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Lower Limb Examinations for Muscular Tension Estimation Methods for Each Muscle Group Based on Functionally Different Effective Muscle Theory*

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Abstract— **Conventional estimation methods distribute tension to muscles by solving optimization problems, because the system is redundant. The theory of functionally different effective muscle, based on 3 antagonistic pairs of muscle groups in limbs, has enabled to calculate the maximum joint torque of each pair, i.e. functionally different effective muscle force. Based on this theory, a method to estimate muscular tension has been proposed, where joint torque of each muscle group is derived by multiplying functionally different effective muscle force, the muscular activity of muscular activity pattern for direction of tip force, and ratio of tip force to maximum output force. The estimation of this method is as good as Crowninshield's method, moreover this method also reduce the computation time if the estimation concerns a selected muscle group.**

I. INTRODUCTION

By knowing muscular activity, it is possible to apply the results to muscle training[1], developing welfare products[2], etc. When muscular activities are measured by electromyography, it is impossible to measure the activity inside the muscle if you use surface electrodes, not to mention how tiresome it is to use surface electrodes. On the other hands, estimation methods of muscular tensions without using electromyography have been proposed, where an optimization problem is solved because the number of muscles is larger than the one of degree of freedom of joints[3][4].

An estimation has been made where each joint torque is composed of 3 antagonistic pairs of muscle groups in limbs. This estimation is derived from the theory of functionally different effective muscle and an optimization problem is applied, this optimization problem can be applied only on a group of muscle[5].

This paper compares the method with the conventional Crowninshield's method from the point of view of estimation accuracy and computation time on lower limb isometric exercise.

II. FUNCTIONALLY DIFFERENT EFFECTIVE MUSCLE THEORY

Muscles of extremities that have been said to be complex and redundant are defined by functionally different effective muscles (FEM) as shown in Fig.1, which has 3 antagonist pairs of muscle groups for 2D motion of 2 joints[6]. Joint torque for each muscle group, i.e. FEM force T_s ($s = e1, e2, e3, f1, f2, f3$), is computed by the FEM theory. Here, the model consists of length of the first link l_1, i.e. upper arm or thigh, and length of the second link l_2, i.e. forearm or leg. The mono-articular muscles around the joint J1 and J2 are respectively $e1$, $f1$ and $e2$, $f2$. The bi-articular muscles are given by $e3$ and $f3$. The relation between each FEM force T_s and the output force at the tip J3 F_s is given by

$$\begin{aligned} |F_{e1}| &= \frac{T_{e1}}{l_1 \sin\theta_2}, \quad |F_{f1}| = \frac{T_{f1}}{l_1 \sin\theta_2} \\ |F_{e2}| &= \frac{T_{e2}}{l_2 \sin\theta_3}, \quad |F_{f2}| = \frac{T_{f2}}{l_2 \sin\theta_3} \\ |F_{e3}| &= \frac{T_{e3}}{l_2 \sin\theta_2}, \quad |F_{f3}| = \frac{T_{f3}}{l_2 \sin\theta_2} \end{aligned} \tag{1}$$

Furthermore, the direction of output force of each muscle is given by

- F_{e1}, F_{f1}: b-e direction that connects J2 and J3
- F_{e2}, F_{f2}: a-d direction that connects J1 and J3
- F_{e3}, F_{f3}: c-f direction that connects J1 and J2

The hexagon shown in Fig.2 shows output force distribution obtained from F_s. The maximum outputs of human limbs are represented by the output distribution[7].

III. PROPOSAL ESTIMATION METHOD OF MUSCULAR TENSIONS (FEMS METHOD)

A. Derivation of instantaneous functionally different effective muscle force

Joint torque of each muscle group corresponds to tip force of limbs, it is defined as an instantaneous functionally different effective muscle force. $\boldsymbol{f}$ and $\overline{\boldsymbol{F}}$ are the tip force vector and the force vector as if it was at the maximum, respectively Fig.3. The ratio R of the tip force $\boldsymbol{f}$ to maximum force $\overline{\boldsymbol{F}}$ is given by

$$R = \frac{|\boldsymbol{f}|}{|\overline{\boldsymbol{F}}|} \tag{2}$$

Kumamoto confirmed that the muscular activity pattern can be obtained as shown in Fig.4 if the maximum force is

