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Development of a muscle strength evaluation system for five muscles classified by function of knee and ankle joints

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***Abstract*—Estimation/evaluation of muscle strength of limbs are needed as an evaluation index for clinical practice and sports training. The evaluation method of muscle strength using functionally effective muscule theory uses a two-dimensional musculoskeletal model of three pairs six muscles, in which the limb muscles are classified according to their functions, and enables the evaluation of muscle strength for each muscle group. In this study, we developed a new system to evaluate the muscle strength of each muscle group in a five muscle model that separates the bi-articular muscle strength of knee and ankle joint using the functionally effective muscular theory. The developed system consists of a device for measuring foot tip force in real time and a calculation algorithm for evaluating the muscle strength of five muscles from the measured data. The former one is a device that measures the foot tip force exerted at the foot by a force sensor attached to the boot. The latter one calculates the position of the exerted force in the boot from the foot tip force, and derives the muscle group torques of the five muscles, taking into account the variation of the exerted force position. In this paper, we show the validity of the developed system by comparing the results from Cybex measurements.**

***Index Terms*—Knee and ankle joints, Muscle strength evaluation, Functionally effective muscular strength, Musculoskeletal Model, Output force distribution, Moment arm, Bi-articular muscle**

I. Introduction

Human motion analysis is used in a wide field of sports, rehabilitation and so on. In particular, the evaluation of maximal muscle strength is needed as an evaluation index for functional recovery and training effects [1]. Since it is difficult to directly measure muscle strength in clinical sites, muscle strength estimation/evaluation is performed noninvasively. In the evaluation of maximal muscle strength, measurement of joint torque is generally used, and has the advantages of easy measurement and high reproducibility [2]. However, it is not possible to evaluate muscle strength separately for monoarticular muscles and bi-articular muscles. On the other hand, in the functionally effective muscular theory, muscle force is evaluated using a simple three pairs six muscle model in which the limb muscles are classified by function in a two-dimensional plane [3]. It is possible to evaluate the muscle strength of individual muscle groups based on the output force distribution (OFD), which indicates the maximum range of force that each muscle group produces at the tip of a limb [4] [5]. However, special equipment and techniques are required to obtain PCSA (physiological cross sectional area) for the muscle strength evaluation.

On the other hand, the functionally effective muscular theory has been extended to the entire lower limb by Nishida et al. to include a five muscle model of the lower leg, and it is possible to estimate muscle strength of the entire lower limb acting on the hip, knee, and ankle joints [6].

However, there has been no evaluation of muscle strength at the knee and ankle joints. In this paper, we present a muscle force evaluation system for each muscle group in the five muscle model based on the functionally effective muscular theory of knee and ankle joints that we developed. Furthermore, we show the validity of the measurement values of the developed system by comparing the results from Cybex measurements.

II. Functionally effective muscular theory [5]

A. Five muscle model of knee and ankle joints

Fig. 1 shows a five muscle model of knee and ankle joints classified according to function in a two-dimensional plane [6]. Muscle groups e2 and f2 are the combination of mono-articular and bi-articular muscles of the front and back of the thigh, respectively. Here, J2, J3 and T indicate the knee joint, ankle joint, and foot tip force exertion position, respectively. The direction of the muscle group foot tip force $\boldsymbol{F}_{\mathrm{s}}$ (s = e2, f2, e4, f4, f5) in Fig. 1 is determined by the posture. $\boldsymbol{F}_{\mathrm{e2,f2}}$ and $\boldsymbol{F}_{\mathrm{e4,f4}}$ are the straight line directions connecting J3 and T, and J2 and T, respectively. The direction of $\boldsymbol{F}_{\mathrm{f5}}$ is the straight line connecting J2 and J3 when the moment arms are equal

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at both ends. As shown in Fig.2, let the lengths of J2 and J3, and J3 and T be l_2 and l_3, respectively, and the angle between their links be θ_3. Furthermore, θ_2 is the knee joint angle with respect to the horizontal direction.

