Advanced technologies to assess motor dysfunction in children with cerebral palsy

Sloot, L.H.

2016

7 Energy exchange between subject and treadmill

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.

LH Sloot, MM van der Krogt & J Harlaar (2014). Energy exchange between subject and belt during treadmill walking.J Biomech, 47(6) 1510-1513.

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 have been questioned, since differences were found in gait pattern [1-4]. Conceptually, it is obvious that gait mechanics are only comparable between treadmill and overground walking if the belt speed is constant [5]. However, significant intra-stride belt speed variations have been measured during treadmill walking [4,6-14].

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 [4,11]. 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 [6]. However, ground reaction forces have been found to be somewhat different during treadmill walking [3,4,15] 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 [6].

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 [16], resulting in long-range stride fluctuations that resemble those seen during natural over ground walking [17,18]. 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.

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 6 min to habituate to both modes and instructed to walk at preferred walking speed. Subjects first walked at SP mode for 3 min, of which 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 [16]. The belt speed was adjusted 60 times per second, using a 4.5 kW motor per belt. Force sensors underneath each belt (50x200 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 [6]. The energy exchange was given for both the braking phase, which ends at the moment F_{ap} 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:

$$\begin{aligned} EE_{POS} &= \int_{braking,POS} EE_i dt + \int_{propulsion,POS} EE_i dt \\ &= \int_{braking,POS} \Delta v \times F_{ap} dt + \int_{propulsion,POS} \Delta v \times F_{ap} dt \end{aligned} \qquad \text{7-1}$$

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 [19]:

$$W_{COM,POS} = \int_{POS} P_{COM,POS} dt = \int_{POS} F_{GRF} \cdot v_{COM} dt \qquad \text{7-2}$$

with $W_{COM,POS}$ the positive COM work and $P_{COM,POS}$ 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 $W_{COM,NEG}$ 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.

