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Determination of the vertical ground reaction forces acting upon individual limbs during healthy and clinical gait

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ABSTRACT

In gait lab, the quantification of the ground reaction forces (GRFs) acting upon individual limbs is required for dynamic analysis. However, using a single force plate, only the resultant GRF acting on both limbs is available.

The aims of this study are (a) to develop an algorithm allowing a reliable detection of the front foot contact (FC) and the back foot off (FO) time events when walking on a single plate, (b) to reconstruct the vertical GRFs acting upon each limb during the double contact phase (DC) and (c) to evaluate this reconstruction on healthy and clinical gait trials.

For the purpose of the study, 811 force measurements during DC were analyzed based on walking trials from 27 healthy subjects and 88 patients. FC and FO are reliably detected using a novel method based on the distance covered by the centre of pressure. The algorithm for the force reconstruction is a revised version of the approach of Davis and Cavanagh [24]. In order to assess the robustness of the algorithm, we compare the resulting GRFs with the real forces measured with individual force plates. The median of the relative error on force reconstruction is 1.8% for the healthy gait and 2.5% for the clinical gait. The reconstructed and the real GRFs during DC are strongly correlated for both healthy and clinical gait data (R^2 = 0.998 and 0.991, respectively).

1. Introduction

Human walking is characterized by the occurrence of the double contact phase (DC), when both feet are on the ground, separating periods of single contact when the contralateral limb is swung forward. The evaluation of the external forces acting upon each lower limb may be required, for example to estimate the joint forces and moments developed at the ankle, knee and hip by the inverse dynamic method [1]. This is classically used for the evaluation of healthy adults [2], advanced age [3], or patients [4]. From a practical perspective, the decomposition of the ground reaction forces (GRFs) into left and right profiles acting upon each limb during DC can be challenging since the subject must perform two consecutive steps with feet on separate force plates. Generally, this implies the subject to target the force plates using visual guidance to place the feet correctly. Even if the variability of GRFs is not affected by 'targeting' [5], kinematic adaptations were shown previously; the motion of the body segments are flawed [6] and the variability of the step length is increased [7]. A counteract is to perform as many trials as necessary but a high number of trials could cause fatigue and could result also in a gait pattern alteration [8]. Moreover, the 'targeting' or the repetition is laborious for the evaluation of patient suffering from neurological or orthopedic disorders.

To overcome this methodological weakness, one solution is to record separately the left and right GRFs by means of a split-belt force treadmill [9,10]. However, this belt design usually constrains the subject to walk with an unnaturally wider base of support [11,12]. Another solution is to use a single belt force treadmill [11,12] or multiple force plates that would measure the sum of GRFs (F_{sum}) and use an algorithm to reconstruct, during DC, the left and right force profiles. However, to get individual GRFs, it is required to first, detect both events defining the beginning and the end of DC (the front foot contact (FC) when the heel strikes the ground and the back foot off (FO) when the toes take off the ground), and secondly, reconstruct the GRFs acting upon each limb by means of an efficient algorithm.

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Additional equipment is often used to detect FC and FO gait events using cameras [13–15], sensors on the sole or the insole of the shoe [16,17], miniature gyroscopes [18] or accelerometers [19]. The precision of the detection is highly variable with these additional measurements and they present at least two disadvantages: a potential discomfort for the subject, and synchronization between devices can be problematic.

More interestingly, the FC and FO gait events can also be detected using only the force plates measurement and without any additional material. For instance, various authors [20–22] determined FC and/or FO by locating a minimum or an inflexion point on either F_{sum} traces or its derivative. Although these detections seem convenient, this inflection point is not systematically present in GRF recordings and they are partly based on expected durations or expected individual GRF patterns. As already spotted by Ballaz et al. [23], those methods are not usable in many cases and particularly when the walking pattern is abnormal and cannot be anticipated. Alternatively, several authors chose to detect FC and FO events using the centre of pressure (CoP). Indeed, in any walking trial, the CoP is relatively constant during single contact phases while it shows large variations during DC, which makes the CoP a very efficient parameter for the FC and FO detection. Davis and Cavanagh [24] determined FC and FO by a visual observation of the CoP while Ballaz et al. [23] and Villeger et al. [25] went one step further using a threshold value. However, the DC detection can be improved, intending to provide an automated and reliable tool without threshold value.

