Available online at www.sciencedirect.com
ScienceDirect
Gait & Posture 28 (2008) 663–667
GAIT & POSTURE
www.elsevier.com/locate/gaitpost

Instantaneous treadmill speed determination using subject's kinematic data

N. Fusco *, A. Crétual

M2S, University Rennes 2, ENS Cachan, UFR APS, Avenue Charles Tillon, CS 24 414, 35 044 Rennes, Bretagne, France

Received 21 September 2007; received in revised form 12 April 2008; accepted 23 April 2008

Abstract

The treadmill is frequently used in research and clinical assessments for gait analysis. To evaluate mechanical energy and dynamics of walking, the fluctuations of the treadmill speed have to be taken into account. A new algorithm is presented in this study to determine instantaneous treadmill speed using solely the kinematic data of subjects. The algorithm uses an automatic detection of heel contact (HC) and toe off (TO) during treadmill walking. Kinematic data were collected from two groups (healthy adult, $n = 11$; hemiplegic adult, $n = 9$). The gait events determination is validated by comparison with two visual inspection methods. Our algorithm is able to determine instantaneous treadmill speed with accuracy. In fact, the root mean square error between the computed speed (CS) and the measure speed (MS) was weak with an average value of 0.04 ± 0.021 m s^{-1}. So, the computed speed reflects the variations of the belt speed and could be an important contribution to energetic and dynamic gait analysis on a treadmill.

Keywords: Belt speed; Algorithm; Treadmill; Kinematic data; Gait events

1. Introduction

The treadmill is widely used in research and clinical assessments because it offers a controlled and convenient environment for gait analysis. The treadmill facilitates the use of monitoring equipment, and it is safe and requires less space. Furthermore, walking speed can be imposed and directly controlled.

In several previous studies variations in belt speed have been pointed out [1–5]. Even though the belt speed fluctuations could be minimized to a desirable level [6], they still exist and have to be taken into account when evaluating treadmill gait dynamics [1,3]. For this reason, it is important to determine instantaneous treadmill speed, even though to our knowledge, few previous studies have proposed methods to obtain it. Recently, Segers et al. [7], registered electronically the actual speed of the treadmill to determine the kinetic energy fluctuations of the center of mass. However, the frequency was very low (5 Hz) and no details were given about the device used and whether it could be implemented on any treadmill. Savelberg et al. [3] used a marker attached to a wooden block placed on the belt. This method implies that an operator replaces this block at the front end of the belt when it reaches the back end. Even though it provides a reliable measure of the treadmill speed, this method does not seem to be useable for routine gait analysis.

An alternative is to use the subject's kinematic data recorded during gait analysis on treadmill. More precisely, the trajectories of markers placed on the foot could be used to determine the belt speed. To validate the negligibility of the slippage between the foot and belt, Alton et al. [8] compared the lateral malleolus marker speed measured during the stance time and the stated belt speed. Although only the mean foot velocity was taken into account, the method appears to be promising.

The identification of the stance period requires an accurate detection of heel contact (HC) and toe off (TO) during treadmill walking. A force plate is frequently used to identify these gait events during overground walking [9,10].

* Corresponding author. Tel.: +33 2 99 141 775; fax: +33 2 99 141 774.
E-mail addresses: nicolas.fusco@univ-rennes2.fr (N. Fusco), armel.cretual@univ-rennes2.fr (A. Crétual).

0966-6362/$ – see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.gaitpost.2008.04.016

On a treadmill, this gold standard method requires specialized equipment which is not available to all labs. Several alternative methods have been developed based on, accelerometers [11,12], gyroscopes [13,14] or instrumented shoes [15–17]. Kinematic data also provide reliable information to determine HC and TO. Some methods have been described in the literatures such as visual inspection [18,19] as well as automatic method through algorithms based on velocity or vertical acceleration curves of heel and toe markers [20,21]. All these methods are reliable but the former are laborious and can hardly be used in routine whereas the latter have never been validated on treadmill. Zeni et al. [22] recently used a kinematic method on the treadmill but they had only examined gait events for one speed walking by subjects.

The purpose of our study is to present a new algorithm for computing the instantaneous treadmill speed based on subject's kinematic data, as well as validate an automatic method for determining gait events during treadmill walking. The HC and TO timing results were compared with the same gait events determined with two methods of visual inspection [18,19]. The belt speed computed by the algorithm was compared to the real belt speed obtained by a method inspired by that of Savelberg et al. [3].

