A feedback-controlled treadmill (treadmill-on-demand) and the spontaneous speed of walking and running in humans

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Minetti, Alberto E., Lorenzo Boldrini, Laura Brusamolin, Paola Zamparo, and Tom McKee. A feedback-controlled treadmill (treadmill-on-demand) and the spontaneous speed of walking and running in humans. J Appl Physiol 95: 838–843, 2003. First published April 11, 2003; 10.1152/japplphysiol.00128.2003.—A novel apparatus, composed by a controllable treadmill, a computer, and an ultrasonic range finder, is here proposed to help investigation of many aspects of spontaneous locomotion. The acceleration or deceleration of the subject, detected by the sensor and processed by the computer, is used to accelerate or decelerate the treadmill in real time. The system has been used to assess, in eight subjects, the self-selected speed of walking and running, the maximum “reasonable” speed of walking, and the minimum reasonable speed of running at different gradients (from level up to +25%). This evidenced the speed range at which humans neither walk nor run, from 7.2 ± 0.6 to 8.4 ± 1.1 km/h for level locomotion, slightly narrowing at steeper slopes. These data confirm previous results, obtained indirectly from stride frequency recordings. The self-selected speed of walking decreases with increasing gradient (from 5.0 ± 0.8 km/h at 0% to 3.0 ± 0.9 km/h at +25%) and seems to be ~30% higher than the speed that minimizes the metabolic energy cost of walking, obtained from the literature, at all the investigated gradients. The advantages, limitations, and potential applications of the newly proposed methodology in physiology, biomechanics, and pathology of locomotion are discussed in this paper.

THE NEED TO OBTAIN reliable, steady-state conditions at which locomotion could be studied, from both biomechanical and physiological points of view, has forced researchers so far to investigate constant speeds along linear paths. Although such choices have unveiled many fundamental aspects of walking and running (2, 4, 7, 12, 14, 15, to name a few), humans’ everyday life is certainly more associated with continuous accelerations and decelerations and with movement along curvilinear paths. Even when we decide to move at almost constant speed and on a linear walkway, long-lasting gait will result in an unsteady progression in speed and direction. The mechanical, metabolic, neuromuscular, and psychological determinants of such unsteadiness will never be discovered as long as we use, for instance, (linear) treadmills set to move at constant speed. The questions needing a different approach to be answered are, for example, 1) How do humans and animals manage the energy sources in endurance locomotor events, 2) Is one gait better than another in quadrupeds that turn in movement, 3) Is there a range of speed between adjacent gaits that is never spontaneously used, or 4) What is the self-selected walking speed at the different gradients in a heterogeneous mountain path simulated on a treadmill?

The transition speed between walking and running (but also between trot and gallop) has been classically studied (for example, Refs. 4, 10, 13, 16) by increasing and/or decreasing the treadmill speed with small discrete steps. This procedure was devoted to measure some variables (oxygen consumption, electromyogram, mechanical work, recovery, gait preference, etc.) at all the speeds within walking and running range, including the ones never used by the investigated species. Then the spontaneous choice of one gait or another at a given speed was discussed depending on the trends of the measured variables. For instance, Hoyt and Taylor (10) showed that horses change from walking to trot and from trot to gallop according to the minimization of the metabolic cost of locomotion (measured as energy per unit distance). In their famous graph they superimposed histograms representing, for each gait, the most frequent speeds adopted by free-ranging horses. The paper was doubly informative, being able to demonstrate both the energy minimization and the specialization of each gait, which were only used in well-separated subsets of the whole speed range.

In humans, such an attempt to find the most realistic subrange of walking and running speeds has been never pursued. As a result, many papers studied and speculated on the determinants of the transition between walking and running in a speed range where our control system, evolved not to operate in those conditions, could have troubles in operating the proper gait choice.

To partially remedy the above-mentioned methodological constraints and to solve some of those prob-
lems, we computerized a controllable treadmill, whose speed was continuously changed by a sensor-program system according to the subject’s “attitude” to accelerate, decelerate, or keep the pace (Treadmill-on-Demand).

The aim of this paper is to describe this system and to apply the new methodology to answer to the above *question 3*, and partially to *question 4*, which deals with the spontaneous walking speed at different gradients, again a measure never published in the literature. It is well known (12) that at each gradient the relationship of metabolic energy cost vs. speed shows a minimum at a given speed range. Although level-walking humans (and horses) spontaneously adopt the optimal speed, we do not know whether this also applies to gradient walking.

