Memoirs of the Faculty of Engineering, Kyushu University, Vol.69, No.4, December 2009

The Model Analysis of Lower Limb at Ascending from Deep Knee Flexion

by

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(Received July 31, 2009)

Abstract

A new type of knee prosthesis capable of making deep knee flexion has been long awaited for Asian and Muslim people. Our research group has developed the prosthesis possible to attain even sedentary sitting and designated it as CFK (Complete Flexion Knee). In order to assess the performance of CFK, we have set up various kinds of simulation or experimental projects, such as a cadaveric study, a mathematical model analysis, a photoelastic analysis and FEM analysis. For carrying out the above-mentioned projects, we faced the most fundamental problem; the information about the forces acting on the joints has been limited for ambulatory activities but not for squatting or sedentary sitting. The objective of this study is to introduce the force acting on the knee joint at deep knee flexion through a 2D mathematical model simulation and some experimental measurements. Double leg ascending motion and single leg ascending motion from kneeling position were studied for 10 healthy male subjects.

The results demonstrated that for double leg ascending, the maximum knee joint forces were 4.9±0.5 times of body weight, and for single leg ascending, the maximum knee joint forces of dominant leg were 5.0±0.2 times of body weight and those of supporting leg were 3.0±0.5 times of body weight. Ascending speeds did not affect the results much as long as the motion was not strenuous like jumping up/down.

Keywords: Knee joint force, Muscle force, Deep squatting, Lower limb model, Biomechanics

1. Introduction

The objective of this study is to introduce the muscle forces around a knee joint and the force acting on a knee joint at ascending from deep squatting, and to get the information on the assessment of knee prostheses at deep knee flexion.

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Conventional artificial knee joints cannot perform some daily activities, such as sedentary sitting, because their range of motion is not good enough for deep knee flexion. The prosthesis of next generation should attain wider range of motion to allow the patients to make more various daily activities. The prosthesis, named CFK: Complete Flexion Knee, which can make 180º of flexion angle is under developing by our research group and now we are investigating how to estimate its kinematics and mechanical strength.

As for a performance assessment of knee prosthesis, such method as a mathematical model analysis, photoelasic analysis, and FEM analysis have been employed. Here, we face the most fundamental problem; the information are crucial for the above mentioned analyses, such as the muscle forces of a lower limb or the knee joint force at deep squatting is still lacking. It is obvious that we will not be able to assess the prosthetic performance properly if the input data are not trustworthy. Unfortunately however, most of the previous studies have introduced the data only about level walking[1), 2), 3), 4)], and rising from a seated position[5), 6)], and the data about deep squatting are quite few[7)].

To overcome these problems, we introduced the muscle forces of a lower limb and knee joint force for deep knee flexion by model analysis. A simple 2D model of lower limb was used. The motions to be studied were double leg ascending and single leg ascending from kneeling respectively, and the results of each motion were compared. Since it was impossible to verify the validity of our model through actual measurement, we compared our results to those from the previous studies not only about deep knee flexion but also other kinds of lower limb activities such as level walking and rising from a seated position.

2. A 2D Model of a Lower Limb

2.1 The structure of the model

By referring to the Dalkavist's model[7)] (**Fig.1**), we constructed the model of a lower limb. The model was composed of three segments: femur, tibia and foot. The upper body including upper limbs and a head was modeled as a simple mass. The model included gluteus, femoral quadriceps, hamstrings and calf muscles: soleus and gastrocnemius. In **Fig.1**, α stands for the hip joint angle, β for knee flexion angle, γ for ankle joint angle, and γ' for the angle between foot and floor face.

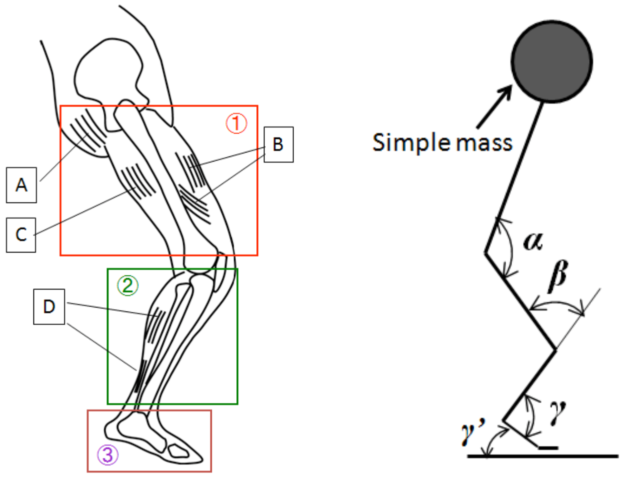


Fig. 1 A 2D model of a lower limb and definition of the joint angles.

