Preferred Transition Speed between Walking and Running: Effects of Training Status

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ABSTRACT

ROTSTEIN, A., O. INBAR, T. BERGINSKY, and Y. MECKEL. Preferred Transition Speed between Walking and Running: Effects of Training Status. Med. Sci. Sports Exerc., Vol. 37, No. 11, pp. 1864–1870, 2005. Purpose: This study was conducted to identify the preferred transition speed (PTS) between walking and running and the energetically optimal transition speed (ETOS), in runners and nonrunners. Methods: A total of 19 young men were asked to walk on a treadmill at 5 km·h⁻¹. Speed was then increased by 0.2 km·h⁻¹ every minute. Subjects were instructed to start running at a particular speed they felt was easier. PTS for each subject was determined as the mean of the walk–run and the run–walk transitions. Subjects were also asked to walk and to run for 5 min at each of the following velocities: PTS − 1 km·h⁻¹, PTS + 0.5 km·h⁻¹, PTS, PTS + 0.5 km·h⁻¹, and PTS + 1 km·h⁻¹. This procedure was performed twice, once walking and once running, at all speeds. Physiologic measurements of oxygen consumption, heart rate, and rate of perceived exertion (RPE) were performed at each stage. ETOS was determined by plotting individual curves for each subject with the energy cost of locomotion as a function of velocity. Results: Preferred transition speed was 7.23 ± 0.25 and 7.42 ± 0.25 km·h⁻¹ for nonrunners and runners, respectively (P > 0.05), and differed significantly (F = 16.47, alpha < 0.001) from the ETOS, which was 8.02 ± 0.84 km·h⁻¹ for nonrunners and 7.90 ± 0.48 km·h⁻¹ for the runners. No significant differences were found between runners and nonrunners in PTS or ETOS. Running at the PTS resulted in a significantly lower RPE and higher energy cost than walking at the PTS in both groups. Conclusion: This study indicates that 1) the preferred PTS is slower than the ETOS, and 2) the PTS and ETOS are not dependent on the aerobic capacity or the training status. Key Words: ENERGETICALLY OPTIMAL TRANSITION SPEED, ENERGY COST OF LOCOMOTION, RATE OF PERCEIVED EXERTION, HEART RATE, OXYGEN CONSUMPTION

Two distinct movement patterns, the walking and the running gaits, characterize human terrestrial locomotion. The transition between the walking and running gait is characterized by a discrete and relatively abrupt change, which is dependent on the movement speed. In humans, this preferred transition speed (PTS) typically occurs at a speed of about 6.84–7.56 km·h⁻¹ (1.9–2.1 m·s⁻¹) (5,16,25).

The exact mechanisms or triggers that determine the PTS of an individual are not entirely understood. It was demonstrated that the transition speed could be accurately predicted from body physical dimensions in quadrupedal mammals (1,13). This, however, is not the case with human bipedal locomotion, where only low correlations were found between the PTS and anthropometric characteristics (11,18). A number of mathematical models were developed to describe bipedal locomotion (3,12,20,21). In these, walking is typically modeled as an inverted pendulum system, whereas running is typically modeled as a bouncing ball. These biomechanical and mathematical models were successful in predicting biomechanical variables such as stride frequency and patterns of vertical ground reaction forces. These models, however, fail to predict the PTS between walking and running (2,3).

Prilutsky et al. (23), examined muscle activation as a possible determinant of gait transitions. Surface electromyographic activity, which was recorded from seven major leg muscles, was used as an indicator for muscle activation. Their results indicated that the preferred walk–run transition might be triggered by the increased sense of effort caused by the exaggerated activation of muscles associated with the higher joint moment demanded to move the swing leg during fast walking. They also demonstrated that the preferred run–walk transition might be similarly triggered by the sense of effort caused by leg muscles that must generate higher forces during slow running than during walking at the same speed.

Thus, biomechanical variables may be of importance in the determination of the PTS. Other factors such as the influence of the human capacity for intentional gait modification and the importance of the physiologic and metabolic demands of the differed gaits, however, may also influence the PTS (12).

