Dynamic analysis of transfemoral amputee's musculoskeletal system using muscle activation control parameters measured by FES experiments

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Abstract— Recently, the increase of transfemoral amputees from industrial disasters, traffic accidents, vascular diseases and aging is emerging as a social issue. For transfemoral amputees, it is very important to recover their lost functions. Myoplasty, which is one of above-knee amputation methods that sutures muscles on the femoral stump, is used more commonly than other operation methods because it is superior in muscle setting and appearance. Myodesis fixes femoral stump muscles onto the femur. For these different operation methods, there have been controversies over which is better due to lack of scientific analysis. Thus, the present study applied electric stimulation to the tibial muscle of dogs *in vivo* and *in situ* and measured the dynamic physical characteristics of the muscle after making the dogs do isokinetic exercise in the state of full activation. In addition, we performed tension experiment with the dogs' medial tibialis cranicalis muscle and tendon to examine the kinetic characteristics of the muscle and tendon, and analyzed isokinetic flexion, extension, adduction and abduction exercise by applying the characteristics to the muscle models of transfemoral amputees who had received different types of operation. In case of isokinetic flexion, adduction and abduction, the model of transfemoral amputees who had myoplasty was superior to that of transfemoral amputees who had myodesis in the moment of coxal articulation and the range of motion. On the contrary, in case of isokinetic extension, no significant change was observed in moment

Keywords-myodesis; myoplasty; isokinetic exercise; forward dynamics; flexion; extension; abduction; adduction

I. INTRODUCTION

Various operation methods are applied to transfemoral amputees from vascular diseases, traffic accidents and industrial disasters, but there have been controversies over which method is more efficient for transfemoral amputees' rehabilitation due to lack of scientific and systematic research [1]. The present study experimented on the physical characteristics of tibial muscle and tibial tendon in vivo and in situ in order to utilize transfemoral amputees' muscle models. For this, using 3-dimensional graphics, we modeled transfemoral amputees who received myoplasty and myodesis. Then, we applied isokinetic flexion, extension, abduction and adduction exercise to the myoplasty and myodesis models, examined the moment and the range of motion of the two models through kinetic analysis and, based on the results, suggested a superior above-knee amputation method.

II. EXPERIEMNT USING DOGS' TIBIAL MUSCLE *IN VIVO* AND *IN SITU*

A. *Experiment method*

In this experiment, we are going to apply more accurate physical characteristics of muscle before making kinetic analysis of transfemoral amputees' isokinetic flexion, extension, abduction and adduction exercise. For this, we obtained the biodynamic and kinetic muscular force characteristics from experiment with large dogs (Korean Mongrel) in vivo and in situ as in Fig. 1. In surgical operation, an ultrasonic sensor (Sonometrics Inc., Canada) was inserted into the dogs' tibial muscle (m. tibialis cranicalis) and data on the length of muscular contraction were obtained. To measure muscular force, we made an s-type force transducer for muscular force measuring as in Fig. 2, referring to Reference [2]. The sensor was attached to the dogs' tibial tendon (m. tibialis cranicalis tendon) and electric stimulation was applied using Functional Electrical Stimulation (Medel GmbH Inc., Germany) and, in the state, the dogs' ankle joint was made to do isokinetic dorsiflexion exercise using an isokinetic machine (Isosport Inc., Australia) and the muscular force of the tibial muscle was measured.

Next, we extracted tibial muscle and tibial tendon, and experimented on the passive force of the tibial muscle according to the length of the muscle and the stretch of the tibial tendon using a universal testing machine (Kyungsung Testing Machine Co., Ltd., Korea).

