Validity of Muscle Force Estimation Utilizing Musculoskeletal Model

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Abstract. Few methods are available for measurement of muscle strength during physical activities. This study addresses the validity of estimating the force of the quadriceps femoris during the forward lunge and squat carried out by 18 healthy men. Data were collected by the utilization of a musculoskeletal model through computer simulation. From the electromyographic (EMG) recordings of the vasti medialis (VM) and lateralis (VL) and rectus femoris (RF) muscles a correlation coefficient (r) was calculated between the estimated value for the muscle force and the root mean square (RMS) value. The median r for VM and VL was found to exceed 0.65 during the flexion and extension phases of forward lunge and below 0.44 for VM and VL during squat for the same phases. For RF, the median r for both tasks was below 0.39 except during the flexion phase of squat. The coefficient of the similarity in the EMG patterns exceeded 0.93 between the estimated muscle force and EMG RMS for both the forward lunge and squat. The value of the estimated muscle force for RF in these 2 tasks was found to be very small. The results show that the musculoskeletal model can be considered a valid measure for estimating muscle force.

Key words: Musculoskeletal model, Forward lunge, Squat

INTRODUCTION

A model simplified for an actual event is normally made in the field of engineering, and a simulation based on such a model in which various data are fed has come into widespread use[1]. In the field of medicine, mechanical analyses of bones and joints by computer simulation such as the finite element method are developing rapidly through the use of the data from 3-dimensional (3D) image technology such as 3D-CT[2]. In the professional practice of physiotherapy it is difficult to calculate the numerical values of muscle force, joint compression force and muscular energy consumed during activities, but these parameters can be estimated by the use of a computer simulation technique. Therefore, this technique is considered to be a useful tool for the elucidation of the pathophysiology and aetiology of musculoskeletal disorders, and has culminated in the development of new approaches to treatment and appropriate selection of treatment modalities, together with the establishment of efficient and safe treatment in physiotherapy[3, 4]. The provision of a physiotherapy-at-a-distance system in sparsely populated areas with availability of few healthcare professionals by computer simulation utilizing a musculoskeletal model has already been conceptualised[5].

Although an analytical method to calculate joint moment is in the realms of completion at the present time, many problems concerning the estimation of muscle force associated with joint moment remain to be resolved[2, 6]. The estimation of muscle force
can be classified roughly into two problem-solving areas. First, on what should a musculoskeletal system be modelled? This problem concerns the point of action and the direction of the muscle force. Second, how should the muscle force be calculated vis-à-vis its balance of moments of force? Because the number of equations for motions is larger than that of the unknowns for muscle force, a solution at the moment cannot be determined. Therefore, currently this problem is being solved by setting an objective function that is considered to be a physiological characteristic, to minimize summation of muscle force, together with the use of an optimization technique\(^5, 7\). Although this technique satisfies kinematic conditions, calculated muscle force may lack validity\(^8\). Therefore, the objectives of this controlled laboratory study were to calculate muscle force while performing the forward lunge and squat, and to examine the validity of the estimated muscle force of these tasks through the use of computer simulation.

**METHODS**

**Participants**

Eighteen healthy men with no history of any orthopaedic condition of either the knee or hip were enrolled in this study. They all gave their consent to participate in the experiment after having been informed of the methods of measurement and the tasks involved. The mean (± standard deviation: SD) age, standing height and body weight of the participants were 20.6 ± 1.4 years, 170.9 ± 4.2 cm and 62.2 ± 5.2 kg, respectively.

**Tasks**

The forward lunge and squat were the specific tasks analysed in this study. The forward lunge was carried out in step standing with the right leg placed forward and the squat task was with the legs in the shoulder-width apart position. For both tasks the arms were in 90 degrees (°) abduction, and when performing forward lunge and squat the participant was instructed to flex the knee or knees to approximately 80°. Each participant performed the 2 sets of tasks separately at a rate of 25 per min synchronised by a digital metronome (DM-17, SEIKO Co., Ltd.). The participants were given adequate opportunity to practise the tasks before the testing took place.

**Data collection**

All participants wore spandex shorts, but no shoes. The right thigh muscles were subjected to surface electromyography (SEMG). The inter-electrode impedance was reduced to less than 5 kΩ by abrasion of the skin surface with an alcohol swab. Analogue SEMG signals were band-pass filtered between 10 and 500 Hz (Polymate P1000, Digitex laboratory Co., Ltd.) and converted into digital signals with a sampling frequency of 1 kHz by a 16-bit iteration method. A pair of 1 cm in diameter surface Ag-AgCl electrodes (Blue Sensor P-00-S, Ambu) and a bipolar lead system were applied to the skin over the rectus femoris (RF), vastus medialis (VM) and vastus lateralis (VL). This positioning of the electrodes for VM and VL was recommended by Cowan, et al.\(^9\) and that for RF by Basmajian\(^10\). The electrodes were placed parallel to the muscle fibres 20 mm apart in order to reduce the influence of cross-talk as much as possible, and were secured to the skin by a piece of tape.

