

The method for separation of superimposed ground reaction forces and center of pressures of gait during double stance phase

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Abstract— This research proposes to develop a method for separation of superimposed ground reaction forces (GRF) and centers of pressure (CoP) during the double stance phase of the normal adult gait. Under the assumption of consistency of the normal adult gait, generic GRF and CoP models were made from gait data of 10 subjects. Moreover, in order to improve the accuracy of the separation, we proposed a fusion model into which these 2 models were combined. This model is able to separate GRF and CoP accurately.

Keywords-component; formatting; style; styling; insert (key words)

I. INTRODUCTION

Gait is a basic feature of daily human life, and gait analysis is especially useful for recovery and improvement of gait in the fields of orthopedics and rehabilitation. Various measurement systems are used in gait analysis. The typically-used device is an optical motion capture system (MoCap), which obtains kinematic measurements, such as displacement, velocity, and acceleration of a subject from markers placed on landmarks on a subject. Furthermore, a force platform which obtains ground reaction force (GRF) measurements is also used; GRF is very important in gait analysis. Recently, reasonably priced MoCap systems have been developed, but force platforms are still expensive. In addition, installation of force platforms takes up a large space; in general clinics, it is difficult to install these systems.

Nagano et al. developed a novel gait analysis system utilizing a treadmill to substitute as a force platform [1]. This force platform can be produced at a low price as it is easy to purchase a regular treadmill, and this platform can be adapted to suit various environments. However, this system only obtains resultant ground reaction forces of both feet during the double stance phase. Furthermore, the system does not separate the CoP of each foot. These problems make biomechanical analysis using human models [2] difficult, as this requires estimation of joint moments or muscle tensions. To solve these problems, methods that separate the superimposed GRF measurements into individual feet using superimposed GRF and CoP measurements have been developed [3][4]. However, these methods do not consider separation of CoP.

We have developed a method to separate the superimposed vertical GRF and anterior posterior CoP into individual feet for a normal gait. The method is as follows: (1) extracting the double stance phase from the time-series measurements of the superimposed GRF using numerical differentiation, (2) separating the superimposed vertical GRF and anterior posterior CoP using the CoP model and GRF model we have proposed. Commonly, characteristics of gaits are consistent regardless of a specific gait condition [5]. Therefore, this research generalizes GRF and CoP, assuming a consistent normal gait.

II. THE PREPARATORY EXPERIMENT AND HYPOTHESIS

A. Measurement of GRF and CoP

In order to set up a hypothesis relating to separation of GRF and CoP, right and left foot normal GRF and CoP measurements were obtained with force platforms (Advanced Mechanical Technology, Inc. BP400600-1000PT) that were allocated as shown in Fig.1. Subjects were 21-33 year-old males and females who had no movement disorders. Their heights ranged between 151.5-180.1 cm, and their weights ranged between 42.0-98.0 kg. The measurements were carried out 5 times for each person, with a sampling frequency of 1 kHz. Fig.2 (A) shows a typical pattern of GRF.

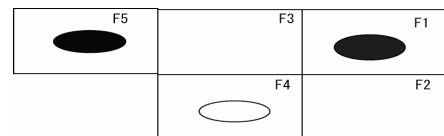


Figure 1. Arrangement of Force plate(black : right foot white: left foot)

B. Characteristics of Superimposed GRF

The superimposed GRF (FG), which is the sum of the vertical GRFs of both feet (FR, FL), is shown in Fig.2 (B). Compared to FR and FL, FG rises sharply at the beginning of the double stance phase, and then varies gradually before rising to the next peak.

