스쿼드운동 중의 하지 근골격 하중 해석
Analysis of Muscle Forces and Joint Moments during Squat Exercise

*#김윤혁 , 브티탄프
*# Y. H. Kim (yoonhkim@khu.ac.kr), B. T. T. Phuong
경희대학교 기계공학과

Key words : Squat, Inverse dynamics analysis, Muscle force, Joint moment

1. Introduction

Squat is a basic exercise that has received considerable biomechanical valuation. It is primary exercise for increasing the strength and size of the legs as well as to train the muscles of the thighs, hips and back, which are very important muscles in daily activities such as running, jumping, or lifting. Researchers and trainers suspect that squats are associated with injuries to the lumbar spine and knees. It is, however, also believed among athletes and coaches that the squat enhances athletic performance. The knowledge of lower extremity biomechanics during squat would be very helpful to trainers, coaches, athletes and researchers who are related to knee, hip rehabilitation and training for sports.

In this paper, we estimated the muscle forces and joint moments during squat exercise. The inverse dynamics analysis program was built to calculate net joint forces and moment. Musculoskeletal model was developed to compute muscular attachments during movement. Muscle forces and joint constraint force are predicted from net joint forces and moments using static optimization.

2. Materials and Methods

Twelve healthy men with no history of neuromuscular disease participated in the study. The average age of the subjects was 20.4 ± 8.4 years, the average height 1.80 ± 0.04 m and the average weight 71.9 ± 8.4 kg. All the subjects were athletes. They have been practicing Taekwondo for more than seven years. They were able to perform squat activity without difficulty.

A high-speed motion capture system (Hawk® Digital Real Time System, Motion Analysis System, Santa Rosa, CA, USA) with six cameras was used to record subjects' movements. The cameras were calibrated prior to data collection each day. Thirty two markers were stuck on the subject's body. Marker locations and fixed body frames were identified in accordance with the recommendation of the International Society of Biomechanics (Wu et al, 2002). For each joint, the local coordinate system in each articulating segment is determined. The position of all markers were recorded every 5ms and processed in EvaRT software to get full data.

External forces and moments were obtained from force plate device (Bertec Corp, Columbus, USA). In this study, we just measured the external force acting on right foot. Because we assumed that the squat movement is symmetric, we considered the ground reactive force acting on left foot and right foot are same. The ground reaction force was collected as 2000 Hz of sampling rate.

The movement began from a standing position. Subjects stood straight on the force plate with the arms put up on the hips. The movement involved bending the knees and hips to lower the torso until the minimum flexion knee angle was about 90 degree, then returning to the upright position. The subjects carried out squat motion at three different speeds. First, the subjects performed this activity at self-selected speed, it was normal speed. Slow speed has execution time of 2 times compared with normal speed. And the subjects work out squat at double speed as fast speed.

The recorded data were conducted with a customized Matlab® (The MathWorks™, Natick, MA, USA) software program. The raw data of the marker positions were filtered by a zero-lag second-order Butterworth filter (cutoff frequency 8 Hz). Filtered data were used to construct segment fixed frames according recommendations from Wu et al. (2002) and then produce direction cosines with respect to the global coordinate system. Joint angle, segmental angular velocity, segmental angular acceleration and segmental translational acceleration relative to the global coordinate system were calculated sequentially (Winter, 2004). These data were combined with force plate data for inverse dynamics analysis that resulted in the calculation of net joint forces and moments

The human body was represented as an articulated multi-segment system with 7 rigid segments. The information about body segments, their mass and moments of inertia is obtained from Zatsiorsky et al. (1996). The musculoskeletal model of right leg consisted of 3 joints and 20 muscles, and was used to compute muscle attachments, muscle force direction throughout the simulation. In this study, we used muscle properties (insertion and origin attached positions on the bone, maximum forces) from Opensim, because it is difficult to measure the object's muscle properties directly.

Inverse dynamics model was used to calculate net joint forces and moments from whole body movement measurements. The only significant external forces and moments are the ground reactions. To solve muscle forces and joint contact forces, an optimization method is used. Muscle forces are estimated by an optimization scheme until the objective function is minimized. The goal of our project is to minimize the total of muscular stresses squared. The sum of the squared muscle stresses was minimized subject to constraints on the minimum and maximum muscle forces.

3. Results

Angular displacements of the ankle, knee, and hip joints are illustrated in Figure 1. Squat movement is divided into 2 phases, the descent phase and the ascent phase. The descent phase was required slightly larger time than the ascent phase. For fast and normal speed, the descent phase was 0-52% of the whole cycle, for slow speed 0- 58% of the whole cycle. During the descent, all three joints flexed. The minimum flexion angles for all three joints occurred at the end of descent.

