GROUND REACTION FORCE ESTIMATION USING MUSCULOSKELETAL SIMULATION

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There are many situations in sports when external forces such as ground reaction force are unobtainable. Musculoskeletal kinetics including joint moments can be calculated when all external force information including ground reaction force are provided. In this study, we developed a simulation method that can predict the center of pressure on the foot and the ground reaction force from kinematics data utilizing artificial muscles between the foot and ground. The artificial muscles on the foot were activated when the distance between a foot node and a ground node is smaller than a pre-definded value. In this study we demonstrated the predictions of ground reaction force and center of pressure on the foot during normal walking. The results were validated against the measured values from a force plate.

KEY WORDS: ground reaction force, center of pressure, virtual force plate.

INTRODUCTION: To analyse human limb kinematics and kinetics, external force and motion capture should be measured (Pandy, 2001; Zatsiorsky, 2002; Riemer, Hsiao-Wecksler, & Zhang, 2008) while there are situations in sports when external forces such as ground reaction force are unobtainable. Force plate information is difficult to obtain during sprinting and walking on slopes. The conditional contact function in Anybody musculoskeletal system allows smart muscles that can be activated depending on conditions (Anybody musculoskeletal system). In this study We developed a virtual force plate system that consists with multiple artificial muscles to estimate ground reaction force from kinematics information from motion capture camera during normal gait (Figure 1). The external forces can be estimated using only kinematic data using this method.

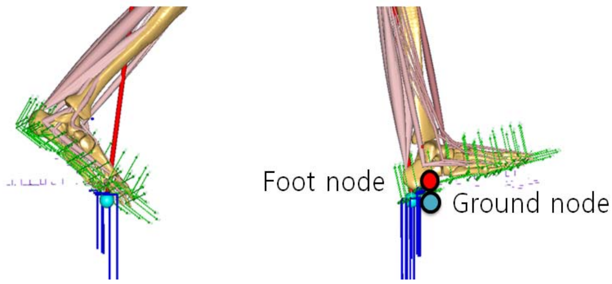


Figure 1: Virtual force plate in which green axes and blue arrows represent artificial muscle attachment points and ground reaction forces, respectively.

METHODS: Motion capture and subject set-up:Seven healthy male participants (age 23±2) were tested for normal gait using motion capture system (Vicon, Oxford, United Kingdom) with a force plate (AMTI, Massachusetts, United States). The Plug-in gait marker set from Vicon was set-up on subjects. IRB approval and consent forms were obtained prior to testing.
Musculoskeletal human model in AnyBody simulation system:Fifty two foot nodes were defined on the bottom of foot segments of AnyBody musculoskeletal human model (AnyBody Technology, Aalborg, Denmark). The foot nodes were attached to the foot segment. The nodes positions were adjusted according to the scaling of the foot model for each subject. The bottom of the foot segment was divided into forefoot, mid-foot and rear-foot regions with equal anterior-posterior length. The forefoot and rear-foot regions were again divided into two

regions. Thus the foot nodes were divided into five groups according to inclusion in the regions (Figure 2). The maximum forces for the reaction elements were determined consistently and heuristically depending on their anterior-posterior on the foot. The reactions elements whose foot nodes were in the forefoot, mid-foot and rear-foot regions had maximum forces of 30N, 20N and 10N for each, respectively (Figure 2).

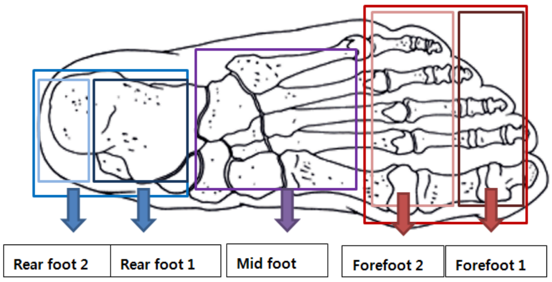


Figure 2: The reactions elements whose foot nodes were in the forefoot, mid-foot and rear-foot regions