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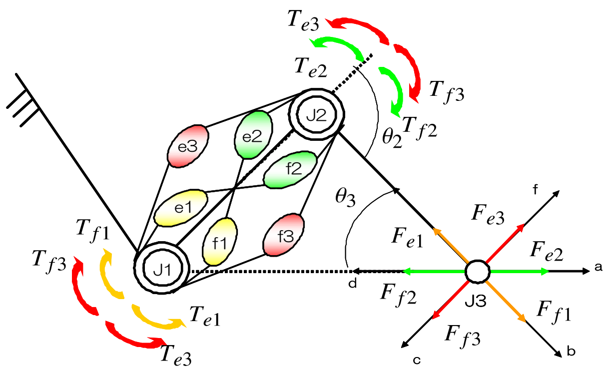

Fig. 1. Functionally different effective muscles (FEM)

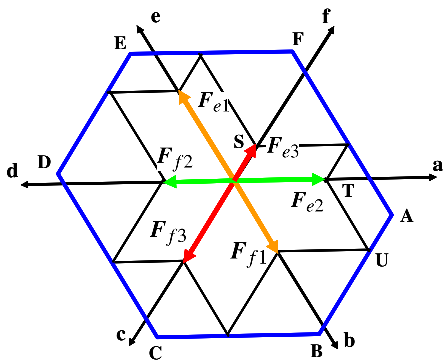

Fig. 2. Output force distribution

generated in all directions[8]. The horizontal axis from a to f shows directions of output force and the vertical axis is integrated electromyogram (IEMG) when people is generating tip force. Moreover, the instantaneous functionally different effective muscle force τ_s ($s = e1, e2, e3, f1, f2, f3$) is defined as the product of T_s, R, and the value from muscle activation pattern P_s .

$$\tau_s = R \cdot P_s \cdot T_s \quad (3)$$

B. Estimation of muscular tension by using FEMs Method

Muscular tension is estimated by applying each τ_s to an optimization problem. A set of F_m that minimizes the sum of squares of muscle stress as shown in (4) under the constraint (5) is calculated,

$$\hat{F_m} = \arg \min_{F_m \geq 0} [\sum_{m \in s} (F_m / A_m)^2] \quad (4)$$

$$Constraints: \quad \tau_s = \sum_{m \in s} [\boldsymbol{r}_m \times (-\hat{F_m} \boldsymbol{f}_m)] \quad (5)$$

$$s : \text{FEM}$$

where m represents muscle number. A_m is the average cross-section area of each muscle. $\boldsymbol{r}_m$ is a position vector of the muscle insertion seen from the joint center. $\boldsymbol{f}_m$ is a unit direction vector from muscle origin to muscle insertion. The average cross-section area of each muscle is determined by the reference [9] as shown in Table I.

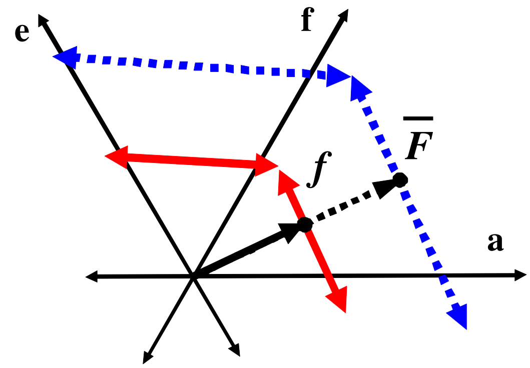

Fig. 3. Ratio of the maximum force and instantaneous force

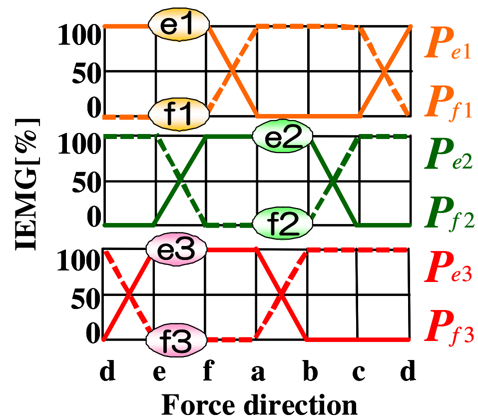

Fig. 4. IEMG Pattern for muscular output direction

IV. Experiment of Muscular Tension Estimation

A. Experimental condition

Experimental condition is as follows:

- Subject: 22 years old male (Experiment A)
  23 years old male (Experiment B)
- Objects of estimations:
  - $e1$: Iliacus (Experiment B)
  - $e2$: Vastus lateralis (Experiment B)
  - $e3$: Rectus femoris (Experiment A and B)
  - $f1$: Giuteus maximus (Experiment B)
  - $f2$: Biceps femoris short head (Experiment B)
  - $f3$: Biceps femoris long head (Experiment B)
- Exercise: Isometric exercise
- Posture:
  - Knee bending of 90 [deg]
  - Hip bending of 45 [deg]
- Inspection: IEMG by surface electrode

$\boldsymbol{r}_m$ and $\boldsymbol{f}_m$ are calculated from the attachment points of the muscles shown in Table II. Fig.1 is a simplified human limb's model, but actually, muscular arrangement of lower limb is complexed as shown in Fig.5. The attachment points of muscles are determined from [10].

