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Using a Musculoskeletal Mathematical Model to Analyze Fatigue of the Muscles in the Lower Limbs during Different Motions

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Abstract: Under the aim of finding effective rehabilitation solutions, the difference between the extents of fatigue of each muscle used in different motions are compared. Previous research suggested methods for estimating muscle torque and muscle tension on the basis of a musculoskeletal model. As a result, it has become possible to quantitatively identify the extent of fatigue in each muscle during motion. Therefore, to evaluate muscle fatigue more quantitatively, driving power and angular momentum are focused on. Based on the driving torque of joints and the muscle torque calculated by using a three-dimensional musculoskeletal model, a method for calculating the driving power of joints and the angular momentum of a muscle is proposed. This method is applied to analysis of different motions. Moreover, fatigue of muscles is quantitatively analyzed on the basis of driving power and angular momentum.

Keywords: Angular momentum, driving power, driving torque, musculoskeletal model.

1 Introduction

In recent years in Japan, the proportion of elderly people (i.e. those aged 65 years or older) of the total population reached 26.0%. This trend is presumed to be due to an extension of life expectancy. In the investigation by the cabinet office of Japan in 2013, for example, average life expectancies for men and women were 80.21 and 86.61 years, respectively. On the other hand, In the investigation by ministry of health of Japan (2012), a "healthy" life expectancy (namely, one during which long-term care, etc. is not required) is 71.19 years for men and 74.21 years for women. As for the reason nursing care is required, 35.3% of cases are accounted for by motion disorders due to arthritic diseases as well as bone fractures and falls. Ellis [Ellis (1998)] reported that through medical diagnosis and advice about bodily functions as well as guidance concerning environmental improvement, serious injuries from falls were reduced by half. Hayashi [Hayashi (2006)] reported that fracture of the femoral neck can be reduced by almost 90% by fitting a protector and treatment with osteoporosis drugs. It is clear from these studies that improving motor functions of elderly people is an effective way of extending their healthy life expectancy.

Currently, by Hayashi [Hayashi (2006)] and Fujimoto [Fujimoto (2008)], as for the level

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of fatigue concerning body motion, most studies are based on the level of muscle activity measured by electromyograph. In addition, the level of fatigue of each muscle involved in a motion can be quantified by calculating muscle torque and level of muscle activity on the basis of a musculoskeletal model. On the other hand, Tsuyuki et al. [Tsuyuki and Misaji (2015)] suggested a method considering motion more quantitatively; namely, they proposed to calculate angular momentum in terms of driving power and momentum exerted around a joint. Driving power is considered to be a value for evaluating actual kinematic performance around a joint motion as energy per unit of time, and angular momentum exerted by each muscle expresses the intensity of motion of that muscle.

In light of the above-mentioned studies, in the present study, extension and flection motions of a leg during the initial motion of standing-up/sitting-down motions (which are essential motions for an elderly person to remain independent) are analyzed. In particular, to consider different extents of fatigue in each muscle, driving torques generated around the knee joint and torque exerted by each muscle during the said motions are used in the analysis in the conventional manner. Next, driving power and angular momentum exerted by each joint during the motion are used in the analysis. From the analysis results, it is concluded that kinematic performance of a joint during motion and the burden on each muscle can be considered in a more quantitative manner in comparison to the conventional method.

2 Analysis method

2.1 Musculoskeletal mathematical model

A three-dimensional musculoskeletal mathematical model of the lower limbs, namely, a musculotendon complex with muscle fibers and tendinous tissue, is shown in Fig. 1.

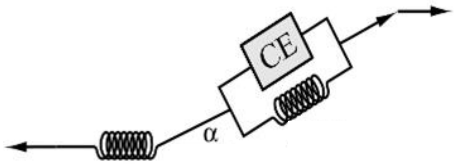

Figure 1: Hill-type model

In this model, muscle is taken as a “contractile element” (CE), which actively exerts a force by muscle contraction, and tendon is taken as an “elastic element” (EE), which exerts a force by muscle contraction. EE is an elastic body, which is passively extended. And α is the “bipennate muscle angle”, namely, the angle at which with the muscle is attached to the tendon.

As for the muscle model used in this study, the model suggested by Zajac [Zajac (1989)] -which is based on the “Hill-type model” suggested by HILL [HILL (1938)]-was used. Joint torque and degree of muscle activity were analyzed by SIMM [Delp and Loan (2007)] (software for motion analysis) on the basis of the musculoskeletal mathematical model shown in Fig. 2.

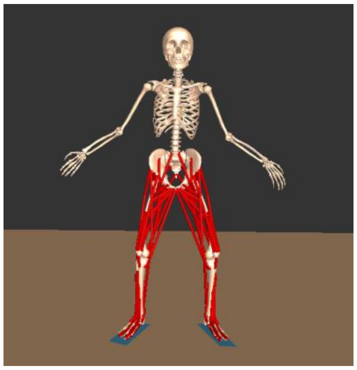

Figure 2: Musculoskeletal mathematical model

2.2 Calculation of muscle activity on the basis of a 3D musculoskeletal model

The procedure for calculating activity level of each muscle is explained as follows. First, joint position and posture at the time of the motion are input. Each joint angle is then calculated on the basis of inverse kinematics. Next, joint torque generated around each joint is calculated on the basis of inverse dynamics. Finally, level of muscle activity of each muscle is calculated from joint torque.

