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MECHANICAL VERIFICATION OF DYNAMIC MUSCULOSKELETAL MODEL WITH MUSCLE – TENDON COMPLEX AT JUMPING MOTION BY BOND GRAPH

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ABSTRACT
Studies are being conducted to model jumping motion mechanically. Conventional studies have been conducted using only Muscle Tendon Complex (MTC), which consists of muscle and tendon. In this study, in addition to MTC, modeling was carried out considering lower limbs including the foot, ankle joint and bone as one system. In the modeling of the system, the idea of bond graph using not only force but power was considered. So far, studies have generally been done on the idea of using the ankle as a pivot. In this study, this idea was changed to the idea with the toe as the pivot. In modeling, this idea of using bond graph was very effective. Based on this method, modeling study was carried out and the model could be constructed. It confirmed that the results were comparatively agreed with the experimental results, and this model was confirmed that the results could be reproduced.

Keywords: bond graph, muscle-tendon complex, jumping motion, modeling

1. INTRODUCTION

Many studies on behavior of Muscle Tendon Complex (MTC) have been carried out so far. These studies which obtains the behavior by calculation, is examined using the mechanical model (Liber, R.L., et al. 1992) or the mathematical model (Maarten F. et al. 1986). Even in that study, many studies including the MTC have been done regarding jumping motion (Fukashiro, S. S. et al. 2005, Fukashiro, S., et al. 2006). For example, a study has been conducted to obtain the jumping height by simulation from the dynamic model mainly based on the MTC. On the other hand, since the development of the ultrasonography that can measure the length of MTC directly *in vivo*, the muscle fascicle length in the jumping motion has been measured (Fukunaga, T., 2002). Also, the relationship between the tension and the length in muscle and tendon, has been examined from the tension obtained from the floor reaction force. These studies have clarified the mechanism of the MTC (Kaneko 2011, Kawakami, et al. 2002, Kawakami and Fukunaga, 2006). In this study, we have studied to construct the model in order to calculate behavior of tension and length of muscle and tendon in MTC during jumping motion. Unlike the above mentioned method, the entire lower limbs including the MTC was considered as one physical system, and was studied based on mechanical engineering system. At the beginning of the study the mechanical model of MTC alone was constructed, and then the whole system including the ankle joint, the tibia, and the foot was constructed (Suzuki and Oida, 2015, 2016). In this system, it was considered to be important to clarify not only the forces transmission but also the power transmission flow. Modeling with the bond graph was performed based on this idea and the simulation was performed. In the first modeling method, the conventional idea in which the ankle joint was the pivot of the lever is considered. However, the calculated value of the tendon tension force was significantly different from the measured value (Kawakami 2002). Therefore, this idea of using the ankle joint as a pivot was studied in detail again. As a result, modeling method was changed to the new idea that the toe of the foot was the pivot. As a result of reconstructing the modeling, good results were obtained.

According to the literature, Thompson et al. have already reported that the action of the force around the ankle joint operates according to the second lever principle. However, there will be perhaps any questions in this idea after that. Moreover, it will be thought that the theoretical examination of this idea has not been done until now, so we report it in this paper. In addition, a simple experimental model was created, the model was dynamically and computationally verified, and the bond graph advantage was verified. This paper reports the result.

2. METHOD

In this study, we considered the whole lower limbs including the MTC as one mechanical system at the jumping motion. This system is constructed with mechanical components such as masses, springs, lever. This schematic models are represented by the bond graph which is one of the modeling methods of the system (Thoma, J. U. and Suda, N. 1996, Kanopp, D.C. et al. 2006). The analysis method of the bond graph is to describe the schematic models by representing the connection form of the components at first. Next, this schematic models is expressed by the word bond graph according to the power flow. Furthermore, the word bond graph is translated to the true bond graph, and analysis is performed by substituting variables into the model.

2.1. Overall composition of the model

In modeling, the musculoskeletal system of the lower limbs was considered as one system, and this system was composed of the MTC, the foot including ankle joint, tibia and fibula. This system is shown in Figure1. Figure 2 shows a schematic model which is rotated to the left by 90 degree from Figure1. In this model, one end of the MTC connects to the heel of the foot and the other end connects to the knee. Furthermore, the weight and the inertial mass of the body are acted on the knee. The knee is connected to the ankle joint through the tibia and fibula. With regard to the foot, it was assumed to be a rigid flat plate that one end is connected to the MTC with heel and the other end connected to the toe acting on the ground. The measuring plate of the force at the toe is set on the ground.

