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Short communication

A new method to assess temporal features of gait initiation with a single force plate

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ABSTRACT

The aim of this study was to investigate whether time of toe-off and heel-contact during gait initiation could be assessed with a single force plate. Twenty subjects performed ten self-paced gait initiations and seven other subjects performed ten gait initiations in four new conditions (slow, fast, obstacle and splint). Several force-plate parameters were measured with a single force plate, and actual toe-off and heel-contact were assessed with a motion analysis system. Results showed strong temporal correlations and closeness (r = .86–.99, mean error = 3–86 ms) between two force-plate parameters and the kinematics events (toe-off and heel-contact). These new parameters may be of interest to easily measure duration of anticipatory postural adjustments and swing phase during clinical assessments.

1. Introduction

Gait initiation is the transition from standing posture to walking and can be divided into three distinct phases. During the postural-adjustments phase, the subject accelerates his body forward and laterally prior to rise his leading limb [1]. Then, during the swing phase, the subject moves his leading limb forward [2]. Finally, there is a bipedal-stance phase between the heel-contact of the leading limb and the foot-off of the trailing limb. Measuring duration of anticipatory postural adjustments could be a way to investigate fear of falling [3], and duration of swing phase could be an indicator of single-limb balance capacity [4]. Gait initiation is often assessed with a force plate reporting center of plantar pressure (CoP) displacements which reveal the postural strategy and the ability to produce ground reaction forces (GRF) [5,6]. A force plate allows the assessment of the onset and end of gait initiation thanks to the initial lateral CoP displacement (CoP_{ini}) [3,7] and to the offset of GRF when the subject leaves the force plate (GRF_{end}), respectively. However, a single force plate does not provide a direct assessment of the leading limb toe-off and heel-contact. To date, assessment of these two events was mainly allowed by use of additional recording systems such as a second force plate [7–9], transducers [4,10] or motion analysis systems [11]. Other studies also proposed to assess time of foot-off by marking the end of the mediolateral CoP shift toward the trailing side [12,13]. The present study aimed at investigating whether the two main kinematic events of gait initiation, that is toe-off and heel-contact, could be estimated accurately from single force plate data.

2. Methods

Twenty healthy adults (age: 23 ± 3 years; height: 172 ± 8 cm; weight: 63 ± 13 kg; mean ± SD) participated in this study after giving their informed consent. Participants initially stood barefoot and motionless on a force plate (46 × 50 cm, model OR6.5, AMTI) with a motion analysis system positioned laterally (OptoTrack 3020, Northern Digital Inc.). Feet were placed equally distributed at the center of the force plate, 30 deg apart and heels 4 cm apart. Two infrared optical markers (diameter 5 mm) were attached to the lateral sides of the heel and the head of the fifth metatarsus of the right feet. Participants were instructed to start walking at a self-paced speed after the "go-signal" of the experimenter. They walked from the force plate to the extremity of a 3 m long walkway positioned against the force plate. Each participant performed ten gait initiation trials with the right limb moving forward first. Force plate and optical data were synchronized and sampled at 100 Hz. Force plate data were filtered with a second order 10 Hz low-pass Butterworth filter [14]. CoP position was calculated by computation of the three orthogonal components of the ground reaction forces and their associated

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moment [14]. The free vertical moment (FVM) was calculated with the following equation: $FVM = Mz + F_{ML}{}^{*}CoP_{AP} + F_{AP}{}^{*}CoP_{ML}$ [15].

Force-plate parameters were manually marked with a MatLab program according to the following definitions: "FVM1" represented the time when the FVM changed direction (i.e., became negative when initiating with the right limb) and "FVM2" represented the last peak of FVM (see Fig. 1A). Note that a positive value of FVM was a counterclockwise vertical moment which indicated a force production aiming to accelerate the body displacement forward and to the left. In addition, the end of the mediolateral CoP shift (ML_{shift}) was marked according to its previous definition (absolute slope < 100 mm/s) [12]. Optical data were used to assess "Toe-off" when the fifth metatarsus marker moved 2 mm upward and "Heel-contact" when the heel marker abruptly stopped moving downward (see Fig. 1B).