Muscle activity level α_i is obtained from Eq. (1). The condition for obtaining α_i is that which minimizes the square sum of the muscle-activity levels of each muscle, namely, $a_i(0 \leq a \leq 1)$ [Crowninshield and Brand (1981); Kaufman, An, Litchy et al. (1991)].

$$\sum_{i=1}^{n}\{ a_i \cdot f(F_0^i, l_i, v_i)\} r_{i,j} = M_j^* \tag{1}$$

Here, under the assumption of a musculoskeletal model, function $f(F_0^i, l_i, v_i)$ generally represents the relationships between power, length, and velocity [Zajac (1989)], where F_0^i is maximum isometric contraction power of the i th muscle, l_i is the length of the i th muscle, and v_i is velocity of shortening of the i th muscle.

M_j^* is driving torque around the j th joint (calculated by using inverse dynamics obtained from motion-capture posture data); $r_{i,j}$ is the moment-arm length of the i th muscle of the j th joint and is given by Eq. (2), where l_i is the length of the i th muscle i , and θ_j is the angle between one bone and another bone in the knee joint.

$$r_{i,j} = \frac{dl_i}{d\theta_j} \tag{2}$$

2.3 Calculation of angular momentum of each muscle

The method used for calculating angular momentum of each muscle around the knee joint is described as follows. The muscles included in the calculation are the semimembranosus, semitendinosus, biceps femoris (long head), biceps femoris (shot head), rectus femoris, vastus medialis, vastus intermedius, vastus lateralis, and gastrocnemius (medialis and lateralis).

First, muscle-activity level a_i of the i th muscle, maximum isometric contraction power F_0^i of the i th muscle, and moment-arm length $r_{i,j}$ of the i th muscle around the j th joint are substituted into Eq. (3). Driving torque $M_{i,j}$ by each muscle around the joint of the target joint is then calculated.

$$M_{i,j} = a_i \cdot f(F_0^i, l_i, v_i) \cdot r_{i,j} \tag{3}$$

Next, an equation of motion, Eq. (4), is obtained by using $M_{i,j}$ (driving torque around the j th joint shown in Fig. 3) given by Eq. (3).

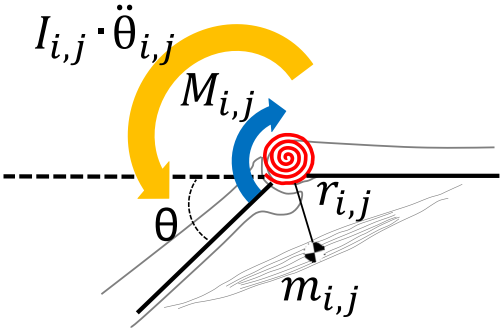

Figure 3: Driving torque around the joint

$$I_{i,j} \cdot \ddot{\theta}_{i,j} = M_{i,j} \tag{4}$$

Here, $I_{i,j}$ is moment of inertia of the i th muscle around the j th joint, and $\ddot{\theta}_{i,j}$ is angular acceleration of the i th muscle around the j th joint. In this motion, $I_{i,j}$ varies with joint extension and flexural motion. Here, $I_{i,j}$ is defined as a constant.

Eq. (5) is then obtained by determining the definite integrals of both sides of Eq. (4) over a cycle (from t_1 to t_2) of the motion. Eq. (6) (which expresses angular momentum of the i th muscle around the j th joint) is obtained by calculating the left side of Eq. (5).

$$I_{i,j} \int_{t_1}^{t_2} \ddot{\theta}_{i,j} dt = \int_{t_1}^{t_2} M_{i,j} dt \tag{5}$$

$$I_{i,j} \cdot \dot{\theta}(t_2) - I_{i,j} \cdot \dot{\theta}(t_1) = \int_{t_1}^{t_2} M_{i,j} dt \tag{6}$$

2.4 Calculation of driving power of each joint

First, definite-integral values of $M_j(\theta)$ in a cycle of the motion from times t_1 to t_2 (during which joint angle changes from θ_1 to θ_2) are obtained. Driving power P_j of the muscles around the joint can then be calculated from Eq. (7) using those values as follows.

$$P_j = \frac{1}{t_2 - t_1}\int_{\theta_1(t_1)}^{\theta_2(t_2)} M_j(\theta)d\theta \tag{7}$$

3 Experimentation

3.1 Creation of rigid-link model (skeletal model)

First, reflection markers are attached to a test subject (as shown in Fig. 4). Next, still images of the subject are recorded by six motion-capture cameras (as shown in Fig. 5), and 3D positional coordinates are obtained from the reflection markers. Finally, the central position of the joint and segment length is determined from the obtained positional coordinates. Accordingly, a rigid-body-link model of the subject is created by calculating the posture of the segment the obtained rigid-body-link model of the subject is shown in Fig. 6.

