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

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Technical Note

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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 1N/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.

Keywords: Double support detection; double support decomposition; center of pressure; single forceplate; asymmetry.

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. 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 towards 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.

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 200Hz and 1000Hz, respectively. Note that AMTI forceplate did not enable us to discriminate the four load cells.

2.2. Assessed and computed parameters

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 10Hz [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.

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 5N on vertical force [12].

PLEASE INSERT FIGURE 1

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 equation 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.

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

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 $t=2T_{ds}$ 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 ($F(2T_{ds})=0$). In the original non-monotonic transition function (Eq. 1) proposed by Ren et al. [8], the Scoeff was fixed at 2/3 (Fig. 2A).

PLEASE INSERT FIGURE 2

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 2.3), ii) a multiple regression was performed to express optimized Scoeff in terms of pre-DS ground reaction force characteristics (see 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.

PLEASE INSERT FIGURE 3

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:

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

where $F_{REAL}(t)$ is the real ground reaction component and F(t) is obtained from equation 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, Massachusetts, 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 absolute force normalized to body mass (BM) from the two frames before the beginning of DS; F_i, the absolute force normalized to BM at the frame before the start of DS; F_{MAX}, the absolute value of maximal force normalized to BM; $2T_{ds}$, the duration of DS phase and V_F, the subject forward velocity. Significant parameters revealed by regression analysis were taken into consideration to compute optimized Scoeff for each GRF and GRM. Hence the signal decomposition shape from our method is dependent on Scoeff, while the optimized Scoeff coefficient came from the multiple regression.

Ground reaction forces and moments under the foot striking the ground were obtained by subtracting the decomposed ground reaction forces and moments to the total ground

reaction forces and moments.

2.5. Computation error

First, the times of heel strike and toe off that determine the DS phase were compared with regard to two conditions: one simulated forceplate and two forceplates (see 2.2). The two forceplates configuration was taken as a standard, and then the absolute error (in seconds) was computed with the single forceplate configuration.

To evaluate model accuracy, decomposed GRF and GRM from our method and decomposed GRF and GRM from the Ren's method were compared to the measured GRF and GRM for each trial. Comparison is limited to the DS phase. The differences between both methods and the real GRF and GRM were quantified by using the square root of the time-averaged squared error, normalized with respect to mean peak-to-peak amplitude, $RMSE_R$ [8,13]. $RMSE_R$ of GRM being dependant on the coordinate system position, an error on CoP for each trial was assessed. It entailed measuring the norms of the vectors between real CoP and decomposed CoP from our method and Ren's method. A mean error (in meters) was computed for each trial and for each decomposition method.

Maximum GRF differences (Δ) were computed between decomposed GRF from both methods and real GRF. They have been normalized to BM.

3. Results

In the current study, the absolute error of timing events is 0.003 seconds (SD 0.002).

The means (interquartile interval IQ) of the computed Scoeff are presented in Table 1. Their ranges were [0.24;0.72], [-1.03;0.30], [-0.16;0.30], [-0.07;0.31], [-0.05;0.19] and [0.19;1.07] for the anterior force, the lateral force, the vertical force, the frontal moment, the sagittal moment and the transverse moment, respectively.

The equations of Scoeff determination from multiple regression are presented in the appendix. Means $RMSE_R$ from both methods are presented in Table 1. Our method allows us to decrease the $RMSE_R$ between 1 and 25% for the GRF and GRM as compared to the Ren's method (Fig. 4).

PLEASE INSERT TABLE 1

The mean distances between real CoP and CoP of the both decomposition method in DS were 0.0135 m (IQ 0.007) and 0.0229 m (IQ 0.007) for our method and the Ren's method (Fig. 5), respectively. In double support, the CoP from the Ren's method remained in a constant position. The CoP components was computed from the ratio of GRM and vertical force, their signal shapes being the same from the Ren's method, the CoP stayed in the same position.

PLEASE INSERT FIGURE 4

Means of maximum GRF differences normalized to BM are presented in Table 2. Our method compared to the Ren's method decreases the Δ in DS phase by 0.55 N/kg and 1.52 N/kg respectively for anterior force and vertical force.

