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Kinetic comparison of walking on a treadmill versus over ground in children with cerebral palsy

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ABSTRACT

Kinetic outcomes are an essential part of clinical gait analysis, and can be collected for many consecutive strides using instrumented treadmills. However, the validity of treadmill kinetic outcomes has not been demonstrated for children with cerebral palsy (CP). In this study we compared ground reaction forces (GRF), center of pressure, and hip, knee and ankle moments, powers and work, between overground (OG) and self-paced treadmill (TM) walking for 11 typically developing (TD) children and 9 children with spastic CP. Considerable differences were found in several outcome parameters. In TM, subjects demonstrated lower ankle power generation and more absorption, and increased hip moments and work. This shift from ankle to hip strategy was likely due to a more backward positioning of the hip and a slightly more forward trunk lean. In mediolateral direction, GRF and hip and knee joint moments were increased in TM due to wider step width. These findings indicate that kinetic data collected on a TM cannot be readily compared with OG data in TD children and children with CP, and that treadmill-specific normative data sets should be used when performing kinetic gait analysis on a treadmill.

1. Introduction

Kinetic outcomes are an essential part of clinical gait analysis. While kinematics are used to quantitatively describe the abnormalities of movement patterns on the level of joint and segment angles, kinetics give an indication of the causes of these motions and the relation with underlying muscle function. Kinetic outcomes of gait analysis typically contain the hip, knee, and ankle joint moments as well as their powers. Joint moments describe the net internal moments delivered by all muscles and ligamentous tissue around the joint, thereby giving an indication of the minimum force level that muscles need to produce at any instant during the gait cycle. Joint powers describe the rate, amount, and timing of energy generation and dissipation around a joint.

Children with cerebral palsy (CP) typically present abnormal patterns of joint moments and powers during gait. For instance, in a crouched gait pattern abnormally high moments can occur around the hip, knee, and ankle, requiring excessively high muscle forces (Lin et al., 2000). Abnormally high or low powers are also typically seen in these patients, in combination with aberrant and inefficient timing. A toe-walking gait pattern for instance can coincide with high power dissipation and generation peaks in early and mid-stance (Svehlik et al., 2010), which do not contribute to efficient propulsion. In contrast, ankle power during push-off is typically diminished (Riad et al., 2008; Svehlik et al., 2010), which may lead to an inefficient gait pattern (Donelan et al., 2002). For a thorough understanding of a patient's gait pattern, it is important to accurately describe the joint moments and powers in combination with the kinematics.

Kinetic data are typically collected using ground-embedded force plates, and a single complete foot contact is needed per plate for correct calculation of joint moments and powers during a stride. This can make it cumbersome and time-consuming to collect only a few good strides. The introduction of instrumented split-belt treadmills with built-in force plates allows for kinetic data collection of many consecutive strides. However, there are several technical challenges inherent of treadmill-embedded force plates, such as increased compliance of the large plates and more low-frequency vibrations compared with ground-mounted force plates (Sloot et al., 2015b). This is expected to increase the noise and decrease the accuracy of the forces and center of pressure, which could negatively affect joint moment and power calculations. Before utilizing instrumented treadmills for kinetic gait analysis in research and clinical practice, it is thus important to critically assess the measured moments and powers.

A few studies have compared treadmill kinetics to overground data. Riley et al. (2007) found that in healthy adults joint moments, powers, and GRF peaks were generally smaller during treadmill walking compared with overground, for the same

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Table 1
Spatiotemporal and kinetic outcome parameters.