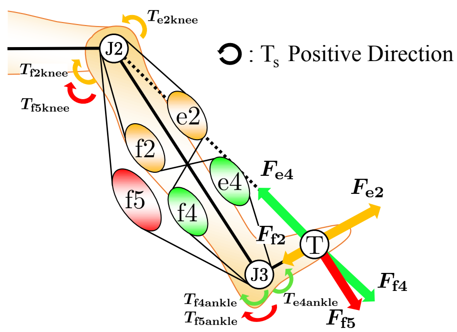

Fig. 1: Five muscle models of knee and ankle joints and the force vector exerted by each muscle group

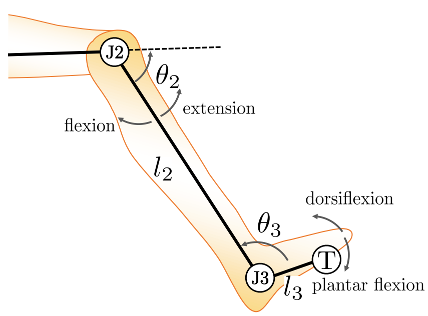

Fig. 2: Parameters of lower leg and foot

B. Output force distribution (OFD) of joint torque

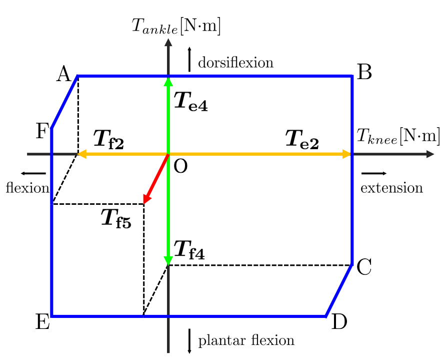

Fig. 3: OFD of joint torque determined by muscle group torque

The magnitude of the muscle group torque $\boldsymbol{T}_s$ is obtained by multiplying the muscle force of the muscle group s f_s by the moment arm of the muscle group A_s, which is expressed as a vector $\boldsymbol{T}_s$ in Fig. 3. In the case of bi-articular muscle f5, let A_{f5knee} and $A_{f5ankle}$ be the moment arms of knee and foot side, respectively, then the muscle group torque $\boldsymbol{T}_{f5}$ is expressed by the following formula from the muscle force f_{f5} of f5.

$$\boldsymbol{T}_{f5} = \begin{bmatrix} -T_{f5knee} \\ -T_{f5ankle} \end{bmatrix} = \begin{bmatrix} -A_{f5knee} \\ -A_{f5ankle} \end{bmatrix} f_{f5} \tag{1}$$

The horizontal axis of Fig.3 is knee torque T_{knee}, and the direction of knee extension is positive. The vertical axis is ankle torque T_{ankle}, and the direction of foot dorsiflexion is positive. The OFD of joint torque shows the range of joint torque $\boldsymbol{T} = [T_{knee}, T_{ankle}]^T$ exerted at each joint, which is obtained by vectorially adding up the muscle group torque $\boldsymbol{T}_s$. The lengths of sides AB and DE of the OFD are the sum of the magnitudes of the muscle group torques $\boldsymbol{T}_{e2}$ and $\boldsymbol{T}_{f2}$ of the knee mono-articular muscles e2 and f2, whose slope is the same as $\boldsymbol{T}_{e2}$ and $\boldsymbol{T}_{f2}$. The lengths of sides BC and EF are the sum of the magnitudes of the ankle mono-articular e4 and f4 muscle group torques $\boldsymbol{T}_{e4}$ and $\boldsymbol{T}_{f4}$, whose slope is the same as $\boldsymbol{T}_{e4}$ and $\boldsymbol{T}_{f4}$. Since there are no antagonistic muscles in bi-articular muscle f5, sides AF and CD are the same as the muscle group torque $\boldsymbol{T}_{f5}$ of f5 in equation (1). From the above, the OFD is defined as a hexagon with all opposite sides parallel and equal in length.