B. Examination of Fig.3 (Experiment A)

Fig.2 and Fig.4 have already confirmed with many subjects by Kumamoto, but Fig.3 had never analyzed. So, we made an examination to detect IEMG of $e3$ when subject generated tip force of 20%, 40%, 60%, 80% to his maximum force in the direction of between e and a (in Fig.4, P_{e3} is 100% in the direction of between e and a, so the muscular activity of $e3$ depends on the ratio R if (3) is correct.).

From Fig.6, we found that muscular activity is in proportion to the ratio R shown in (2).

C. Results of muscular tension estimation (Experiment B)

Before experiment, we obtained each FEM force T_s as shown in Table III by using the method proposed by Kumamoto[1]. Estimation results of Crowninshield's method, FEMs method are shown in Fig.7. There is no value of IEMG about Biceps femoris short head ($f2$) because it can't be measured from the surface of the skin.

In Rectus femoris ($e3$), since the estimated value of Crowninshield's method is close to null even though IEMG is not close to null, the estimated form of the wave of FEMs method is close to IEMG than one of Crowninshield's method.

Table IV shows Pearson correlation coefficients between the measured form of the wave of IEMG and the estimated muscular tension form of the wave of each method. In this table, FEMs correlations are less than Crowninshield's in Vastus lateralis ($e2$) and Rectus femoris ($e3$). But in Iliacus ($e1$) and Biceps femoris long head ($f3$), FEMs correlations are as good as Crowninshield's method. Therefore, from the point of view of Pearson correlation coefficient, FEMs method can estimate muscular tensions as well as Crowninshield's method about Iliacus ($e1$) and Biceps femoris long head ($f3$).

Table V shows computation time of each estimation method. FEMs Method can estimate muscular tensions of muscles which are concerned with 2D motion of hip and knee in sagittal plane as quickly as Crowninshield's method. If estimated muscles are limited, it is possible to estimate muscular tension faster by using FEMs Method as shown in Table VI. From these tables, FEMs method is more appropriate to realize realtime biofeedback or control welfare products than Crowninshield's method.

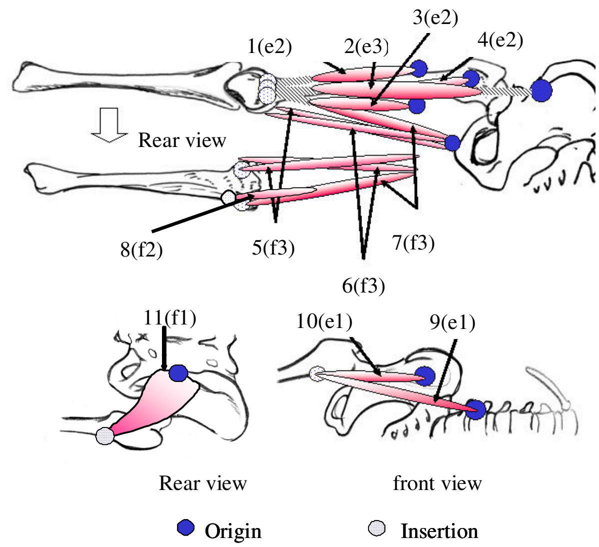

Fig. 5. Position of each FEM

TABLE II
ATTACHMENT POINTS OF MUSCLES BASED ON THIGH

Muscle Number	Origin / Insertion	x[m]	y[m]	z[m]
1	Origin	-0.230	-0.044	-0.070
1	Insertion	0.036	0.049	0.130
2	Origin	-0.090	-0.025	0.000
2	Insertion	0.060	0.074	0.130
3	Origin	0.086	0.086	0.052
3	Insertion	0.267	0.338	0.010
4	Origin	0.077	0.077	0.013
4	Insertion	0.267	0.338	-0.010
5	Origin	0.043	0.055	0.039
5	Insertion	0.267	0.338	0.000
6	Origin	-0.029	0.029	0.015
6	Insertion	0.267	0.338	0.000
7	Origin	-0.020	-0.092	-0.066
7	Insertion	0.032	-0.027	-0.018
8	Origin	0.129	0.116	0.034
8	Insertion	0.300	0.215	0.030
9	Origin	0.045	-0.045	-0.042
9	Insertion	0.300	0.215	-0.030
10	Origin	0.038	-0.038	-0.030
10	Insertion	0.305	0.220	-0.040
11	Origin	0.034	-0.034	-0.024
11	Insertion	0.300	0.215	0.030