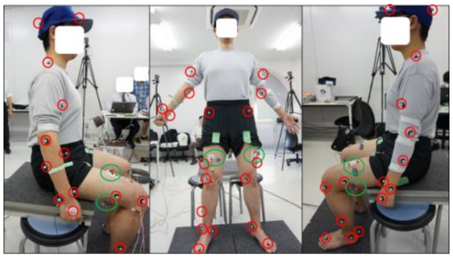

Figure 4: Position of reflection markers

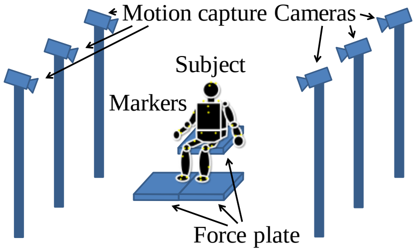

Figure 5: Outline of measurement set up

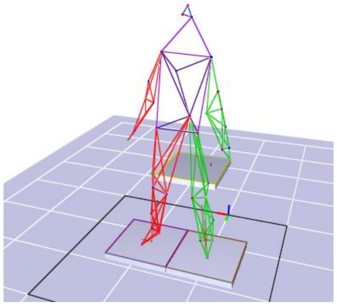

Figure 6: Rigid-body-link model

3.2 Measurement of motion data

During the measurement, the subject moved in the following sequences of two motions: (1) extension and flection of the right leg three times; extension and flection of the left leg three times; (2) standing up and sitting down three times. The extension and flection motions (left) and standing-up/sitting-down motions (right) are shown in Fig. 7.

Figure 7: Extension and flection motion (left) and standing-up/sitting-down motion (right)

3.3 Measurement of muscle-activity level

Telemetry electromyography (EMG) was used to measure active electric potentials from muscular contractions during the motion measurement. The EMG was attached to the rectus femoris muscle and biceps femoris (long head) of both legs (see Fig. 4). Level of muscle activity of each muscle during the motions could thereby be measured.

3.4 Measurement of maximum muscle strength

To measure the extent to which the muscles are activated in response to maximum level of muscular activity, maximum strength of the subject (at the same places at which the EMG was attached) was measured.

4 Analysis result

The analysis method described in Section 2 was used to calculate driving torque and power around of the knee joint as well as angular momentum and driving torque of each muscle around the knee joint, and the influences of the differences between the motion of the joint during the extension and flection motions and during the standing-up/sitting-down motions were compared.

4.1 Validation of accuracy of 3D musculoskeletal model

To verify the accuracy of the constructed 3D musculoskeletal model, the total of each muscle moment around the knee joint is compared with the torque of the knee joint calculated by means of inverse dynamics and motion-capture cameras.

Torques of the knee joint during the extension and flection motions are shown in Fig. 8 and 9, and the torques of the knee joint during the standing-up/sitting-down motions are shown in Fig. 10 and 11. The blue line in each figure represents the torque exerted on the knee joint calculated by inverse dynamics, and the red dotted line represents the total of each muscle moment around the knee joint.

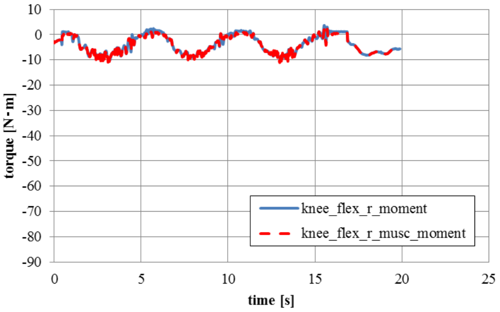

Figure 8: Torques exerted on right knee joint during extension and flection motion

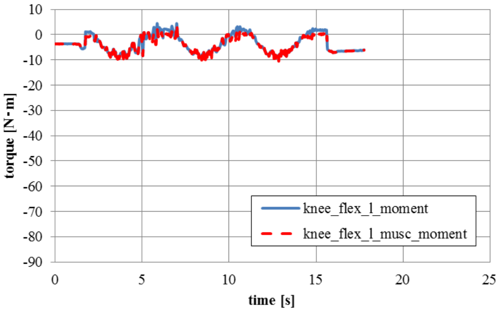

Figure 9: Torques exerted on left knee joint during extension and flection motion