Correlation coefficient (Pearson) and mean differences were calculated between Toe-off and FVM1 and ML_{shift}, and between Heel-contact and FVM2. A correlation coefficient close to 1 and a time difference close to 0 were supposed to evidence strong similarities [16] between kinematics and force-plate variables.

In order to further verify the results at self-paced speed, an additional experiment was conducted with seven new healthy participants (24 ± 5 years; 166 ± 7 cm; 58 ± 12 kg). Ten gait initiations were assessed with the same method in four new conditions: (1) slower than spontaneously, (2) faster than spontaneously, (3) with a 23 cm high obstacle to step over, and (4) with a splint preventing knee flexion.

3. Results

FVM1 and FVM2 exhibited strong correlations with Toe-off and Heel-contact, respectively (r = .86–.99) and mean time differences ranging from 3 to 86 ms. The ML_{shift} parameter appeared to be less accurate than FVM1 to assess time of toe-off. Mean differences and correlation coefficients between force-plate and kinematics events are presented in Table 1.

4. Discussion

The aim of the present study was to investigate whether the two main gait initiation events could be estimated with single force plate data. Results showed that times of toe-off and heel-contact of the leading limb can be estimated through two free vertical moment parameters: FVM1 and FVM2. Indeed, the three phases of gait initiation (postural adjustments phase, swing phase, and bipedal stance phase) matched the three phases of FVM (first rise, main sign inversion and last decrease), although the beginning of postural adjustments had to be assessed with the initial mediolateral CoP displacement [7], CoP_{ini} (Fig. 1). During the first phase, when leading with the right limb, the FVM increased counterclockwise revealing an acceleration of body movement directed forward and to the left (toward the trailing limb). During the second phase, the clockwise FVM evidenced a propulsive force applied by the left limb to accelerate the body forward and to the right (toward the leading limb). The last phase showed a fast decrease of FVM down to zero indicating that body weight was carried off the force plate. Thus, analysis of gait initiation by means of FVM provided information consistent with both the force production and CoP displacement previously described [1,9].

To sum-up, FVM1 and FVM2 have shown to be pertinent outcomes in terms of reliability (strong temporal correlation), time closeness (short time difference) and validity (consistency with previously described GRF and CoP displacements) to estimate the