Curves of the torques acting in the joints are presented in Figure 2. The estimated torque about each joint was normalized with respect to body-mass time height. Joint moments were varied when we changed activity speed. The joint moments at normal and slow speed seemed to be similar. At fast speed, the joint moments increased considerably compared with the others.

The muscle forces during squat are displayed in Figure 3. These curves showed that tibialis anterior (tibant) and rectus femoris (rf) are more active in the descent phase than in the ascent phase, whereas soleus (sol) is more active in the ascent phase.

Quadriceps (QUAD), biceps femoris long head (BFLH), gastrocnemius medial (GASM), gastrocnemius lateral (GASL), iliacus (il), gluteus maximus (gmax), all got the maximum value at about 45% of the motion cycle.

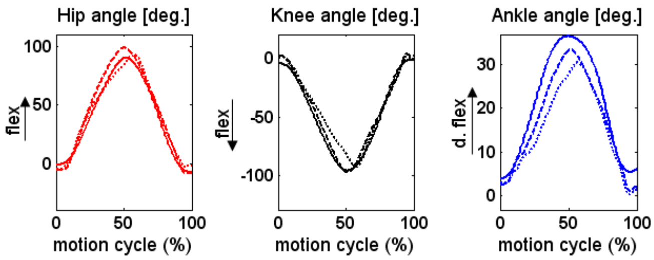

Fig. 1 Joint angles at fast (solid), normal (dashed), slow (dot) speed

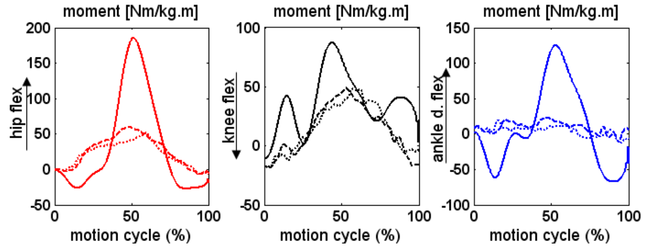

Fig. 2 Joint moments of hip, knee and ankle joints at fast (solid), normal (dashed), slow (dot) speed

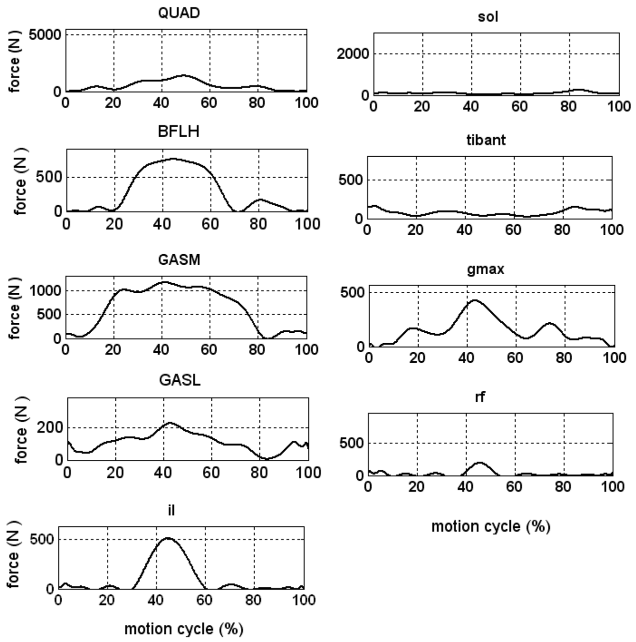

Figure 3: Muscle forces during squat exercise at normal speed

4. Discussion

The result showed the muscle forces of nine muscles, the joint moments as well as the joint angles during two legs squat. As the body descends, the hips and knees undergo flexion, the ankle dorsiflexes and muscles around the joint contract. Before reaching the bottom of movement, muscle forces get the maximal values. The muscles achieve maximal contraction at the bottom of movement while the body starts reversing ascent. This study is the starting point to understand the biomechanical functions and performances of squat exercises using biomechanical analysis.

Acknowledgements

This work was supported by the Sports Promotion Fund of Seoul Olympic Sports Promotion Foundation from Ministry of Culture, Sports and Tourism.

Reference

1. Lei, R., Richard, K.J., David, H., "Whole body inverse dynamics over a complete gait cycle based only on measured kinematics," Journal of Biomechanics, **41**, 2750– 2759, 2008.
2. Robertson, D.G.E, Wilson, J.M.J., and Pierre, T.A.S., "Lower Extremity Muscle Functions During Full Squats," Journal of Applied Biomechanics, **24**, 333-339, 2008.