PLEASE INSERT FIGURE 5

PLEASE INSERT TABLE 2

Moreover, the $RMSE_R$'s and the Δ's IQ of 8 over 9 ground reaction components are

higher when computed from the Ren's method than computed using our method (Table 1 and Table 2).

4. Discussion

To improve the estimation of ground reaction forces and moments in DS phase, the aim of the study was to enhance the original transition function presented by Ren et al. [8] by including pre-DS ground reaction force characteristics and walking speed, especially as a relationship between ground reaction forces, moments and speed exists [9]. The speed displacement can be a parameter of experimental conditions as can constrained speeds and frequencies. Also, some specific gaits induce lower spontaneous, comfortable and maximal speed, especially in the elderly [14,15], children [16,17] and the obese [18].

There are many benefits of using a single force platform. Indeed, it is a simple way to access a lot of information, such as the locomotion phases, the action forces of the whole body and the displacement of the centre of pressure. The method to detect the overground walking DS is inspired from Verkerke et al. [7] and allows us to determine DS events with a 3‰ error, according to Roerdink et al. [19]. On the experimental plan, the single force platform configuration avoids us having to worry about the step length of the tested subjects, which is especially useful in i) cases of material constraints, ii) constrained speed and / or step frequency conditions and iii) studying particular gait [14–18].

Admitting that the approximation is far from ideal, Ren et al. [8] reported $RMSE_R$ of the walking cycle of 10.9%, 20%, 5.6%, 32.5% 12.2% and 26.2% for the anterior force, the lateral force, the vertical force, the frontal moment, the sagittal moment and the transverse moment, respectively. Our method based on kinetic data of a single force platform enables us to estimate GRF and GRM. Our adaptive transition function induces errors during DS that are lower than the errors during the walking cycle from the original kinematic model [8]. There is

247 a benefit to be gained from being more accurate as to the estimation of the GRF and GRM
248 during the DS phase. First, our method decreases errors to a level lower than intra-individual
249 variability values reported by Winter [20] for anterior and vertical forces (respectively 20%
250 and 7%) whereas the errors from the Ren's method are higher. The errors on GRM and CoP
251 were reduced with our method, hence the errors on lever arm to compute moment using
252 inverse dynamic were reduced. Then, it appears that a best estimation of the CoP, the GRF
253 and the GRM will have a beneficial impact on the computations of net joint torque from the
254 ankle to the hip. Using the both methods to study asymmetries, the maximum GRF
255 differences normalized to BM for anterior and lateral forces in gait cycle are lower than
256 1 N/kg i.e. the minimum difference in GRF parameter values that are biomechanically
257 significant [12]. Our method is the only one that allows us to get maximum vertical GRF
258 difference normalized to BM lower than 1 N/kg (0.73 vs. 2.25). Taking into account the GRF
259 characteristics, our method is adjusted to the step-to-step variability reported by Winter [20].
260 The lower error and variability from our method enable clinicians and researchers to easily
261 highlight statistically significant differences.

262 The difficulties concerning the decomposition methods are to estimate the GRF and
263 GRM in DS phase with the lowest error. A descriptive analysis of errors reveals that mean
264 error and error variability with our method were reduced by more than 50% compared to the
265 Ren's method, except for the lateral force's errors. Our method leads to an error of 3.8% on
266 the vertical force during DS phase. Davis and Cavanagh [2] reported an error on vertical
267 impulse during DS of 1.5% (3.6%, 0.3% and 0.6% for low, medium and high speed,
268 respectively). These errors were computed from one subject who carried out two trials at
269 three different speeds. Robustness and adaptation to the inter-individual variability have not
270 been widely tested. A more recent study [1] reported errors of 3.8% just as our method does.
271 The advantage of our algorithm compared to these of Davis and Cavanagh [2] and Ballaz et

al. [1] is that it can be used without accessing the four load cells; also, the decomposition of all GRF and GRM is feasible. Thus a two or three dimensional analysis is possible.

From a single force platform, the study of a healthy walking gait along a cycle is feasible by discriminating left and right action force during DS with our method. An accurate estimation of the GRF and GRM during DS associated with a motion analysis system would allow researchers and clinicians to assess all the kinetic parameters during a complete walking cycle. The Scoeff determination equations presented in the Appendix are generics and could be used for all subjects. Further studies are necessary to assess the effects of our method on inverse dynamics calculations and the applicability of our algorithm to pathological gaits.