Parameter	Unit	TD		CP		p-values		
		OG	TM	OG	TM	CON	GRP	Inter
Walking speed	m/s	1.34 ± 0.15	1.28 ± 0.20	1.12 ± 0.17	1.04 ± 0.31	0.229	0.009	0.901
GRF vert peak1	N/kg	11.03 ± 1.34	11.29 ± 0.79	11.73 ± 1.59	12.56 ± 1.02	0.134	0.031	0.428
GRF vert peak2	N/kg	10.46 ± 1.52	10.93 ± 0.57	10.24 ± 1.07	10.32 ± 0.60	0.254	0.310	0.418
GRF ap brake peak	N/kg	1.82 ± 0.45	1.98 ± 0.29	1.57 ± 0.30	1.80 ± 0.59	0.100	0.180	0.728
GRF ap propul peak	N/kg	1.90 ± 0.33	1.92 ± 0.43	1.53 ± 0.37	1.66 ± 0.63	0.569	0.061	0.638
GRF ml peak	N/kg	0.45 ± 0.12	0.88 ± 0.19	0.56 ± 0.17	1.09 ± 0.22	0.000	0.017	0.314
CoP ap mean	%	81.26 ± 11.34	71.03 ± 10.76	87.77 ± 22.78	100.48 ± 20.12	0.564	0.021	0.000
CoP ml mean	%	44.76 ± 5.71	25.18 ± 12.39	45.73 ± 10.77	45.46 ± 20.24	0.002	0.055	0.002
Trunk lean fw mean	deg	4.58 ± 4.82	7.99 ± 4.70	4.64 ± 5.81	6.68 ± 7.75	0.037	0.982	0.649
Moment								
Hip extension M peak	Nm/kg	0.79 ± 0.20	1.12 ± 0.22	0.79 ± 0.23	1.02 ± 0.28	0.000	0.558	0.458
Hip flexion M range	Nm/kg	1.54 ± 0.40	1.71 ± 0.26	1.53 ± 0.47	1.52 ± 0.43	0.403	0.505	0.369
Hip abduction M peak	Nm/kg	0.60 ± 0.20	0.83 ± 0.26	0.42 ± 0.08	0.55 ± 0.22	0.001	0.012	0.238
Knee extension M peak	Nm/kg	0.56 ± 0.27	0.52 ± 0.25	0.50 ± 0.21	0.38 ± 0.27	0.140	0.341	0.452
Knee extension M mean	Nm/kg	0.00 ± 0.08	−0.02 ± 0.06	0.00 ± 0.08	−0.09 ± 0.10	0.002	0.231	0.070
Knee abduction M peak	Nm/kg	0.33 ± 0.10	0.49 ± 0.17	0.29 ± 0.13	0.36 ± 0.26	0.008	0.220	0.212
Ankle extension M peak	Nm/kg	1.19 ± 0.20	1.11 ± 0.17	1.17 ± 0.26	1.27 ± 0.26	0.780	0.469	0.039
Ankle extension M DBI	–	0.14 ± 0.20	0.02 ± 0.23	0.45 ± 0.42	0.70 ± 0.25	0.162	0.001	0.000
Power/work								
Hip work generated S	J/kg	0.43 ± 0.13	0.46 ± 0.19	0.46 ± 0.14	0.53 ± 0.10	0.104	0.434	0.509
Hip work absorbed S	J/kg	0.12 ± 0.07	0.12 ± 0.06	0.12 ± 0.06	0.08 ± 0.08	0.357	0.379	0.504
Knee work generated S	J/kg	0.15 ± 0.08	0.18 ± 0.08	0.11 ± 0.06	0.11 ± 0.04	0.394	0.034	0.439
Knee work absorbed S	J/kg	0.51 ± 0.16	0.42 ± 0.14	0.39 ± 0.18	0.34 ± 0.14	0.035	0.136	0.464
Ankle power peak S	W/kg	2.01 ± 0.52	1.64 ± 0.67	1.16 ± 0.58	1.01 ± 0.59	0.079	0.004	0.444
Ankle work generated S	J/kg	0.18 ± 0.05	0.12 ± 0.05	0.13 ± 0.08	0.10 ± 0.05	0.005	0.131	0.306
Ankle work absorbed S	J/kg	0.15 ± 0.04	0.17 ± 0.06	0.16 ± 0.06	0.20 ± 0.10	0.006	0.575	0.248
Total net hip work	J/kg	0.31 ± 0.13	0.34 ± 0.22	0.34 ± 0.11	0.45 ± 0.09	0.090	0.223	0.395
Total net knee work	J/kg	−0.36 ± 0.11	−0.24 ± 0.14	−0.28 ± 0.16	−0.23 ± 0.14	0.023	0.413	0.279
Total net ankle work	J/kg	0.02 ± 0.07	−0.05 ± 0.09	−0.03 ± 0.07	−0.10 ± 0.08	0.000	0.121	0.985
Total net work	J/kg	−0.02 ± 0.12	0.05 ± 0.22	0.03 ± 0.13	0.11 ± 0.15	0.114	0.320	0.974

