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Short communication

Energy exchange between subject and belt during treadmill walking

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ABSTRACT

Treadmill walking aims to simulate overground walking, but intra-stride belt speed variations of treadmills result in some interaction between treadmill and subject, possibly obstructing this aim. Especially in self-paced treadmill walking, in which the belt speed constantly adjusts to the subject, these interactions might affect the gait pattern significantly. The aim of this study was to quantify the energy exchange between subject and treadmill, during the fixed speed (FS) and self-paced (SP) modes of treadmill walking. Eighteen subjects walked on a dual-belt instrumented treadmill at both modes. The energy exchange was calculated as the integration of the product of the belt speed deviation and the fore-aft ground reaction force over the stride cycle. The total positive energy exchange was 0.44 J/stride and the negative exchange was 0.11 J/stride, which was both less than 1.6% of the performed work on the center of mass. Energy was mainly exchanged from subject to treadmill during both the braking and propulsive phase of gait. The two treadmill modes showed a similar pattern of energy exchange, with a slightly increased energy exchange during the braking phase of SP walking. It is concluded that treadmill walking is only mildly disturbed by subject-belt interactions when using instrumented treadmills with adequate belt control.

1. Introduction

Treadmills are increasingly used for gait analysis because of their efficient measurement of many strides in a small volume. However, generalization of treadmill to overground based gait analysis is questioned, since differences have been found in gait pattern (Stolze et al., 1997; Alton et al., 1998; Lee and Hidler, 2008; Riley et al., 2007). Conceptually, it is obvious that gait mechanics are only comparable between treadmill and overground walking if the belt speed is constant (van Ingen Schenau, 1980). However, significant intra-stride belt speed variations have been measured during treadmill walking (Savelberg et al., 1998; Kram et al., 1998; Belli et al., 2001; Verkerke et al., 2005; Dierick et al., 2004; Paolini et al., 2007; Tesio and Rota, 2008; Bagesteiro et al., 2011; Collins et al., 2009; Riley et al., 2007).

Belt speed variations are mainly the result of changes in the fore-aft ground reaction force during the stance phase and inadequate belt control to comply with that. The latter can be caused by limited motor power, belt slip over the drive rollers or insufficient speed update frequency (Riley et al., 2007; Paolini et al., 2007). A measure of the resulting disturbance is the energy exchange, that relates speed variability to the fore-aft ground reaction force. A first attempt to quantify the energy exchange between subject and treadmill used forces measured during normal overground walking (Savelberg et al., 1998). However, ground reaction forces have been found to be somewhat different during treadmill walking (Lee and Hidler, 2008; Riley et al., 2007; Goldberg et al., 2008) and treadmills have been further developed since, possibly resulting in reduced or altered belt speed fluctuations. In addition, dual-belt treadmills have been introduced, with isolated control of the left and right belt instead of shared control of the single belt used previously (Savelberg et al., 1998).

Furthermore, self-paced (SP) walking is increasingly used, during which the belt speed is not fixed but adaptive to the position and velocity of the subject. This SP walking allows for more stride variability (Sloot et al., 2014), resulting in long-range stride fluctuations that resemble those seen during natural over ground walking (Hausdorff et al., 1995; Dingwell et al., 2001). However, the accelerations and decelerations of the belt necessary to keep the subject within the boundaries of the treadmill could possibly result in increased energy exchange, thereby further limiting the comparison to overground walking.

Our aim was to quantify the energy exchange between treadmill and subject during both fixed speed (FS) and self-paced (SP) treadmill walking, in state of the art treadmill technology.

2. Methods

Eighteen subjects (23.2 ± 2.0 yr; 10 female; 75.3 ± 9.6 kg) signed informed consent and walked on a dual-belt instrumented treadmill (R-Mill, ForceLink, the Netherlands) in a speed-matched virtual environment (GRAIL, Motek Medical, the Netherlands). Subjects were given six minutes to habituate to both modes and instructed to walk at preferred walking speed. Subjects first walked at SP mode for three minutes, of which

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the average speed was used for the subsequent 3 min FS trial. Subjects got off the treadmill in between trials and were given several minutes rest if appreciated. During SP walking (D-flow v3.12, Motek Medical, The Netherlands), the speed correction was proportional to the distance between subject and the middle of the treadmill and to the subject's speed, with the speed gain as function of the distance (Sloot et al., 2014). The belt speed was adjusted 60 times per second, using a 4.5 kW motor per belt. Force sensors underneath each belt (50 × 200 cm) recorded the ground reaction forces. Motion of the COM was tracked by a cluster marker on a pelvic belt using an active motion capture system (Optotrak, NDI, Canada). Belt speed was registered by the controller of the treadmill. The last minute of each trial was recorded and all data, i.e. force, motion and belt speed, were sampled at 100 Hz. The protocol was approved by the ethics committee of the local institution.