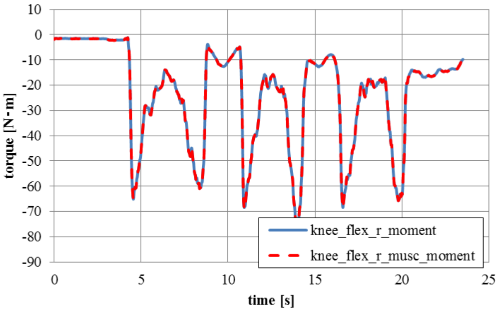

Figure 10: Torques exerted on right knee joint during standing-sitting motion

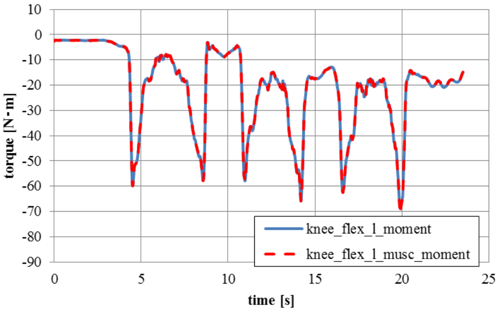

Figure 11: Torques exerted on left knee joint during standing-sitting motion

It is clear from Fig. 8-11 that the drive torque exerted on the knee joint (blue lines) and the total of the drive torques of each muscle (red lines) are in good agreement during both the extension and flection motions and the standing-up/sitting-down motions. In other words, the musculoskeletal model gives results that are fairly consistent with the results of inverse dynamics analysis; therefore, it is verified that the constructed model has sufficient accuracy.

4.2 Joint Torque

Driving torques exerted around the knee joint were calculated by using inverse dynamics with the motion-capture data. The extension motion was compared with the standing-up motion and the flection motion was compared with the sitting motion in terms of those driving torques.

Driving torque exerted around the right knee joint during the extension (red line) and flection (orange line) motions and the standing-up (purple) and sitting-down (blue) motions are shown in Fig. 12.

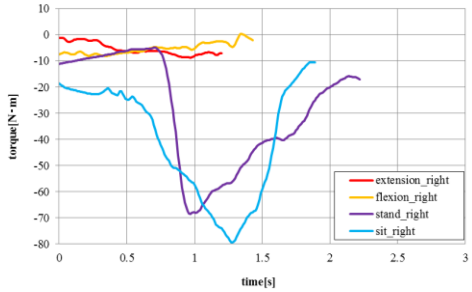

Figure 12: Driving torque exerted on right knee joint during extension and flection motions and standing-up/sitting-down motions

The corresponding results for the left knee joint during the same motions are shown in Fig. 13.

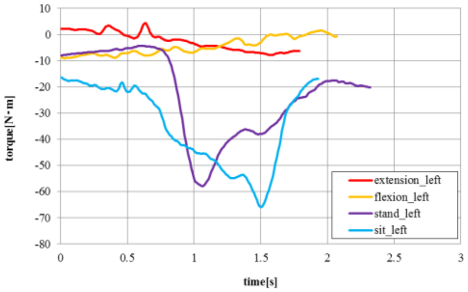

Figure 13: Driving torque exerted on left knee joint during extension and flection motions and standing-up and sitting-down motions

When maximal driving torques exerted around the knee joint are compared in terms of absolute values, Fig. 12 and 13 show the torque during the standing-up motion is about

7.4-7.9 times bigger than that during the extension motion. Moreover, as for the sitting-down motion, it is about 7.3-9.9 times bigger than that during the flection motion.

In conclusion, the mass of the lower legs exerts a load on the knee joints during the extension and flection motions. On the other hand, the mass of the upper body and thighs exerts a load on the knee joints during the standing-up/sitting-down motions. It is therefore concluded that the different motions produce different driving torques exerted on the knee joints.

In addition, from Fig. 12 and 13, it is clear that driving torques exerted around the knee joint during the extension and flection motions are about the same. On the other hand, the driving torques exerted around the knee joint suddenly act just after the standing-up motion and just before the sitting-down motions. This is because when the subject is the sitting on the chair, a reaction force from the chair is exerted on the subject, and almost no moment from the load of the thighs effects on the knee joints. As a result, the reaction force from the chair just after the subject stands up disappears, so the mass of upper body and thighs act as a knee-joint moment in one go and exerts a significant burden on the knee joints. In addition, the burden on the knee joints is decreased by the reaction force from the chair just before the subject sits on the chair.

4.3 Driving power

Driving power generated around the knee joint was calculated from the driving torques exerted around the knee joint, given by Eq. (7), and the extension and flection motions were compared with the standing-up and sitting-down motions in terms of that driving power.

Driving power generated around the knee joints in each motion is plotted in Fig. 14. Red, orange, purple, and blue bar graphs represent the extension, flexion, sitting-down, and standing-up motions, respectively.

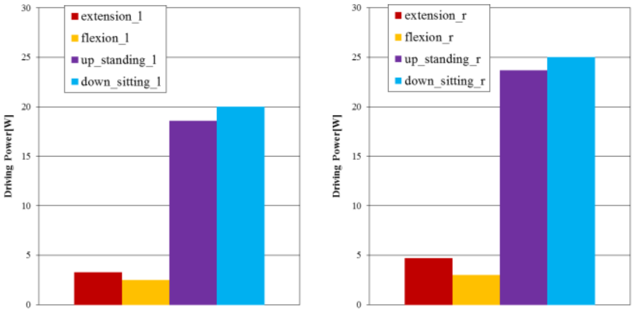

Figure 14: Driving power generated by left knee joint (left) and by right knee joint (right)

According to these Figures, driving power generated during the standing-up motion is about 5.0 times bigger than that during the extension motion, and that during the sitting-down motion is about 8.3 times bigger than that during the flection motion. It is therefore quantitatively shown by these results that the standing-up/sitting-down motion puts a relatively bigger burden on the knee joints per unit time than that during the extension and flection motions.