Conflict of interest

None.

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Declarations

Funding: This study has been supported by the University of Toulouse 3 that is a public establishment. No private grant has been perceived.

Competing interests: There is no conflict of interest

Ethical approval: The subjects have written informed consents approve by the ethic committee of the University of Toulouse 3. This procedure is a simplified one approved when the protocol of the studies are non-invasive

297

298 **References**

299 [1] Ballaz L, Raison M, Detrembleur C. Decomposition of the vertical ground reaction
300 forces during gait on a single force plate. J Musculoskelet Neuronal Interactions 2013;
301 13: 236-43.

302 [2] Davis B, Cavanagh P. Decomposition of Superimposed Ground Reaction Forces into
303 Left and Right Force Profiles. J Biomech 1993; 26: 593-7.

304 [3] Kram R, Powell A. A Treadmill-Mounted Force Platform. J Appl Physiol 1989; 67:
305 1692-8.

306 [4] Kram R, Griffin TM, Donelan JM, Chang YH. Force treadmill for measuring vertical
307 and horizontal ground reaction forces. J Appl Physiol 1998; 85: 764-9.

308 [5] Goldberg SR, Stanhope SJ. Sensitivity of joint moments to changes in walking speed
309 and body-weight-support are interdependent and vary across joints. J Biomech 2013;
310 46: 1176-83.

311 [6] Potdevin F, Gillet C, Barbier F, Coello Y, Moretto P. Propulsion and Braking in the
312 Study of Asymmetry in Able-Bodied Men's Gaits. Percept Mot Skills 2008; 107: 849-
313 61.

314 [7] Verkerke GJ, Hof AL, Zijlstra W, Ament W, Rakhorst G. Determining the centre of
315 pressure during walking and running using an instrumented treadmill. J Biomech
316 2005; 38: 1881-5.

317 [8] Ren L, Jones RK, Howard D. Whole body inverse dynamics over a complete gait
318 cycle based only on measured kinematics. J Biomech 2008; 41: 2750-9.

319 [9] Nilsson J, Thorstensson A. Ground Reaction Forces at Different Speeds of Human
320 Walking and Running. Acta Physiol Scand 1989; 136: 217-27.

321 [10] Hamill J, Mcniven S. Reliability of Selected Ground Reaction Force Parameters

During Walking. Hum Mov Sci 1990; 9: 117-31.

[11] Kristianslund E, Krosshaug T, van den Bogert AJ. Effect of low pass filtering on joint moments from inverse dynamics: Implications for injury prevention. J Biomech 2012; 45: 666-71.

[12] Devita P, Bates B. Intraday Reliability of Ground Reaction Force Data. Hum Mov Sci 1988; 7: 73-85.

[13] Cahouet V, Martin L, Amarantini D. Static optimal estimation of joint accelerations for inverse dynamics problem solution. J Biomech 2002; 35: 1507-13.

[14] Winter DA, Patla AE, Frank JS, Walt SE. Biomechanical walking pattern changes in the fit and healthy elderly. Phys Ther 1990; 70: 340-7.

[15] Zijlstra A, de Bruin E, Bruins N, Zijlstra W. The step length–frequency relationship in physically active community-dwelling older women - Springer. Eur J Appl Physiol 2008; 104: 427-34.

[16] Lythgo N, Wilson C, Galea M. Basic gait and symmetry measures for primary school-aged children and young adults. II: Walking at slow, free and fast speed. Gait Posture 2011; 33: 29-35.

[17] Oberg T, Karsznia A, Oberg K. Basic Gait Parameters - Reference Data for Normal Subjects, 10-79 Years. J Rehabil Res Dev 1993; 30: 210-23.

[18] Lai PPK, Leung AKL, Li ANM, Zhang M. Three-dimensional gait analysis of obese adults. Clin Biomech 2008;23, Supplement 1:S2-S6.

[19] Roerdink M, Coolen B, Clairbois BE, Lamoth CJC, Beek PJ. Online gait event detection using a large force platform embedded in a treadmill. J Biomech 2008; 41: 2628-32.

