Review article

Walking and running on treadmill: the standard criteria for kinematics studies

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Summary

In humans, walking and running represent the most studied locomotion forms. The motorized treadmill has always been a very useful scientific tool, because it allows administer a variety of speed/slope combinations, which is not always easy-to-find in nature. The purpose of this short communication is to help improve the scientific use of the treadmill and explain some simple kinematics variables together with simple ways to measure/calculate them.

KEY WORDS: biomechanics, evaluation, gait analysis, physical activity measurement, sports rehabilitation programs.

Introduction

Over the past decade there has been an increasing interest about the use of the motorized treadmill for studies about walking and running. However, any scientific study can lead to a valuable scientific progress only if the resulting study report results to be easily understood by others. Compliance to standard rules such as definitions, reliability (precision and accuracy), and accuracy of measurement is required[1]. To the authors' opinion, to improve the quality of the research, the correct treadmill use should be described in three common contexts:
1. Measurement reliability
2. Video Analysis
3. Kinematics.

Measurement reliability

For the use of a treadmill, in addition to the guidelines of its manufacturer, there are several suggestions about its' calibration (i.e., speed and slope check) for a good experimental set-up. Moreover, the calibration phase is necessary to guarantee the reproducibility of the measures[1]. Some authors[2-4] have shown a simple, very accurate and easy calibration method by using an odometer (Trumeter, Radcliffe, UK). The total distance covered was recorded by the odometer attached to the treadmill. The accuracy of the odometer is verified by comparing the results obtained by the odometer with those obtained by multiplying the actual number of complete treadmill belt revolutions in 6 minutes by the length of the belt.
The easiest way to calibrate the speed of a treadmill is to measure the length of the belt and count the number of belt revolutions over a certain amount of time. To calibrate the treadmill speed[5], these steps has to be followed:
1. Measure the length of the belt in meters.
   a. Place a meter stick on the belt surface and mark a starting point.
   b. Advance the belt by hand, marking the belt 1 m at a time until you return to the starting point. Note the resulting value as the *belt length*. The belt length measurement has to be done on a side (right or left) of the belt, near its edge. Indeed, "central" measurements could allow non-vertical measures and thus biasing the resulting length. For instance, any lateral deviation of the meter stick (even of few millimeters) will automatically result in a measure error.
2. Draw a small piece of tape – as a reference – on the treadmill belt and a corresponding piece of tape on the treadmill.
3. Turn on the treadmill and accelerate it to a given speed by using the speed control.
4. Count 20 revolutions of the tape on the belt while tracking the time with a stopwatch. Start your watch as the tape first moves past a taped point beside the belt, beginning the count with 0.

5. Convert the number of revolution to *revolutions per minute* (rev · min^{-1}). For example, if the belt made 20 complete revolutions in 35 sec, then 35 sec/60 sec · min^{-1} = 0.58 min, 20 rev/0.58 min = 34.3 rev · min^{-1}.
6. Multiply the calculated revolutions *per* minute (Step 5) by the belt length (Step 1). This gives the *belt speed* in meters *per* minute (m·min^{-1}). For example, if the belt length is 5.03 m, then 34.3 rev · min^{-1} · 5.03 m · rev^{-1}= 172.53 m · min^{-1}.
7. To convert meters *per* minute to miles *per* hour, divide the result of Step 6 by 26.8 (m · min^{-1}) · (mi · hr^{-1})$^{-1}$: 172.53 m · min^{-1}/[26.8 (m · min^{-1}) · (mi · hr^{-1})$^{-1}$] = 6.44 mi · hr^{-1}; to convert meters *per* minute to kilometer *per h*our, divide the result of Step 6 by 16.7 (m · min^{-1}) · (km · h^{-1}): 172.53 m · min^{-1}/16.7 = 10.33 km · h^{-1}.

The slope calibration requires a very simple method, which, even if rudimentary, is yet very effective:

1. Use a carpenter's level to ensure that the treadmill is leveled-off, and check the zero output on the grade meter under this condition (with the treadmill electronics turned on). If the grade meter does not read zero, follow these steps to make the adjustment (usually by using a small screw on the face of the treadmill controller dial).
2. Elevate the treadmill so that the percentage grade dial reads approximately 20%. Measure the exact rise and run of the bubble inside the tube of the level.
3. Calculate the grade from the rise over the run and adjust the treadmill meter to read that exact grade. For example, if the rise is 4.5 in (11.4 cm) and the run is 22.5 in (57.2 cm), the fractional grade is calculated as follows:

Grade = rise/run = 4.5 in/22.5 in = 0.20 or 20%.

