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Emulating constant acceleration locomotion mechanics on a treadmill

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ABSTRACT

Locomotion on an accelerating treadmill belt is not dynamically similar to overground acceleration. The purpose of this study was to test if providing an external force to compensate for inertial forces during locomotion on an accelerating treadmill belt could induce locomotor dynamics similar to real accelerations. Nine males (mean ± sd age = 26 ± 4 years, mass = 81 ± 9 kg, height = 1.8 ± 0.05 m) began walking and transitioned to running on an accelerating instrumented treadmill belt at three accelerations (0.27 m s^{-2}, 0.42 m s^{-2}, 0.76 m s^{-2}). Half the trials were typical treadmill locomotion (TT) and half were emulated acceleration (EA), where elastic tubing harnessed to the participant provided a horizontal force equal to mass multiplied by acceleration. Net mechanical work (W_{COM}) and ground reaction force impulses (I_{GRF}) were calculated for individual steps and a linear regression was performed with these experimental measures as independent variables and theoretically derived values of work and impulse as predictor variables. For EA, linear fits were significant for W_{COM} ($y = 1.19x + 10.5$, $P < 0.001$, $R^2 = 0.41$) and I_{GRF} ($y = 0.95x + 8.1$, $P < 0.001$, $R^2 = 0.3$). For TT, linear fits were not significant and explained virtually no variance for W_{COM} ($y = 0.06x + 1.6$, $P = 0.29$, $R^2 < 0.01$) and I_{GRF} ($y = 0.10x + 0.4$, $P = 0.06$, $R^2 = 0.01$). This suggested that the EA condition was a better representation of real acceleration dynamics than TT. Running steps from EA where work and impulse closely matched theoretical values showed similar adaptations to increasing acceleration as have been previously observed overground (forward reorientation of GRF vector without an increase in magnitude or change in spatio-temporal metrics).

1. Introduction

The mechanics of human locomotion have been studied extensively. It is now relatively commonplace for research and rehabilitation laboratories to combine motion capture systems with instrumented treadmills to readily obtain many consecutive steps or strides of walking or running data. The use of instrumented treadmills as opposed to in ground force plates also facilitates the use of tethered devices such as stationary bodyweight support systems (Donelan and Kram, 1997), robotic testbeds (Caputo and Collins, 2013) and wired measurement systems (e.g. ultrasound imaging platforms). Although treadmills provide a convenient means of collecting data, under some circumstances they do not provide an accurate replication of overground locomotion dynamics.

Van Ingen Schenau (1980) provided a detailed proof that the dynamics of locomotion on a treadmill with constant belt speed are dynamically similar to constant speed locomotion overground when considered in a reference frame that moves with the belt. However, theoretical and experimental evidence shows that locomotion on an accelerating treadmill belt is not dynamically similar to accelerating overground (Christensen et al., 2000; Van Caekenberghe et al., 2013b). Perhaps the simplest explanation for this is that the person on an accelerating treadmill belt is not actually accelerating in a fixed inertial reference frame, unlike a person accelerating overground. It is also the case that the previously noted reference frame that is attached to the belt is accelerating relative to the world and is considered a non-inertial reference frame. When the belt is accelerated, it causes an inertial force to act upon the user that is opposite in direction to the acceleration and equal to the user's mass multiplied by the acceleration of the belt. This force effectively accelerates the user in the belt frame of reference and the user does not have to actively generate propulsive horizontal ground reaction forces to accelerate their body, as they would have to overground. As a result, the mechanics of running on an accelerating treadmill belt have been experimentally shown to be fundamentally different from those for accelerative running overground (Van Caekenberghe et al., 2013b). Therefore it is not appropriate to study accelerative locomotion mechanics during normal walking and running on an accelerating treadmill, unless the acceleration is very low (Goldberg et al., 2008;

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Peterson et al., 2011). This is inconvenient, because overground studies limit the use of wired/tethered systems; make it hard to control speed and require either many trials or multiple force platforms to obtain multiple steps. Often human locomotion is not at constant speed and so it would be useful to find an appropriate means of studying accelerative locomotion on a treadmill.