2.2. Modeling of the MTC

The MTC is an important factor, and it is assumed that the gastrocnemius muscle and soleus muscle in the human body is as one MTC. This MTC has two components, that is, muscle and tendon. According to the Hill-type model as shown in Figure 3, the muscle is composed of elastic element and power input element. On the other hand the tendon is composed of elastic element only. These can be represented by the word bond graph as shown in Figure 4. Furthermore, it is translated to the true bond graph as shown in Figure 5 In this true bond graph, the C element is an elastic element, and the SE element is the input source element that represents the power emitted by the chemical change such as glucide. We explain the input force acting on the human body here. In the mechanical systems, the external forces generally act on the mass from the outside of the mass. On the other hand the input force acted by muscle act inside of the human body. Then the action force and the reaction force for this input act inside of the human body. Therefore the direction of input forces in the bond graph is shown in both side from 0-junction to 1-junction.

2.3. Detail consideration of the model relating to the ankle joint

As before described, the foot is assumed to be a flat rigid plate and that have each named heel, toe and ankle joint. In the initial study, it was considered to be acted by two moments, that was the moment by the toe force and the moment by heel force (the Achilles tendon force), being balanced at the ankle joint so as the pivot. These are shown in Figure 6. In this schematic and the bond graph model, the weight force acting on the ankle joint will be assumed to be ignored. From this assumption, the Achilles tendon force is obtained from the force acting on the "toe", where the I element means the force plate, that is, measuring plate and the ground. So it represents the earth mass, and the TF elements represent the ratio of the length from the ankle joint to the toe and the heel. Using the bond graph of Figure 6, the whole bond graph of the musculoskeletal model system can be represented as shown in Figure 7.

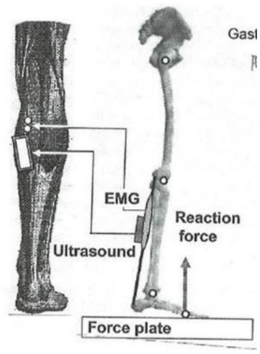


Figure 1 Musculoskeletal of the lower limbs (Fukashiro S. et al. 2006)

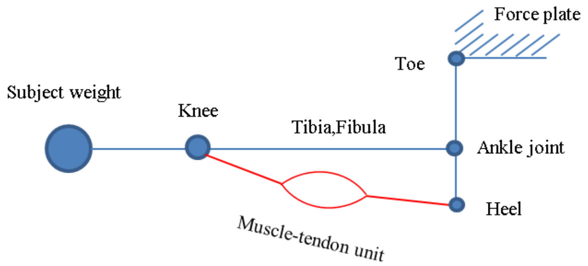


Figure 2 Schematics Musculoskeletal Model

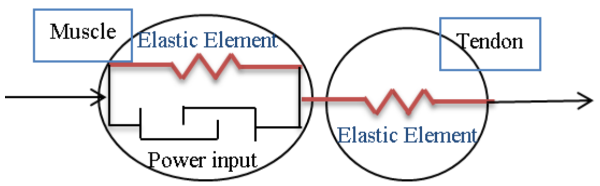


Figure 3 Schematics MTC model

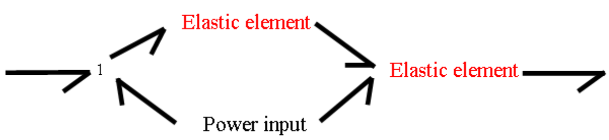


Figure 4 Word Bond Graph of MTC

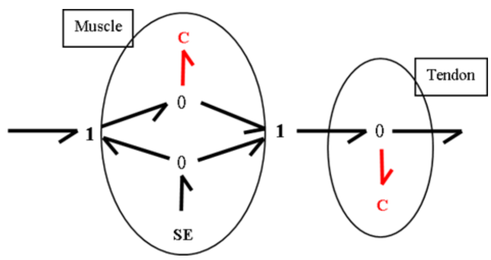


Figure 5 True Bond Graph of MTC

2.4. Comparison of calculated results and experiment value

This simulation results was compared with the experimental value 3081 ± 667 N (Kawakami et al. 2002). The simulation results are shown in Figure 8. The tendon force at the maximum value of the toe force was 350 N, which was about 1 / 8.5 times the experimental value of the tendon force

2.5. Reconsideration of the model relating to the foot and the ankle joint

Therefore, the model was reconsidered as follows. Unlike the conventional idea of sec. 2.3, the new idea that use the toe as the pivot instead of the ankle joint as the pivot, is considered to be a right one. Therefore it is thought that the force acting on the heel and the force acting on the ankle joint respectively act on the toe. As shown in Figure 9, the human weight and so on forces act on the point B (ankle joint), where the length l_1 is A to B. While the tendon force act on the point C (heel), where the length l_2 is A to C.