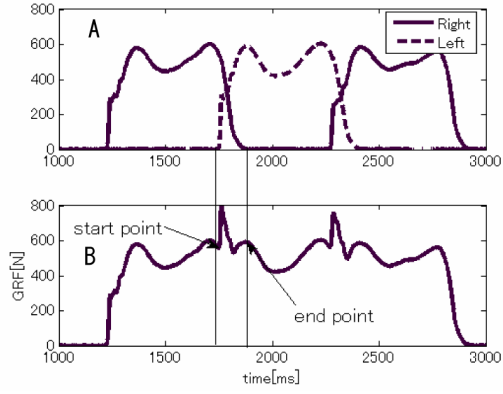


Figure 2. Separated GRF and Superimposed GRF

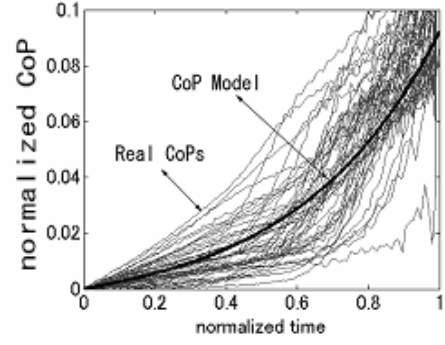


Figure 5. CoP Model

C. Extracting the Double Stance Phase from the Time-series

Section II B notes that this research found characteristics of FG. After processing this result with a 300 Hz low-pass filter, we compared the differential values of GRFs and superimposed values of GRFs. From this, we defined the start point and end point of the double stance phase as follows:

the start time of the phase was determined to be the point on the convex line just before the peak; the end time was determined to be when the differentiated value of FG was close to zero, approximately 100-150 ms after the end of the peak (Fig.3).

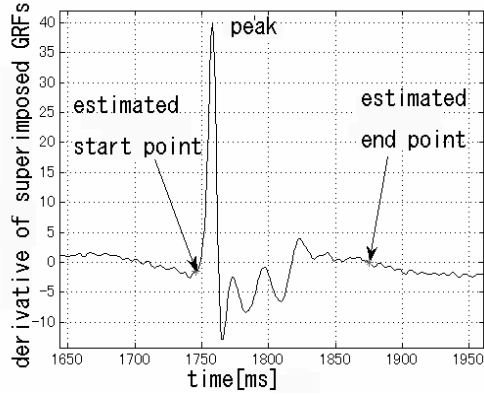


Figure 3. Clipping the Double Stance Phase

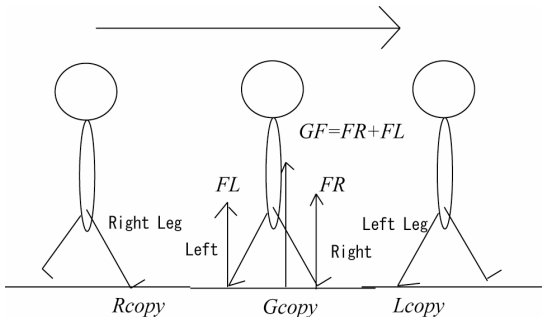


Figure 4. Mean of Symbols

D. CoP Model

Right and left anterior-posterior CoPs (Rcopy, Lcopy) were obtained from GRF measurements as mentioned in II .A. The superimposed CoP (Gcopy) was calculated from these measurements. Following this, the distance from Gcopy at the first heel point of contact to Gcopy at the next opposite heel point of contact was defined as ST; Fig.4 shows the definitions of these symbols. Though each CoP has lateral and anterior-posterior components, we have focused on just the anterior-posterior components. The beginning of the sequential measuring time was at the first heel contact, and the time was normalized with the length of the time required to calculate the CoP.

In this research we modeled the CoP of the right foot. In this modeling, the value of Rcopy was normalized with ST and was approximated by a polynomial function; a typical form of this is shown in Fig.5. In addition, the calculated coefficients of the function are mentioned in III .B.

E. GRF Model

This research measured the vertical GRF of the right foot as it lifts off the ground, and proposes a support ratio for the GRF of the right foot relative to total GRF during the double stance phase; this is presented as Equation 1.

$$W_{rate} = \frac{F_R}{F_R + F_L} \quad 0 \leq W_{rate} \leq 1 \quad (1)$$

The relationship between FR, FG and Wrate is described in Equation 2.

$$F_R = F_G \times W_{rate} \quad (2)$$

At first, the ratios were calculated in Equation 1 using the GRF measurements of all subjects. Following this, they were approximated by a 15-degree polynomial of normalized time. These optimized coefficients from the Equation were averaged, and the averaged coefficients constitute the GRF model shown in Fig.6. The origin (beginning) of the sequential measuring time was at the first heel contact, and the time was normalized with the length of the double stance phase.