[20] Winter D. Kinematic and Kinetic Patterns in Human Gait - Variability and Compensating Effects. Hum Mov Sci 1984; 3: 51-76.

347

APPENDIX

Computation of Scoeff for each GRF and GRM and correlation R^2 with the optimized Scoeff

For anterio force Fx (R^2=0.87):

$$Scoeff = 0.283 - 1.248 \cdot 2T_{ds} - 0.219Fx_i - 0.003Fx_{slope} + 0.04Fx_{max} + 0.03Fz_i + 0.002Fz_{slope} + 0.034Fz_{max}$$

For lateral force Fy (R^2=0.45):

$$Scoeff = 0.691 - 0.312V_F - 2.867 \cdot 2T_{ds} - 0.121Fx_i + 0.083Fx_{max} + 0.007Fy_{slope} + 0.022Fz_i - 0.002Fz_{slope}$$

For vertical force Fz (R^2=0.8):

$$Scoeff = 0.398 - 0.149V_F - 1.064 \cdot 2T_{ds} - 0.043Fx_i + 0.014Fx_{max} - 0.036Fy_{max} - 0.011Fz_i + 0.001Fz_{slope} + 0.026Fz_{max}$$

For frontal moment Mx (R^2=0.78):

$$Scoeff = 0.448 - 0.113V_F - 1.08 \cdot 2T_{ds} - 0.05Fx_i - 0.001Fx_{slope} + 0.018Fx_{max} - 0.017Fz_i + 0.001Fz_{slope} + 0.029Fz_{max}$$

For sagittal moment My (R^2=0.74):

$$Scoeff = 0.363 - 0.107V_F - 0.921 \cdot 2T_{ds} - 0.045Fx_i - 0.001Fx_{slope} + 0.016Fx_{max} - 0.017Fz_i + 0.001Fz_{slope} + 0.029Fz_{max}$$

For transverse moment Mz (R^2=0.64):

$$Scoeff = 0.96 - 2.445 \cdot 2T_{ds} - 0.326\,Fx_i - 0.003Fx_{slope} + 0.095Fx_{max} + 0.131Fy_i + 0.01Fy_{slope} + 0.002Fz_{slope} + 0.031Fz_{max}$$

Transition function (see 2.3)

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

with

$$t_p = Scoeff \cdot T_{ds} \quad k_1 = e^{Scoeff^2} \quad k_2 = \frac{1}{2} k_1 e^{-(2-Scoeff)^2}$$

Table1

$RMSE_R$ assessed on DS (%) and Scoeff values

	Ren's method (IQ)	Our method (IQ)	Scoeff (IQ)
Anterior force	20.62 (13.2)	6.01 (2.8)	0.49 (0.1)
Lateral force	19.05 (17.1)	18.01 (16)	-0.37 (0.3)
Vertical force	11.70 (4)	3.83 (1.5)	0.18 (0.1)
Frontal moment	11.52 (4.1)	4.31 (1.3)	0.18 (0.1)
Sagittal moment	9.17 (3.8)	2.99 (1.5)	0.20 (0.0)
Transverse moment	37.40 (26.4)	12.29 (9.4)	0.54 (0.2)

373

Table 2

Maximum GRF differences normalized to BM (Δ) (N/kg)

	Ren's method (IQ)	Our method (IQ)
Anterior force	0.77 (0.6)	0.22 (0.1)
Lateral force	0.13 (0.1)	0.13 (0.1)
Vertical force	2.28 (0.8)	0.76 (0.3)