Morin et al. (2010) examined accelerations on a torque treadmill where the user drove the belt acceleration and was rigidly tethered to allow an appropriate body posture. However, without controlling the force in the tether and making it proportional to belt acceleration, one cannot accurately reproduce the forces required to overcome body inertia. An approach presented by Christensen et al. (2000), was to compensate for the inertial forces resulting from belt acceleration by applying a proportional horizontal force (mass multiplied by belt acceleration) in the opposite direction via a tether. In their system, the force was feedback controlled according to belt acceleration and the position of the user on the treadmill. However, the purpose of Christensen et al. (2000) was not to examine the mechanics of the user and so they did not report if similar mechanics to those observed overground were induced by this approach.

This study aimed to assess the effects of emulating acceleration by providing a compensatory horizontal force to negate the inertial effect of belt acceleration on treadmill walking and running mechanics. Two hypotheses were proposed: (1) Providing a compensatory force would induce net mechanical work and net impulses more similar to theoretically derived true values than walking and running on a treadmill without a compensatory force. (2) The effects of emulated acceleration on ground reaction forces (GRF) and temporal metrics for running would be the same as have been observed for overground acceleration (Kugler and Janshen, 2010; Van Caekenberghe et al., 2013a, 2013b). Specifically, increasing belt acceleration would cause a more anterior orientation of the GRF vector during running without affecting the magnitude of the vector or step and stance times. To provide proof of concept, a simplified case is presented where belt acceleration is constant, and therefore the inertial and compensatory forces are constant, negating the need for feedback control.

2. Methods

2.1. Participants and protocol

Nine male participants (mean ± sd age = 26 ± 4 years, mass = 81 ± 9 kg, height = 1.8 ± 0.05 m) gave written informed consent to participate in this study that was approved by an institutional ethics review committee. Each participant initially walked on a split belt instrumented treadmill (DBCEEWI, AMTI, USA) at 0.75 m s^{-1} and naturally transitioned to a run during a period of treadmill belt acceleration that increased belt speed to 2.75 m s^{-1}. This was repeated four times at each of three accelerations (A1: 0.27 m s^{-2}, A2: 0.42 m s^{-2}, A3: 0.76 m s^{-2}) for two experimental conditions (total of 24 trials). One experimental condition was typical treadmill locomotion (TT) and the other was emulated acceleration (EA) where a backward horizontal force was applied to the user via a tensioned rubber spring element attached to a harness worn by the user (Fig. 1). For TT, participants also completed constant speed (A0) trials for walking (1.25 m s^{-1}) and running (2.25 m s^{-1}). Comparing the accelerations used with previous studies, they fall within the mid-range for volitional overground running accelerations (Van Caekenberghe et al., 2013b) and the A1 and A2 conditions are similar to volitional overground walking accelerations (Qiao and Jindrich, in press).

2.2. Emulating acceleration mechanics

The EA condition was intended to induce mechanics (GRF impulse, external net mechanical work) similar to that which would be required for overground accelerations. Ignoring frictional and aerodynamic forces, a person accelerating overground has these dynamics:

$$F_h = ma_g \quad (1)$$

Where F_h is the net horizontal GRF, m is the person's mass and a_g is the horizontal acceleration of the body in a ground-based fixed reference frame. For typical treadmill locomotion where the belt is accelerated relative to the ground-based reference frame the dynamics can be described by:

