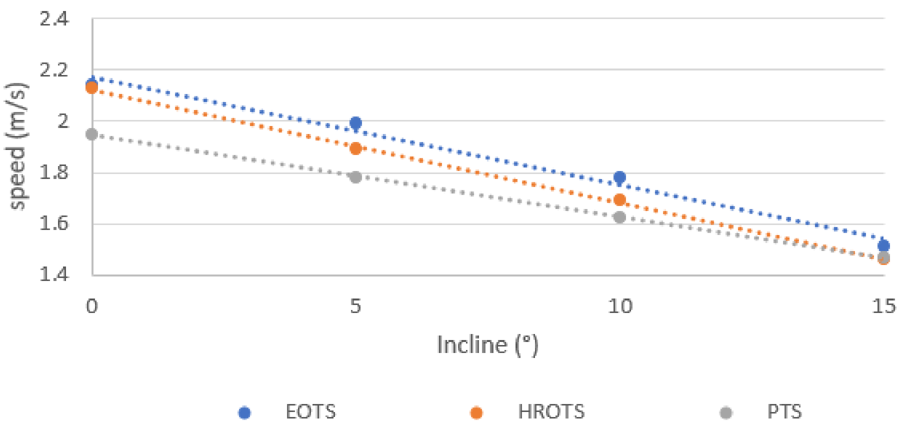

Figure 7: Average PTS, EOTS, and HROTS for each incline. For 0°, 5°, and 10°, PTS was the slowest speed, HROTS was intermediate and EOTS was the fastest speed. At 15°, HROTS was the slowest speed, PTS was intermediate and EOTS was the fastest speed.

DISCUSSION

I retain my first hypothesis that PTS and EOTS would both become slower on steeper inclines. This is consistent with what previous research has found. Minetti et. al. [21] determined that both PTS and EOTS are slower on steeper inclines up to 8.5° and Diedrich and Warren [4] determined that PTS decreased with incline (but did not measure EOTS).

I also retain my second hypothesis that PTS and EOTS would converge at steeper inclines. The difference between the average PTS and EOTS was 0.19 m/s at 0°, 0.21 m/s at 5°, 0.16 m/s at 10°, and 0.04 m/s at 15°, with EOTS always faster than PTS. Statistical analysis revealed that the PTS was slower than EOTS at 0°, 5°, and 10° but not at 15° (p-values of 0.002, 0.107, 0.006, and 0.930, respectively).

The finding that PTS<EOTS on flat terrain was previously well established [8] [21] [30], with relatively little conflicting research [20]. Only Minetti et. al. [21] have studied how the relationship between PTS and EOTS is affected by grade. They concluded that the absolute

difference (m/s) between PTS and EOTS does not change with gradient, but they only studied moderate inclines up to 8.5°.

My data demonstrate that the difference between PTS and EOTS remained roughly constant up to 10°, but not up to 15°. Perhaps optimizing energetic economy does not notably influence PTS at moderate grades, where humans are not working at a high rate of exertion, but as grade steepens, it may be that energetic cost becomes paramount. However, the regression line comparing PTS and EOTS at 15° (Figure 6) casts some doubt onto this finding. The R^2 value of the regression is only 0.498, meaning PTS only explains half of the variance in EOTS. Moreover, the slope of the line was 0.800, while a perfect correlation of PTS and EOTS at 15° would result in a slope of 1. Despite the fact that PTS and EOTS did converge at 15°, further investigation on the relationship between PTS and EOTS as a function incline is still necessary.