Retroreflective markers with a diameter of 10 mm were bilaterally placed on the head of the 5th metatarsal, lateral malleolus, lateral epicondyle of the femur, greater trochanter and acromion process. Three high-speed cameras (FASTCAM-Net, Photron Co., Ltd.) operating at 125 frames per second were used to record the 3D kinematics data of the forward lunge and squat movements. Following this, the image data from the 3 cameras were stored on videotape. The position of each marker was reproduced as a 3D coordinate on the computer screen, using the Frame-DIAS II motion analysis program (DKH Co., Ltd.). Ground reaction forces through the right leg were recorded with a Kistler force plate (9286AA, Kistler Co., Ltd.) at a sampling frequency of 1 kHz. The recording of the EMG and ground reaction force were synchronised with the video by a switch.

**Data reduction**

The SEMG signals that were produced during forward lunge and squat were analysed using BIMUTAS II (Kissei Com-Tech Co., Ltd.). The EMG recording of the motion that yielded maximum flexion of the knee during an eight-second period for the performance of both the forward lunge and squat tasks was the data used for the analysis. The root mean square (RMS) was calculated from the EMG values at intervals of 8
The muscle force was estimated using the ARMO program (GSPORT Inc.) on the basis of information gathered from the location of each marker and the data for the ground reaction force. The forward lunge and squat motions were divided into 3 phases as follows: flexion movement, static period and extension movement (Fig. 1). Following this, the correlation between the estimated value and the RMS value were analysed for each phase. The static phase was defined as that in which the knee joint was at 5° or less.

Electromyographic RMS was digitally low-pass filtered at a cut-off frequency of 6 Hz for comparison of the patterns of the muscular activity with that of the output patterns of the muscle force. Furthermore, the two waveforms derived from electromyographic RMS and muscle force were normalised with the time required for the forward lunge or squat being deemed as 100 percent. This was followed by averaging of the RMS and values estimated for all of the participants. In addition, the coefficient of similarity (γ) used for a pattern matching technique was calculated to examine the similarity between the RMS waveform and the estimated muscle force waveform.

### Statistical analysis

Spearman’s rank correlation coefficients (r) were calculated in order to examine the correlation between the estimated muscle force and RMS value for EMG during forward lunge and squat. The paired t test was employed to compare the maximum value for the estimated muscle force between that of forward lunge and squat. An alpha

| Table 1. Correlation coefficients between the estimated value for the muscle force and RMS value |
|---------------------------------|---------------------------------|---------------------------------|
| a: Forward lunge                | Flexion phase                  | Static phase                  | Extension phase                |
|                                 | VM     | VL     | RF     | VM     | VL     | RF     | VM     | VL     | RF     |
| Median                          | 0.71   | 0.70   | 0.17   | 0.23   | 0.22   | 0.23   | 0.67   | 0.65   | 0.25   |
| SD                              | 0.15   | 0.12   | 0.25   | 0.16   | 0.16   | 0.12   | 0.17   | 0.17   | 0.23   |
| b: Squat                        | Flexion phase                  | Static phase                  | Extension phase                |
|                                 | VM     | VL     | RF     | VM     | VL     | RF     | VM     | VL     | RF     |
| Median                          | 0.31   | 0.44   | 0.44   | 0.12   | 0.24   | 0.08   | 0.22   | 0.40   | 0.39   |
| SD                              | 0.24   | 0.22   | 0.22   | 0.17   | 0.16   | 0.14   | 0.17   | 0.29   | 0.21   |

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**Fig. 1.** Motion phase.
level of 0.05 was selected for statistical significance in this study, using the Statistics Package for Social Sciences version 11.5 (SPSS Japan Inc.).

RESULTS

The maximum load was found to be 96.6 ± 7.5 percent and 65.5 ± 5.0 percent of the participants’ body weight for the forward lunge and squat motions, respectively.

Table 1 shows the correlation coefficients, r, between RMS value and estimated muscle force for forward lunge and squat. The median r ranged from 0.65 to 0.71, which was relatively high during forward lunge for VM and VL in the flexion and extension phases, but was found to be low (0.31–0.44) for squat. In the static phase, the r for VM and VL was smaller than 0.24 during the performance of both tasks. The r for RF was found to be low in all of the 3 phases for both forward lunge and squat.

The waveform patterns for both the estimated muscle force and RMS were found to be similar during 1 cycle of movement for both forward lunge and squat (Figs. 2 and 3). The similarity of the 2-waveform pattern for the forward lunge was more marked than that for the squat. The coefficients of similarity, γ, was larger than 0.9 during both the forward lunge and squat tasks and that of the waveform pattern of RMS for RF, VM, and VL, together with the estimated muscle force was found to be similarly large (Table 2).

