Estimating Knee Adduction Moment From Joint Kinematics and Foot Pressure: Validation using Force Plate Embedded Treadmill

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Introduction: Treadmill walking is frequently used for gait analyses. Treadmill gait experiment has advantages that multiple strides can be measured at a controlled speed and in a limited space. In some situations such as bi-plane fluoroscopy based gait studies it can help capture knee kinematics within a certain field of view (Tashman et al. 2004). Though force plate embedded treadmill systems are being adopted for gait studies (Dierick et al. 2004) most laboratories are not afford to it. As an alternative to the expensive treadmill, pressure mat embedded treadmill systems are available (Luessi et al. 2012). Previous studies investigated methods for estimating ground reaction forces from only joint kinematics or from joint kinematics combined with ground vertical force (Forner-Cordero et al. 2006). In our previous study, we developed a musculoskeletal-simulation-based method to estimate ground contact shear forces and knee adduction moment from joint kinematics and foot pressure data obtained with insole type pressure mat during ground walking (Jung et al. 2012). The objective of this study was to estimate the ground reaction shear forces during a treadmill walking using the joint kinematics and pressure mat data. In this study the musculoskeletal simulation model has been modified from our previous model to estimate the ground reaction force during walking on a pressure mat embedded treadmill. This method is free from coordinate transform errors of pressure mat data which existed in our previous study (Jung et al. 2012). Accuracy of the estimation was validated on two different treadmill walking speeds.

Methods: Data acquisition: The study was approved by the IRB of Chung-Ang University and an informed consent was obtained from each subject prior to testing. Five healthy subjects (all males, Age: 21.8±0.8, Weight: 71.4±4.2 kg) performed treadmill walking at slow (1.0 m/s) and normal (1.4 m/s) walking speeds. Fifty optical markers were placed on bony landmarks around joints of each subject. Motion data was obtained by a Qualisys motion capture system (Qualisys, Sweden) and ground reaction force was obtained by a force plate embedded treadmill (Bertec, USA). The pressure mat data can be converted to a vertical force at a center of pressure. Thus only the vertical force and center of pressure from the force plate embedded treadmill were used to simulate a pressure mat embedded treadmill.

Musculoskeletal model: We developed an optimization-based method to estimate ground reaction shear forces during walking. It basically uses a reaction element between the foot and ground. In solving motion equations of body movements joint reaction forces and ground reaction forces are optimized simultaneously to match the body inertial forces. To implement this method we used a musculoskeletal model in AnyBody (AnyBody Technology, Aarborg, Denmark). The original model in Anybody has 36 degrees of freedom, 18 joints and more than 1000 muscles.

Reaction elements: A reaction element was set up between the foot and ground to estimate anterior-posterior (AP) shear force, medial-lateral (ML) shear force and free moment along the vertical axis. The attachment point of the reaction element on the foot moved along the center of pressure on the foot during walking. The other side of the reaction element was not attached to a specific position on the ground but could support reaction forces. The reaction element contained force elements in four directions parallel to the ground, and moment elements along the clockwise and counter-clockwise directions of the vertical axis. The reaction element was activated when ground vertical force was larger than 250N.

Knee moment estimation: The estimated ground shear forces and free moment could be combined with the given joint kinematics, ground vertical force and center of pressure on the foot to calculate joint kinetics. In our optimization-based method all joint kinetics including knee adduction moment were calculated in estimating the ground shear forces and free moment.

Results: Ground shear forces and knee adduction moments were estimated during treadmill walking for five subjects (Table 1 and Figure 1). The estimated shear forces and knee adduction moment were compared with the measured shear forces. The root means square (RMS) errors were quantified during the stance phase of walking (Table 1). The coefficient of determination (R²) were also calculated during the stance phase to quantify the linear regression between the measured and estimated values (Table 1). RMS errors were lower in estimating AP shear forces than ML shear forces for both slow and normal walking. Coefficients of determination were very similar for AP and ML shear forces estimations but they were higher in estimating AP shear forces for both slow and normal walking.

Discussion: The purpose of this research was developing and validating a reaction element based method to estimate the ground reaction force during walking on a pressure mat embedded treadmill. In our previous study, mean RMS error of shear forces and knee adduction moment were 5.91 %BW and 1.43 %BW×HT, respectively. The result obtained in this study shows...
that ground shear forces could be estimated within 3.11 %BW and knee adduction moment could be estimated within 0.4 %BW×HT. These results show that the accuracy of the modified method is almost two times better than the method in our previous study. Furthermore the coefficients of determination of knee adduction moment were above 0.95. This shows that the estimated knee adduction moment has a high correlation with the measured knee adduction moment. The larger RMS errors in normal walking speed than slow walking speed should be due to increase of body inertia forces during faster movements of body segments. The proposed method will allow us to calculate joint kinetics using a pressure mat embedded treadmill.

**Significance:** The study showed that ground contact shear forces can be accurately estimated when using a pressure mat embedded treadmill. This will help calculate joint kinetics during gait when only foot pressure data is available.

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<tr>
<th>GRF and knee moment estimation during slow and normal speed gait</th>
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<tr>
<td><strong>Medial-lateral force (%BW)</strong></td>
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<td><strong>Mean RMS error (SD)</strong></td>
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<td>Slow speed gait (1.0 m/s)</td>
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<td>Normal speed gait (1.4 m/s)</td>
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Figure 1. GRF and Knee moment estimation results for a representative subject

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