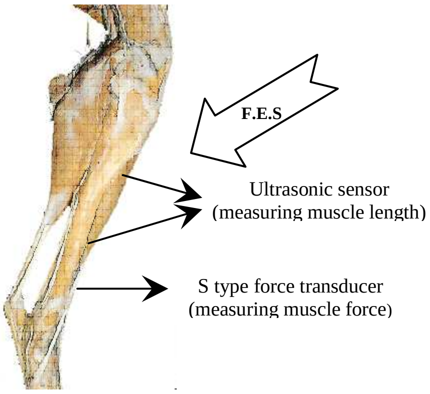

Figure 1. Experiment outline

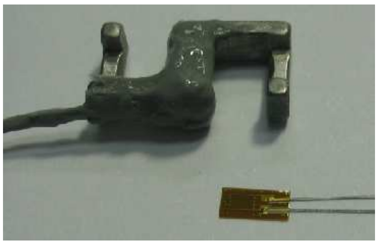

Figure 2. S-type force transducer

B. *Kinetic and physical characteristics of muscle and tendon*

In Fig. 3, when the dog's ankle joint was made to do isokinetic flexion exercise at 30 rad/sec, the change in the length of the tibial muscle was as in (a) and the change in the muscular force was as in (b). (c) shows the tension of the tibial tendon and (d) shows characteristics according to the passive force of the tibial muscle. In this study, we made kinetic analysis using the function between muscle length - muscle force, the function of muscle resting tension and the function of tendon resting tension.

III. TRANSFEMORAL AMPUTEE MODELLING

A. *Subjects*

In this research, we performed modeling by quantifying the size, the length and the weight of the femur and the pelvis in a transfemoral amputee who was 64.7kg heavy, 171.9 cm tall and 24.2 years old, and a third of whose femur was amputated [3], [4].

B. *Myoplasty modelling*

Based on clinicians' advice and myoplasty, which is one of surgical operation methods, we completed a 3-dimensional computer kinetic analysis model as in Fig. 3. Myoplasty cuts flaps and sutures them to the lower stump of the amputated femur. Because it sutures cut femoral muscle and fascia together, it is reported to be outstanding in muscle stability. For the modeling of femoral stump in myoplasty, we defined the anterior muscle group and the posterior muscle group on the horizontal plane of the femur into four steps as in Fig. 4. To the first and most anterior constraint was bound and to the second constraint was bound adductor magnus. To the third constraint were bound semimembranosus and short head of biceps femoris, and lastly to the fourth constraint were bound rectus femoris, sartorius, gracilis, semitendinosus, long head of biceps femoris, and tensor fasciae latae. To apply the four groups to the 3-dimensional model, we applied the four constraints to the end of the femoral stump. Considering the characteristics of myoplasty, in order to express the motion of muscles on the femoral stump according to flexion, extension, abduction and adduction, we formed a virtual rigid body, the mass and mass moment of inertia which are 0, and completed the model through examining the condition of muscles remaining on the cut part through MRI.

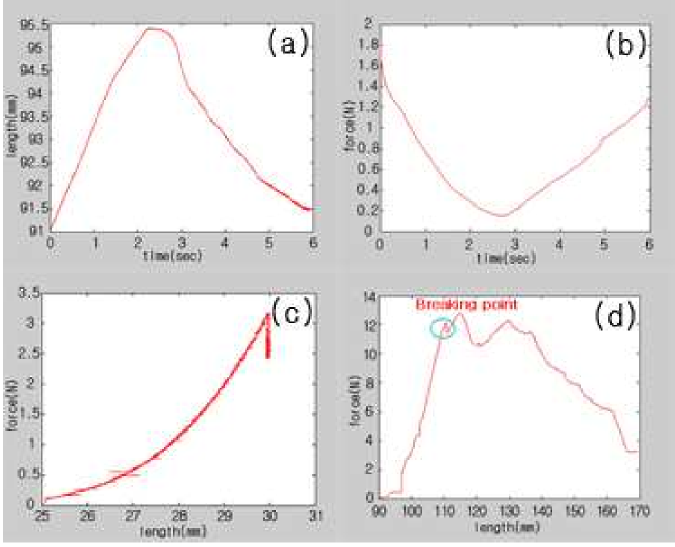

Figure 3. The characteristics of tibial muscle and tibial tendon: (a) change in the length of tibial muscle, (b) change in the force of tibial muscle, (c) tension of tibial tendon, (d) passive force of tibial muscle

Concerning the motion of stump in myoplasty, we measured the motion of muscles on the terminal part of the femur in actual transfemoral amputees' isokinetic flexion, extension, abduction and adduction exercise. In addition, to express the motion in 3-dimensional computer graphics, we formulated a virtual rigid body, the weight and mass moment of inertia which were 0. To secure the range of motion of the stump obtained in the next experiment, we completed a more precise model by assigning the value of function in inverse proportion to coxal articulation angle.