374

Figure legends

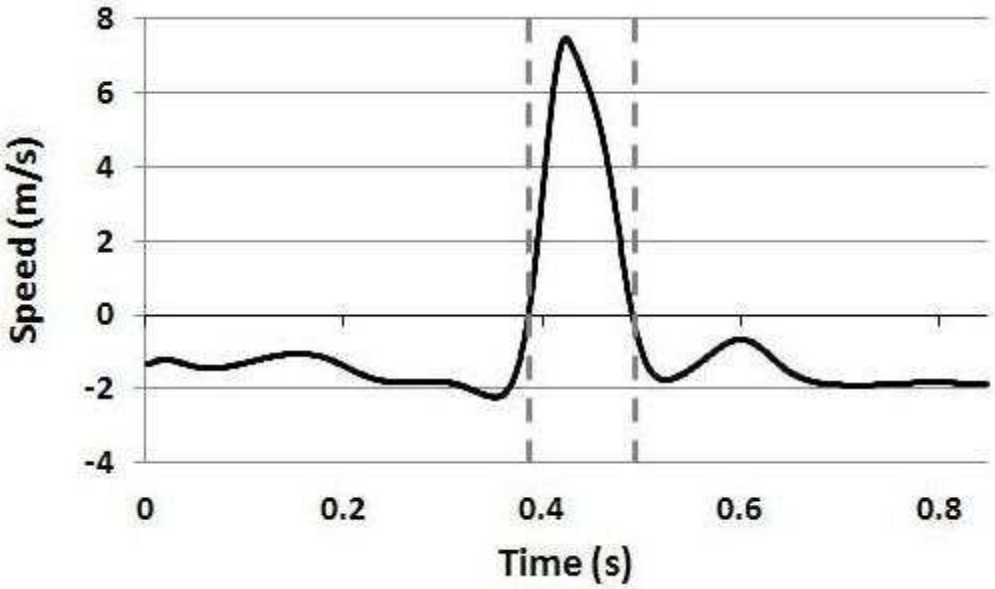
Fig. 1. Example of CoP forward speed minus subject forward speed.

Fig. 2. The respective contributions of (A) Ren et al. (2008) and (B) the current work brought to the transition functions.

Fig. 3. Various signal shapes in DS phase with different values of Scoeff. From top to bottom the Scoeff was set at: 1.25, 1, 0.75, 0.5, 0.25, 0, -0.25, -0.5, -0.75, -1 and -1.25.

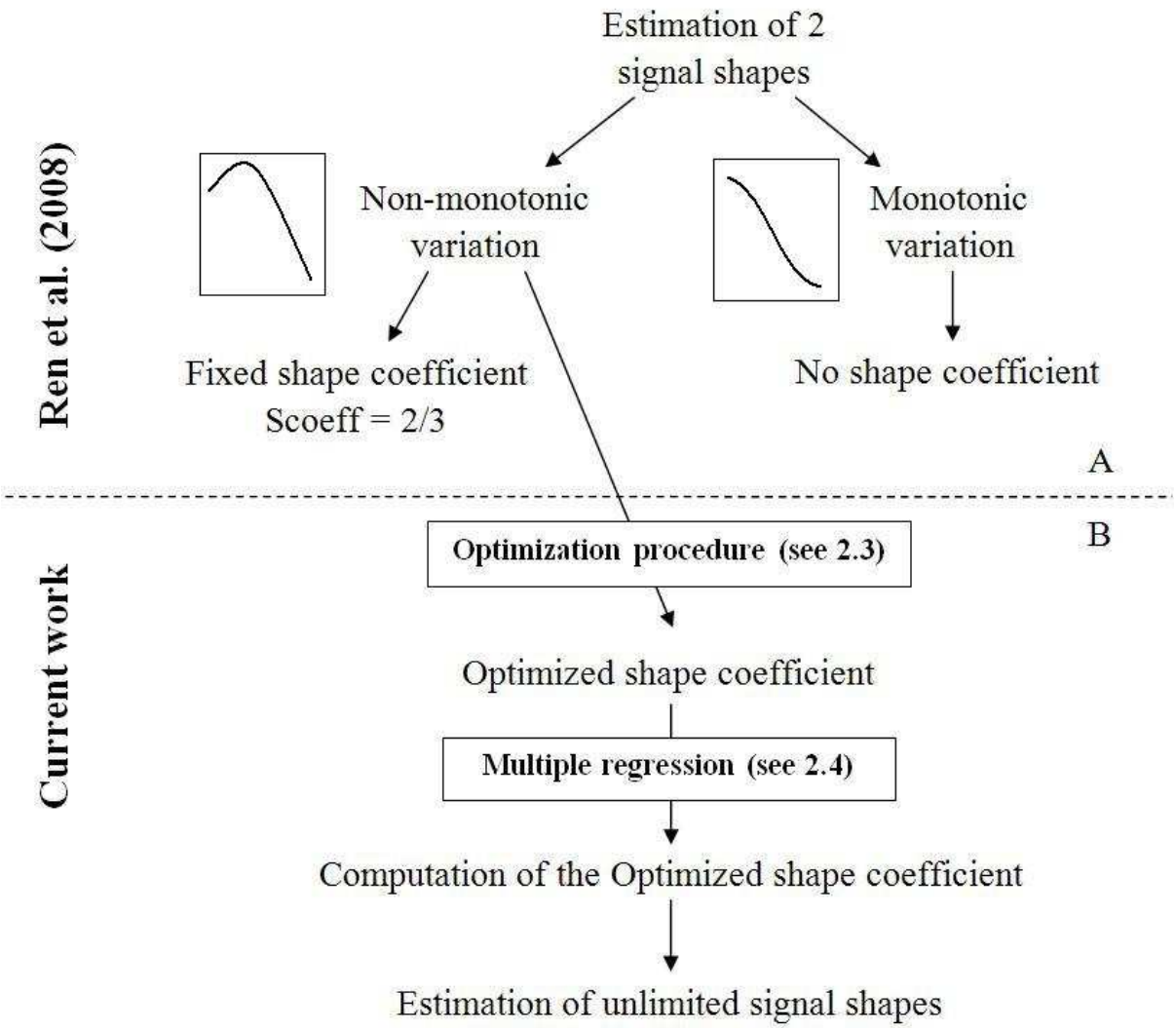
Fig. 4. Illustration of total GRF and GRM (black line), real GRF and GRM (large gray line), GRF and GRM from our method (black dashed line) and GRF and GRM from Ren's method (black pointed line) for the foot leaving the ground.