Video analysis

The video analysis (VA) represents the most reliable and easy method for studying the human movement. VA based on motion capture with passive or active markers is useful for reconstructing along the trigonometric axes the movement in the space (*x* and *y* over a two-dimensional [*2D*] plane and *x-y-z* within a three-dimensional [*3D*] volume). Such a reconstruction can also be performed over time on a single-axis basis. *2D* analysis represents the most used method, because its experimental set-up requires relatively low cost tools. Moreover and recently, different manufactures of camcorders placed on the market different models[6] capable of high-speed recordings (60 ÷ 1000 fps [frames per second] or Hz) and different resolutions (i.e., FH20: 480 [rows] · 360 [columns] at 210 fps, 224 · 168 at 420 fps, 224 · 56 at 1,000 fps). To calculate the error (E) of the *2D* spatial resolution is very easy with the following equation:

E e.g., y (vertical) (mm) = 210 (fps)/[(D×1000)/R (480)];

where D (meters) is the vertical length of the sagittal plane studied and R the resolution of the camera (a 480 [rows] at 210 [fps] one, as an example here in the equation). Moreover, a proper sample frequency (fps or Hz) is necessary, especially to assess CT (contact time) or FT (flight time) during running when the speed is high. In fact, at speed > 14 km · h^{-1}, the average SF (Stride Frequency) is 3.5 Hz and to study the time (ms) of CT and FT is desirable to use a high-speed instrumentation. As an alternative you may detect by eye and count the steps *per* one minute and, by knowing the treadmill speed, calculate SF and SL (stride length)[7,8].

The 30 fps traditional camera sample rate is effective for low speed (≤ 9 km · h^{-1}), while for 9 ÷ 14.4 km · h^{-1} a 50 fps is required[9,10]. The 100 fps sampling showed a good reliability at 14.4 ÷ 20 km · h^{-1} [11], and for speeds exceeding 20 km · h^{-1} is recommended a device with ≥ 250 fps sampling rate[12,13]. In every case, the optimal sample rate should be calculated following the Nyquist–Shannon sampling theorem[14]. In particular, the theorem states that, under suitable assumptions, in an analog-to-digital conversion the minimum sampling frequency necessary to avoid ambiguity and loss of information (e.g., aliasing) in the reconstruction of the original analog signal is equal to twice its maximum frequency. The theorem, which appeared for the first time in 1949 in an article by C. E. Shannon[14], should be ascribed to Whittaker-Nyquist-Kotelnikov-Shannon, according to the chronological order of those scientists who proposed increasingly generalized versions of the theorem. Sampling is the first step of the process of analog-to-digital conversion of a signal. It means taking a certain number of samples every second from a continuous analog signal. Δt is the sampling interval, while f_x = 1/Δt is the sampling frequency. The result is an analog signal over discrete time.

Once chosen a certain sampling, particular attention should be used for the positioning of the camera, which is normally located on a 1.5 m-height tripod, ~ 4 m from and perpendicular to the acquisition space, in order to be perpendicular to the subjects' sagittal plane[15]. There should always be verification about the proper placement of the objective of the camera with respect of the field of view of interest. The more you get closer to the object to be recorded and the smaller the field of acquisition is, but the more accurate (low error)[15] is the resulting movie as well. Then the recorded movie will be studied with some motion analysis software.

Kinematics

A habituation of the subject with the locomotion on the treadmill is needed to allow the reliability of a proper measurement on it. Usually, the subjects' previous treadmill experience is not taken into consideration and they are asked to complete an adequate habituation session on it (see for a simple experimental set-up as well).

Moreover, a lot of attention has to be paid to the shoes[16] for the reliability of the measures[17]. This is especially true for shoes which are worn in longitudinal studies[18]. Besides, it is possible to calculate the mechanical energy absorbed by the shoe. In fact the shoe's kinetic energy (KEY) at its initial impact on the ground may be calculated with this equation: $KEY = \frac{1}{2} \cdot m \cdot v^2$ (where m is the shoe's mass and v its speed at the impact)[16]. Usually, the mass of the shoes is highly variable (0.1 ÷ 0.5 kg) and depends on the runner's body weight and his/her usual speed[18-20].

A simple kinematics study is represented by the footstep analysis in terms of CT, FT, step frequency (SF [Hz]), and step length (SL [m]) detection. These data may be analyzed after video recording according to the method of Mero and Komi[21]. In some cases, footstep data (CT, FT, SF, SL; with a precision of 1 ms) are measured by using photocells-based timing system. A 2-m length of this system may be secured along a treadmill belt[22]. With this photogrammetric system CT and FT may be calculated for both the left and right foot together. Running CT is defined and calculated as the time between the initial foot/shoe contact/frame with the ground and the last foot/shoe contact/frame before the take-off. FT is defined and calculated as the time between the take-off and the next initial contact of the contra-lateral foot. Initial contact and take-off may be visually detected. Stride frequency is calculated as $SF = 1/(CT+FT)$. SL is calculated with the following equation: $SL = \text{speed } [m \cdot s^{-1}]/SF$. Some authors indentified in the stride cycle: Foot Strike (FS as to corresponding to the first photogram in which the foot in contact with the ground); Toe Off (TO as to corresponding to the first photogram in which the foot is no more in contact with the ground)[23,24]. As an example of a specific matter investigated by using the simple kinematics analysis just described, Ardigò et al.[25] and Hasegawa et al.[24] classified subjects' FS by three different patterns: rear-foot strike (RFS), mid-foot strike (MFS) and fore-foot strike (FFS). RFS was defined as a foot strike in which the point of the first contact of the foot with the ground was the heel, the rear third part of the sole and in which the mid-foot or forefoot portion did not have any contact at foot strike[24]. MFS was defined as a foot strike in which the point of the first contact of the foot with the ground were the rear third of the sole and the mid-foot together, i.e., the whole sole[24]. FFS was defined as a foot strike in which the point of the first contact of the foot with the ground was the fore-foot, the front half of the sole, and in which the heel did not have any contact at the foot strike (see for a simple experimental set-up as well)[24].