The myoplasty model has the problem that muscles pass through the bone depending on the excessive angle of flexion, extension, abduction and adduction exercise. This can be a problem in analyzing passive force. To solve the problem,

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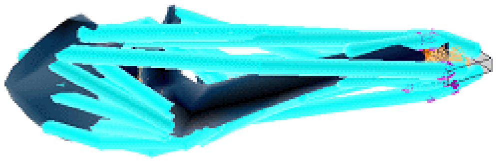

Figure 4. Transfemoral amputee model treated by myoplasty method

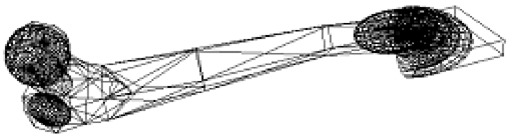

Figure 5. Constraint wrap object in femur

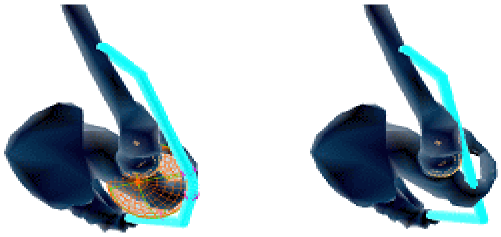

Figure 6. Constraint wrap object in pelvis

constraints (warp) were added to pelvis and ischial tuberosity as well as fovea of head, neck and greater trochanter in the femur as in Fig. 5 and 6.

C. Myodesis modelling

Based on clinicians' advice and surgical operation methods, we completed the model of myodesis by arranging cut muscles on the stump of an amputated femur as in Fig. 7.

Myodesis is an operation method that fixes cut femoral muscles to the bone. Compared to myoplasty, it cuts away a large part of the femur, so it is reported to have relatively fewer times of operation than myoplasty.

To prevent muscles from passing through the bone depending on the range of flexion, extension, abduction and adduction exercise, we gave the same constraints as those in the myoplasty method. Lastly, we formed a virtual rigid body on the end of the femoral stump, and fixed muscles from femoral amputation. In addition, as in the myoplasty model, constraints were given to femur and pelvis for accurate kinetic analysis of passive force.

To apply accurate muscle - tendon length ratio in myoplasty transfemoral amputees and myodesis transfemoral amputees, we calculated muscle length based on muscle – tendon length defined in myoplasty using SIMM at the initial angle of coxal articulation flexion exercise. Then, we calculated difference in the terminal part of muscle between the myoplasty method and the myodesis method, and applied muscle – tendon length to muscles forming the myodesis model [5].

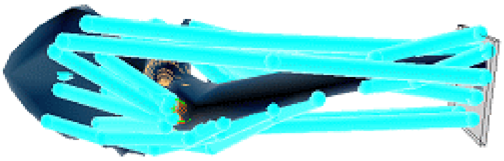

Figure 7. Tranfemoral amputee model treated by myodesis method

In case of stump in the myodesis method, to express muscles fixed and sutured to the femur using seams in 3-dimensional computer graphics, we fixed a virtual rigid body, the weight and inertia moment of which were 0, onto the terminal part of the femur vertically. Then, we completed the model by attaching muscles to the formulated virtual rigid body.

D. Transfemoral amputee kinetic analysis

Before the kinetic analysis of the transfemoral amputee model, we obtained data about the actual length of femur according to transfemoral amputees' height and weight. Then, the mass, the center of mass and the mass moment of inertia were calculated [6]. In this research, we included all muscles that form transfemoral amputees' coxal articulation, and made kinetic analysis by investigating the prime movers of flexion and extension exercise considering isokinetic flexion and extension exercise and calculating the muscular activation for these prime movers using linear differential equations. For musculoskeletal kinetic analysis, we performed modeling using SIMM (ver. 4.1, Musculographics Inc., USA) by quantifying transfemoral amputees who received myoplasty and those who received myodesis. Next, we formulated exercise equations for the kinetic analysis using SD/FAST (B2.8 Symbolic Dynamics, USA), and made forward dynamic analysis using Dynamic Pipeline (Musculographics Inc., USA). We implemented the state of isokinetic exercise by giving the motions of flexion, extension, abduction, adduction at a constant angular velocity with the maximum activation of coxal articulation prime movers forming the myoplasty model and the myodesis model, and performed kinetic analysis of each musculoskeletal model. In order to produce the maximum moment as large as actual experiment values obtained through literature review, we assigned constant angular velocity of 60rad/sec. For the muscle characteristic of the models, we used the kinetic characteristic experimented previously with the tibial muscle of dogs in situ and in vivo. Reported prime movers in the flexion exercise of oxal articulation include iliopsoas, tensor fasciae latae, sartorius, rectus femoris, adductor longus, pectineus, adductor brevis, gracilis and gluteus minimus (anterior fiber) [7]. Muscles cut in femoral amputation are tensor fasciae latae, sartorius, rectus femoris, adductor longus and gracilis. For these muscles, the optimal fiber length and tendon slack length were calculated and applied in consideration of pennation angle according to the length of the amputated femur. In addition, the physiological cross section of transfemoral amputees' muscle was compared with that of normal persons' femur using MRI, and the maximum muscular force of each muscle was defined and applied.