Finally, different methods to reconstruct the individual GRFs during DC have been suggested in the literature. These methods mainly focus on the largest GRF component, the vertical, even though the fore–aft and lateral components may also be needed in analyses like the inverse dynamic. For instance, Davis and Cavanagh [24] proposed a method based on the lateral CoP location and GRFs by means of two simultaneous equations; Begg and Rahman [20] used the forces measured during the previous step, Ballaz et al. [23] used a cubic spline to approximate the vertical GRFs acting upon the back limb during DC, and Villeger et al. [25] enhanced the original algorithm of vertical GRF reconstruction developed by Ren et al. [26] by including pre-DC GRF characteristics and walking speed. However, none of these methods were evaluated on a large sample of healthy or pathological subjects or at different walking speeds. Additionally, although the pioneering reconstruction method of Davis and Cavanagh is the most attractive, some adaptations of their algorithm are needed. Indeed, when a subject walks with a narrowed sustentation base, the feet tend to be aligned, the left foot lever arm becomes equivalent to the right foot lever arm and their equations can no longer be solved.

The aims of this study are the following; (a) to develop an algorithm allowing an automatic, systematic and reliable detection of FC and FO, (b) to improve the Davis and Cavanagh's vertical GRF reconstruction algorithm and (c) to evaluate this new procedure on a large number of steps collected in healthy subjects and patients.

2. Methods

2.1. Subjects

Twenty-seven young healthy subjects (mean age: 22.8 ± 2.6 years, weight: 71.6 ± 9.5 kg) and 88 patients (33 adults, mean age: 40.2 ± 15.5 years, weight: 67.2 ± 17.7 kg and 55 children, mean age: 9.5 ± 3.0 years, weight 31.2 ± 13.4 kg) were enrolled in the study. The inclusion criteria for the healthy subjects were; age over 18 years, no current locomotor system injury complaints, and no history of neurological disorder. Before the experiments, the purpose and the nature of the study were explained to the subjects. Patients' data are issued from the gait laboratory of Saint-Luc university Hospital (Brussels, Belgium) and collected between 2000 and 2002 for medical evaluations. All experiments were performed according to the Declaration of Helsinki and were approved by the local ethics committee.

Table 1
Diagnoses of the patients.

	Numbers of patients	Numbers of steps
Neurological diseases		
Periventricular leukomalacia	2	10
Idiopathic toe-walker	2	11
Hemiplegia	24	117
Diplegia	7	42
Cerebral palsy	29	126
Arnold-Chiari malformation	1	5
Myopathy	1	7
Paraparesis	3	17
Childhood polio	1	5
Quadriparesis	2	12
Orthopedic diseases		
Ankle sprain	2	10
Osteoarthritis of the knee	1	4
Lower limb fracture	1	7
Spondylolysis	1	7
Equinovarus	4	16
Foot valgus	1	11
Spasticity	1	8
Others diseases		
Fibromyalgia	2	10
Walking unstable	2	9
Psychomotor retardation	1	3
Total	88	437

The subjects were asked to walk across a force platform. The mean walking speed was measured by two photocells placed at the beginning and the end of the walkway. A total of 374 steps were recorded for healthy gait where subjects were requested to walk at different speeds ranging from 0.83 to 1.94 m s^{-1}. A total of 437 steps were recorded for clinical gait (352 steps for neurological disorders; 63 steps for orthopedic disorders; and 22 steps for other disorders, Table 1). In all cases, the patients were recorded at their spontaneous walking speed.

2.2. Force platform measurement

The GRFs were measured by means of a force platform mounted at floor level and embedded in the center of a long walkway. All GRFs are reported according to the ISB referential recommendation [27]. The individual signals of the force plates data were collected independently with three different set-ups: either eight 1000 mm × 1000 mm force plates as described in Genin et al. [28], four Arsalis 800 mm × 500 mm force plates as described in Pozo et al. [29] or seven force plates of different sizes as described in Detrembleur et al. [30]. The amplified signals of the force plates were processed by means of a computer with dedicated software. For each of these set-ups, the sample rate was, respectively, 500, 250 and 100 Hz. A complete step cycle was selected for analysis only when the feet were on different force plates in order to compare the real and the reconstructed individual GRFs.

2.3. Calculation of the real FC, FO and GRFs with two force plates

The real vertical component of the GRF acting upon the back limb (F_{back}) and the front limb (F_{front}) were measured from two individual force plates. The real FC timestamp was determined when F_{front} exceeds 10 N (two times the maximum of noise signal) and the real FO timestamp when F_{back} falls below 10 N.