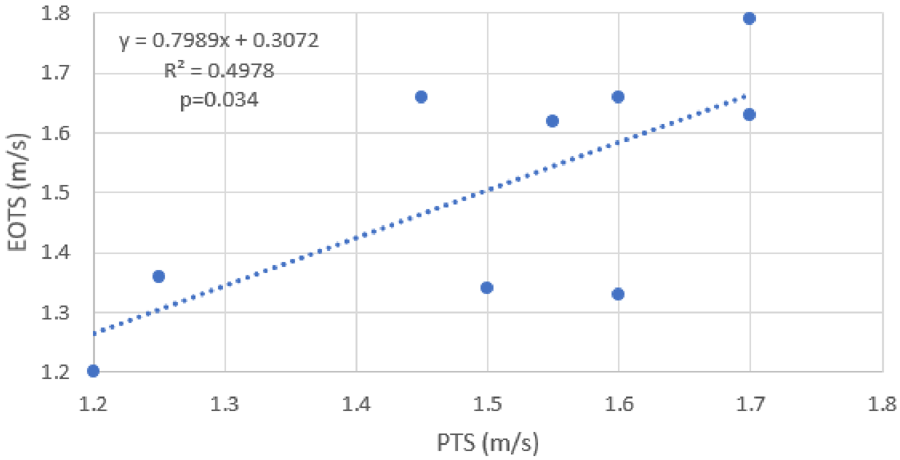

Figure 8: PTS vs. EOTS data (n=9) at 15°. P-value is comparing the slope of the regression line to zero.

My third hypothesis was that HROTS would equal EOTS at all inclines. EOTS and HROTS were similar at 0° but diverged at 5° and 10° and were similar at 15° (p-values of 0.847, 0.003, 0.118 and 0.511, respectively). The correlations between EOTS and HROTS (R^2 values of 0.658, 0.708, 0.567, and 0.376 at 0°, 5°, 10°, and 15°, respectively) were not consistent enough to have practical predictive application; heart rate is not an accurate predictor of EOTS for trail and mountain runners. Thus, I reject my third hypothesis for all inclines besides 0°. Rotstein et. al. [30] and Mercier et. al. [20] found that that HROTS = PTS on flat terrain, although Mercier et. al. also found that PTS = EOTS, which differs from the rest of the research done on this topic.

Table 2: Average differences and coefficient of determinations (R^2) among subjects in the transition speeds for each incline. Results presented as mean ± SD (R^2). Differences for each subject were averaged, as opposed to taking the difference of the average PTS, EOTS, and HROTS.

	0°	**5°**	**10°**	**15°**
EOTS-PTS (m/s)	0.19 ± 0.14 (0.045)	0.21 ± 0.38 (0.478)	0.16 ± 0.14 (0.193)	0.00 ± 0.15 (0.498)
HROTS-PTS (m/s)	0.19 ± 0.12 (0.270)	0.11 ± 0.37 (0.371)	0.09 ± 0.22 (0.133)	-0.01 ± 0.31 (0.002)
EOTS-HROTS (m/s)	0.01 ± 0.08 (0.658)	0.10 ± 0.08 (0.708)	0.09 ± 0.16 (0.567)	0.05 ± 0.21 (0.376)

Previous research on steep uphill running and walking has focused on 30° [7] [25] because it is a common incline for vertical kilometer races and the optimal incline for maximizing vertical rate of ascent [7]. When extrapolating the PTS and EOTS to 30° using equations 1 and 2 respectively, the values are 0.983 m/s for the PTS and 0.909 m/s for the EOTS. From Ortiz et. al. [25], this EOTS closely corresponds to the single subject who had the aerobic fitness needed to reach EOTS at such a steep incline.

Limitations

My study had some limitations. First, when trail and mountain runners walk on inclined terrain outdoors, they often place their hands on their quadriceps to facilitate in knee extension during late stance. However, due to the constraints of the mouthpiece and breathing tube that were collecting the expired air, subjects were unable to comfortably place their hands on their knees during inclined walking. This may have influenced metabolic cost and discomfort in walking, especially at 10° and 15°, and thus artificially distorted the calculated EOTS.

Second, there were three subjects who were unable to reach a 1% difference between the energetic cost of running and walking, all at 15°, because subjects were unable to complete the trials with an RER < 1. During EOTS determination, in which metabolic data was collected at three or four speeds per incline, the goal was to capture at least one speed above and at least one speed below subjects' EOTS. Three subjects did not have enough aerobic fitness to perform steady state walking at or slightly above their EOTS at 15°. As a result, those three subjects' EOTS regression analyses failed to capture (or come within a 1% difference of capturing) the linear regression equation intersection point and mild extrapolation was required. This extrapolation may have increased the variability of the calculated EOTS at 15°.