4.4 Muscle torque

Driving torques exerted by each muscle were calculated from Eq. (3), and the extension motion was compared with the standing motion in terms of the difference in those torques. The flection motion was compared with the sitting-down motion in terms of the respective driving torques of each muscle. The muscles included in this study (because they are assumed to mainly contribute to the motions of the knee joint) were the semimembranosus, semitendinosus, biceps femoris (long head), biceps femoris (short head), rectus femoris, vastus medialis, vastus intermedius, vastus lateralis, gastrocnemius (medial head), and gastrocnemius (lateral head).

The positions of each muscle in this study are shown in Fig. 15. In the graphs presented in this section, red, orange, purple, and blue represent muscle torque during the extension, flection, standing-up, and sitting-down motions, respectively.

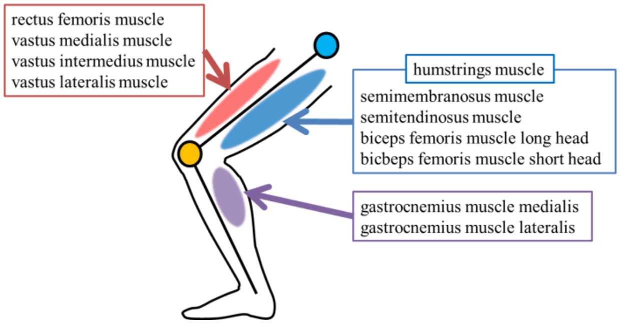

Figure 15: Position of each muscle

Driving torques exerted by the semimembranosus muscle during each motion are plotted in Fig. 16.

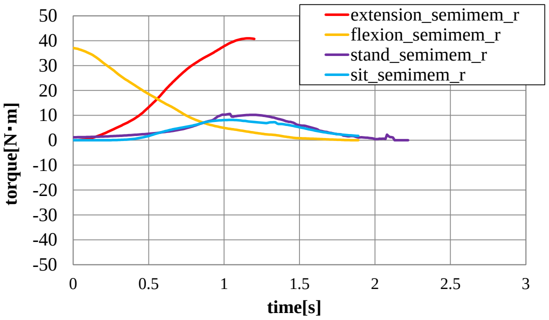

Figure 16: Driving torques exerted by semimembranosus muscle during each motion

Driving torques generated by the semitendinosus muscle during each motion are plotted in Fig. 17.

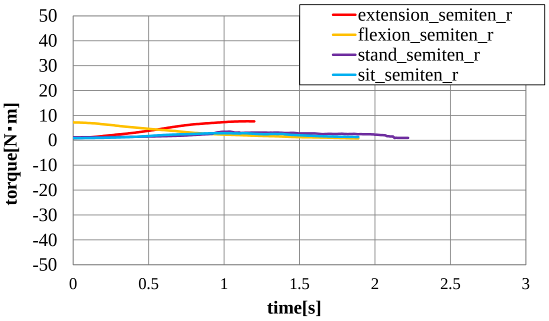

Figure 17: Driving torques exerted by semitendinosus muscle during each motion

Driving torques exerted by the biceps femoris muscle (long head) during each motion are plotted in Fig. 18.

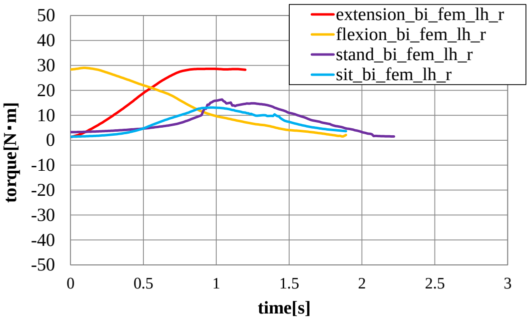

Figure 18: Driving torques exerted by biceps femoris muscle (long head) during each motion

Driving torques exerted by the biceps femoris muscle (short head) during each motion are plotted in Fig. 19.

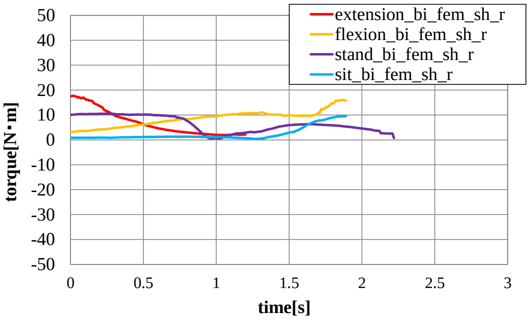

Figure 19: Driving torques exerted by biceps femoris muscle (short head) during each motion

Driving torques exerted by the rectus femoris muscle during each motion are plotted in Fig. 20.