Before the kinetic analysis of transfemoral amputees' flexion exercise, we investigated the range of transfemoral amputees' flexion exercise based on the range of normal persons' flexion exercise with their knee joint fully extended. In addition, we investigated the range of normal persons' flexion exercise with their knee joint fully bent [8]. Next, based on data in literature, we assigned an appropriate range of motion to the transfemoral amputee model and applied 1 degree of freedom by fixing the motion of abduction, adduction, external rotation and internal rotation in consideration of flexion and extension exercise [9],[10]. In coxal articulation extension exercise, prime movers include gluteus maximus, long head of biceps femoris, semitendinosus, semimembranosus, adductor magnus (occipital) and gluteus medius (posterior fiber) and, among these, long head of biceps femoris, semitendinosus and semimembranosus are affected by femoral amputation, for which we calculated and applied adequate pennation angle, optimal fiber length, tendon slack length and maximum muscular force. Kinetic analysis for isokinetic coxal articulation extension exercise was made after applying the range of coxal articulation motion to each model based on the results of previous isokinetic coxal articulation flexion exercise. When coxal articulation does abduction exercise, prime movers are sartorius, tensor fasciae latae, piriformis, gluteus medius and gluteus minimus. Among them, sartorius and tensor fasciae latae are affected by femoral amputation. Thus, for the two muscles, we calculated and applied adequate pennation angle, optimal fiber length, tendon slack length and maximum muscular force.

We defined the radius of exercise in the transfemoral amputee models based on data in literature, and applied 1 degree of freedom by fixing the motion of abduction, adduction, external rotation and internal rotation in consideration of the special environment of abduction and adduction exercise. In coxal articulation adduction exercise, prime movers are adductor longus, adductor brevis, pectineus, gracilis, frontal and occipital adductor magnus, long head of biceps femoris, quadriceps femoris and the lower fiber of gluteus maximus. Among them, lower fiber of the lower fiber of gluteus maximus and gracilis are damaged by femoral amputation. Thus, for the two muscles, we calculated and applied adequate pennation angle, optimal fiber length, tendon slack length and maximum muscular force. Kinetic analysis for isokinetic coxal articulation adduction exercise was made after applying the range of coxal articulation motion to each model based on the results of previous isokinetic coxal articulation abduction exercise.

IV. RESULT

A. The moment of coxal articulation in isokinetic flexion exercise

The present study made kinetic analysis of the characteristics of all muscles composing transfemoral amputees' coxal articulation in order to examine passive force between a myoplasty model and a myodesis model. To examine the scale of passive force, we applied the flexion angle of coxal articulation exercise investigated in relevant literature to the kinetic analysis. According to the result of the kinetic analysis as shown in Fig. 7, the maximum flexion angle in the myoplasty model was 77° and the maximum flexion angle in the myoplasty model was 62°. This suggests that the myoplasty model has a larger range of motion for flexion exercise than the myodesis model.

B. The moment of coxal articulation in isokinetic extension exercise

We made kinetic analysis of isokinetic extension exercise of coxal articulation in the myoplasty model and the myodesis model after applying an adequate range of coxal articulation motion to each model using the result of analyzing the isokinetic flexion exercise of coxal articulation. The range of motion in the myoplasty model was set at 72°~-20° and that in the myodesis model at 66°~-20°. According to the result of the kinetic analysis as shown in Fig. 8, the myodesis model was somewhat better than the myoplasty model in the maximum moment of coxal articulation.