As another example of simple kinematics application, by knowing the timing of the step it is possible to calculate the mechanical internal kinematic work (W_{INT}) with a simple equation by Nardello et al.:[26] $W_{INT} = SF \cdot v \cdot (1 + (DF \cdot (1 - DF)^{-1})^2) \cdot q$. Here DF is the duty factor, i.e., the average % of the total cycle duration, at which a foot is in contact with the ground. q is a compound dimensionless term with constant value of 0.08 (in level, 0.10 in slope) referring to the inertial properties of the limbs and the mass partitioned between the limbs and the rest of the body. Other biomechanical more complex variables featuring running can be estimated by using the simple kinematics variables just described. For example, Morin et al.[27] proposed a method for measuring the leg and the vertical stiffness from CT (expressed in s), FT (expressed in s), *v,* leg length (l, expressed in m) and body mass. In particular, the vertical stiffness is calculated as:

$$K_{VERT} = m \cdot g \cdot \frac{\pi}{2} \cdot \left(\frac{FT}{CT}+1\right) \cdot \left(\frac{m \cdot g \cdot \frac{\pi}{2} \cdot \left(\frac{FT}{CT}+1\right)}{m} \cdot \frac{CT^2}{\pi^2} + g \cdot \frac{CT^2}{8} \right)^{-1},$$

and the leg stiffness is calculated as:

$$K_{LEG} = m \cdot g \cdot \frac{\pi}{2} \cdot \left(\frac{FT}{CT}+1\right) \cdot \left(l - \sqrt{l^2 - \left(\frac{v \cdot CT}{2}\right)^2} + \left(\frac{m \cdot g \cdot \frac{\pi}{2} \cdot \left(\frac{FT}{CT}+1\right)}{m} \right) \cdot \frac{CT^2}{\pi^2} + g \cdot \frac{CT^2}{8} \right)^{-1},$$

where g is the gravity acceleration constant (in $m \cdot s^{-2}$).

For a simple experimental set-up

- The first step is about the reliability of the kinematics analysis on treadmill *vs* field (track and field). Jones and Doust solved this issue[28]. In particular, a 1% treadmill slope replies most accurately an outdoor track and field setting on the measurement/calculation of the metabolic cost (Cr, i.e., the metabolic expenditure over resting *per* unit distance travelled [$J \cdot kg^{-1} \cdot m^{-1}$]) at different speeds ($10.51 < 18.00\ km \cdot h^{-1}$).
- The second step is about the selection of some meaningful speed value. In this regard Padulo et al. (2012) proposed a simple Iso-Efficiency Speed over slope (IES, $km \cdot h^{-1}$) equation for trained runners[20]. IES for each participant at a 0% slope (IES_0) was calculated as the average speed featuring the participant's best performance in a 10,000 m race (recorded within the 6 month period prior to testing), minus 1 $km \cdot h^{-1}$. Research suggested this corresponds to ~50% maximal oxygen consumption[29] and requires a metabolic cost (Cr_0) of 4.0 $J \cdot kg^{-1} \cdot m^{-1}$.[30] Slope IES results from the following equation:

$$IES = \frac{IES_0 \cdot (0.20 \cdot slope\% + Cr_0)}{Cr_0}$$

- The third step is about the habituation. The subjects should practice on the treadmill for at least 10 min[31], which represent the good time for treadmill familiarization for subjects up to 65 yrs, while at least 15 min are necessary for ages over 65 yrs[32].
- The fourth step concerns the time needed in case of a metabolic cost investigation together with a kinematics one. For each speed the minimum time must not be less than 5 min, because it takes 4 min to the metabolic cost to attain a physiological steady state[33,34].

- The fifth step concerns the minimum step number required for high quality research. It is 64 steps[35] for subject[18-20,36,37] with a lot of experience and 400 steps for beginners[38]. Such step number choices are considered adequate to cope adequately with actual footstep variability[35,38].

The present article synthesizes the current knowledge about the use of the treadmill as a device for studies about gait kinematics. Therefore it can be of interest for sport scientists and coaches, who aim to perform effectively simple tests to assess athletes' gait kinematics variables. This review conforms to required ethical standards[39].

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