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Prediction of ground reaction forces during gait based on kinematics and a neural network model

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ABSTRACT

Kinetic information during human gait can be estimated with inverse dynamics, which is based on anthropometric, kinematic, and ground reaction data. While collecting ground reaction data with a force plate is useful, it is costly and requires regulated space. The goal of this study was to propose a new, accurate methodology for predicting ground reaction forces (GRFs) during level walking without the help of a force plate. To predict GRFs without a force plate, the traditional method of Newtonian mechanics was used for the single support phase. In addition, an artificial neural network (ANN) model was applied for the double support phase to solve statically indeterminate structure problems. The input variables of the ANN model, which were selected to have both dependency and independency, were limited to the trajectory, velocity, and acceleration of the whole segment's mass centre to minimise errors. The predicted GRFs were validated with actual GRFs through a ten-fold cross-validation method, and the correlation coefficients (R) for the ground forces were 0.918 in the medial–lateral axis, 0.985 in the anterior–posterior axis, and 0.991 in the vertical axis during gait. The ground moments were 0.987 in the sagittal plane, 0.841 in the frontal plane, and 0.868 in the transverse plane during gait. The high correlation coefficients(R) are due to the improvement of the prediction rate in the double support phase. This study also proved the possibility of calculating joint forces and moments based on the GRFs predicted with the proposed new hybrid method. Data generated with the proposed method may thus be used instead of raw GRF data in gait analysis and in calculating joint dynamic data using inverse dynamics.

1. Introduction

Ground reaction forces and moments (GRF&M) are very important in gait analysis to study the kinetic interaction with the ground and to estimate joint kinetics by inverse dynamics (Winter, 1991). GRF&M data are usually acquired using a force platform. But this technique is limited because force platforms only allow collecting a few steps, making it difficult to analyse fluctuations in gait patterns (Chau et al., 2005; Senden et al., 2009). Moreover, force platforms should be properly fixed to the ground and are therefore not available everywhere. For these reasons, various methods have been proposed to predict the GRF&M during gait based on the subject's kinematics (Ren et al., 2005, 2008; Lugrís et al., 2011; Xiang et al., 2011).

The human gait is divided into a single support phase (SSP) and a double support phase (DSP). Although the DSP only constitutes 20 to 25% of one gait cycle, it is valuable for the diagnosis of disease and assessment of gait (Davis and Cavanagh, 1993; Goldberg et al., 2006). While GRF&M can be accurately predicted by Newtonian mechanics in SSP since GRF only acts as an external force, during the DSP, when both legs and the ground surface form a closed loop, the GRF&M under each foot cannot be determined; thus, some assumptions or applications of other methods are needed to address this limitation; hence recently published papers have focused on the prediction of GRF&M during DSP. Ren et al. (2005) proposed a linear transfer relationship model based on empirical data to solve the statically indeterminate problem that occurs during the DSP. Nevertheless, the results were limited to horizontal and vertical forces and the resultant moments. Ren et al. (2008) also proposed the smooth transition assumption (STA) during the DSP. In that study, the GRF&M of whole axes in three-dimensional (3D) space were predicted based on measured 3D kinematic data alone. As a result, reasonably good GRF estimates in the sagittal plane were obtained. However, the relative RMSEs of the estimated GRF&M in the lateral axis and the frontal and transverse planes with relatively small magnitudes were weaker (26% to 33%). The two previous studies by Ren et al. were limited by the assumption that the motions of the right and left limbs during the DSP were symmetrical. Lugrís et al. (2011) estimated the GRFs during the DSP using a foot-ground contact model(FCM)-based optimisation method. Their proposed method

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resulted in better correlation coefficients and RMSEs than the STA method. However, they did not resolve the issue of clinical application because discontinuities in the predicted values occurred during the optimisation process (Lugrís et al., 2011). Using an optimisation-based predictive dynamics approach, Xiang et al. (2011) calculated the joint torques and the GRFs during asymmetric gait motion. However, in the optimisation-based method, the objective function only partially represents the human neural control system and has drawbacks in predicting a completely natural motion (Xiang et al., 2011). In a comprehensive manner, the methods used in the prior studies that were related to the GRF prediction still have limitations for clinical application due to the assumptions regarding human movements and drawbacks in application techniques.

According to Liu et al. (1999), the predicted results were considered excellent if the cross-correlation coefficient is greater than 0.9 and the relative RMSE is smaller than 15%. Nonetheless, there have been few studies on joint force and moment predictions without the use of force plates during gait. However, while the SSP prediction using a conventional method already shows high accuracy, the gait cycle has a statically indeterminate structure during the DSP, and new algorithms are needed for more accurate reaction force estimations.

ANNs are an extraordinarily flexible tool for nonlinear modelling and are especially useful in gait analysis (Kaczmarczyk et al., 2009). Many studies (Holzreiter and Köhle, 1993; Barton and Lees, 1995, 1997; Lafuente et al., 1998; Schöllhorn, 2004) have shown that ANNs can be useful in predicting or distinguishing gait patterns. Recently, new studies predicting lower body joint loads using an ANN instead of an inverse dynamic approach but have been reported (Favre et al., 2012; Liu et al., 2009). However, typically an ANN needs training data to make a prediction, and it has a difficulty in making decisions without the training data (Vijayakumar and Ramamurthy, 2013).