Future studies

There are many future areas of interest to study on the topic of human gait transition on inclined terrain. While it was not one of my original hypotheses, I would like to further investigate the RER differences between walking and running to see if metabolic substrate utilization could potentially be a trigger for the PTS or EOTS, as Ganley [6] proposed. I also plan on investigating additional metrics from the ParvoMedics software. I will analyze if variables such as expired volume of air (V_E), respiratory rate (RR), or tidal volume (V_T) correlate with either PTS or EOTS, because these ventilatory measurements could all be monitored with portable sensors. Thus, if V_E, RR, or V_T correlate with PTS or EOTS, they could have practical application in predicting optimal gait transition for trail and mountain runners during training and racing.

Continuing to consider gait transition from a metabolic perspective, it would be beneficial to do a future study to test the idea that energetics have a greater influence on PTS at higher exercise intensities. Such a study could test athletes with different levels of aerobic fitness at inclines that match exercise intensity (measured as a % of maximum heart rate or $\dot{V}O_{2max}$) and could ascertain if the PTS and EOTS converge at a certain exercise intensity for all subjects.

Considering the strong evidence for a biomechanical trigger for the PTS on flat terrain, future inclined gait transition research should study the influence of biomechanical parameters. Determining if any joint kinetic or kinematic variables, such as joint power, joint angle, joint velocity, joint acceleration, or joint forces trigger the PTS are logical future aspects to study. Likewise, pairing the kinetic and kinematic investigation with a neuromuscular component, measuring electromyography (EMG) activity of surface leg muscles would be helpful in determining how biomechanical parameters influence gait transition speed. Furthermore, performing more sophisticated biomechanical measurements concurrently with EMG measurements would allow for follow-up of Neptune and Sasaki's findings that force-length optimization is hindering the plantar flexors when walking at the PTS [23], a noteworthy result that has not been followed up on, to my knowledge.

A clever and effective way to determine causality between a proposed trigger for the PTS is by manipulating the trigger variable and seeing if that has the expected effect on the PTS. This has been achieved in multiple studies [3] [18]; both experiments found that manipulating a proposed trigger for the PTS could elicit a change in the PTS.

Gait transition on inclined terrain is of particular interest to trail and mountain runners, due to the performance implications of optimal gait choice in training and racing. There is currently no research comparing the performance differences in transitioning gaits at PTS vs. EOTS. Therefore, a useful future study could involve performing time to exhaustion (TTE) tests for walking and running at the EOTS and determining which gait results in the better performance. Since EOTS>PTS (up to 10°), one would expect running to result in a greater TTE than walking at the EOTS if the optimal speed for gait transition occurred at the PTS. If running TTE was the same as walking TTE, then that would provide evidence for EOTS being the optimal speed for gait transition. Performing a field study on the topic of gait transition on inclined terrain is also important to investigate how well laboratory findings hold up on the side of a mountain, where confounding variables such as ground surface or environmental conditions exist. Finally, because trail and mountain running performance often involves mitigating fatigue and fatiguability, determining how the two gaits differ in regard to those parameters will have important implications as well.

CONCLUSION

In conclusion, I studied the PTS and EOTS at a range of inclines that mimic the grades that trail and mountain runners commonly face. I found that the PTS, EOTS, and HROTS are slower on inclines. PTS is slower than EOTS up to 10° but they converge at 15°. HROTS does not appear to be an accurate predictor of EOTS. Coaches and athletes should exercise caution when using heart rate monitors to determine which gait is the most efficacious for performance. Energetic, biomechanical, and neuromuscular factors may influence gait transition, and these should be studied in further detail, especially on inclines commonly experienced by trail and mountain runners, where the question of gait transition has large performance implications.

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