Fig. 5. Illustration of the CoP positions on X and Y axis of the experimental coordinate system from real data (large grey line), our method (black dashed line) and Ren's method (black pointed line) under the foot leaving the ground. Vertical lines correspond to the double support beginning.



394

395 Fig. 1


Ren et al. (2008)
Estimation of 2 signal shapes
Non-monotonic variation
Monotonic variation
Fixed shape coefficient
Scoeff = 2/3
No shape coefficient
A
B
Current work
Optimization procedure (see 2.3)
Optimized shape coefficient
Multiple regression (see 2.4)
Computation of the Optimized shape coefficient
Estimation of unlimited signal shapes

396
397 Fig. 2

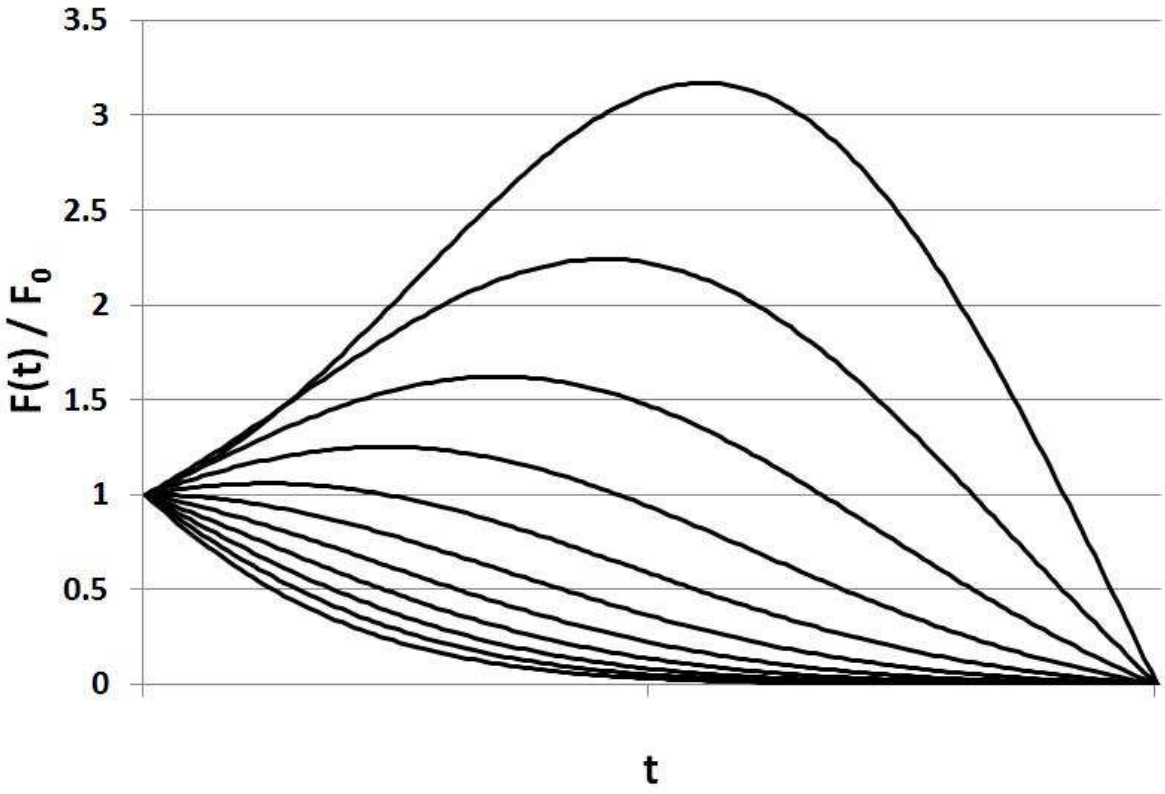
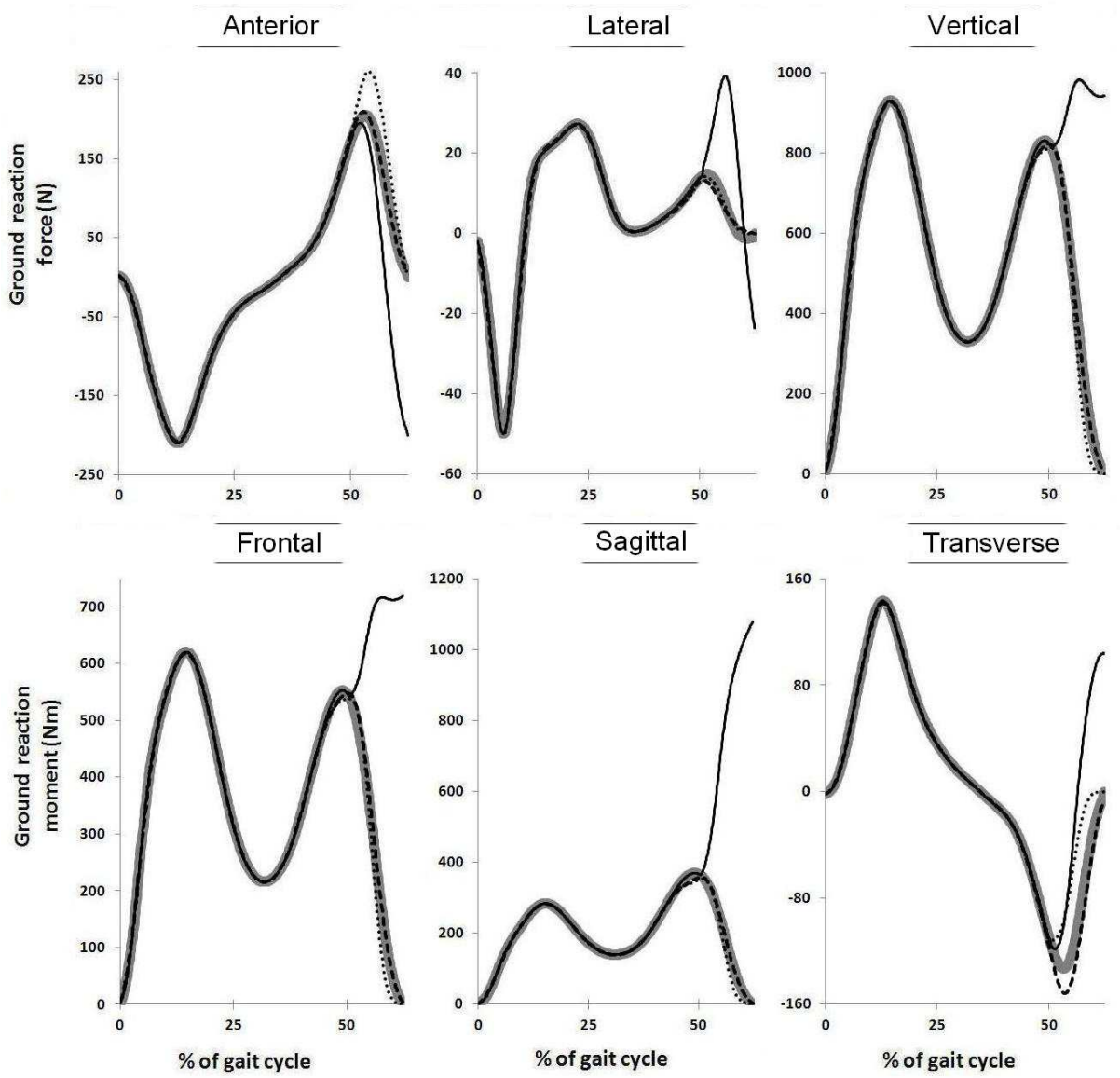