According to Figure 9, the schematic model and the bond graph model is represented as shown in Figure 10. The whole musculoskeletal system model including new idea is shown as the word bond graph in Figure 11. This word bond graph is translated to the true bond graph as shown in Figure 12.

The input power due to muscle contraction is generated from the SE element. One is transmitted from the heel to the toe by the transfer element TF of length l_2 through the C element of the tendon. The other muscle contraction power is input to the knee. In this knee, the SE element by the body weight and the I element of the inertial mass in the body, are added together and transferred to the ankle joint through the tibia and fibula. These combined powers are transmitted from the ankle joint to the toe by the transfer element TF of length l_1. Both powers

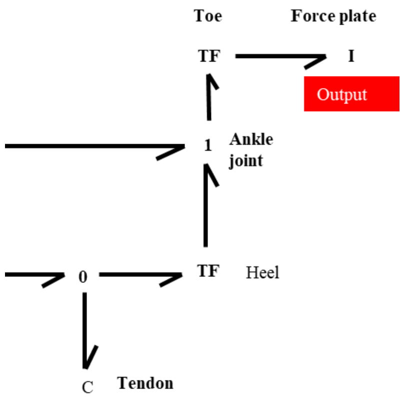


Figure 6 True Bond Graph where the Achilles Tendon Force Moment and the Toe Force Moment are balanced

