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Mechanics of overground accelerated running vs. running on an accelerated treadmill

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ABSTRACT

Unsteady state gait involving net accelerations has been studied overground and on a treadmill. Yet it has never been tested if and to what extent both set-ups are mechanically equal.

This study documents the differences in ground reaction forces for accelerated running on an instrumented runway and running on an accelerating treadmill by building a theoretical framework which is experimentally put to the test.

It is demonstrated that, in contrast to overground, no mean fore-after force impulse should be generated to follow an accelerating treadmill due to the absence of linear whole body acceleration. Accordingly, the adaptations in the braking phase (less braking) and propulsive phase (more propulsion) to accelerate overground are not present to follow an accelerating treadmill.

It can be concluded that running on an accelerating treadmill is mechanically different from accelerated running overground.

1. Introduction

The mechanics of locomotion have primarily been studied when moving in a straight line at a constant average speed [1]. Nevertheless, the interest for unsteady and transient aspects of overground (OV) locomotion has been growing [2–8], particularly in situations where the Body Centre Of Mass (BCOM) presents a net acceleration in an Earth Bound (EB) reference frame [6,7,9,10]. For example, by studying gait transitions (occurring spontaneously when speed changes/increases) researchers hope to gain insight into neuromechanics of locomotion [11]. Moreover, many daily [12] and sport-related [13,14] locomotion activities are characterized rather by short intermittent bursts of movement (thus necessitating accelerations) than steady movements.

Using a treadmill (TM) may offer practical advantages for such studies like a confined set-up in which conditions can easily be controlled and reproduced [15–20]. While the treadmill is validated for steady state walking and running [21–23], one study compared the overground and the treadmill walk-to-run transitions for which differences in execution were hypothesized to originate from the mechanical inequality of overground and treadmill unsteady locomotion [24]. Understanding the causes and nature of these differences is important for the interpretation of accelerating treadmill experiments, for development of new methodologies (e.g. treadmill on demand in which the treadmill accelerates in response to actions of the subject) and for functional rehabilitation and sport training during which people learn/train to change speed during locomotion.

On theoretical bases one can prove that accelerated overground and treadmill locomotion must differ. Nevertheless confusion on the biomechanics of locomotion on accelerating treadmills remains. In this paper a mechanical framework based on Newtonian equations will be established first. Next, experimental evidence in support will be provided.

Accelerated running overground is not mechanically equivalent to running on an accelerated treadmill (Fig. 1). The reference frame associated with the accelerating belt is a non-inertial reference frame. Due to its non-uniform motion relative to the inertial EB frame, a fictitious force, F_{fx}, must be introduced in the equation of the forces ($\sum F = m\,a$), to account for the observed motion of the BCOM in this non-inertial frame. F_{fx} is proportional to the mass acted upon and to the acceleration of the frame, and modifies the magnitude of the ground reaction force, F_{grfx}, exerted by the belt on the subject and measured by the transducers between belt and ground.

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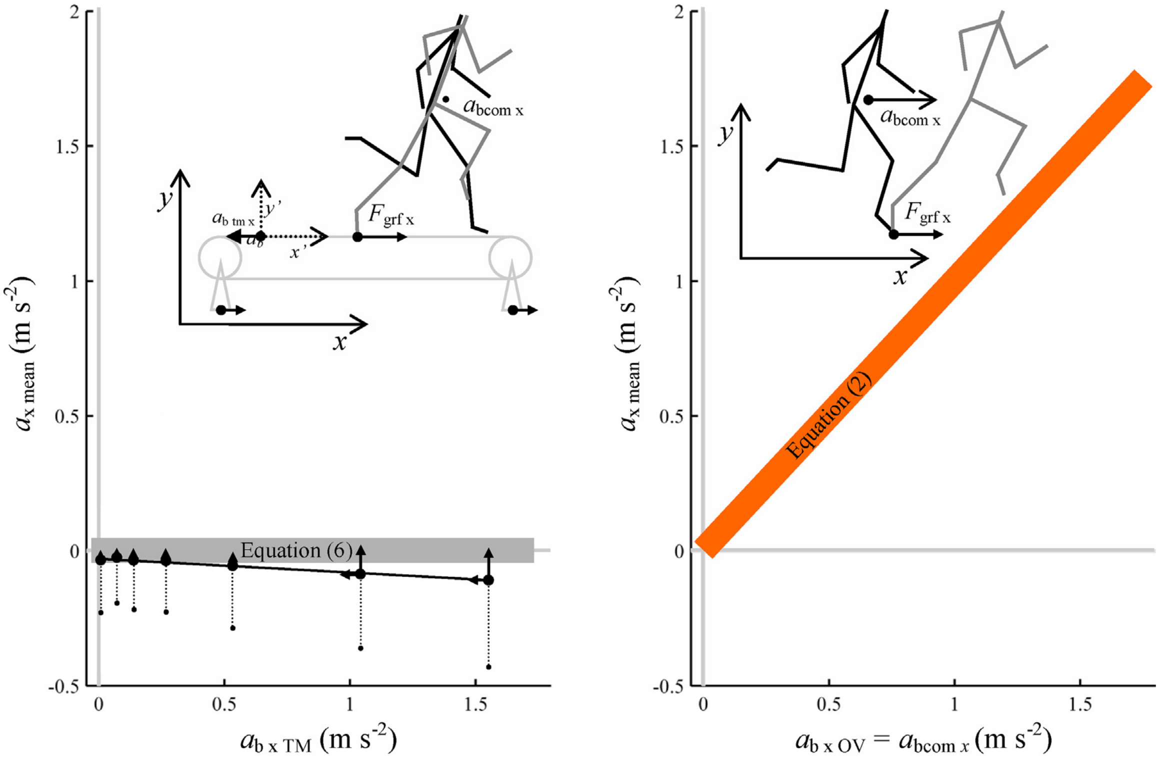