2. Methods

2.1. Normal gait data

The normal gait group was composed of 11 non-pathological adults (8 males, 3 females, age 23–34 years, mean $\pm$ standard deviation 27.4 ± 3.2 years). Normal gait data was used to evaluate our algorithm. Each subject, wearing his or her own shoes, walked on the treadmill at three imposed speeds (0.8, 1.4 and 1.9 m s^{-1}). All subjects were accustomed to treadmill locomotion. In addition, subjects were given time to become acclimated to the treadmill condition at each trial before captured motion. The 3D kinematic data were recorded using a Vicon MX40 motion analysis system (Vicon, Oxford, UK) at a sampling frequency of 120 Hz. A set of 32 markers was attached to the subject's skin on anatomical landmarks. However, only the hip (greater trochanter), the heel and the toe (head of the second metatarsus) markers were used in this study. Reconstruction and labellisation were performed using Vicon IQ software (Vicon, Oxford, UK) and computations using Matlab 6.5 (The Mathworks, Natick, Massachusetts, US).

2.2. Pathological gait data

Nine adults hemiplegic post-stroke patients (7 males, 2 females, age 25–45 years, 32.0 ± 9.9 years) were recruited to compose the impairment group. All were able to walk without aids, handrails or cane. Pathological gait data was used to apply our algorithm on an specific population and to emphasize the variation of the belt speed. All subjects, wearing their own shoes, were instructed to walk on the treadmill at a comfortable speed. To determine this comfortable speed, the belt speed was initiated at 0.3 m s^{-1}. A gradual increase by increments of 0.15 m s^{-1} was then executed until the subject signaled that to be his or her speed. Before testing began, all subjects were given 3 min to become familiarized to the treadmill. In addition, they were provided with a 10-min session of treadmill training, some days prior to testing. Kinematic data were captured at 60 Hz, thanks to a seven camera Vicon 370 motion analysis system (Vicon, Oxford, UK). The same markers set previously described for healthy subjects was used to capture kinematic data of hemiplegic subjects.

Each volunteer (i.e. hemiplegic and healthy) provided written, informed consent prior to participation in this study, which had been conducted in accordance with the Helsinki declaration.

2.3. Instantaneous treadmill speed algorithm

Treadmill walking is always characterized by at least one contact point between the treadmill and one foot whether it is the heel or the toe. Consequently, we hypothesize that the velocity of this point is the same as the actual belt speed. Thus, the algorithm consists of calculating the instantaneous treadmill speed using the coordinates of the heel and the toe markers in the direction of the progression. To do this, the 3D kinematic data of the subject are reoriented by adjusting the walking direction with the anteroposterior displacement of the markers. Then, the horizontal velocity of the former markers is calculated by taking the first derivative of the horizontal coordinates using finite difference equations. The computed speed (CS) of the treadmill is obtained by selecting the appropriate velocity among the four markers' velocities. This selection depends on the phase of the gait cycle as illustrated in Fig. 1. During the gait phase C, the anteroposterior velocities of the toe and heel markers are respectively, influenced by the toe and ankle rockers. Because the markers were placed on shoes, they did not match with the joint center and an anteroposterior translation appeared during rotation. As a consequence, the left toe marker is preferred until the first ankle rocker finishes.

In order to evaluate its accuracy and reliability, the algorithm has been tested on the normal gait group by comparing CS to the measured speed (MS) of the treadmill. MS was determined from the horizontal velocity of reflective markers attached to the belt using a method similar to Savelberg et al. [3]. A cubic spline smoothing was applied on MS and CS to reduce noise. Finally, both curves were compared for each trial of the normal gait group.

HC and TO were automatically identified using hip, heel and toe trajectories along the direction of progression. To determine HC, a new signal was created representing the heel trajectory along the direction of progression relatively to the hip reference frame. This signal was low pass filtered with a cutoff frequency of 10 Hz using a Butterworth filter. Then the velocity was obtained by calculating the first derivative of the trajectory. The algorithm automatically identifies the HC events when the velocity of the heel marker becomes negative, which corresponds to the contact of the heel on the treadmill.

The algorithm detects TO events using the displacement of the toe marker along the direction of progression. This trajectory is derived by finite difference equations to obtain the velocity curve. The timing of the TO is identified when the velocity becomes positive which matches with the beginning of forward displacement of toe.

To validate the HC and TO obtained with our algorithm, we compared them to the timing of gait events using two reliable manual visual inspections previously reported.