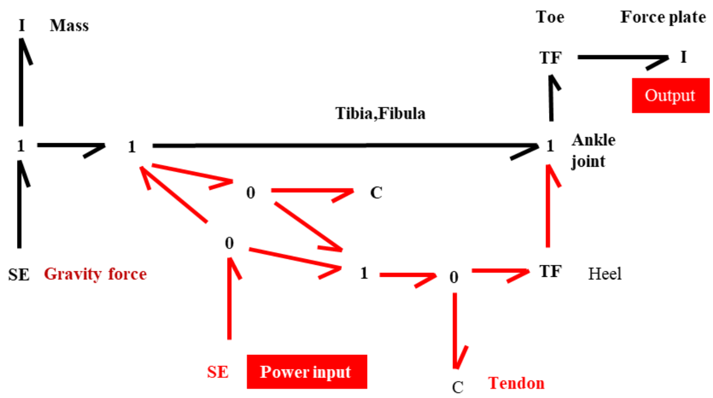


Figure 7 True Bond Graph of musculoskeletal model

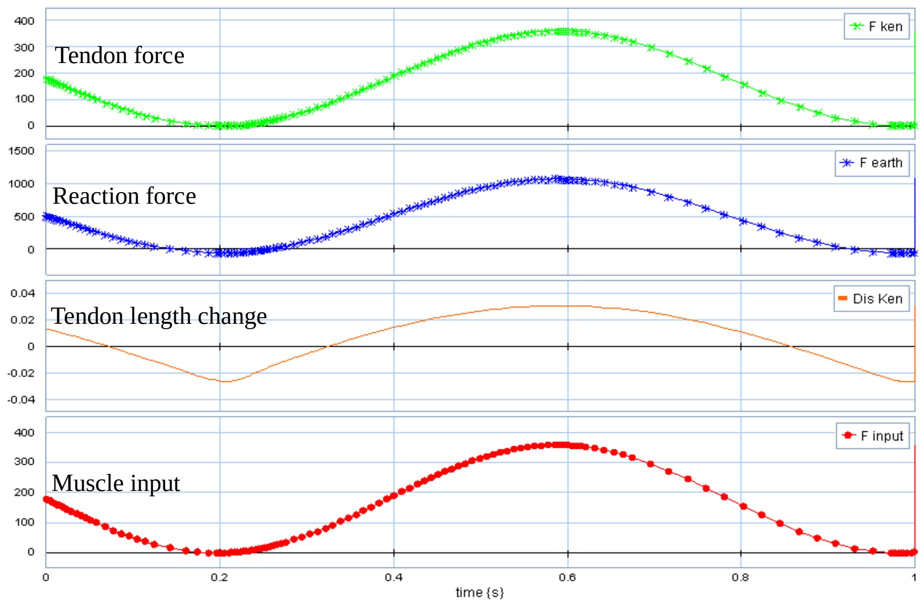


Figure 8 The Simulation Results

generated by MTC are combined and act on the toe force plate (measurement plate) to become an output power. In translating this word bond graph to the true bond graph in Figure 12, we add the direction of power flow. According to the mechanical bond graph construction procedure (System Dynamics: Karnopp et al., 2006), the downward speed of 1-junction (right direction in Figure 2) is defined as the positive direction in the direction of power flow. The spring is therefore positive in the compression direction.

2.6. Setting of calculation conditions

The following approximate conditions were assumed to carry out the calculation. In order to compare with the experimental results of Kawakami et al. (Figure 13), the output characteristics was the toe force (floor reaction force in Figure 13) acting on the force plate. The calculation was performed by approximately setting the following condition. That is, if the output characteristic of the experimental data (Kawakami, 2002) approximately are assumed to be a sine curve, then the muscle contraction force (that is input force) is also to be a sine curve. The sine curve of this muscle contraction force F is shown in Equation (1).

$$F = C + A\sin(\omega t) \qquad (1)$$

where the amplitude A, the frequency ω and the constant C were identified to fit the experimental data These numerical values are A = -1300 N, ω = 5.5 rad / s, and C = -1300 N. Moreover the characteristics of the tendon stiffness were set on as following conditions. Based on the experimental results of Fukunaga as shown in Figure 14 (Fukunaga, 2002), it was assumed that the tendon tension was proportional to the square of the tendon length, and the stiffness C of the tendon was set. Furthermore, other element coefficients were set as shown in Table 1. From the experimental conditions of Kawakami et al., the lengths, l_1 and l_2 from the toe are 0.15 m and 0.2 m, respectively. Based on these lengths, coefficients for TF are 1 / 0.15 = 6.7 and 1 / 0.2 = 5.