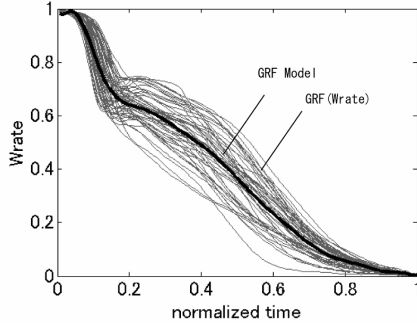


Figure 6. GRF Model

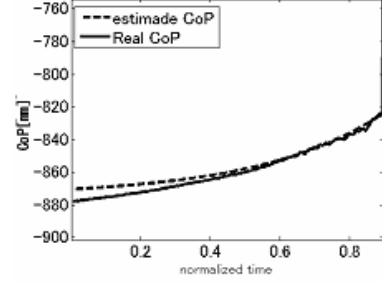


Figure 8. CoP Estimation by CoP Model

F. Estimation of GRF and CoP using Fusion Model

As normal adult gait is GUAS-static and inertial force is assumed not to have an influence, equilibrium of force as presented in Equation 3 consists of W_{rate} , R_{copy} , and G_{copy} .

$$W_{rate} = \frac{-R_{copy} + G_{copy}}{ST} + 1 \quad (3)$$

W_{rate} can be used to calculate R_{copy} , and FR can be calculated from R_{copy} using Equations 2 and 3. In addition, Equation 3 is transformed and presented as Equation 4.

$$R_{copy} = ST \times (1 - W_{rate}) + G_{copy} \quad (4)$$

Fig.7 is a histogram produced with respect to normalized time, which shows how GRF and CoP measurements of each subject varied in each model. The variance of CoP was less correlated with normalized time, while the variance of the support ratio of GRF was substantial during the first half of normalized time. This is because the GRF model during this time was affected by the impact of heel contact, which was not static and varied widely for each subject. Furthermore, the impact was very large in comparison with the magnitude of the support force reaction of the opposite leg. The CoP model was developed using data of the right foot only, so the accuracy is high because of limited influence of the left foot.

Therefore CoP can be estimated from the CoP model, and GRF can be estimated from a combination of the static CoP model and the kinetic GRF model. Up until the normalized time of 0.6, GRF was rigorously estimated from the CoP model using Equation 3; during the normalized time of 0.6-1.0, GRF was estimated from the GRF model. After the estimation, a low pass filter processed the estimated measurements, using a cut off frequency of 30 Hz to reduce discontinuity: we call this a fusion model.

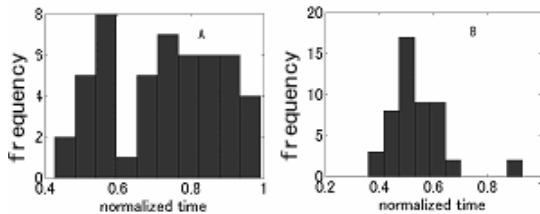


Figure 7. Max variability point(A : Cop variability B:GRF variability)

III. VERIFICATION

A. Extracting the Double Stance Phase from the Time-series

From superimposed GRF values, we estimated the start time and the end time of the double stance phase. In comparison with the actual times, the error in the start time was 0.3 ± 3.2 ms, and the error in the end time was 1.3 ± 12.1 ms. The error in the end time was greater than that in the start time because the support ratio of GRF changed more gradually during the toe-off movement. However, this error is not serious for reasonable MoCaps using general video cameras with a sampling frequency of almost 60Hz; the error is within the split time of the cameras.

B. Estimation of CoP from the CoP Model

Each subject's R_{copy} was normalized with ST, and then the normalized CoPs of all subjects were averaged. Using these normalized CoPs, coefficients of the CoP model mentioned in II.D were defined in Equation 5.

$$CoP_{model} = 0.1 \times \exp(2.5 \times (t - 1)) - 0.008 \quad (5)$$

The value t represents the normalized time that was defined in section II.D. The estimated CoP using this model is shown in Fig.8; the horizontal axis of this graph was defined in section II.E. The average of the absolute error of the modeled values compared with real values is 7.3 ± 2.8 mm. The estimation was carried out at the normalized time of 0.8; after that point, measured GRF was too small to calculate CoP.

C. Estimation of GRF from Fusion Model

Fig.9 shows the result of GRF estimation from the fusion model. The average of absolute errors was 27 ± 9 N.