An obvious candidate for a physiologic determinant of the PTS is the minimization of the metabolic energy cost of locomotion. During walking, the cost of locomotion is clearly dependent on the velocity. The minimal value for the cost of locomotion is approximately 0.79 kcal·kg⁻¹·km⁻¹, and it occurs at approximately 5.5 km·h⁻¹, (1.25–1.3 m·s⁻¹) (15,16). This speed is also the mean speed preferentially selected by human subjects for walking. Walking at speeds below or above this energetically optimal speed...
increases the energy cost of locomotion much beyond the minimal value of 0.79 kcal·kg⁻¹·km⁻¹ (19,24).

The running gait displays a significantly different relation between the energy cost for a covered distance and the running speed. During running, the energy cost of locomotion is virtually independent of speed over a relatively wide range of velocities, and has a constant value of approximately 1 kcal·kg⁻¹·km⁻¹, or an oxygen consumption rate of approximately 200 mL O₂·kg⁻¹·min⁻¹ (10,19).

From the above discussion, it is clear that when walking at increasing speeds, a speed is reached where, from an energy expenditure perspective, it is advantageous to change gait and start running. This speed is referred to as the energetically optimal transition speed (EOTS).

Only limited and equivocal information is available concerning the relation between the preferred transition speed in humans and the minimization of the energy cost of locomotion (9,12,16,22), and the possible physiologic determinants of the PTS and the EOTS. It may be expected that the PTS of trained runners will be closer to the EOTS than in nonrunners. We could not find any reports on differences in these aspects between trained and nontrained subjects.

Because trained runners are characterized by significant physiologic adaptations, such as improved aerobic capacity and increased leg muscle strength and endurance, we hypothesized that they would have a significantly higher PTS and EOTS and that their PTS would be closer to their EOTS than in untrained nonrunners. Thus, the purpose of the present investigation was to explore the link between the PTS and the EOTS in trained runners and in nonrunners.

METHODS

Subjects. A total of 19 healthy young men volunteered to participate in the study. The subjects were drawn from two populations. One consisted of trained long-distance runners and the other of active but nonrunner students. The trained group included 10 runners specializing in running distances of 5,000–10,000 m, who trained every day with an average distance of about 60–100 km·wk⁻¹. The nonrunners group included nine recreationally active physical education students, who on the average exercised twice weekly (45–60 min of ball games such as soccer or basketball). The subjects’ physical characteristics, including maximal aerobic power, are presented in Table 1.

Subjects were fully informed of the procedures and the possible discomfort and risks involved in all testing procedures. Each of the subjects signed a written informed consent for participation. All procedures were conducted in accordance with ethical standards of the committee on human experimentation at the host institution and with the Helsinki Declaration of 1975.

Testing procedures. Each subject reported to the laboratory four times. Sessions were spaced at intervals of 3–6 d. In the first session, an incremental maximal running test on a motor-driven treadmill (Woodway, PPS MED, Weil am Rhein, Germany), was carried out to determine maximal aerobic power (VO₂max). All the subjects were accustomed to running and walking on a treadmill before the beginning of the study. The initial conditions of the treadmill were set at zero grade with a speed of 9 and 13 km·h⁻¹ for the nonrunners and the trained group, respectively. Speed was increased by 1 km·h⁻¹ every minute for both groups until the fourth stage. From this point on, grade was increased by 2% every minute while speed was kept constant until volitional exhaustion occurred. The test was considered maximal if at least two of the following criteria were achieved: a plateau in oxygen consumption with increased exercise intensity, a maximal heart rate within 10 bpm of age-predicted maximal heart rate, and a respiratory exchange ratio exceeding 1.15. Expired air was collected and analyzed breath-by-breath using an automated online system (SensorMedics, Vmax 29, Yorba Linda, CA). The flow and gas concentration sensors of the system were calibrated before each test according to the manufacturer’s instructions.