The purpose of this study is to develop an improved method for predicting GRF&M for a normal gait with high accuracy, and without the need for GRF-measuring devices during level walking (especially during the DSP in a gait). To verify the proposed method, normal gait experiments were carried out on force plates (to collect data of the normal gait with the ease of data acquisition), and the instrument-measured and predicted results were compared. In addition, the same experimental gait dataset obtained in our study was applied to the STA method (Ren et al., 2008), and then we determined whether the method suggested in this study was better than previously developed approaches. The goal of this study is to provide basic research with a verified novel method.

2. Materials and Methods

2.1. Subjects

Forty-eight subjects (28 males and 20 females, age: 25.4 ± 3.1 years; height: 1.72 ± 0.07 m; weight: 66.2 ± 7.5 kg) with no history of musculoskeletal disorders volunteered for the study in the BME laboratory at Sungkyunkwan University. The local ethics committee approved the study protocol, and informed consent was obtained from all subjects before the study. Of the 48 participants, 43 were randomly selected and used to collect training data for the ANNs, and the remaining subjects were used to collect validation data.

2.2. Instrumentation

The 3D kinematics of 35 reflective markers placed on each subject's body (modified Helen Hayes markerset) were recorded at 120 Hz using six MCAM2 cameras, a Vicon 460 motion analysis system (Vicon Motion Systems, Oxford, UK), and SB-Clinic software (SWING BANK Ltd., Korea). The global *X*-axis was set to the right, the *Y*-axis was in the direction of progression, and the *Z*-axis was vertical. Ground reaction data were recorded synchronously with kinematics at 1080 Hz from two force plates (AMTI, Model OR6-6-2000, MA, USA) that were fixed at the centre of a 10-m-long walkway, but were not apparent to the subjects.

2.3. Experimental protocol and data processing

Subjects were asked to walk barefoot at their own preferred walking speed. The subjects were given sufficient training trials before the recording session. The motion was repeated at least five times and only one arbitrary experimental data set per subject was used for training and validating the neural network. Fifteen rigid segments (head, thorax, humeri, radii, hands, pelvis, femora, tibiae, and feet) were modelled using commercial software, BodyBuilder v3.6, the PlugInGait model (Vicon Motion System, Oxford, UK), and the 3D position data of the markers were recorded. Motion information on the centre of mass of each segment was acquired. Both the kinematic and GRF datasets were low-pass filtered with a 4th-order Butterworth filter using a cut-off frequency of 6 Hz to remove noise. The cut-off frequency was determined based on a previous study (Winter, 2009). Also, the gait event timings were determined using the foot velocity algorithm method, which is based on kinematic data without force plates (O'Connor et al., 2007). The schematic of the overall GRF prediction procedure is shown in Fig. 1.

2.4. Single support phase: conventional method

Since the only external forces acting in a human body during a SSP are GRFs, a traditional method that calculates the GRFs inversely by subtracting the gravitational acceleration from segmental acceleration for each body segment was applied (Siegler and Liu, 1997). Since the Newtonian mechanics-based method already reports high prediction accuracy, the method used in this study is the same as the method used to predict a SSP in a preceding study (Ren et al., 2008). In this regard, all components of the calculated GRFs were computed at the ground surface in the vertical direction from the mass centre of the ankle segment.

2.5. Double support phase: artificial neural network method

Because both legs and the ground surface form a closed loop during the DSP, the redundant system was not able to resolve to a solution by the application of the conventional method detailed in Section 2.4 to determine indeterminate problems. Therefore, after performing Section 2.3, which was done to determine the GRFs without the use of force plates during the DSP, an ANN model was constructed.

In this study, a feed-forward network with one input layer, one hidden layer and one output layer was used to predict the GRF&M for F_x, F_y, F_z, M_x, M_y, and M_z. The network utilised a back-propagation algorithm and the gradient steepest descent method (Schalkoff, 1997). The hidden layer with three nodes consisted of a bipolar sigmoid transfer function. The gait data of 43 randomly-selected subjects (one trial per training subject) among the total of 48 subjects are considered in the ANN training, and the remaining 5 subjects (one trial per validation subject) were used as a test sample to validate the developed ANN.

The predictive ability of the ANN model is strongly affected by the suitable selection of input variables (Fernando et al., 2009; Noori et al., 2011). Among the

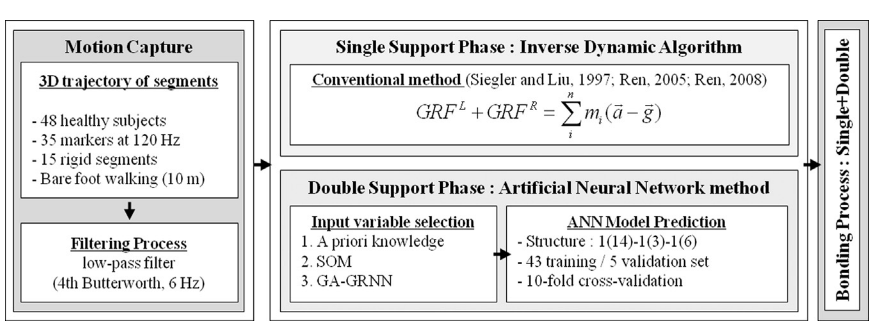

Fig. 1. Flowchart of the process for predicting ground reaction forces and moments.