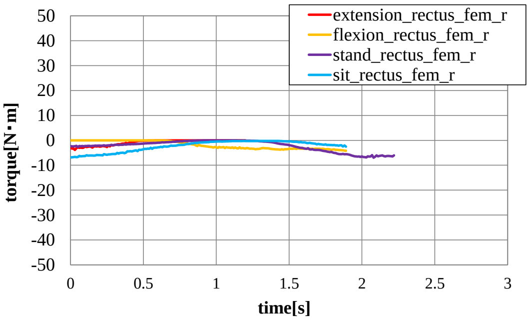

Figure 20: Driving torques exerted by rectus femoris muscle during each motion

Driving torques exerted by the vastus medialis muscle during each motion are plotted in Fig. 21.

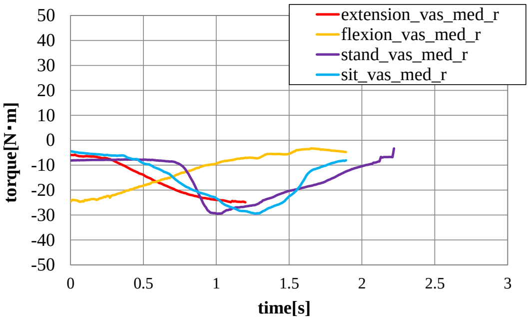

Figure 21: Driving torques exerted by vastus medialis muscle during each motion

Driving torques exerted by the vastus intermedius muscle during each motion are plotted in Fig. 22.

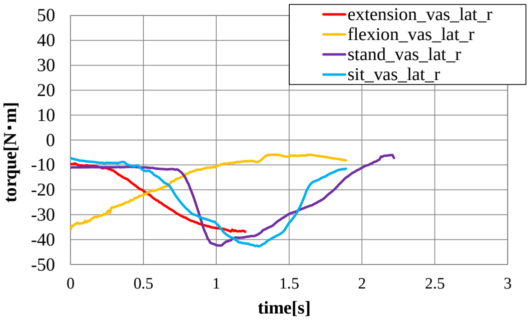

Figure 22: Driving torques exerted by vastus intermedius muscle during each motion

Driving torques exerted by the vastus lateralis muscle during each motion are plotted in Fig. 23.

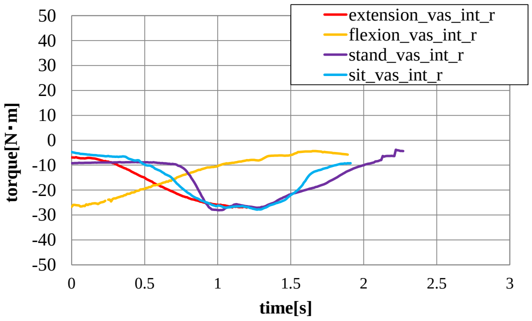

Figure 23: Driving torques exerted by vastus lateralis muscle during each motion

Driving torques exerted by the gastrocnemius muscle (medial head) during each motion are plotted in Fig. 24.

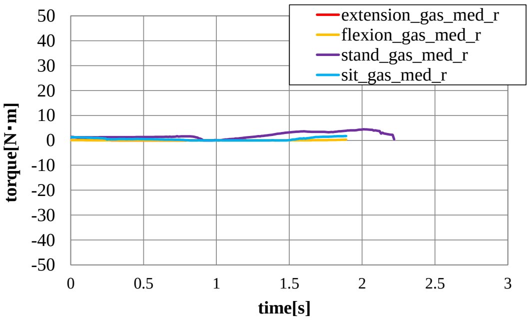

Figure 24: Driving torques exerted by gastrocnemius muscle (medial head) during each motion

Driving torques exerted by the gastrocnemius muscle (lateral head) during each motion are plotted in Fig. 25.

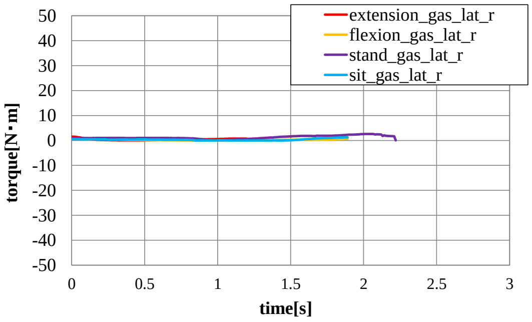

Figure 25: Driving torques exerted by gastrocnemius muscle (lateral head) during each motion

Fig. 16-25 show the driving torques exerted by each muscle during each motion. Differences in the motions are compared in terms of these driving torques. In addition, maximal driving torques exerted by each muscle are compared in terms of absolute values.

According to Fig. 16, the driving torques exerted by the semimembranosus muscle during the extension and flection motions are about 3.8 times bigger than those exerted during the standing-up/sitting-down motions.