Determination of preferred transition speed. During the second session, the subjects’ individual PTS between walking and running were established. This was defined as the lowest velocity at which the subject chose to start running. For that purpose, the treadmill speed was initially set at a comfortable walking speed of 5 km·h⁻¹, which was increased by 0.2 km·h⁻¹ every minute. Subjects were asked to walk as long as they were comfortable and to start running at a particular speed they felt running was more comfortable. At the point where running was initiated, the subject was asked by the experimenter to run for 30 s and then walk for 30 s at that same speed. These walking–running intervals were repeated at least twice until the subject was sure that at this speed running was preferred. If the subject decided walking was preferred, the speed was increased to the next higher level and the walking–running 30-s interval procedure was repeated, until the subject was certain that running was preferred.

After a 20-min rest, a similar procedure was performed by starting the treadmill at a relatively fast speed of 9 km·h⁻¹ while the subjects were running. Speed was then decreased gradually by 0.2 km·h⁻¹ every minute until a velocity was reached where the subject preferred to walk. This posttransition walking speed was defined as the run–walk transition. To obtain a single PTS value, the average of the two transition speeds (walk–run and run–walk transitions) was defined as the PTS of the subject. The order of the two procedures within each subject was randomly assigned.

### TABLE 1. Anthropometric and aerobic capacity characteristics of the two groups.

<table>
<thead>
<tr>
<th></th>
<th>Nonrunners</th>
<th>Runners</th>
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<tbody>
<tr>
<td><strong>Means ± SD</strong></td>
<td><strong>Means ± SD</strong></td>
<td></td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>81.39 ± 8.74</td>
<td>66.95 ± 5.64*</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>177.0 ± 5.59</td>
<td>175.0 ± 4.57</td>
</tr>
<tr>
<td>Fat (%)</td>
<td>26.67 ± 1.87</td>
<td>25.66 ± 4.32</td>
</tr>
<tr>
<td>Leg length (cm)</td>
<td>90.89 ± 3.39</td>
<td>90.30 ± 2.54</td>
</tr>
<tr>
<td>VO₂max (mL·kg⁻¹·min⁻¹)</td>
<td>45.09 ± 3.60</td>
<td>65.37 ± 1.86*</td>
</tr>
</tbody>
</table>

* Significantly different from the nonrunners, alpha < 0.001.
Determination of the energetically optimal transition speed. To identify the individual EOTS, subjects were asked during the third and fourth sessions to walk or run at, below, and above their PTS. The following five velocities were selected: PTS \( \pm 0.5 \text{ km} \cdot \text{h}^{-1} \); PTS \( \pm 0.5 \text{ km} \cdot \text{h}^{-1} \); and PTS \( \pm 1 \text{ km} \cdot \text{h}^{-1} \). The various velocities were performed in a random order. Each stage lasted 5 min and a rest period was given between the different speeds until the heart rate decreased to below 90 bpm. This procedure was performed twice. At one session, subjects were required to walk, and at the other to run, at all velocities. The order of the walking and running protocols was counterbalanced among subjects. During these two sessions, the subjects were connected to a metabolic cart while oxygen consumption (\( \dot{V}O_2 \)) and heart rate (Polar Vantage XL, Stamford, CT) were measured and recorded continuously. The average values for the last 2 min of each velocity were calculated and recorded. At the last 15 s of each speed, subjects were also asked to report their rate of perceived exertion (RPE) (6).

Calculations. Energy cost of locomotion was calculated by dividing the weight-specific oxygen consumption per hour (\( \text{mL} \ O_2 \cdot \text{kg}^{-1} \cdot \text{h}^{-1} \)) by the velocity (km \cdot h^{-1}). This represents the energy required to move a 1-kg mass for 1 km (\( \text{mL} \ O_2 \cdot \text{kg}^{-1} \cdot \text{km}^{-1} \)). The energy cost of locomotion was calculated for each velocity in both the running and walking gaits.

To identify the individual EOTS, curves were plotted for each subject with the energy cost of locomotion as a function of velocity. After experimenting with linear and curvilinear models, the linear model was found to be appropriate at the range of velocities applied in the present study. For the walking data, \( R^2 \) were above 0.92 except for two subjects with \( R^2 \) of 0.69 and 0.87. For the running data, \( R^2 \) were above 0.92 except for two subjects with \( R^2 \) of 0.79 and 0.89. Thus, regression lines for the energy cost of locomotion were fitted by a linear model for both running and walking data. The intersection of the lines describing the walking data with the line describing the running data represents the EOTS. Average group lines (Fig. 1) were plotted from individual regression lines by calculating the average intercept and the average slope from the corresponding values of the individual lines.