In addition, we used the newly proposed methodology to measure the gap between the spontaneously chosen walking and running speeds (*question 3*), as a function of gradient, reinforcing the findings already obtained in horses (10) and hypothesized in humans (13).

**MATERIALS AND METHODS**

*Treadmill-on-demand.* The system (see Fig. 1) is composed of a treadmill, an ultrasonic range finder, and a computer. The treadmill (Ergo LG70, Woodway, Germany) allows speeds in the range 0–30 (step 0.1) km/h, gradients from −10 to +30% (step 0.1%), and a maximum acceleration of 5 m/s². Both speed and gradient are controllable manually and externally, via an RS-232 serial port. Also, the electronics of the device send out information about the current speed and gradient. The ultrasonic probe was derived from a commercial device for a camera range finder (Sonar Ranging Module 6500, Polaroid).

The control software, programmed in QBASIC (Microsoft), used the serial port to communicate data to and from the range finder and the serial port to control the treadmill. The ultrasonic range finder was aligned with a passive reflector on the subject’s chest and measured the range at a 10-Hz rate. The control system, sketched as a flow chart in Fig. 2, compared the subject’s actual position with the desired position and determined the change in treadmill speed required to correct any error. The inherent second-order response of the inertial system was damped by adding the first derivative term (i.e., the rate of change of position) to the feedback equation (proportional derivative algorithm). A limit, set to the speed change communicated to the treadmill, prevented that loss, and reacquisition of the target could be misinterpreted as rapid speed changes. The system allowed the subject’s position to be maintained in a limited central zone on the treadmill despite changes in their apparent speed. The output of the computer was an ASCII file containing the treadmill speed and the subject position, sampled at 1 Hz.

*Experimental measurements.* Eight healthy subjects (6 men, average ± SD age 31.8 ± 8.4 yr, mass 80.1 ± 16.5 kg, stature 1.743 ± 0.088 m) were first asked to reach habituation on the system, and then they walked and ran at different gradients (0%, 5%, 10%). At each gradient they were instructed to walk at their self-selected speed (W_SSS) and at the maximum spontaneous speed (W_MAX). To obtain W_MAX, they were told “to walk as if they were in a hurry in a crowded city and not to force the speed beyond the maximum they would spontaneously choose.” Also, they were instructed to run at the self-selected speed (R_SSS) and at the lowest possible speed (R_MIN). To obtain R_MIN, they were told “not to slow down below the speed they felt reasonable for running, as they would do in the same situation of W_MAX.” These four conditions were repeated twice. Six of the subjects extended the W_SSS measurements to steeper gradients, namely 15, 20, 25%.

The statistical analysis for the difference between W_MAX and R_MIN included a parametric test (1-factor, gradient, ANOVA for repeated measurements). Because of the small sample size (8 subjects), a nonparametric test (Wilcoxon’s signed-rank) for the same comparisons at each gradient was additionally performed.

The subjects were asked to move from one condition to the next after the experimenter subjectively evaluated that a speed plateau (visible in the monitor on-line graph) was reached (see Fig. 3) and never before 30 s of exercise at that level. Concurrently, the stride frequency was measured by means of a chronometer.

The experiments, in which subjects wore a safety harness also connected to an emergency stop switch, involved no discomfort and were previously approved by the local ethics committee.

**RESULTS**

We measured the response time of the sensor-computer-treadmill system, and we obtained a 0.42-s delay of the treadmill acceleration with respect to the subject acceleration (in that trial equal to 3.1 m/s² and starting at a speed of 4.07 km/h). The slowest controllable speed is 0.2 km/h, and if the subject stops moving on the

![Fig. 1. Treadmill-on-demand, consisting of an ultrasonic range finder (US), the treadmill, and a computer. The US is controlled by the computer via the bidirectional parallel port (P). It emits ultrasonic bursts that bounce back because of a passive reflector (R) located on the chest and that are detected by the same transducer. The distance between the subject and the probe is calculated at the rate of 10 Hz by the time of flight of the pulse. The program processes the distance data and controls the treadmill speed via an RS-232 serial port (S); see Fig. 2 for the system diagram. The system is complemented by a safety harness, a bar circling the subject on three sides, and the emergency stop switch (not shown).](http://jap.physiology.org/ by 10.1530.38.4 on April 26, 2017)
treadmill at a speed of 2.99 km/h, the treadmill comes to a halt in 1.22 s. Subjects reported a very smooth transition between speeds and felt comfortable with all the aspects of the measuring procedure.