TABLE I
MUSCLES IN EACH MUSCLE GROUP AND THEIR PCSA

FEM	Muscle Number	Muscle Name	PCSA $[\mathbf{cm^2}]$
$e1$	1	Psoas major	25.70
$e1$	2	Iliacus	23.00
$e2$	3	Vastus lateralis	64.41
$e2$	4	Vastus midialis	66.87
$e2$	5	Vastus intermedius	82.00
$e3$	6	Rectus femoris	42.96
$f1$	7	Giuteus maximus	30.00
$f2$	8	Biceps femoris short head	8.14
$f3$	9	Semitendinosus	23.27
$f3$	10	Semimembranosus	46.33
$f3$	11	Biceps femoris long head	27.34

V. CONCLUSIONS

This paper compares the Crowninshield's method and the FEMs method from the point of view of an estimation accuracy and computation time. An estimation accuracy of the FEMs method is similar to the Crowninshield's method. Computation time of the FEMs method is reduced if the estimation is restricted to a selected muscle group. From the result, FEMs method is more appropriate to realize realtime biofeedback or control welfare products than the Crowninshield's method. Moreover, it is necessary to evaluate this result on many people.

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TABLE III
FEM FORCE T_s

T_s	FEM force [Nm]
T_e1	91.3
T_e2	168.4
T_e3	20.1
T_f1	15.4
T_f2	17.7
T_f3	44.7

TABLE IV
PEARSON CORRELATION COEFFICIENTS

Muscle Name	Crowninshield's	FEM Method
Iliacus ($e1$)	0.82	0.75
Vastus lateralis ($e2$)	0.65	0.50
Rectus femoris ($e3$)	0.49	0.35
Giuteus maximus ($f1$)	0.57	0.59
Biceps femoris long head ($f3$)	0.84	0.85

TABLE V
COMPUTATION TIME

Estimation Method	Computation Time [sec/data]
Crowninshield's	0.237
FEM Method	0.245

TABLE VI
COMPUTATION TIME IN EACH MUSCLE GROUP

Muscle	Computation Time [sec/data]
$e1$	0.065
$e2$	0.062
$e3$	0.002
$f1$	0.008
$f2$	0.004
$f3$	0.104

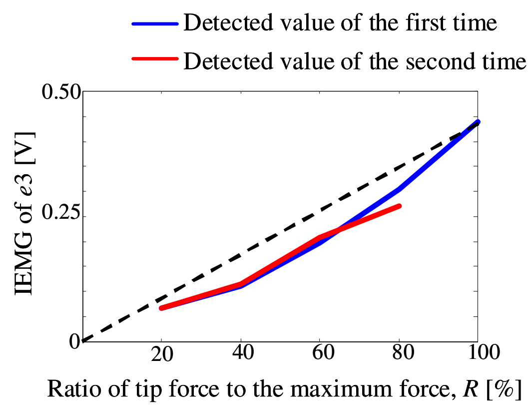

Fig. 6. Comparison between the ratio R and IEMG of $e3$

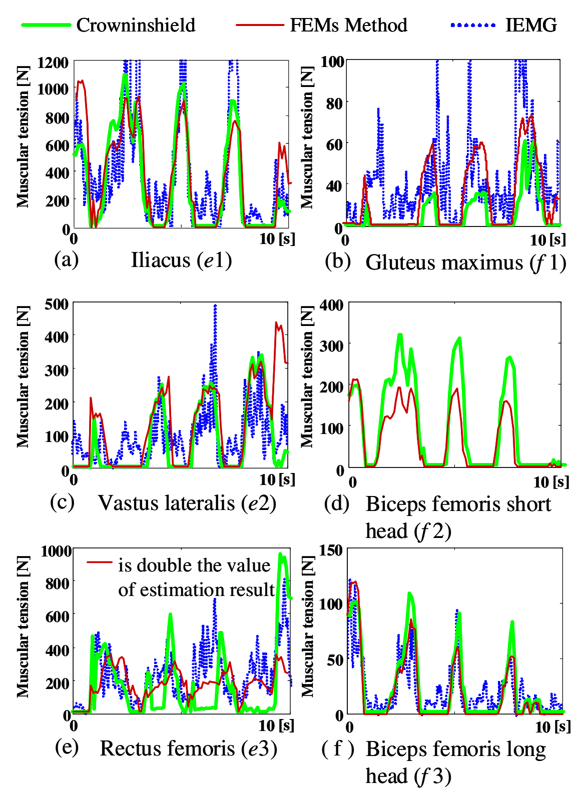

Fig. 7. Estimation result of muscular tensions during isometric exercise