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Technical note

An algorithm to decompose ground reaction forces and moments from a single force platform in walking gait

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ABSTRACT

In walking experimental conditions, subjects are sometimes unable to perform two steps on two different forceplates. This leads the authors to develop methods for discerning right and left ground reaction data while they are summed during the double support in walking. The aim of this study is to propose an adaptive transition function that considers the walking speed and ground reaction forces (GRF). A transition function is used to estimate left and right side GRF signals in double support. It includes a shape coefficient adjusted using single support GRF parameters. This shape coefficient is optimized by a non-linear least-square curve-fitting procedure to match the estimated signals with real GRF. A multiple regression is then performed to identify GRF parameters of major importance selected to compute the right and left GRF of the double support. Relative RMSE ($RMSE_R$), maximum GRF differences normalized to body mass and differences of center of pressure (CoP) are computed between real and decomposed signals. During double support, $RMSE_R$ are 6%, 18%, 3.8%, 4.3%, 3%, and 12.3% for anterior force, lateral force, vertical force, frontal moment, sagittal moment and transverse moment, respectively. Maximum GRF differences normalized to body mass are lower than 1 N/kg and mean CoP difference is 0.0135 m, when comparing real to decomposed signals during double support. This work shows the accuracy of an adaptive transition function to decompose GRF and moment of right and left sides. This method is especially useful to accurately discern right and left GRF data in single force platform configurations.

1. Introduction

A common problem met with in walking analysis is that the subject may be unable to perform two steps on two force platforms. Constrained by the experimental conditions, the number and the size of the force platform, subjects have to respect a minimum step length maintaining a natural behavior. Some authors have suggested methods using a single force platform to study walking gait cycle [1–4].

Using a single force platform, measurements match the sum of the action forces. However, the discrimination of right and left action forces and moments is required to study walking gait using inverse dynamic and asymmetry analysis [5,6]. The difficulty with using a single platform is to detect the double support (DS) phase and to decompose the whole signals into left and right body parts. To identify heel strike and toe off of each foot, some studies proposed to use the lateral center of pressure (CoP) position [2] or the forward CoP speed [7]. Based on the DS detection, the whole signals can be decomposed.

Two options can be used to distinguish right to left action forces and moments. In the first, an algorithm is carried out using the four load cells of a forceplate [1,2]. However, access to the different load cells is not always possible depending on which platform is used. Moreover, these studies are limited to the determination of the right and the left vertical components of the ground reaction force (GRF). The second option involves decomposing GRF and moments (GRM). This allows us to estimate the shape of the signal corresponding to those of the right and left foot contact [8]. Ren et al. [8] used transition functions to estimate decreases in three dimensional forces and moments applied by the foot leaving the ground during DS phase. These transition functions were developed to respect two conditions in the DS phase:

(1) The GRF and the GRM on the leaving foot change toward zero.
(2) The ratio of GRF and GRM during DS to their values at contralateral heel strike can be expressed as a function of DS duration.

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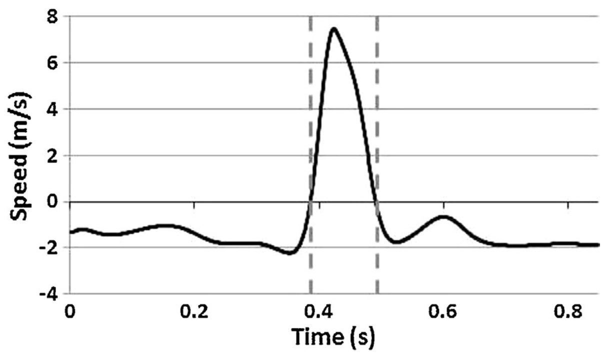

Fig. 1. Example of CoP forward speed minus subject forward speed.

However, Ren's method allowed them to use only two shapes of signal decrease.

The shapes of the ground reaction force and moment being walking-speed dependent [9], this study aims to enhance the transition functions of Ren et al. [8] by including pre-DS ground reaction force characteristics and taking into account the walking speed to determine three dimensional forces and moments of both right and left sides.

2. Methods

2.1. Walking test

Seven healthy subjects with a mean age (SD) of 23.4 (3.5) yr; a height (SD) of 1.73 (0.07) m and a body mass (SD) of 72.1 (6) kg took part in the study after signing an informed consent document. They performed walking tests at three different velocities: low 1.1 (0.13) m/s, normal 1.4 (0.1) m/s and high speed 1.9 (0.15) m/s on a walkway including two force plates (AMTI, Watertown, MA, USA). Twelve infrared cameras (Vicon, Oxford Metrics, Oxford, UK) were used to measure the subject walking speed. They performed ten trials per walking condition after a familiarization period to ensure data reproducibility [10]; hence 210 trials were recorded for this study. The kinematic and force platform data were sampled at 200 Hz and 1000 Hz, respectively. Note that AMTI forceplate did not enable us to discriminate the four load cells.