Statistical analyses. Two-way analysis of variance with repeated measures was used to assess differences between runners and nonrunners for the PTS and the EOTS. The responses of RPE, heart rate, and \( \dot{V}O_2 \) while walking and running at the PTS were also compared within and between the two groups. Pearson correlations coefficients were calculated for the relation among aerobic capacity, PTS, and EOTS, and among anthropometrical measures, PTS and EOTS. A probability level of 0.05 was used as a criterion for acceptance of statistical significance.

RESULTS

Anthropometric and aerobic capacity data describing the two groups are presented in Table 1. Runners had a significantly higher \( \dot{V}O_2\text{max} \) than the nonrunners (65.37 ± 1.86 and 45.09 ± 3.60 mL \( \dot{O}_2 \cdot \text{kg}^{-1} \cdot \text{min}^{-1} \), respectively) and a significantly lower body mass and fat percent (8.94 ± 2.13 and 21.61 ± 5.62% fat for the runners and nonrunners, respectively). The two groups did not differ significantly in height, leg length, or age.

Table 2 presents group means (±SD) of the PTS and EOTS. Although both PTS and EOTS were similar in the nonrunners and the runners groups, in both groups PTS was significantly lower than the EOTS. The combined average PTS for both groups was 7.332 ± 0.263 km \cdot h^{-1}, whereas the combined average EOTS was 7.959 ± 0.658 km \cdot h^{-1}. No significant differences were found between runners and nonrunners in PTS or EOTS.

Table 3 presents means (±SD) of the oxygen consumption rate, energy cost of locomotion, RPE, and heart rate at the preferred transition speed while walking and running. In
both the nonrunners and the runners, the oxygen consumption rate, and thus the energy cost of locomotion, were significantly higher while running than while walking at the PTS. In contrast, in both groups RPE was higher while walking at the PTS than while running at the same speed. Heart rate did not differ in the two groups between walking and running at the PTS.

The group means of energy cost of locomotion while walking and running at each of the selected velocities are presented in Figure 1. It is clear that in both groups the PTS is significantly lower than the EOTS. It is also clear that at velocities lower than the PTS, energy cost of locomotion is significantly higher while running than while walking at the same velocities, whereas the opposite is true for velocities higher than the EOTS.

The rates of perceived exertion while walking and running at the different speeds are presented for each group in Figure 2. As expected, RPE was higher for the nonrunners while running as well as walking at all studied velocities. Further, in both the runners and the nonrunners, RPE during walking at the PTS and at velocities faster than the PTS was significantly higher than during running at the same speeds.

The correlations among the PTS, the EOTS, and the aerobic capacity (VO$_2$max) were calculated for the combined group ($N=19$). Very low and nonsignificant correlations were found between the aerobic capacity and PTS ($r=0.34; P=0.15$), as well as between aerobic capacity and EOTS ($r=-0.034; P=0.89$).

**DISCUSSION**

The main findings of the present study indicate that the PTS occurs at a velocity significantly lower than the EOTS, calculated from the energy cost of locomotion. This is true for both runners and nonrunners, with no significant differences in either the PTS or the EOTS between the two groups (see Table 2). Thus, the study’s original hypothesis that trained runners differ from nonrunners in their PTS and EOTS was not supported.

The mean PTS in the present study was found at 7.23 km·h$^{-1}$ for the nonrunners and at 7.42 km·h$^{-1}$ for the runners (2.009 and 2.061 m·s$^{-1}$, respectively) ($P>0.05$). These PTS values are within the range of preferred transition speeds reported in previous studies, such as 2.067 ± 0.125 m·s$^{-1}$ (16), 7.89 ± 0.34 km·h$^{-1}$ (7), 2.16 ± 0.2 m·s$^{-1}$ (12), 2.07 ± 0.21 m·s$^{-1}$ (8), and 1.88 m·s$^{-1}$ (24).