Setup virtual force plate: The virtual force plate consisted of fifty two ground nodes that supported the compressive force between the foot and ground. The ground node should be placed on and attached to ground. The position of ground node should exactly match the location where the matching foot node on the foot touches the ground during walking. Thus the positions of ground nodes were determined for each trial of walking. The stance phase of a walking cycle was divided into heel-strike, mid-stance, and toe-off. The ground node positions in the rear-foot, mid-foot and fore-foot regions were determined during heel-strike, mid-stance and toe-off, respectively as shown in Figure 3. Each ground node had an effective cylindrical space with a diameter 10 mm and height 50 mm on top of the node for its activation regions. If a matching foot node for each ground node enters the cylindrical space the artificial muscle that supports the compression between the two nodes was activated. The maximum forces for the artificial muscles between the foot and ground were determined consistently and heuristically depending on their anterior-posterior location on the foot. The artificial muscles whose foot nodes were in the forefoot, mid-foot and rear-foot regions had maximum forces of 30N, 20N and 10N, respectively.

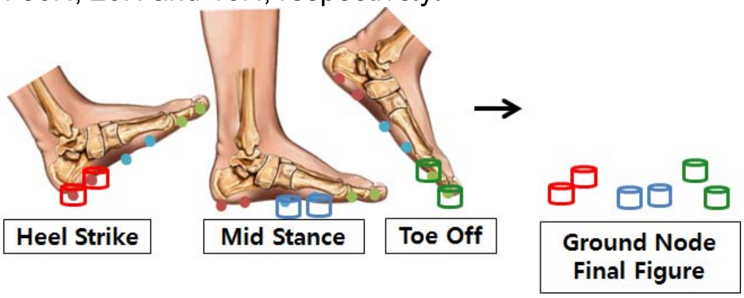


Figure 3: Ground nodes positions on the ground

Joint kinematics estimation: To understand the effectiveness of estimations of center of pressure and ground reaction force, the knee adduction moment obtained with virtual force plate was compared against the knee adduction moment obtained with real force plate which was the reference model. Using AnyBody simulation both knee kinetics were analysed and compared.

Coordinate system in the analysis: The subjects were asked to walk on the force plate from a corner to a corner because of the setting of the force plate. Thus the X- and Y-directions were set-up as shown in Figure 4. Z-direction was set-up to head up-ward from ground.

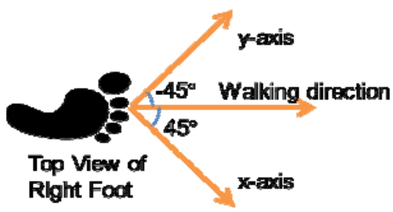


Figure 4: Coordinate system in the analysis

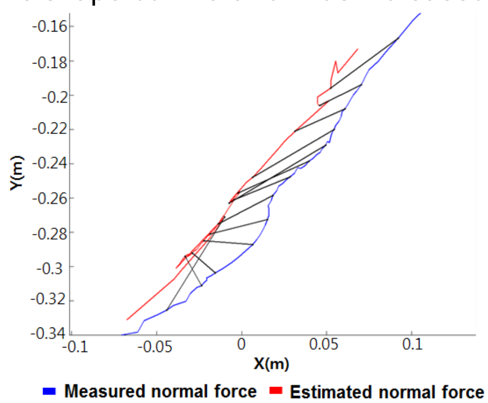
RESULTS: Ground reaction force estimation: Estimated ground reaction force was compared with measured ground reaction force. Root mean square error of estimated ground reaction force was normalized by body weight. Average error of the estimated ground reaction in X-, Y- and Z-directions were 4%, 5.2% and 26.4%, respectively as shown in Table 1.

Center of pressure estimation: Estimated center of pressure was compared with measured center of pressure. Average root mean square errors of the estimated center of pressure in X- and Y-directions were 21.6 mm and 25.4 mm, respectively (Table 1).