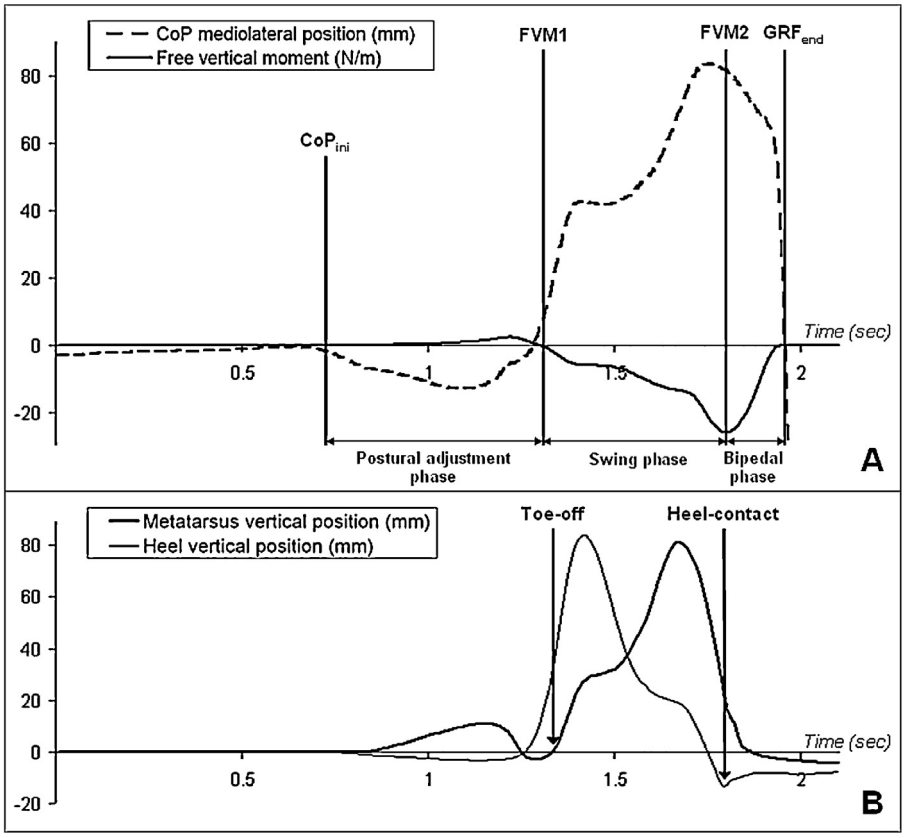

Fig. 1. A. Assessment of duration of gait initiation phases in a single trial at self selected speed. CoP position and free vertical moment are presented here on the same axis (in mm and N/m respectively). CoP_{ini}: initial lateral displacement of the center of plantar pressure toward the leading limb; FVM1: sign reversal of the free vertical moment; FVM2: last peak of the free vertical moment; GRF_{end}: time when ground reaction forces became null. B. Vertical positions of the head of the fifth metatarsus and heel optical markers for the same trial. Toe-off: Time when the metatarsus had moved 2 mm upward; Heel-contact: Time when the heel abruptly stopped moving downward.

Table 1
Mean difference (± standard deviation, in ms) and Pearson coefficient of correlation between kinematic events assessed with a motion analysis system (Toe-off and Heel-contact) and events assessed with a force plate (FVM1, ML_{shift} and FVM2) during gait initiation in five different conditions. FVM1: Sign reversal of the free vertical moment; ML_{shift}: Deceleration of the mediolateral CoP displacement toward the trailing limb; FVM2: Last peak of the free vertical moment; *r*: Pearson correlation coefficient. A positive difference reflected a temporal lead of the force plate parameter relative to the kinematics event, whereas a negative difference reflected a temporal lead of the kinematics event relative to the force plate parameter.

	Self-paced speed condition	Slow condition	Fast condition	Obstacle condition	Knee splint condition
Toe-off – FVM1	12 ± 32	86 ± 84	34 ± 32	44 ± 33	78 ± 31
	r = .98	*r* = .86	*r* = .95	*r* = .96	*r* = .97
Toe-off – ML_{shift}	−105 ± 53	−85 ± 68	−90 ± 72	−57 ± 40	−68 ± 61
	r = .95	*r* = .93	*r* = .76	*r* = .94	*r* = .89
Heel-contact – FVM2	−31 ± 26	−12 ± 33	−7 ± 24	3 ± 25	3 ± 22
	r = .99	*r* = .99	*r* = .98	*r* = .99	*r* = .99

moments of leading limb toe-off and heel-contact, respectively. In light of these results, we propose to estimate the duration of the gait initiation phases using these new temporal force-plate parameters (Fig. 1):

- Postural adjustments phase = FVM1 − CoP_{ini}
- Swing phase = FVM2 − FVM1
- Bipedal standing phase = GRF_{end} − FVM2

Like other methods for data analysis [12,16], the present method is not perfect but appears to be accurate enough to separate the different phases of gait initiation enabling the assessment of the locomotor strategies adopted in various experimental or clinical contexts.

This new method only requires single force-plate data and therefore allows simpler data acquisition and shorter processing time to discriminate the different phases of gait initiation. In addition, the vertical moment pattern used in this method was also observed in gait initiation of highly disabled patients such as hip-disarticulated amputees (unpublished data).

In conclusion, this method seems to be appropriate to assess temporal phases of gait initiation in clinical evaluations in which a kinematics analysis could be too complex and time-consuming.

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Conflict of interest statement

There is no conflict of interest.

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