2.2. Assessed and computed parameters

2.2.1. Assessed parameters

X, *Y* and *Z* were respectively anterior, lateral and vertical axis. The forward velocity was measured from a virtual point corresponding to the middle of two markers placed at both anterior iliac spines. The GRF and GRM of both platforms were transferred to a corner of the first platform. Then, to simulate single data recordings, data of the two force platforms were summed and then filtered. 4th order zero lag Butterworth filters with a cut off frequency of 10 Hz [11] were applied to kinematic and kinetic data. The GRF and GRM transfers also allowed to improve the GRM decompositions because of no sign changes.

2.2.2. Computed parameters

Referring to Verkerke et al. [7], the transitions from the single to the double stance and from the double to the single stance were estimated when the forward CoP speed reached the zero level. As the authors used a treadmill, we decided to subtract the mean subject forward speed on the cycle from the forward CoP velocity (Fig. 1), to match their procedure and detect DS phase events. CoPx and CoPy were computed from the ratios −My/Fz and Mx/Fz (with Mx the frontal moment, My the sagittal moment and Fz the vertical force), respectively. The determination of DS events from two force platforms was detected with a threshold of 5 N on vertical force [12].

The transition function used in this paper has been optimized with respect to the original used by Ren et al. [8] (Eq. (1)). The transition function allows us to estimate the force decrease of the foot leaving the ground during DS from the force recorded one frame before DS. The force shape decrease depended on the GRF and GRM components. Indeed, Ren et al. [8] suggested two shapes of decrease in the DS phase; (i) a non monotonic (Fig. 2A) which corresponded to an alternation of positive and negative variations and (ii) a monotonic (Fig. 2A). They suggested using Eq. (1) to estimate anterior ground reaction force decrease (non monotonic) and a monotonic transition function to estimate the other ground reaction force and moment decreases.

$$F(t) = F_0 \cdot (k_1 \cdot e^{-[(t-t_p)/T_{ds}]^2} - k_2 \cdot \frac{t}{T_{ds}}) \quad (1)$$

According to Ren et al. [8], F_0 is the force at contralateral heel strike at the frame before the beginning of DS; T_{ds} is the half DS duration; t is the time ($t = 0$ at the frame before DS beginning and $t = 2\,T_{ds}$ at DS end); $t_p = \text{Scoeff}\cdot T_{ds}$ with Scoeff the shape coefficient. Both constants $k_1 = e^{\text{Scoeff}}2$ and $k_2 = (k_1/2)\cdot e^{-(2-\text{Scoeff})}2$ allow the function to respect condition at contralateral heel strike ($F(0) = F_0$) and toe off ($F(2\,T_{ds}) = 0$). In the original non-monotonic transition function (Eq. (1)) proposed by Ren et al. [8], the Scoeff was fixed at 2/3 (Fig. 2A).

For a more accurate adaptation of Scoeff (Fig. 2B), we retain the non-monotonic transition function (Eq. (1)) for all GRF and GRM. The optimization was performed to adjust Scoeff, GRF and GRM shapes from GRF characteristics and subject speed. The procedure comprises two steps (Fig. 2B), (i) the Scoeff was optimized to best fit decomposed GRF and GRM to real GRF and GRM (see Section 2.3), (ii) a multiple regression was performed to express optimized Scoeff in terms of pre-DS ground reaction force characteristics (see Section 2.4). The third figure shows a set of possible signal shapes by varying Scoeff in Eq. (1) which is the single transition function used in our method.

2.3. Optimized shape coefficient

The Scoeff coefficient establishing the force at contralateral heel strike to decomposed GRF and GRM relation was first optimally estimated by means of a nonlinear unconstrained least-square curve-fitting procedure using data relating to the two forceplates. For each ground reaction component (force and moment), the optimization problem was formulated as:

Find Scoeff that minimizes:

$$A_F = \sum_t (F_{REAL}(t) - F(t))^2 \quad (2)$$

where $F_{REAL}(t)$ is the real ground reaction component and $F(t)$ is obtained from Eq. (1) for the corresponding ground reaction component. The optimization procedure was realized by using the function fminsearch found in MATLAB and Optimization Toolbox (R2007b, The MathWorks, Inc., Natick, MA, United States).

2.4. GRF characteristics and multiple regression

A multiple regression was then performed to express optimized Scoeff from GRF characteristics. This determination allows us to calculate the optimized coefficient of each recording using a single force plate. Different GRF parameters were taken into account to identify their power in the determination of the optimized Scoeff. Their powers were determined using a multiple regression analysis ($p < 0.05$) which takes into consideration: F_{SLOPE}, the slope of