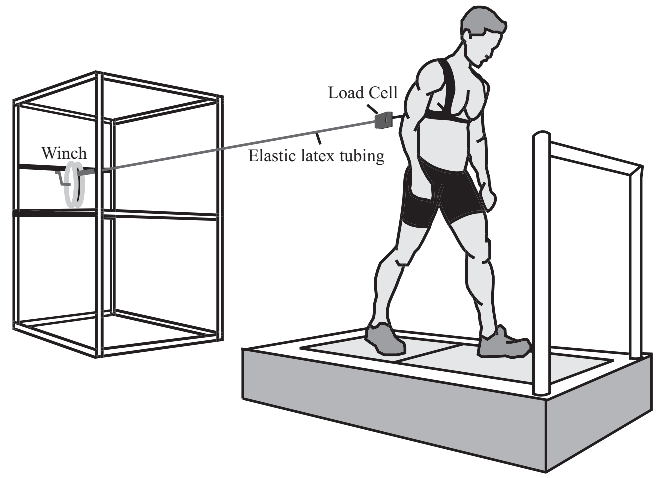

Fig. 1. Schematic illustration of the experimental setup for emulated acceleration. Participants walked and ran over the split in the treadmill belts while wearing a harness attached to a length of rubber tubing. A lockable winch situated 4 m behind the treadmill was used to tension the rubber tubing and a load cell in series between the tubing and the harness measured the force in the tubing. The rubber tubing and load cell were disconnected from the harness for the typical treadmill locomotion condition.

$$F_h = ma_{p/b} + ma_{b/g} \quad (2)$$

Where $a_{p/b}$ is the acceleration of the person in a frame of reference moving with the treadmill belt and $a_{b/g}$ is acceleration of the treadmill belt in the ground-based frame of reference. The term $ma_{b/g}$ represents the inertial force acting on the person as a result of the acceleration of the belt. If the person remains in the same position on the treadmill, then $a_{p/b}$ must be equal and opposite to $a_{b/g}$ and F_h will equal zero. From Eq. (1), we see that overground, F_h cannot be zero if the person is accelerating and therefore typical treadmill locomotion is not dynamically similar to overground. As proposed by Christensen et al. (2000), we can treat the inertial force $ma_{b/g}$ as an external force and apply an opposing horizontal external force to get the following dynamics:

$$F_h - ma_{b/g} + F_{app} = ma_{p/b} \quad (3)$$

Where, F_{app} is the horizontal external applied force. If F_{app} and $ma_{b/g}$ are equal and opposite in direction they cancel, giving:

$$F_h = ma_{p/b} \quad (4)$$

Thus, by adding F_{app} and making it equal to $ma_{b/g}$, the dynamics of the person in the treadmill belt-based frame of reference are equivalent to those describing overground acceleration in a ground-based frame of reference (Eq. (1)).

In a simple case where $ma_{p/b}$ is constant, F_{app} needs to be constant and assuming the person can maintain a consistent fore-aft position on the treadmill, can be applied by a tensioned spring element. Therefore in the EA condition, a force equal to body mass multiplied by belt acceleration was generated in a rubber spring element using a winch, and measured via a load cell (Tedea Huntleigh 614, Vishay Precision Group, PA, USA) in series. The rubber spring was attached to the person via a torso harness so that the force was applied close to the body centre of mass. Any fore-aft oscillation of the body during each stride would potentially increase or decrease tension in the tubing. To minimise the effect of oscillations, compliant latex surgical tubing (inner diameter: 3.0 mm, outer diameter: 5.0 mm, Gecko Optical, WA, Australia) was used and stretched from an original length of 1.5 m to at least 4.0 m at all accelerations. By using a spring of low stiffness at a large strain, the effects of oscillations of the body on spring tension are minimised (Donelan and Kram, 1997).

2.3. Force and work calculations

The instrumented treadmill has two belts (front and back) with a tri-axial force plate under each. Participants were instructed to walk/run over the join in the belts to maintain a constant fore-aft position on the treadmill. GRF data and the analogue signal from the load cell were sampled at 2000 Hz in Qualisys Track Manager software (Qualisys, Sweden). Raw GRF and load cell signals were filtered using a second order bidirectional low-pass Butterworth digital filter at a cut off of 25 Hz. To calculate the net fore-aft impulse generated by GRF (I_{GRF}) in each step, the fore-aft GRF signals from both force plates were summed and integrated with respect to time from each heel strike to the subsequent contralateral heel strike. Over each