Figure 2 shows the forces acting on the segments and the symbols in the figure are explained below the figure title.

When knee flexion angle becomes larger than about 130° , the thigh and the calf muscles make a contact and the contact force between these two muscles has to be taken into account as shown in **Fig.3**. Referring to the literature[8)], we will determine the value and the position of this contact force.

Finally, as moments acting on the lower limb joints, we will denote M_h as the moment about the hip joint, M_k about the knee joint, and M_a about the ankle joint respectively.

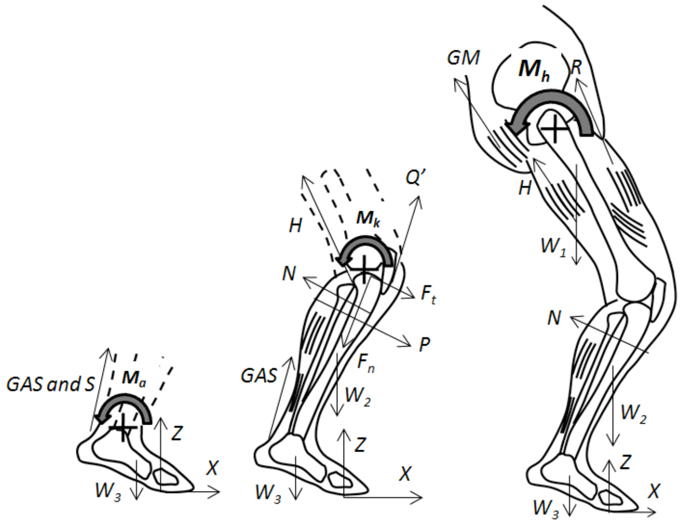


Fig. 2 Forces for calculating the moment equilibrium condition around each joint.

・tensile force of the muscle/tendon

H :hamstrings, *GM* :gluteus, *R* :rectus femoris, *GAS* :gastrocnemius, *S*:soleus , *Q′* :patella tendon

・force acting on the knee joint

F_n :the normal component, which is parallel to the tibial axis

F_t : the tangential component

・external forces,

W: the gravity force

Z, *X*: the normal and tangential component of the floor reacting force

N : the normal component of the floor reacting force during kneeling

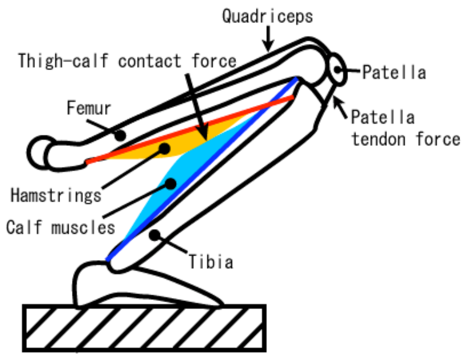


Fig. 3 Thigh calf contact.

2.2 Calculation method

In the following equations, symbol *a*, *b* and *c* stand for the lengths of the moment arm about the hip, the knee and the ankle joints respectively. The forces to generate each moment arm were indicated at the lower right of the figure. For example, a_z stands for the moment arm of *Z* (Floor reacting force) about the hip joint.

The moment about the hip joint by external forces is expressed as,

$$M_h = Za_z + Xa_x - W_1a_{W1} - W_2a_{W2} - W_3a_{W3} \quad (1)$$

The moment about the hip joint by muscle forces is expressed as,

$$M_h = GMa_{GM} + Ha_H - Ra_R + Na_N \quad (2)$$

Since the values from equation (1) and (2) must be identical with each other, the following equation holds,

$$Za_z + Xa_x - W_1a_{W1} - W_2a_{W2} - W_3a_{W3} - GMa_{GM} - Ha_H + Ra_R - Na_N = 0 \quad (3)$$

By the same way as the above, the equations for the knee and the ankle joints are introduced as the following equations respectively,

$$-Zb_z + Xb_x + W_2b_{W2} + W_3b_{W3} - GASb_{GAS} + Q'b_{Q'} - Hb_H - Nb_N + Pb_P = 0 \quad (4)$$

$$Zc_z + Xc_x - W_3a_{W3} - (GAS + S)c_{GAS} = 0 \quad (5)$$

From equation (3) through (5), the number of equations is three while the number of unknowns is six: *GM*, *H*, *R*, *GAS*, *Q'* and *S*. In order to solve this statically-indeterminate equation, the following three assumptions are to be employed;

1. Hamstrings and gluteus work synchronously.
2. Gastrocnemius and soleus work synchronously.
3. The ratio between the tension of patella tendon and the force of the quadriceps is the function of the knee flexion angle, decided referring to the literature[9].