Force and motion data were low-pass filtered at 20 Hz with a bi-directional 2nd order Butterworth filter. Initial contact and toe-off were based on a threshold of 50 N of the vertical force. Strides with incorrect foot placement, i.e. not on a single belt, were excluded. All signals were time-normalized to 0–100% of the gait cycle. Since the control of the left and right belt was similar, only the results for the left belt and strides are presented. Instantaneous energy exchange between subject and treadmill was calculated as the product of the belt speed deviation (Δv) and the fore-aft ground reaction force (F_{ap}). For SP walking, belt speed deviation was defined as the relative deviation from the mean belt speed per stride. The instantaneous energy exchange (EE_i) was integrated over positive (i.e. exchange from subject to treadmill) and negative (exchange from treadmill to subject) values separately to avoid mathematical cancellation (Savelberg et al., 1998). The energy exchange was given for both the braking phase, which ends at the moment Fap changes sign (at approximately 35% of the gait cycle), and the propulsive phase (lasting from the end of braking phase until toe-off) to indicate the exchange resulting from initial contact and push off separately. Thus, the total positive energy exchange was calculated as:

$$EE_{POS} = \int_{\text{Braking,POS}} EE_i dt + \int_{\text{Propulsion,POS}} EE_i dt = \int_{\text{Braking,POS}} \Delta v \times F_{ap} dt + \int_{\text{Propulsion,POS}} \Delta v \times F_{ap} dt \quad (1)$$

A similar equation applies to the negative EE. The total positive and negative energy exchange was subsequently compared with the work performed on the center of mass (COM work). The positive COM work was calculated as the integration over the positive values of the COM power (Donelan et al., 2002):

$$W_{COM,POS} = \int_{POS} P_{COM,POS} dt = \int_{POS} F_{GRF} \times v_{COM} dt \quad (2)$$

with $W_{\text{COM,POS}}$ the positive COM work and $P_{\text{COM,POS}}$ the positive COM power, which is the dot product of the ground reaction force (F_{GRF}) and the velocity of the COM derived from the pelvis marker data (v_{COM}). Similarly $W_{\text{COM,NEG}}$ was calculated separately.

To determine differences between SP and FS treadmill walking, non-parametric sign rank tests were performed on the walking speed; belt speed variations; as well as on the mean stride and intra-subject stride variation of the energy exchange parameters, with a significance level of 0.05.

3. Results

Walking speed was equal between FS and SP walking: 1.33 ± 0.18 and 1.31 ± 0.18 m/s, respectively. During SP walking, walking speed varied by 0.29 ± 0.09 m/s. The fore-aft forces were comparable between SP and FS walking (Fig. 1A). The belt speed variation showed a clear deceleration during the braking phase, followed by some overshoot in the compensating acceleration and a small acceleration during the propulsive phase (Fig. 1B). The pattern was comparable between conditions, with peak deviations of 3.22 ± 1.06% for FS and 3.17 ± 1.11% for SP walking.

The energy exchange was characterized by an energy flow from the subject to the treadmill during the braking and propulsive

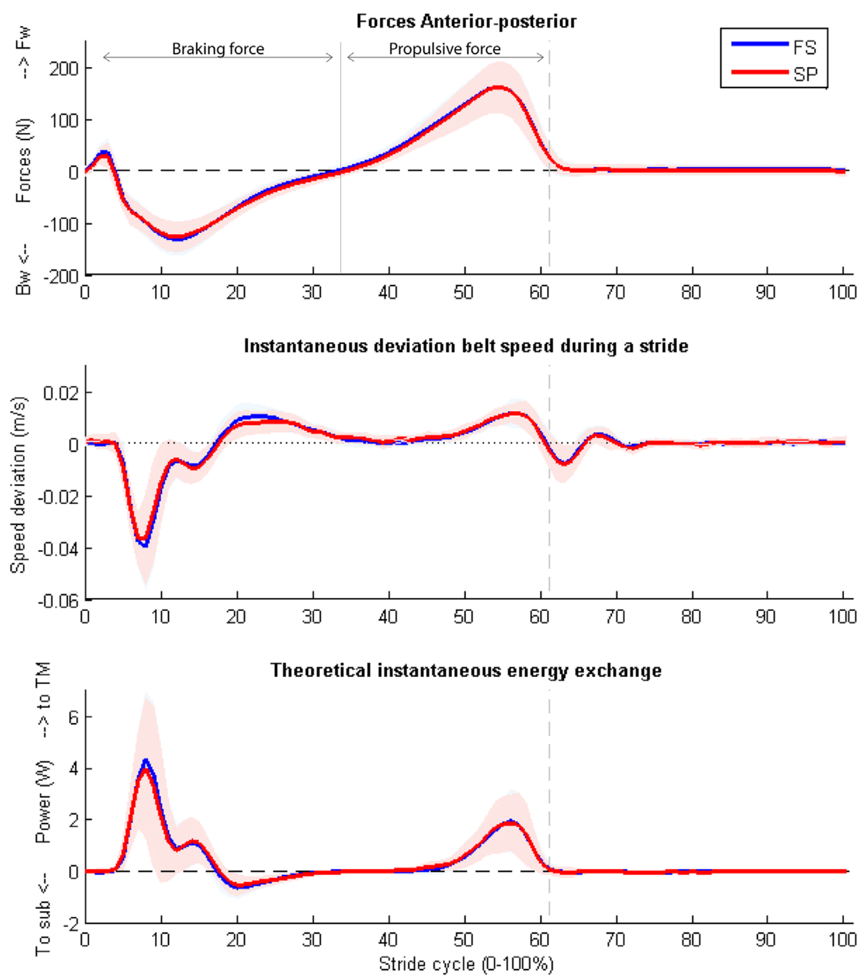

Fig. 1. Anterior–posterior GRF's (A), instantaneous deviation of the belt speed (B), and instantaneous energy exchange (C) normalized to the stride cycle, for both fixed speed (FS, blue) and self-paced (SP, red) treadmill walking. Vertical striped grey line indicates the toe off. Mean values (lines) and standard deviation (coloured areas) over all subjects are given. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)