Mean calculated EOTS for the runners and the nonrunners was found at velocities of 2.20 and 2.23 m·s$^{-1}$, respectively, with no significant difference between the groups (Table 2). Brisswalter and Mottet (7), testing 10 young subjects (aerobic capacity or training status not reported), also found a significantly higher EOTS (7.89 ± 0.34 km·h$^{-1}$, or 2.19 m·s$^{-1}$) than the PTS (7.66 ± 0.57 km·h$^{-1}$, or 2.13 m·s$^{-1}$). The significant difference between the PTS and the EOTS found in the present study is also in line with the report of Hreljac (16), who, when working with a mixed male and female group, found a significantly lower PTS than EOTS. Tseh et al. (26), testing three age groups of adolescent subjects, also found significant higher mean EOTS than the mean PTS in each age group. For the subjects 15 yr of age, they reported a mean PTS of 2.12 m·s$^{-1}$ and an EOTS of 2.25 m·s$^{-1}$.

Hanna et al. (12), however, testing 15 subjects (aerobic capacities not reported), found a very close proximity of the PTS and the EOTS. They found the EOTS to be 99.6 and 100.5% of the PTS when calculated from oxygen consumption rate and from the energy cost of locomotion, respectively. Merecier et al. (22) also reported almost identical oxygen consumption for running and walking at the PTS (23.7 ± 0.8 and 23.9 ± 1.18 mL O$_2$·kg$^{-1}$·min$^{-1}$, respectively). Their report, however, is based on only seven subjects.

Determination of the preferred transition speed poses some methodological difficulties that deserve consideration. Preferred transition speed is actually a theoretical (and subjective) entity, and cannot be accurately determined by using an incremental protocol. Usually we can only measure the pre- or the posttransition speeds. Thus, the term “transition speed” is not standardized, and is rather arbitrarily defined in the different studies.

Hanna et al. (12) and Diedrich and Warren (8) termed the transition speed as the mean PTS of the walk–run and the run–walk transitions, and PTS was defined as the pretransition speed for both the walk–run and the run–walk transitions. Hreljac (16) also used the mean of the walk–run and run–walk PTS and used the posttransition velocities to define the PTS for the walk–run transition. Mercier et al. (22) used only the walk–run transition, and defined the PTS as the posttransition speed. Brisswalter and Mottet (7) also used only the walk–run transition, and most probably defined their PTS as the posttransition speed, although this is not clearly stated in their methods.

In the present study we used the mean PTS of the walk–run and the run–walk transitions, and the PTS was defined as the...
posttransition speed in both. It should also be pointed out that
the PTS may be influenced by test protocol variations, such as
the length of time allocated for each stage, the velocity incre-
ments, the acceleration characteristics of the treadmill used,
and whether a ramped or incremental protocol is used (12). All
these variations should be considered when comparing results
of different studies, and may at least partially explain discrep-
ancies or differences among them. Hence, it seems that an
accepted standardized method for evaluation of the PTS and
the EOTS would be of importance.

Our present findings also indicate that at the PTS, a
significantly higher energy cost of locomotion was recorded
while running than while walking (see Table 3). It is clear,
therefore, that the gait change from walking to running at
the PTS occurs despite the higher energy demand of run-
ning. This may indicate that the optimization of energy
expenditure has a limited role in the selection of gait tran-
sition speed in human locomotion. It is indeed questionable
whether humans have the capacity to perceive small
changes in energy expenditure. It is plausible that the PTS
is a result of the action of neural mechanisms responding to
physical and biomechanical triggers that are optimized with
increasing speeds of locomotion, such as resonant fre-
quency, musculoskeletal strain, and postural stability
(8,14,17). Thus, a PTS lower than the EOTS may indicate a
situation of optimizing musculoskeletal stress or postural
stability at the cost of a nonoptimized EOTS.