IV. VALIDATIONS AND COMPARISON OF EACH MODEL

In this research we proposed a CoP model, a GRF model and a fusion model. We compared each model to confirm that the fusion model can estimate GRF and CoP more precisely than the individual models.

A. CoP Estimation by GRF Model

Fig.10 shows CoPs that were estimated with the GRF model (using Equation 5) and with the CoP model. Using the GRF model, the average of absolute error was 31 ± 15 mm, while using the CoP model, the average of absolute error was 7.4 ± 2.8 mm. The CoP model is therefore concluded to be a more precise model than the GRF model for CoP estimation.

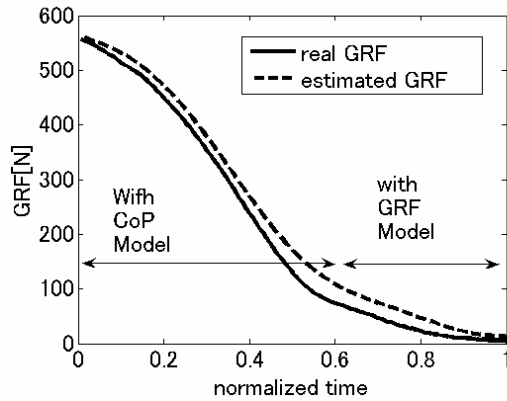


Figure 9. Fusion Model

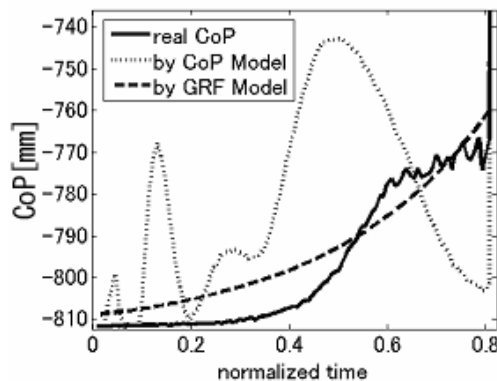


Figure 10. Comparison of COP Estimation

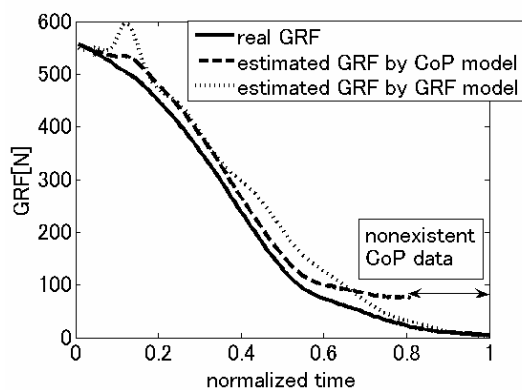


Figure 11. Comparison of GRF Estimation

B. Validation by CoP model

Fig.11 shows GRFs that were estimated with the CoP model and with the GRF model. As stated in III.B, CoP was not calculated after a normalized time of 0.8, so GRF cannot be estimated after this time either.

The average of the absolute error of GRF during the normalized time of 0-0.8 was 43 ± 23 N with the GRF model, and was 34 ± 10 N with the CoP model. With the proposed fusion model, the absolute error was 27 ± 9 N. Therefore, the fusion model is considered to estimate GRF the most precisely.

V. CONCLUSION

We proposed two methods to separate the superimposed GRF and CoP into individual feet for a normal gait.

The first method determines the double stance phase in a time series.

The second method is the fusion model: a GRF model and a COP model are combined in this model. Using this fusion model, we can separate GRF and CoP readings from measured superimposed readings more accurately

However, it is difficult to apply this method to analysis of an abnormal gait. In the future, we will attempt to improve this method for various gait analyses using not only force platform measurements but also kinematic measurements from a MoCap device.

NOKENCLATURE

F_R : Right GRF

F_L : Left GRF

F_G : Superimposed GRF

R_{copy} : Right anterior-posterior CoP

L_{copy} : Left anterior-posterior CoP

G_{copy} : Superimposed anterior-posterior CoP

W_{rate} : The support ratio of GRF

ST : the distance from G_{copy} at first heel contact to one at the next opposite heel contact

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