Assumption 1 may be reasonable because these muscles are treated as the same group in EMG analysis[10]. Same is true for assumption 2.

From equation (3) through (5) and the above mentioned three assumptions, we are able to introduce the muscle forces acting on the joints. Then using the values of muscle forces around the knee joint, we are able to introduce the forces acting on the knee joint.

3. Materials and Methods

Some measurement experiments were carried out for 10 healthy male subjects. The average age was 24±2 years, the average height was 172±4.2cm and the average weight was 65.1±8.7kg. The lengths of the segments were measured for each subject. Since the mass and the location of center of gravity for each segment could not be measured, these values had to be determined by referring to the literature[11].

The motions to be studied were a double leg ascending and a single leg ascending. The double leg ascending is the motion from kneeling to standing with both the legs moving together (**Fig.4**). The single leg ascending is the same motion as the double leg ascending, but either leg begins to stand under the condition that the other leg is in contact on the floor with its toe and knee (**Fig.5**). In **Fig.5**, we will call the standing leg (right leg) as the dominant leg and the contacting leg with the floor (left leg) as the supporting leg.

The floor reacting forces on the foot and the knee were measured from the force plate. Markers were attached on the joints, video images were taken during the standing motion, the joint angles were measured from each frame of the video images.

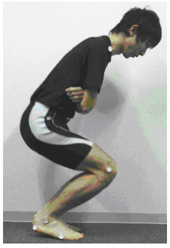


Fig. 4 Double leg ascending.

Fig. 5 Single leg ascending.

4. Results

4.1 The knee flexion angle

Figure 6 shows the variations of the knee flexion angles on each leg of subject C, as an example.

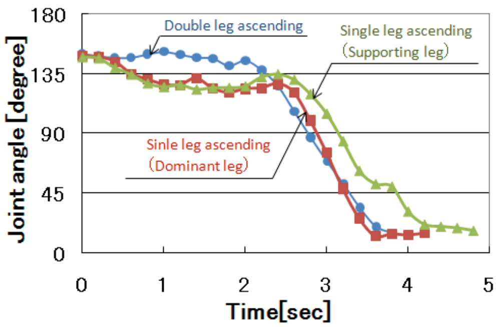


Fig. 6 Knee flexion angle variations.

4.2 Muscle forces

Figure 7 shows the variations of the quadriceps forces on each leg of subject C. The quadriceps muscle forces for all the legs reached at maximum at t=2.4s, and the maximum values were 3.6kN (6.8BW) for the dominant leg during single leg ascending, 2.7kN (5.1BW) for the legs during double leg ascending, and 1.8kN (3.3BW) for the supporting leg during single leg ascending respectively. Here the value in a parenthesis indicates the ratio of the muscle force to the body weight (BW).

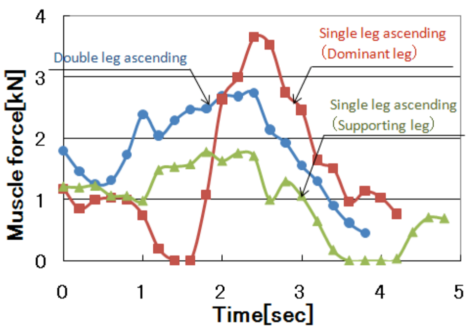
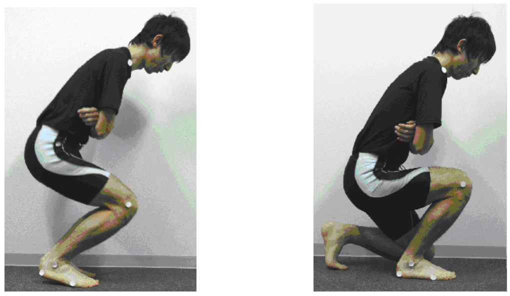


Fig. 7 Quadriceps force variations.



(a) double leg ascending (b) single leg ascending

Fig. 8 The posture when the quadriceps force reached maximum.

Figure 8 (a), (b) show the postures of subject C when his quadriceps forces reached at maximum during double leg ascending and single leg ascending respectively. The knee flexion angles at this moment were 125.7° for double leg ascending, 127.6° for dominant leg and 134.5° for supporting leg for single leg ascending respectively; nearly same angle at which the thigh-calf contact initiates.