According to Fig. 17, the driving torques exerted by the semitendinosus muscle during the extension and flection motions is about 2.1 times bigger than those exerted during the standing-up/sitting down motions.

According to Fig. 18, the driving torques exerted by the biceps femoris muscle (long head) during the extension and flection motions are about 1.8 times bigger than those exerted during the standing-up/sitting-down motions.

According to Fig. 19, the driving torques exerted by the biceps femoris muscle (short head) during the extension and flection motions are about 1.7 times bigger than those exerted during the standing-up/sitting-down motions.

According to Fig. 20, the driving torques exerted by the rectus femoris muscle during the standing-up/sitting-down motions are about 1.8 times bigger than those exerted during the extension and flection motions.

According to Fig. 21, driving torques exerted by the vastus medialis muscle during both motions (extension/flection and standing up/sitting down) show almost no difference. Moreover, driving torques exerted by this muscle increase considerably during standing up and just before sitting down.

According to Fig. 22, driving torques exerted by the vastus intermedius muscle during both motions (extension/flection and standing up/sitting down) show almost no difference. Moreover, driving torques exerted by this muscle increase considerably during standing up and just before sitting down.

According to Fig. 23, driving torques exerted by the vastus lateralis muscle during both motions show almost no difference. Moreover, driving torques exerted by this muscle increase considerably during standing up and just before sitting down.

According to Fig. 24, the driving torques exerted by the gastrocnemius muscle (medial head) during the standing-up/sitting-down motions are about 3.1 times bigger than those exerted during the extension and flection motions.

According to Fig. 25, the driving torques exerted by the gastrocnemius muscle (lateral head) during the standing-up/sitting-down motions are about 1.7 times bigger than those exerted during the extension and flection motions.

From the above-described results, it is concluded that the driving torques exerted by the muscles of the back of the thigh [namely, the semimembranosus, the semitendinosus, the biceps femoris (long head), and the biceps femoris (short head)] during the extension and flection motions are bigger than those exerted by those muscles during the standing-up/sitting-down motions. On the other hand, the driving torques exerted by the rectus femoris muscle, gastrocnemius muscle (medial head), and gastrocnemius muscle (lateral head) during the standing-up/sitting-down motions are bigger than those exerted by those muscles during the extension and flection motions. In addition, the driving torques exerted by the vastus medialis, vastus intermedius and vastus lateralis muscles rapidly increase just after standing up and just before sitting down.

4.5 Angular momentum

Angular momentum generated by each muscle is calculated from Eq. (6) using driving torques of each muscle given in Section 4.4, and the four different motions are compares in terms of the calculated angular momentum.

Angular momentums generated by the muscles around the right knee joint during the four motions are compared in Fig. 26. Red, orange, purple, and blue represent angular momentum generated during the flection, extension, standing-up, and sitting-down motions, respectively.

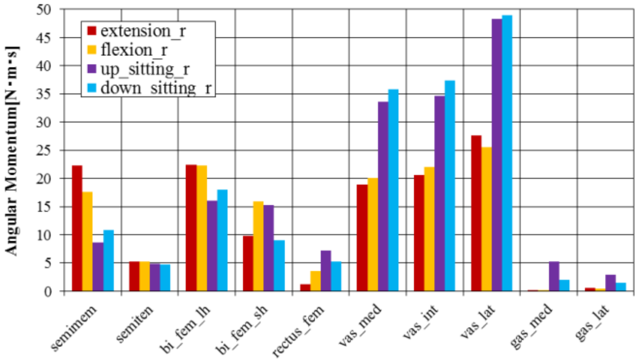

Figure 26: Angular momentum generated around right knee joint

Angular momentums generated by the muscles around the left knee joint during the four motions are compared in Fig. 27.

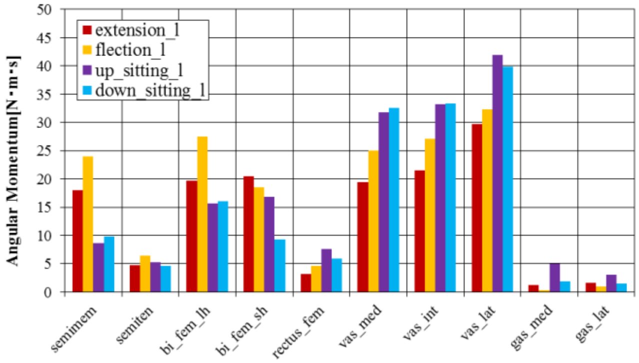

Figure 27: Angular momentum generated around left knee joint

The following conclusions can be drawn from Fig. 26 and 27. Angular momentum generated by the semimembranosus, semitendinosus, biceps femoris (long head), and biceps femoris (short head) during the extension and flection motions is bigger than that generated by those muscles during the standing-up/sitting-down motions [namely, about 1.6-2.6 times bigger for the semimembranosus, about 1.1-1.5 times for the semitendinosus, about 1.2-1.7 times for the biceps femoris (long head), and about 1.1-2.1 times for the biceps femoris (short head)]. On the other hand, the angular momentum generated by the rectus femoris, vastus medialis, vastus intermedius, vastus lateralis, gastrocnemius (medial head), and gastrocnemius (lateral head) during the standing-up/sitting-down motions is bigger than that generated by those muscles during the extension and flection motions [namely, about 1.3-5.7 times bigger for the rectus femoris, about 1.2-1.7 times for the vastus medialis, about 1.2-1.7 times for the vastus intermedius, about 1.2-1.9 times for the vastus lateralis, about 5.4-36.0 times for the gastrocnemius (medial head), and about 1.6-5.5 times for the gastrocnemius (lateral head)].