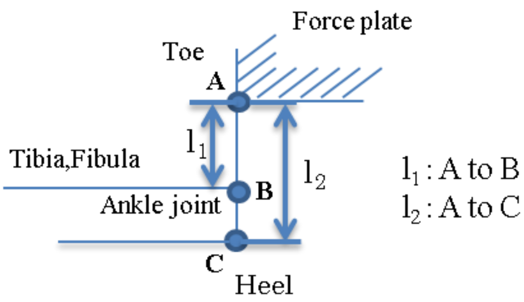


Figure 9 Detailed model around the ankle joint

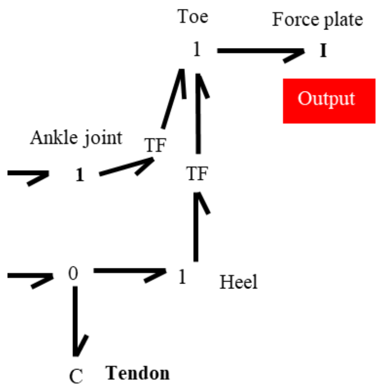


Figure 10 True Bond Graph around the ankle joint

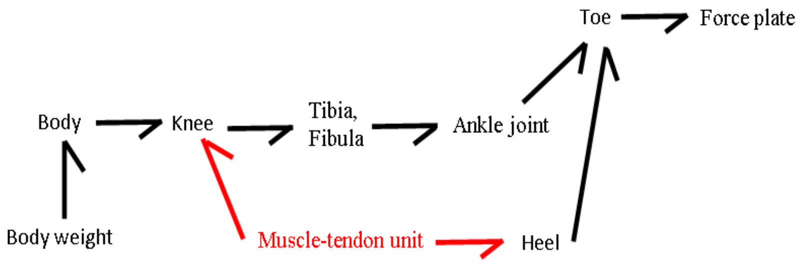


Figure 11 Word Bond Graph of Musculoskeletal Model

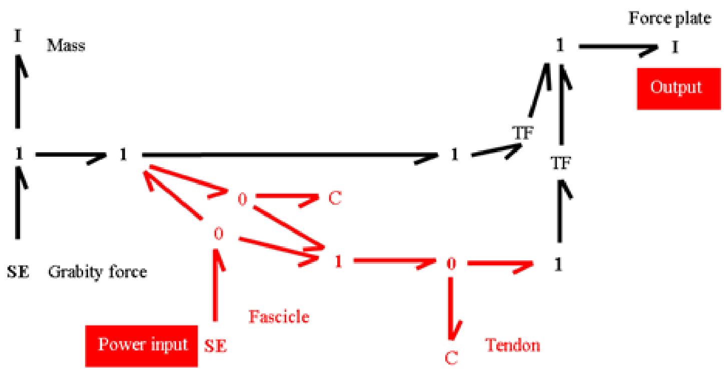


Figure 12 True Bond Graph of Musculoskeletal Model

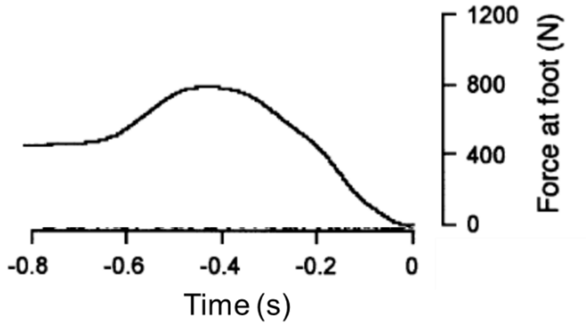


Figure 13 Force at foot (Kawakami et al., 2002)

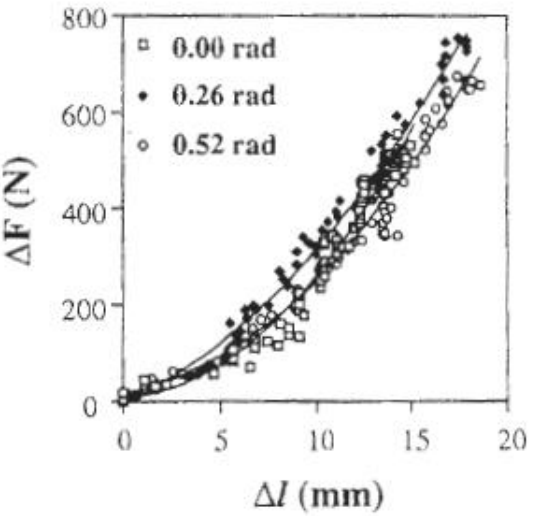


Figure 14 Relationship between tension and length of tendon in Fukashiro S. et al. Experiment (Fukuashiro, S. et al. 1995)

Table 1 Input value of element coefficient

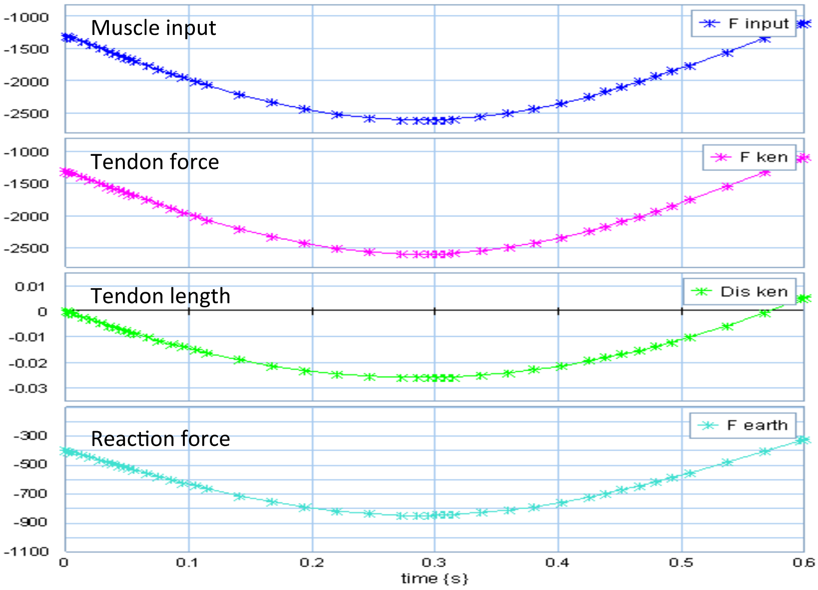
TF（Between point A and B）	6.7
TF（Between point A and C）	5.0
Se [N]	400
I (Force plate) [kg]	10^8
I (Weight) [kg]	40
C (Muscle) [m / N]	0.1
C (Tendon) [m / N]	3.0×10^{-6}