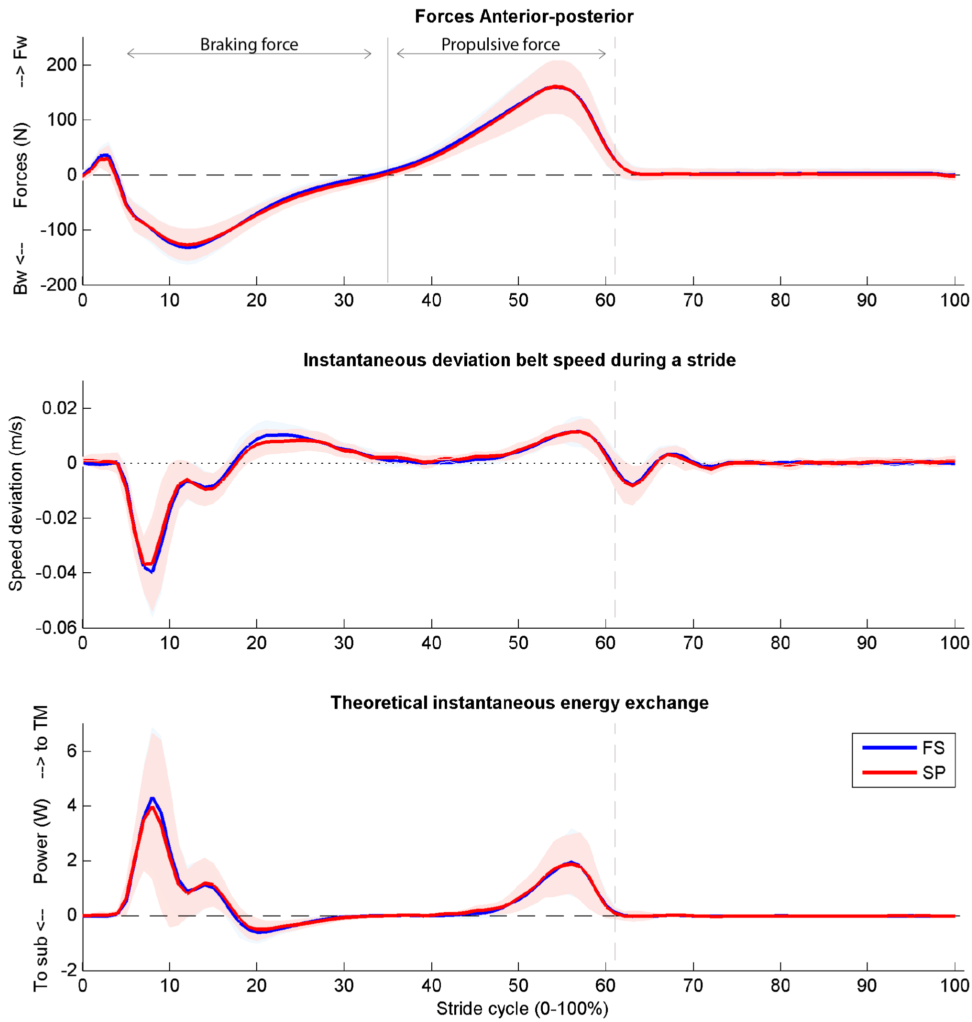

Fig 7-1. Anterior-posterior GRF's (A), instantaneous deviation of belt speed (B), and instantaneous energy exchange (C) normalized to the stride cycle, for both FS and SP. Vertical striped line indicates toe off., lines the mean value over subjects and colored areas standard deviation.

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 speed varied by 0.29±0.09 m/s. The fore-aft forces were comparable between SP and FS walking (Fig. 7-1A). 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. 7-1B). 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 phases (Fig. 7-1C). FS and SP walking

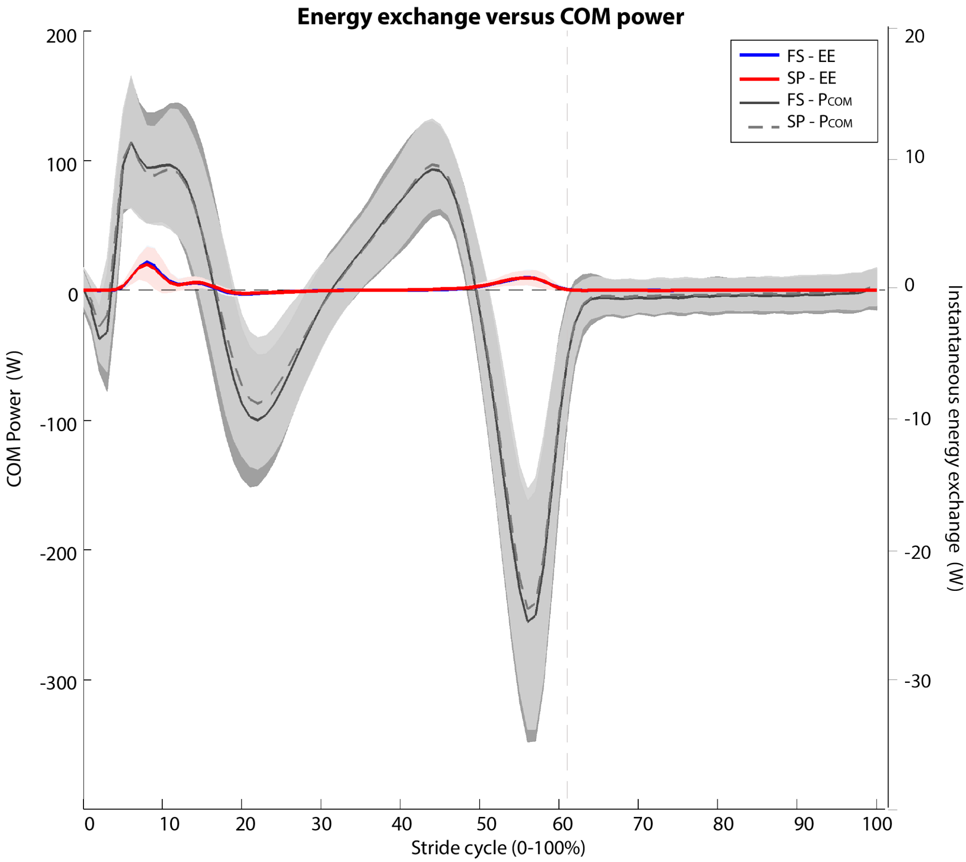

Fig 7-2. Energy exchange (EE) and COM power (P_{COM}) for both FS and SP. Note that the energy exchange is multiplied with a gain of 10 to enhance visual impression. Vertical striped line indicates toe off. Lines the mean value over subjects and colored areas standard deviation.

showed a similar pattern of energy exchange, although slightly more work was performed during the braking phase in SP, with an increase of 0.011 W in positive work and 0.013 W in negative work compared to FS (Table 7-1). During SP walking, the variability of energy exchange between strides was significantly increased for the peak power and positive and negative work during the braking phase.

The energy exchange between subject and treadmill was relatively small (Fig. 7-2), with an exchange of 1.4% (FS) and 1.6% (SP) of the COM work to the treadmill and 0.4% and 0.5% to the subject (Table 7-1).