Figure 4 shows the results obtained for \( W_{\text{MAX}} \), \( R_{\text{MIN}} \), and their associated stride frequencies. The one-factor ANOVA for repeated measurement showed a highly significant \( (P < 0.01) \) difference between \( W_{\text{MAX}} \) and \( R_{\text{MIN}} \) speeds and between stride frequencies, with no effect of gradient. At each gradient, the Wilcoxon signed-rank test showed significant \( (P < 0.05) \) differences in the two conditions for both speed and frequency. On level ground, \( W_{\text{SSS}} = 5.04 \pm 0.79 \), \( W_{\text{MAX}} = 7.24 \pm 0.63 \), \( R_{\text{MIN}} = 8.41 \pm 1.07 \), and \( R_{\text{SSS}} = 9.87 \pm 1.47 \) km/h.

Figure 5 reports the results for \( W_{\text{SSS}} \) and \( R_{\text{SSS}} \) experiments at six different gradients, in terms of both speed and stride frequency.

DISCUSSION

The treadmill-on-demand proved to be a very useful tool for reproducing, in the small space of the laboratory, the same conditions for spontaneous locomotion measurements normally available on a long (uphill, level, downhill) walkway, with the obvious advantages of having the subjects stationary with respect to the external environment and assessing them in a standardized way.

The subjects reported a smooth response of the feedback system, after a short habituation period was allowed. Despite this, the newly proposed methodology has limitations, which have to be considered. First, a continuously speed-changing treadmill introduces bias in the mechanics of locomotion. Such an effect, owing to the noninertial system, adds energy to the body during accelerations (virtual work). If the body dynamics is calculated from the measured kinematics, we could be induced to consider the resulting energy changes as provoked by the muscles, although actually part of them is caused by the treadmill motor. We can expect, though, that this is a major bias with experimental protocols devoted to investigating repeated sequences of consistent and rapid acceleration and deceleration (in sprints, for instance). When long-lasting and...
smooth changes in speed are sampled, as in the present experiments, the treadmill-on-demand can be considered as an inertial system and the bias negligible.

Another important issue is the feedback feeling the subjects experience on the treadmill. The responsiveness, the length constraints, and the unusual situation are potentially conditioning the subjects’ behavior and could influence the gait and speed choice. The habituation time may vary according to the experimental design, and it is very important to adapt the control algorithm to operate smoothly in the specifically investigated speed range. Although the feedback responsiveness has been designed so far to work in the “normal” walk-jog range, we could expect that for a protocol on elderly subjects or on marathon runners it could be adjusted to account for very low or very high speed, respectively. This would involve also new settings for the safety thresholds (maximum speed and acceleration) and the “neutral zone” on the treadmill. Lastly, the experimenter and the subjects have to be aware that no object may be placed between the chest and the range finder or it could alter the behavior of the control system. For this reason, lateral drift should not exceed the normal physiological range and upper limbs should be moved just with the usual walking and running pattern.

The gap between the $W_{\text{MAX}}$ and the $R_{\text{MIN}}$ was equal to $\sim 1.2$ km/h at 0 gradient and still consistent at the incline of $+5\%$ and $+10\%$ (see Fig. 4). This reinforces the rationale (13) that there are speeds at which humans neither walk nor run. These two gaits, like walk, trot, and gallop in horses (10), appear well specialized in their own speed ranges. This means that many experimental protocols designed to shed light on the determinants of the transition speed between walking and running, by allowing the speed to continuously increase and decrease across the entire range, have actually investigated a speed range in which it is unnatural to use a given gait. It is possible that part of the difficulties in explaining the mechanical determinants of the metabolic advantage associated to the gait choice as a function of speed originates from such an experimental bias. Also the stride frequency graph presented in Fig. 4 demonstrates the frequency gap existing between $W_{\text{MAX}}$ and $R_{\text{MIN}}$. Although this is expected on the different speeds measured, we have to remember that even at the same progression speed, within or close to the “unrealistic” range, running always involves a higher frequency than walking. Such effect, together with the indirect measurement of the “spontaneous” change of stride frequency on a walkway when accelerating from walking to running, allowed a
first estimate (on one subject) of $W_{\text{MAX}}$ and $R_{\text{MIN}}$ (Fig. 2a in Ref. 13), ~6.7 and 8.1 km/h, respectively, which are consistent with the present measurements. The present results show that despite the decrease in the speed gap between $W_{\text{MAX}}$ and $R_{\text{MIN}}$ at increasing gradients, the gap between stride frequency widens further.