3. COMPARISON OF CALCULATION RESULTS VS. EXPERIMENTAL RESULTS AND CONSIDERATION ENERAL GUIDELINES

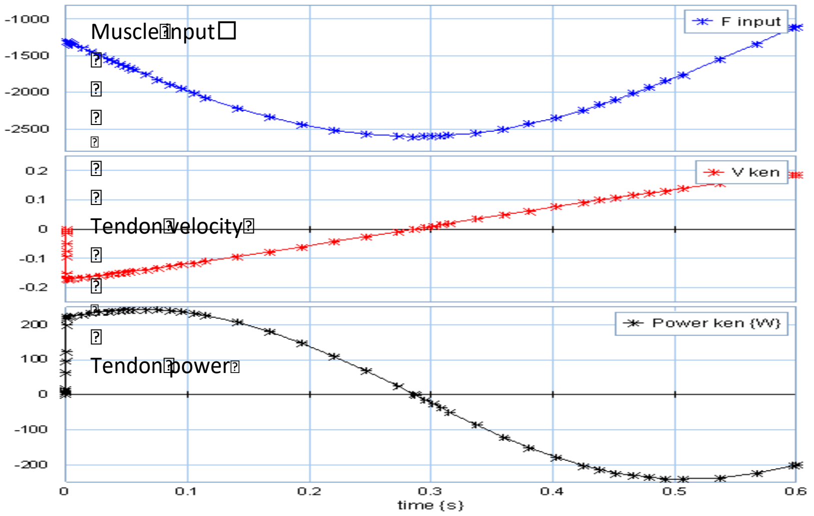
At first, the muscle tension is generally compressive force, then the input tension is negative (-). However in this paper, the input tension is set positive in the section 2: method.

The simulation was performed using modeling and simulation software (20-sim) where input specification was muscle contraction force (-) and major other specification were shown in Table 1. As a result, tendon force, tendon length and reaction force were obtained by continuous characteristics in time as shown in Figure 15 (a). The maximum tendon force (in this simulation result) was 2600 N. The experimental measure & estimated result was 3081 ±667 N. About the maximum tendon length, the calculated length was 25.8 mm, however the experimental measure & estimated result was about 30 mm, From these results, difference between the maximum force and length showed the same tendency for both the calculated and experimental results. From these results, this Musculoskeletal Model is considered to be almost valid.

In the paper of Kawakami et al. 2002, tendon elongation speed and tendon power have been obtained as estimated some points calculated from experimental measurements. However by use of this model, tendon elongation speed and tendon power could be obtained as continuous lines of the time function as shown in Figure 15 (b). Focusing on the speed and power that change with time, the speed reached its maximum immediately after the input force supply, then gradually decreased, and changed to speed in the negative direction. In addition, the tendon power was accumulated with positive energy in the first half. When the extension speed became negative, the power became negative, and it was possible to observe the progress of the stored energy being released. In this way, we were able to estimate characteristics of tendon speed and consumption energy that were difficult to estimate using conventional experiments alone. It will be considered that this estimation by use of this model has roughly established the fundamental foundation that enables quantitative prediction of the required characteristics in the future study of jumping motion. However, it cannot be said that the response was sufficiently obtained with respect to the experimental results of Kawakami et al. 2002 in which the muscle elongation changes in conjunction with the tendon. It is presumed that this is because the tension-extension properties of the muscle are not expressed as a function of simple displacement. Also, the angles of the ankle joints cannot be modeled. These are future issues. The operation principle of ankle joint in the lower limbs is described in section 1: introduction by Thompson et al. according to the second lever principle. This principle will be considered to have been proved by theoretical consideration in this paper.



(a)



(b)

Figure 15 Calculation Results of Tendon Characteristics

4. CONCLUSION

Dynamic mechanical model was constructed for the lower limbs of the human body including the MTU, and simulation calculations were performed by bond graphs. As a result, the tendon extension length and tension force in the MTU (muscle-tendon unit) at the jumping motion could almost be reproduced same as the experimental values (Kawakami et al. 2002). On the other hand, instead of that the tendon extension speed and power have been estimated, continuous characteristics of them were made possible by the graph. It was possible to see from the graph how the extension speed and power of the tendon change in extension and contraction at the jumping motion.

An experimental model that reproduces the movement of the human body was created and the dynamic model will be dynamically verified from now on.

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