4.3 Knee joint forces

Figure 9 shows the variations of the normal component of knee joint force on each leg of subject C. The maximum value for the legs during double leg ascending and that for the dominant leg during single leg ascending were almost equal: 2.5kN (4.5BW). The maximum value for the supporting leg during single leg ascending was 1.3kN (2.3BW).

Being different from the case of muscle forces, the normal component of knee joint force on each leg reached at maximum at various positions respectively. They were 145° for double leg ascending, 26.2° for dominant leg and 119.6° for supporting leg for single leg ascending respectively.

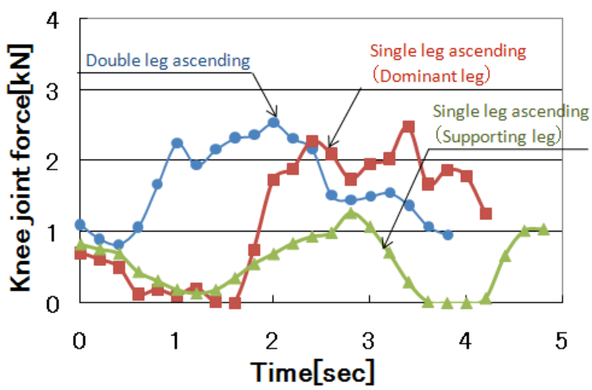


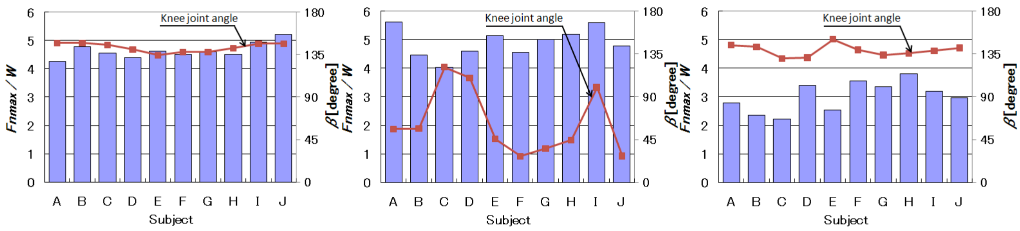
Fig. 9 Variations of the normal component of the knee joint force.

4.4 The body weight ratio of the maximum knee joint force

Figure 10 shows for each subject, the bar graph of the ratio between the maximum value of normal component of knee joint force and the body weight and the line graph of knee angle at the time when the normal component reaches at maximum. In the figure, (a) shows for the legs during double leg ascending, and (b) for the dominant leg and (c) for the supporting leg during single leg ascending respectively. From **Fig.10** (a), we found that during double leg ascending, the average value of the maximum normal component of knee joint force was 5.0±0.2BW (4.3～5.2BW), and the average flexion angle at that moment was 142±4° (134～147°); nearly same angle at which the thigh-calf contact initiates.

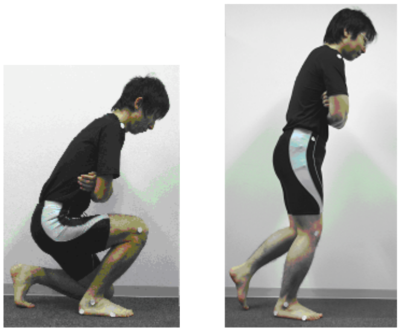
During single leg ascending, the average value of the maximum normal component of knee joint force for the dominant leg was 4.9±0.5BW (4.0～5.6BW) and the average flexion angle at that time was 62±33º (28～110º), showing the wide variability (**Fig.10** (b)). For the supporting leg (**Fig.10** (c)), the average value of normal component of knee joint force was 3.0±0.5BW (2.2～3.8BW) and the average flexion angle at that time was 138±6º (130～150º).

We found the average flexion angles at which the average normal component of knee joint force became maximum were divided into two groups as shown in **Fig.11**; one group (subject C, D and I) showed such a posture as the supporting leg was about to leave from the floor, and the other group (subject A,B,E,F,H and J) showed a posture as the toe of the supporting leg was about to leave from the floor.



(a) Double leg ascending (b) Dominant leg (c) Supporting leg

Fig. 10 Body weight ratio of maximum knee joint force and the knee flexion angle at that time.



(a) Subject C (b) Subject H

Fig. 11 Postures when the normal component of knee joint force of the dominant leg reached maximum.

5. Discussions

5.1 Comparison between two motions

We introduced the muscle forces and the knee joint forces during double and single leg ascendings.