Discussion

In this study we examined the energy exchange between treadmill and subject for both FS and SP treadmill walking. The pattern of the belt speed deviation we measured was in accordance with descriptions of high powered treadmills in literature, with a deceleration following initial contact [3,4], as well as some overshoot and acceleration during the push-off [6]. With 3.2%, the belt speed deviation was within the reported range [7,12,14] or smaller [6,8-11,13,20].

These belt speed variations are a sign of subject-treadmill interactions. Similar to Savelberg *et al.* we found a flow of energy from the subject to the treadmill during both the braking and propulsive phase [6]. The total energy exchange we found was 0.33 J/stride for both modes (Table 7-1), with a peak power of 5.1 W for FS and 4.9 W for SP walking. This is lower than the 0.70 J/stride and 10 W reported previously [6], even though we used a much lower powered treadmill, *i.e.* 4.5 kW per belt vs. 22 kW. Although their maximum difference in belt speed was lower than ours (3.8% versus 3%), their belt speed was more fluctuating from the mean belt speed during the entire stride, possibly resulting in the increased energy exchange. It has also been found that ground reaction forces are smaller during treadmill compared to overground walking[3,4,15]. Taken relative to the work of the COM, the energy exchange with the treadmill was less than 1.6% of the COM work. So, the interaction of treadmill and subject seemed only a minor effect.

It is important to note that both belts of the treadmill used in this study were independently controlled for belt speed by a separate motor. Therefore, the interaction with the treadmill was isolated for the left and right leg, whereas in a single belt the deceleration due to foot impact is more or less cancelled by acceleration due

Table 7-1. Comparison of FS and SP walking for both mean stride and stride variability

	Mean stride		**Stride variability**	
	FS	SP	FS	SP
Peak power				
Braking phase (W)	5.08±2.78	4.86±2.90	1.55±0.58	1.90±0.76*
Propulsive phase (W)	3.02±1.27	3.07±1.45	0.97±0.37	0.99±0.38
Energy exchange				
Braking phase: pos. (J/stride)	0.25±0.11	0.26±0.12*	0.07±0.02	0.13±0.05**
Braking phase: neg. (J/stride)	-0.07±0.02	-0.08±0.03*	0.03±0.01	0.06±0.04**
Propulsive phase: pos. (J/stride)	0.19±0.09	0.19±0.10	0.05±0.02	0.05±0.02
Propulsive phase: neg. (J/stride)	-0.04±0.02	-0.03±0.02	0.02±0.01	0.02±0.01
Total pos. (J/stride)	0.43±0.20	0.44±0.22	0.12±0.04	0.18±0.06**
Total neg. (J/stride)	-0.10±0.04	-0.11±0.05	0.05±0.02	0.09±0.05**
Total net (J/stride)	0.33±0.16	0.33±0.18	0.16±0.05	0.27±0.10**
COM work				
Total pos. (J/stride)	32.20±17.58	29.42±17.90**		
Total neg. (J/stride)	-23.52±5.33	-23.30±5.35		
EE relative to COM work				
Total pos. (%)	1.37±0.32	1.56±0.35**		
Total neg. (%)	0.44±0.12	0.48±0.13		

The parameters constitute the peak powers calculated for the first peak during the braking phase and for the peak during the propulsive phase, and the energy exchange (EE) during both the phases. Positive values indicate energy exchange from subject to treadmill, negative values vice versa. In addition, COM work and EE relative to COM work are given. Mean and standard deviation are shown, with significant differences indicated: * as $p<0.05$, ** as $p<0.001$.

to the push-off of the other foot. It was expected that a single-belt treadmill with similar specifications had less belt speed variation and therefore less energy exchange. However, we found a lower energy exchange for the split-belt treadmill than reported previously for the single-belt treadmill. This cannot be explained by inadequate motor power in their study, but it could be related to a higher update frequency in our treadmill, less belt slip over the rollers, or a superior control loop algorithm. Thus, adequate motor power alone is not a guarantee for low subject-treadmill energy exchange.

A similar pattern of instantaneous energy exchange was found for FS and SP walking, although slightly more energy was exchanged during SP. This difference was smaller than 0.013 J/stride for both the positive and negative work. So the gait pattern is marginally more disturbed by accelerations of the belt in SP mode compared to FS walking. This is in agreement with earlier findings, showing only minor differences in kinematics and kinetics between SP and FS walking [16].

Conclusion

This study directly measured treadmill-subject interactions during FS and SP treadmill walking. In total, 0.44 J/stride was transferred to the treadmill, and 0.11 J/stride to the subject, which was less than 1.6% of the performed COM work. Minor differences were found between SP and FS treadmill walking. Overall, these results suggest that treadmill walking is only very mildly disturbed by treadmill-subject interactions, when using instrumented treadmills with adequate belt control.