C. The moment of coxal articulation in isokinetic abduction exercise

In order to consider the passive force between the myoplasty model and the myodesis model, we made kinetic analysis of the characteristics of all muscles composing transfemoral amputees' coxal articulation. According to the result of the kinetic analysis as shown in Fig. 9, the moment of abduction was higher in the myoplasty model than in the myodesis model. In addition, the range of motion was 24° in the myodesis model while 31° in the myoplasty model, so the myoplasty model had a larger range of motion.

D. The moment of coxal articulation in isokinetic adduction exercise

We made kinetic analysis of isokinetic adduction exercise of coxal articulation in the myoplasty model and the myodesis model after applying an adequate range of coxal articulation motion to each model using the result of analyzing the isokinetic abduction exercise of coxal articulation. Referring to the range of isokinetic abduction exercise, the range of motion in the myoplasty model was set at -32°~25° and that in the myodesis model at -24°~25°. According to the result of the kinetic analysis as shown in Fig. 10, the myodesis model was somewhat better than the myoplasty model in the maximum moment of coxal articulation. This is because the lower fiber of the primer movers, namely, gracilis and adductor brevis in the remaining damaged muscles in the myoplasty model is longer than the remaining muscles in the myodesis model, so it can produce a higher muscular force.

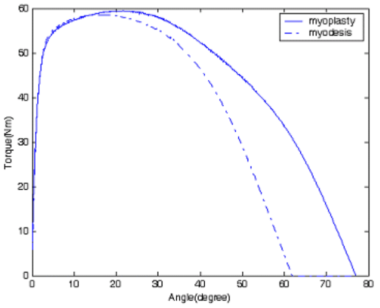

Figure 8. Comparison of flexion moment between myoplasty and myodesis

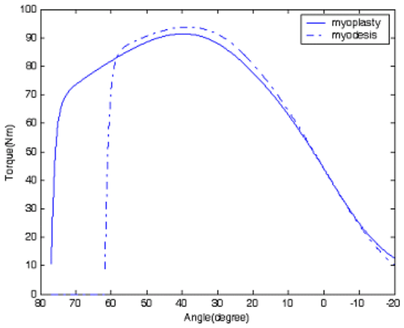

Figure 9. Comparison of extension moment between myoplasty and myodesis

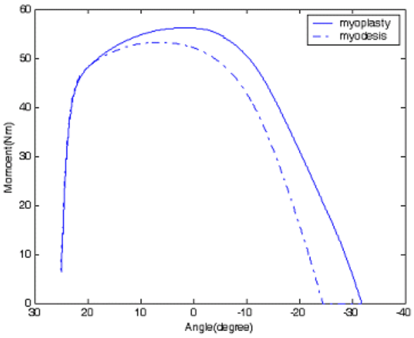

Figure 10. Comparison of abduction moment between myoplasty and myodesis

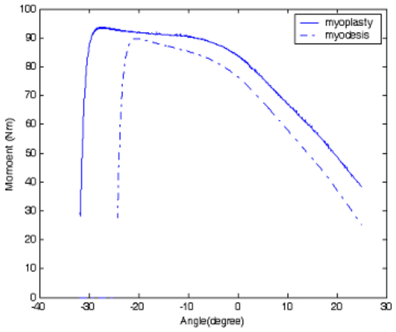

Figure 11. Comparison of adduction moment between myoplasty and myodesis

V. CONCLUSIONS

The present study implemented 3-dimensional models of transfemoral amputees who had myoplasty and myodesis, and performed experiment on muscle length – force using the tibial muscle of dogs in vivo and in situ, activating the tibial muscle to the maximum and making the angle joint do isokinetic exercise at different angular velocity. In addition, we induced the passive force of muscle through experimenting upon the tension of muscle and tendon, and compared the kinetic characteristics of flexion, extension, abduction and adduction exercise by applying the muscle parameters of the transfemoral amputee models of different operation methods. According to the result, the myoplasty model had a larger range of motion and a higher moment of coxal articulation than the myodesis model in isokinetic flexion, abduction and adduction exercise. No significant difference was observed in the moment of isokinetic extension exercise between the two models.

The present study performed kinetic analysis with dividing muscles into prime movers and non-prime movers and giving full activation only to the prime movers. Future research needs to examine the activation of all muscles through each type of exercise

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