Abbreviations: TD, typically developing; CP, cerebral palsy; OG, overground; TM, treadmill; CON, condition effect (OG versus TM); GRP, group effect (TD versus CP); Inter, interaction effect between condition and group. GRF, ground reaction force; CoP, center of pressure; vert, vertical; ap, anteroposterior; ml, mediolateral; fw, forward; M, moment; DBI, double bump index (see Section 2); S, stride. CoP ap mean and CoP ml mean are taken as percentage of footlength and footwidth respectively.

walking speed, but within normal gait variability. In healthy elderly, Watt et al. (2010) also found small reductions in the majority of moments and powers when compared to speed-matched overground walking, and Parvataneni et al. (2009) showed a decrease in the second GRF peak, associated with reduced push-off. Thus, the differences found in healthy (older) adults seemed consistent but small. Contrarily, in typically developing children, Rozumalski et al. found considerable differences between overground and treadmill running (Rozumalski et al., 2015) and walking (Rozumalski et al., 2014), due to a more anteriorly oriented ground reaction force vector on the treadmill. This indicates that different subject groups may behave differently on the treadmill, and warrants the need for further study in children with CP.

Therefore, the aim of this study was to compare kinetic data between overground and self-paced treadmill walking for TD children and children with spastic CP. We assessed hip, knee, and ankle joint moments and powers, as well as the underlying ground reaction forces (GRF) and centers of pressure (CoP).

2. Methods

2.1. Subjects

9 children with spastic CP (4 male, 5 female; age 11.6 ± 2.1 years, range 8–14; height 1.49 ± 0.13 m; weight 40.9 ± 10.3 kg) and 11 TD children similar in age, height, and weight (7 male, 4 female; age 10.6 ± 2.2 years, range 8–15; height 1.52 ± 0.15 m; weight 38.2 ± 10.5 kg) participated in this study. The subjects and set of experiments were the same as in our recently published kinematic comparison between overground walking, treadmill walking, and natural walking outside of a lab environment (Van der Krogt et al., 2014). The methods are briefly repeated here, with an emphasis on the kinetic measurements. Children with CP were randomly selected from our database and only included if they were able to walk independently without walking aids for at least 5 min on end and 30 min in total within two hours; were classified as level I or II on the gross motor function classification scale (GMFCS) (Palisano et al., 1997); had received no multilevel surgery, selective dorsal rhizotomy or intrathecal baclofen treatment within the last year; nor botulinum toxin A treatment within the previous 16 weeks. All parents and children aged 12 years and older provided written informed consent prior to participation. The protocol was approved by the local ethics committee of the VU University Medical Center Amsterdam.

2.2. Design and materials

Subjects walked in random order (1) overground (OG) in a conventional gait lab and (2) on a self-paced treadmill (TM) placed in an immersive virtual environment. They wore their own shoes, which had to be low models with flat soles, and orthoses (3 CP subjects) or insoles (1 CP subject) if used on a regular basis. A safety harness was worn in both conditions, and attached loosely to the ceiling only in TM for safety reasons.

OG consisted of a 10 m walkway with two embedded force plates (AMTI, Watertown, MA USA). A target of 5 trials with correct force plate hits was collected for both legs. Subjects were not instructed to target the force plates, but only to walk at their self-selected pace across the walkway.

TM consisted of a dual-belt instrumented treadmill (R-Mill, Motekforce Link, Amsterdam, the Netherlands) in a speed-matched virtual environment projected on a 180° semi-cylindrical screen, displaying an endless, straight forest road and scenery (Gait Real-time Analysis Interactive Lab (GRAIL) system, Motekforce Link, Amsterdam, The Netherlands). The speed of the belt was real-time adjusted to