Acknowledgements

This study was financially supported by grant 10733 from the Dutch Technology Foundation STW. We are grateful to Marjolein Booij and Lisa Bosman for their assistance in collecting the data.

References

1. Stolze H, Kuhtz-Buschbeck JP, Mondwurf C, Boczek-Funcke A, Johnk K, Deuschl G, Illert M. Gait analysis during treadmill and overground locomotion in children and adults. Electroencephalography and Clinical Neurophysiology 1997; 105(6): 490-497
2. Alton F, Baldey L, Caplan S, Morrissey MC. A kinematic comparison of overground and treadmill walking. Clinical Biomechanics 1998; 13(6): 434-440
3. Lee SJ, Hidler J. Biomechanics of overground vs. treadmill walking in healthy individuals. Journal of Applied Physiology 2008; 104(3): 747-755
4. Riley PO, Paolini G, Della Croce U, Paylo KW, Kerrigan DC. A kinematic and kinetic comparison of overground and treadmill walking in healthy subjects. Gait & Posture 2007; 26(1): 17-24
5. van Ingen Schenau GJ. Some fundamental aspects of the biomechanics of overground versus treadmill locomotion. Medicine and science in sports and exercise 1980; 12(4): 257-261
6. Savelberg HHCM, Vorstenbosch MATM, Kamman EH, van de Weijer JGW, Schamhardt HC. Intra-stride belt-speed variation affects treadmill locomotion. Gait & Posture 1998; 7(1): 26-34
7. Kram R, Griffin TM, Donelan JM, Chang YH. Force treadmill for measuring vertical and horizontal ground reaction forces. Journal of Applied Physiology 1998; 85(2): 764-769
8. Belli A, Bui P, Berger A, Geyssant A, Lacour JR. A treadmill ergometer for three-dimensional ground reaction forces measurement during walking. Journal of Biomechanics 2001; 34(1): 105-112

9. Verkerke GJ, Hof AL, Zijlstra W., Ament W, Rakhorst G. Determining the centre of pressure during walking and running using an instrumented treadmill. Journal of Biomechanics 2005; 38(1): 1881-1885
10. Dierick F, Penta M, Renaut D, Detrembleur C. A force measuring treadmill in clinical gait analysis. Gait & Posture 2004; 20(3): 299-303
11. Paolini G, Della Croce U, Riley PO, Newton FK, Kerrigan DC. Testing of a tri-instrumented-treadmill unit for kinetic analysis of locomotion tasks in static and dynamic loading conditions. Medical Engineering & Physics 2007; 29(3): 404-411
12. Tesio L, Rota V. Gait analysis on split-belt force treadmills - Validation of an instrument. American Journal of Physical Medicine & Rehabilitation 2008; 87(7): 515-526
13. Bagesteiro LB, Gould D, Ewins DJ. A vertical ground reaction force-measuring treadmill for the analysis of prosthetic limbs. Brazilian Journal of Biomedical Engineering 2011; 27(1): 3-77
14. Collins SH, Adamczyk PG, Ferris DP, Kuo AD. A simple method for calibrating force plates and force treadmills using an instrumented pole. Gait & Posture 2009; 29(1): 59-64
15. Goldberg EJ, Kautz SA, Neptune RR. Can treadmill walking be used to assess propulsion generation? Journal of Biomechanics 2008; 41(8): 1805-1808
16. Sloot LH, van der Krogt MM, Harlaar J. Self-paced versus fixed speed treadmill walking. Gait & Posture 2014; 39(1): 478-484
17. Hausdorff JM, Peng CK, Ladin Z, Wei JY, Goldberger AL. Is Walking A Random-Walk - Evidence for Long-Range Correlations in Stride Interval of Human Gait. Journal of Applied Physiology 1995; 78(1): 349-358
18. Dingwell JB, Cusumano JP, Cavanagh PR, Sternad D. Local dynamic stability versus kinematic variability of continuous overground and treadmill walking. Journal of Biomechanical Engineering-Transactions of the Asme 2001; 123(1): 27-32
19. Donelan JM, Kram R, Kuo AD. Simultaneous positive and negative external mechanical work in human walking. Journal of Biomechanics 2002; 35(1): 117-124
20. Cretual A, Fusco N. Additional energetic cost due to belt speed variations when walking on a treadmill. Journal of Electromyography and Kinesiology 2011; 21(3): 551-556