Fig. 1. Treadmill belt (left) and overground BCOM (right) acceleration vs. mean fore-after acceleration due to F_{grfx}. The bold line indicates the theoretical expectation as given by the equations in the introduction. On treadmill it is assumed that the BCOM remains motionless over the course of a cycle. *xyz* indicates the inertial EB reference frame. *x′y′z′* indicates the non-inertial frame of reference associated with the accelerating treadmill belt. Triangles indicate the force transducers supporting the treadmill and measuring the F_{grf}. Horizontal full arrows indicate one intersubject sd. on the *x*-axis. Vertical full arrows indicate one intersubject standard deviation. on the *y*-axis. Vertical dotted lines indicate one intrasubject standard deviation. on the *y*-axis. Linear regressions are indicated by —.

Compare a runner with mass m accelerating overground with an average acceleration a_{bx} and running on an accelerating belt imposing the same acceleration a_{bx}. All friction forces are assumed negligible. During the contact phase the instantaneous acceleration of the BCOM (a_{bcomx}) varies around a_{bx}. The acceleration a_{bcomx} can thus be expressed as:

$$a_{bcomx} = a_{bx} + a_{rx}, \quad (1)$$

where a_{rx} is the oscillation (including the bimodal pattern of braking and propulsing) of a_{bcomx} around a_{bx}.

When running overground with an acceleration a_{bcomx}, the equation of the forces in the inertial EB frame is given by:

$$F_{grfx} = m\,a_{bcomx}. \quad (2)$$

Substituting Eq. (1) into Eq. (2):

$$F_{grfx} = m(a_{bx} + a_{rx}). \quad (3)$$

This shows that, at each instant, the BCOM is submitted to a horizontal F_{grfx}, which generates a horizontal acceleration (a_{bcomx}). Overground, joint moments are contributing to the average acceleration of the BCOM (a_{bx}) and to overcome the change in acceleration of the BCOM during the contact phase (a_{rx}).

Now, let us have the same subject running on a belt which is accelerating backwards with an acceleration a_{bx}. We suppose that the instantaneous acceleration of the BCOM (a_{bcomx}) relative to the non-inertial reference frame of the belt has the same magnitude as the a_{bcomx} when running overground (Eq. (2)). This task constraint is typical for habituated running on a treadmill, during which the runner remains in place while the stance leg can be considered to be pulled underneath the BCOM.

When the subject is running on the accelerating belt, part of a_{bcomx} is due to the acceleration of the reference frame (a_{bx}) and not to a real acceleration of the subject. To take into account the acceleration of the reference frame, the fictitious force, F_{fx}, must be added:

$$F_{fx} = m\,a_{bx}. \quad (4)$$

In the non-inertial reference frame of the belt, the equation of the forces becomes thus:

$$F_{fx} + F_{grfx} = m\,a_{bcomx}. \quad (5)$$

Substituting (1) and (4) in (5), the BCOM is only submitted to a F_{grf} equal to:

$$F_{grfx} = m\,a_{rx}. \quad (6)$$

By comparing Eqs. (2) and (6), one can observe that $F_{grfx} = m\,a_{bcomx}$ during accelerated running overground, whereas $F_{grfx} = m\,a_{rx}$ during running on an accelerated belt. Appendix 1 elaborates on these equations.

This study is intended to experimentally validate the above theoretical model showing that running on an accelerating belt mechanically differs from accelerating overground. Overground, the subject has to create F_{grfx} to produce the mean acceleration of the BCOM as well as the oscillation around this mean. On treadmill F_{grfx} only have to account for the oscillations of the BCOM, whereas the net acceleration is provided passively by the accelerating belt. Therefore, it is hypothesized that overground the mean fore-aft F_{grf} will increase proportionally to the acceleration, whereas on treadmill the mean fore-aft F_{grf} will remain zero regardless of acceleration. Therefore, the fore-after F_{grf} are different between treadmill and overground conditions when accelerating. To experimentally validate these predictions, we will examine the acceleration influence on mean fore-after F_{grf} and braking and propulsing impulses. Next to these expected differences in the