Another interesting result is the decrease of the $W_{\text{SSS}}$ at increasing gradients (Fig. 5). Compared with the optimal speed of walking (minimum metabolic cost, Ref. 12), $W_{\text{SSS}}$ appears to be always higher. A potential explanation is that each curve (cost vs. speed at each given gradient) obtained by Margaria (12) displays quite a broad minimum, such that a range of speeds shares almost the same metabolic cost. If this were taken into account, the resulting confidence band (replacing the interrupted curve in Fig. 5) would partially overlap with the data lower SD bars at all gradients. It is also possible that the instrumented treadmill, and its control system, induces the subjects to adopt slightly higher speed than in a spontaneous experiment on a walkway (see below). Nevertheless, the almost parallel distance between $W_{\text{SSS}}$ and optimal speed of walking indicates that the $W_{\text{SSS}}$ at each gradient could be chosen according to some energy-saving criterion. Another comment regards the stride length variation: it is also possible that the instrumented treadmill, and its control system, induces the subjects to adopt a length suitable for steady-state conditions. As far as the $R_{\text{SSS}}$ experiments are concerned, speed declines with gradient whereas the stride frequency tends to remain constant, at least within the investigated gradient range. In contrast to walking, when the speed and frequency information is combined (Fig. 5), the stride length appears to steadily decrease with gradient.

The near independence of running frequency on speed and gradient, apparent in Fig. 5, witnesses the bouncy paradigm of that gait and confirms previously obtained data (13).

A deeper analysis of the obtained results is beyond the scope of this paper, which is meant to show the potential application of a new methodology. Here the heterogeneity and size of the subject group limit the strength of further arguments, but a focused experimental design is likely to obtain reliable information about the effects of age, gender, body mass, added mass, training status, rate of perceived exertion, materials, et cetera on the self-selected speed. For instance, there are no data in the literature about $W_{\text{SSS}}, W_{\text{MIN}}, R_{\text{MIN}}$, and $R_{\text{SSS}}$ in children in the age range from 5 to 13 yr, which could shed light on their dynamically equivalent speeds and gait transition with respect to adults. Although some of the measurements made on the treadmill at 0% gradient could be replaced by data from experiments on a level walkway (provided it is a very extended and instrumented linear path), it is virtually impossible to find constant-gradient paths with a length suitable for steady-state conditions.

During the last decade, in particular, the need for a treadmill-on-demand where spontaneous speeds could be reliably measured emerged in many different fields. Apart from the incompletely solved problem about the transition speed between walking and running (13), other issues were the attentional cost of transition (1), the parameterization and estimation of spontaneous gait (3), the economy of mobility in the elderly (5), the stride characteristics of chronic heart failure patients (6) and of hemiparetic subjects (8), the locomotor change of carrying heavy school bags in children (9), the locomotor-respiratory coupling during crutch ambulation (11), the coordination of arm and leg movement at different walking speeds (17), and the comparison between overground and treadmill walking (18), to name a few.

We anticipate that the treadmill-on-demand, which allows the assessment of totally unconstrained and spontaneous gaits on the treadmill, will contribute to insights in a number of locomotor problems. Perspectives, in addition to the ones mentioned above, include the study on the self-selected speed of $J$ endurance events and the effects of fatigue, 2) “virtual” mountain-ering, with real paths being input to the treadmill in terms of gradient (according to the distance achieved), and 3) pathological locomotor impairments, as in cardiac and respiratory failure and lower limb vascular diseases [like, for example, thromboangiitis obliterans (Bürger’s disease), diabetic arteritis, athrosclerosis, and secondary vasculitis], in which the maximum walking distance achievable (6-min walking test) and the related speed are used as indexes of the disease severity and markers of the rehabilitation progresses.

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DISCLOSURES

The software program and hardware assembly of the illustrated innovation (treadmill-on-demand) are under Manchester Metropolitan University copyright.

REFERENCES


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