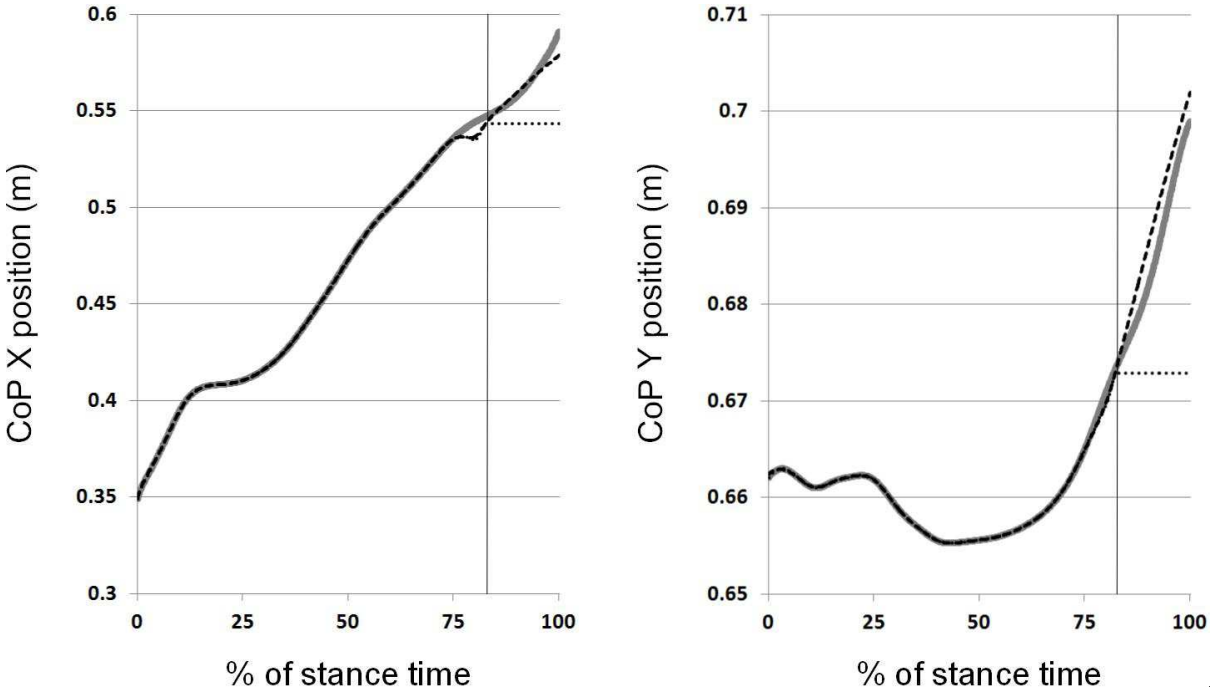


Fig. 3


Anterior
Lateral
Vertical
Frontal
Sagittal
Transverse
Ground reaction force (N)
Ground reaction moment (Nm)
% of gait cycle
% of gait cycle
% of gait cycle

400

401 Fig. 4


CoP X position (m)
0.6
0.55
0.5
0.45
0.4
0.35
0.3
0
25
50
75
100
% of stance time
CoP Y position (m)
0.71
0.7
0.69
0.68
0.67
0.66
0.65
0
25
50
75
100
% of stance time

402

403 Fig. 5