Table 1
Estimation error of ground reaction force and center of pressure for seven subjects

	RMS Error of Ground Reaction Force Estimation (%BW)			RMS Error of center of Pressure estimation (mm)	
Subject	X	Y	Z	X	Y
#1	3.8	5.4	27.8	20.2	33.9
#2	5.2	7.6	31.0	18.0	26.3
#3	2.7	4.5	28.0	14.3	15.8
#4	4.1	4.1	24.9	20.4	22.8
#5	4.7	4.0	21.8	28.3	24.5
#6	3.2	4.8	25.9	28.0	37.7
#7	4.4	5.9	25.4	21.8	17.1

Center of pressure estimation: The representative estimation for the center of pressure and the force in Z-direction of a subject is illustrated in Figure 5 and Figure 6. The estimated center of pressure was straight while the measured center of pressure were curved to the lateral side of the foot. The estimated force in Z-direction was close to the measured force in the shape but the error was increased during the double support phase during walking.



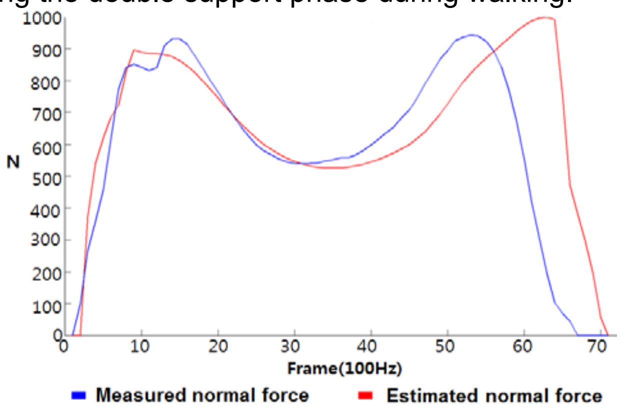


Figure 5: Loci of center of pressure **Figure 6: Normal Force**

Knee kinetics estimation result: Knee kinetics obtained using the virtual force plate was compared against the knee kinetics obtained using real force plate in AnyBody (Figure 7).

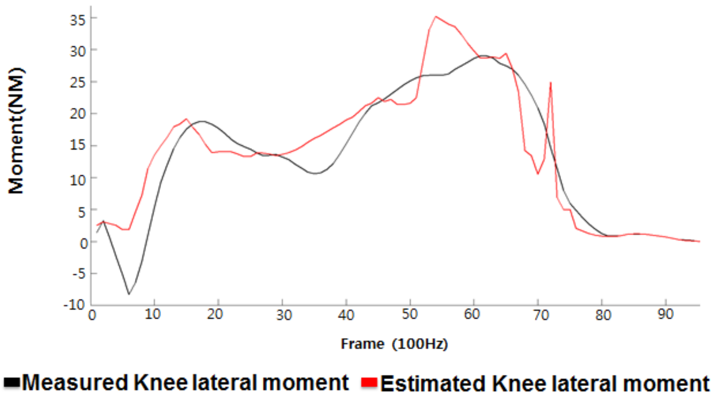


Figure 7: Estimation of knee adduction moment (black line from real force plate, red line from virtual force plate)

DISCUSSION: To analyse athletic exercise using musculoskeletal simulation, external force especially ground reaction force is needed. Measuring ground reaction force is mainly using force plate. But force plate cannot be easily set-up in the special athletic exercise such as sprinting. Therefore it is hard to analyse kinetics of human athletic exercise. In this study we developed a virtual force plate system using artificial muscles between a human body and a contacting object, ground. So that even if we cannot measure ground reaction force, we can estimate ground reaction force and center of pressure using virtual force plate.
The location of center of pressure on the foot had RMS error of about 30mm to 50 mm. While the actual ground reaction force passed the lateral side of the foot during the stance phase the virtual force plate system estimated that the ground reaction force passed the center of the foot. Further study includes the better location of the foot node on the foot for more accurate estimation of the center of pressure and ground reaction force.

CONCLUSION: In this study we developed virtual force plate using conditional contact muscle. The virtual force plate technique combined with full body kinematics could predict ground reaction force and center of pressure for the normal walking of seven subjects. The suggested methodology could help calculate joint kinetics for athletic exercise or when actual force place information is not available.

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