In the present study, the RPE reported by the subjects
while walking or running at all speeds was also recorded. In
both groups, RPE for walking at or faster than the PTS were
significantly higher than for running at the same speeds (see
Fig. 2 and Table 3). Such patterns of change in RPE with
velocity may indicate that perceived exertion, being sensi-
tive, among other factors, to proprioceptive input at low
intensity exercise, may be a significant determinant of the
PTS. From Figure 2, it is also clear that RPE in the non-
runners are consistently higher than for the runners, both
while walking and running, at all speeds. These results are
to be expected in view of the significant difference in the
aerobic capacities of the two groups.

We found only two studies that measured RPE and its
relation to the PTS. Hreljac (16), in line with the present

FIGURE 2—Average rate of perceived exer-
tion (RPE) for runners and nonrunners while
walking and running at different speeds.

FIGURE 3—Average heart rate for runners
and nonrunners while walking and running at
different speeds.
study's results, reported higher RPE while walking (13.54 ± 1.39) than while running (10 ± 1.18) at the PTS. He also reported higher oxygen consumption while running than while walking at the PTS. Hanna et al. (12) found that RPE tends to be higher while walking than running at velocities above the PTS. Nevertheless, they found no differences in the RPE between walking and running at or below the PTS. Because no significant differences were found between the well-trained runners and the nonrunners tested in the present study, either in the PTS or in the EOTS, we looked for the relations among the PTS, the EOTS, and the aerobic capacity (V\textsubscript{O2max}) of the combined sample (N = 19). We found very low and nonsignificant correlations between aerobic capacity and PTS (r = 0.34, P = 0.15) as well as between aerobic capacity and EOTS (r = −0.034, P = 0.89). Thus, from the present results it seems that at least within the range of the aerobic capacities of our subjects, the PTS and the EOTS are not influenced by either the aerobic capacity or the specific training mode (running). Also, no significant correlations were found between the PTS or the EOTS and the anthropometrical measures of height, weight, or leg length (P ≤ 0.05). These findings are in line with the low and nonsignificant correlations reported by Hanna et al. (12) for anthropometric measures such as standing height, leg length, or shank length, and the PTS.

Recently, Beaupied et al. (4) investigated the energetic of gait transfer in relation to training status; however, they did not measure the PTS of their subjects. They calculated and compared two energetically optimal transition speeds. One was based on metabolic energy expenditure, and the other was based on estimation of internal work calculated from three-dimensional kinematics data collected at different speeds while walking and running. They compared five untrained subjects, five sprinters, and five endurance-trained subjects. No data were provided, however, concerning their aerobic capacities or age range. Based on oxygen consumption rates, they reported theoretical optimal transition speeds of 2.29 ± 0.04, 2.44 ± 0.06, and 2.30 ± 0.05 m·s\(^{-1}\) for the untrained, sprint, and endurance-trained subjects, respectively, with significant differences among the groups (α < 0.05).

In the present study we also measured heart rate while walking and running at, below, and above the PTS. No significant differences were found in heart rate while running and walking at the PTS (see Table 3). Higher values were recorded, however, when walking (compared with running) at velocities faster than the PTS and EOTS, and lower values were recorded when walking at velocities below the PTS (see Fig. 3). This was the case in both groups. The higher heart rate response of the nonrunners group, in both gaits and at all velocities, is in accordance with the significant difference in the aerobic capacities between the two groups (see Table 1). These results (heart rate) are in agreement with the only report we could find (22) that measured physiologic responses related to gait transition other than oxygen consumption.

In conclusion, the present findings do not support our original hypothesis that trained runners have a significantly higher PTS and EOTS, or that their PTS should be closer to their EOTS than in untrained nonrunners. Thus, the results herein indicate that neither the PTS nor the EOTS is dependent on the training status, at least in the range of aerobic capacities represented by the subjects in the present study. The results also indicate, in line with previous studies, that the preferred transition speed between walking and running occurs at velocities significantly lower than the energetically optimal transition speed.

It remains to be tested whether specific PTS can be demonstrated for other unique populations, such as highly trained sprinters and walkers or, on the other hand, extremely sedentary, untrained populations, or obese subjects. It is also not clear whether specific training programs, aimed, for instance, at decreasing musculoskeletal stress, can induce changes in the PTS or its relations with the EOTS.

REFERENCES