In other words, angular momentums generated by the semimembranosus, biceps femoris (long head), biceps femoris (short head), vastus medialis muscle, vastus intermedius and vastus lateralis muscle during the extension and flection motions are bigger than those generated by the other muscles. Moreover, angular momentum generated by the semimembranosus during the standing-up/sitting-down motions is smaller than that generated during the extension and flection motions. In addition, the angular momentums generated by the vastus medialis, vastus intermedius and vastus lateralis are bigger than those generated by other muscles.

It can therefore be concluded that the extension and flection motions are executed by all the muscles of the thigh working in a well-balanced manner. On the other hand, the standing-up/sitting-down motions are mainly executed by using the muscles in the front of the thigh.

5 Conclusion

[1] According to conventional techniques, since joint torque and muscle torque change with time, the level of burden on each muscle around the knee joint and its kinematic performance was considered quantitatively. It was revealed that as for the standing-up/sitting-down motions and extension and flection motions, the torque exerted on the knee joint is bigger during the former motion than that during the latter motion. Moreover, it was quantitatively determined that the torque generated by each muscle during these motions depends on the position at which each muscle is attached. In concrete terms, it was revealed that during the extension and flection motion, the muscles in the back of the thigh exert large torque. In contrast, during the standing-up/sitting-down motion, the muscles in the front of the thigh exert large torque. Driving power generated around the knee joint (a measure of kinematic performance) and angular momentum exerted by each muscle (which expresses the intensity of motion) were considered by calculating load on each muscle.

It was revealed that since driving power generated around the knee joint can be considered an instantaneous force, the instantaneous force generated during the standing-up/sitting-down motion is bigger than that generated during the extension and flection motions.

[2] As for angular momentum, which is used to evaluate momentum during motion, it is considered to represent the level of fatigue. During the extension and flection motions, the semimembranosus muscle, biceps femoris muscle (long head), biceps femoris muscle (short head), vastus medialis muscle, vastus intermedius and vastus lateralis muscle generate

bigger angular momentum than the other muscles. During the standing-up/sitting-down motions, the vastus medialis, vastus intermedius and vastus lateralis muscles generate bigger angular momentum than the other muscles.

[3] In addition to the conventional evaluation of different motions of the same person on the basis of joint torque and torque generated by each muscle on a time basis, it is considered that even higher accuracy can be attained by evaluation of these motions in terms of driving power generated around the knee joint during successive motions and angular momentum bore by each muscle.

In future, in regard to the conclusions stated above, we want to take physiological considerations into account.

References

Cabinet Office Government of Japan (2015): Aging Society White Paper in 2015.

Crowninshield, R. D.; Brand, R. A. (1981): A physiologically based criterion of muscle force prediction in locomotion. *Journal of Biomechanics*, vol. 14, pp. 793-801.

Delp, S. L.; Loan, J. P. (2000): A computational framework for simulating and analyzing human and animal movement. *IEEE Computing in Science and Engineering*, vol. 2, pp. 46-55.

Ellis, M. (1998): Efficiently preventing falling in an aged society. -Achievement of falling in outpatient treatment at King's College London. Osteoporosis, Jpn, vol. 6, pp. 573-578.

Fujimoto, K. (2008): Characteristics of the tricep muscles by electrography frequency analysis of a tennis player. *Japanese Physical Therapy Association*, A3P3008-A3P3008, 2009.

Hayashi, Y. (2007): Prevention of the falls in the elderly. *Nippon Ronen Igakkai Zasshi,* vol. 44, no. 5, pp. 591-594.

Kaufman, K. R.; An, K. N.; Litchy, W. J.; Chao, E. Y. S. (1991): Physiological prediction of muscle forces- II. Application to isokinetic exercise. *Neuroscience*, vol. 40, pp. 793-804.

Tsuyuki, M.; Kazuhito, M.; Kyo, S. (2015): Consideration for the up and down motion of the leg by the driving power and angular momentum analysis around the knee joint. *The Proceedings of the Bioengineering Conference Annual Meeting of BED/JSME,* vol. 27.

Ministry of Health (2012): Labour and Welfare: Health Japan 21 (second term).

Zajac, F. E. (1989): *Muscle and tendon: properties, models, scaling, and application to biomechanics and motor control*. CRC Critical Reviews in Biomedical Engineering, CRC Press, Boca Raton, vol. 19, pp. 359-411.