The estimated VM and VL force was significantly greater during forward lunge than during squat. However, the estimated muscle force for RF was significantly greater during squat than during forward lunge (Table 3).

DISCUSSION

The estimated muscle force in this study was calculated by the use of the inverse dynamics technique, a musculoskeletal model and the optimization technique. It is a known fact that the force added to an object can be calculated from its movement using the inverse dynamics technique7). In other words, the joint moments and inter-segmental forces can be calculated using the rigid link model, that is an inverse dynamics technique based on kinematics data, and the data from the ground reaction force. The muscle force was estimated in this study by equilibrium of the joint moment and the inter-segmental forces through making use of the musculoskeletal model on the basis of the origin and insertion of muscles, together with the optimization technique. The muscle model
of Hill\textsuperscript{12}) was used to calculate the muscle force. The correlation coefficients, r, was large for the monoarticular muscles (VM and VL) compared to the biarticular muscle (RF). The estimated RF force was very small during the performance of the two tasks, and some participants’ estimated RF force was calculated as 0. While the estimated RF force was found to be greater during squat than during forward lunge, the RMS value for RF was larger during forward lunge than during squat. These findings indicate that the method of calculation used in this study probably yielded sufficient validity for VM and VL, but not for RF.

RF, which is a biarticular muscle, acts as both a knee extensor and hip flexor, and its function becomes complicated during activities in the closed kinetic chain (CKC) condition. The activity of RF is inhibited because forward lunge and squat require simultaneous extensor force to the knee and to the hip\textsuperscript{13}). In addition, RF is reported to be active during the flexion phase, but inactive as an agonist when faster squat is performed\textsuperscript{14}). The optimization technique that is recommended by Crowninshield et al. is a method in which an unknown is selected to minimize a certain value of an objective function. The objective function used in this study was one that minimised the sum of the squared values following the division of the values for each muscular force by the physiological cross-sectional area of the muscle. This objective function produces a sum of muscle force that is smallest when each muscle exerts its force as evenly as possible\textsuperscript{7}). Thus, if RF becomes activated in a situation such as in forward lunge, with larger movement at the knee than at the hip, an increase in the hip extensor activity becomes mandatory, and the sum of the muscle force is not at its smallest. This may be the reason why the RF force in this study, due to the utilization of the optimisation technique, showed a very small value.

The high degree of similarity ($\gamma$: 0.94–0.99) obtained between the waveform patterns for both the estimated muscle force and RMS in this study suggests that the pattern for the muscle force during the performance of the 2 tasks is highly likely to be valid. Escamilla, et al.\textsuperscript{16}) and Wretenberg, et al.\textsuperscript{17}) reported that the activity of the 2 vasti muscles produced approximately 50\% greater activity than that of RF during squat because of RF being a biarticular muscle. According to Fujiwara, et al.\textsuperscript{18}) the activity of RF becomes inhibited in knee extension with hip flexion compared to when knee extension occurs without hip involvement. The value of estimated RF force was small compared to VM and VL in this study, reflecting the inhibition in its activity. Further study, therefore, is required to examine the value per se of force, in particular, of a biarticular muscle such as RF, because the calculated value itself is very small.

A goal-specific strengthening exercise is possible if muscle force can be ascertained for activities during daily living. When recovery of muscle strength cannot be expected for the performance of certain daily activities, the force may be estimated for other muscles and its magnitude determined to compensate for the inactive muscles. The validity of the value itself of estimated muscle force was low in this study, so that it would be inappropriate to use this value alone as an indicator of the strength of a muscle during activity. However, the findings may be of value as a time course for muscle force during activities if we integrate them with the findings of the EMG and joint moment.

In conclusion, the output pattern for the estimated muscle force was found to be valid during forward lunge and squat tasks. However, the value of estimated muscle force was found to be excessively small for the biarticular muscle.

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### Table 3. Comparison of the estimated muscle force between forward lunge and squat

<table>
<thead>
<tr>
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<th>Forward lunge N/kg</th>
<th>Squat N/kg</th>
</tr>
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<tbody>
<tr>
<td>RF</td>
<td>$1.3 \pm 1.9^{**}$</td>
<td>$2.9 \pm 1.5$</td>
</tr>
<tr>
<td>VM</td>
<td>$14.5 \pm 2.2^{**}$</td>
<td>$10.3 \pm 1.2$</td>
</tr>
<tr>
<td>VL</td>
<td>$24.3 \pm 5.2^{**}$</td>
<td>$17.1 \pm 3.6$</td>
</tr>
</tbody>
</table>

****: $p<0.01$.
RF: Rectus femoris; VM: Vastus medialis; VL: Vastus lateralis.
REFERENCES