The results showed that the muscle forces were largest at the dominant leg, followed the legs at double leg ascending and those at the supporting leg were smallest. It might be remarked that the motions requiring larger muscle forces are harder to perform. Therefore, according to the results, we would feel relatively hard at the dominant leg during single leg ascending. However, we generally perform single leg ascending because the motion is easier than double leg ascending. The reason for this might be that, in single leg ascending, it is easier to balance the entire body than in double leg ascending.

On the other hand, the knee joint force was the smallest at the supporting leg. And the force at the dominant leg was almost the same as at double leg ascending. Therefore it might be remarked that the single leg ascending is better than the double leg ascending because of the small knee joint force at the supporting leg. Especially as for the prosthetic patients, they should perform single leg ascending and their supporting leg should be their prosthetic legs.

5.2 The insertions of the tendons to the bones

We could not measure the accurate position which the tendons attached to the bones, and we had to estimate the length of moment arm. **Figure 12** shows the knee joint force during the double leg ascending, demonstrating how it changed in cases of $b_{Q'}$ being 4cm and 5cm. By increasing it by only 1cm, the joint force decreased as much as 0.6kN with their maximum values.

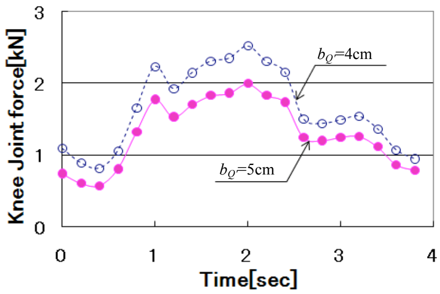


Fig. 12 Variations of the knee joint forces with the different $b_{Q'}$.

It shows that the length of moment arm affected the results much. Therefore the insertions of the tendons must be measured accurately to introduce the proper results.

The lengths of the moment arms difficult to estimate are: the rectus, gluteus and hamstrings about the hip joint, a_R, a_{GM} and a_H, and of hamstrings and gastrocnemius about the knee joint, b_H and b_{GAS}, besides $b_{Q'}$. And we confirmed that the results were greatly affected by $b_{Q'}$ and b_H.

Since the values of the results could be changed by putting various parameters, we could not conclude that our results were absolutely proper. However, our results could hold from the standpoint of comparative study. Therefore we concluded that the knee joint force was the smallest at supporting leg and that the joint forces at dominant leg and double leg ascending were almost the same.

5.3 The comparison of the results to the previous studies

We had to confirm the validity of our results by comparing them to the other studies. Unfortunately however, there are few data for deep knee flexion. Therefore we performed the simulations for level walking and rising from seated position, because there were a lot of data for such motions.

Table 1 shows the results of this study and other studies. $F_{n\max}$ stands for the maximum value of the normal component of the knee joint forces.

Table 1 Results from other studies.

(a) Rising from a deep squat

Activity	Method	F_{nmax} [BW]
Dahlkvist[7]	Model analysis	5.0
This study		5.0

(b) Walking

Activity	Method	F_{nmax} [BW]
Paul[1]	Model analysis	2.7～4.3
Morrison[2]		2.1～4.0
Komistek[3]		1.7～2.3
Taylor[4]	Telemeter	2.2～2.5
This study	Model analysis	2.8

(c) Rising from a seated position

Activity	Method	F_{nmax} [BW]
Ellis[5]	Model analysis	4.3
Varadarajan[6]	Telemeter	2.0
This study	Model analysis	2.5

According to **Table 1 (a)**, $F_{n\max}$ of the motion from squatting to standing which Dahlkvist introduced by model analysis[7] was almost same to that introduced by our model.

Table 1 (b) shows the results of the level walking. Paul[1], Morrison[2] and Komistec[3] had performed the model analyses and Taylor[4] preformed the in-vivo experiment using telemeter respectively. The results of the model analyses had large variability, which is particular for a model analysis as mentioned in 5.3. It would be caused by the parameters, especially by the lengths of the moment arm. Our results were close to the results of in-vivo study.

Table 1 (c) shows the results of rising from a seated position. Ellis[5] performed the model analysis and Varadarajan[6] performed the in-vivo experiments respectively. Our result and the result of in-vivo study were close relatively to that of Ellis. It might be caused by the affection of some parameters.

Our results were almost same as the results from the in-vivo studies for level walking and rising from a seated position, thereby indicating the validity of our model. Therefore it could be said that our results for deep flexion might be appropriate.

6. Conclusion

We introduced the muscle forces of a lower limb and the knee joint force during double leg ascending and single leg ascending by the 2D model analysis and confirmed their validity comparing them to the results of some other studies. Our future plan is to analyze the ascending motion with the support of the upper limbs, or to perform the experiments of various test objects and discuss the affects of their age, sex or corpulence.

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