III. Muscle strength evaluation system (MSES) for 5 muscles of the knee and ankle joints

In this section, we explain a device for measuring foot tip forces exerted at the knee and ankle joints in real time, and an off-line software for calculating the muscle group forces of five muscles from the measured data.

A. Foot tip force measuring device (FTFMD)

1) Device: The foot tip force measurement device (FTFMD) is shown in Fig. 4. During the measurement, the subject puts on the boot and secures it by fastening the adjuster so that the subject's foot does not move inside the boots. The subject then fastens the waist and thighs with belts and crosses arms in front of the chest for measurement (Fig. 5).

The six-axis force sensor (model: BFS067XS901U, Leptrino Co., Ltd.) on the sole of the boot is connected to a computer to measure the isometric foot tip force $\boldsymbol{F}$ and the moment around each axis $\boldsymbol{M}$ exerted by the subject in the boot.

2) Software for real time measurements: In the measurement, force exertion is performed in the following steps: 1. knee extension, 2. foot dorsiflexion, 3. knee flexion, and 4. foot plantar flexion. Each measurement is performed in the order of "Practice Mode" and "Measurement Mode".

B. Calculation algorithm for evaluating the muscle strength of five muscles

1) Calculation of the position of force exertion in the boot: The foot tip force $\boldsymbol{F}$ measured real time by FTFMD is exerted at a certain force exertion position in the boot T as shown in Fig. 6, and T varies depending on the direction of $\boldsymbol{F}$.

Fig. 4: Foot tip force measuring device (FTFMD)

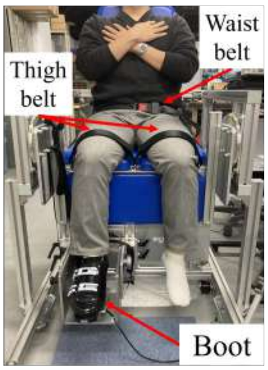

Fig. 5: Measurement posture when measuring the foot tip force

The moment M_z^{cal} around z axis of the force sensor can be calculated from the foot tip force $\boldsymbol{F} = [F_x, F_y]^T$ by the following equation.

$$M_z^{cal}(x, y) = -y \times F_x + x \times F_y \quad (2)$$

Here, we define the boot shape function $y = f(x)$ with $y = f_n(x)$ (n=1, 2, 3, 4, 5) as in Fig. 7, and assign $f_n(x)$ to y in (2). The difference between the moment around z-axis $M_z^{cal}(x)$ calculated in this way and the moment around z-axis M_z^{mea} measured by the actual force sensor is defined as e. Then, the position $(x, f_n(x))$ at which the square of e is minimized is defined as T.

$$\min_x e^2 = (M_z^{cal}(x) - M_z^{mea})^2 \quad (3)$$

2) Conversion from foot tip force $\boldsymbol{F}$ to joint torque $\boldsymbol{T}$ using force exertion position T*:* The joint torque $\boldsymbol{T}$ is obtained from the foot tip force $\boldsymbol{F}$ using the transpose matrix of the Jacobi matrix $\boldsymbol{J}$.

$$\boldsymbol{T} = \boldsymbol{J}^{\mathrm{T}}\boldsymbol{F} \quad (4)$$

$$\boldsymbol{J} = \begin{pmatrix} -l_2 \sin\theta_2 + l_3 \sin(\theta_2 + \theta_3) & l_3 \sin(\theta_2 + \theta_3) \\ -l_2 \cos\theta_2 + l_3 \cos(\theta_2 + \theta_3) & l_3 \cos(\theta_2 + \theta_3) \end{pmatrix} \quad (5)$$

Using $\boldsymbol{J}$ composed of l_3 and θ_3 corresponding to the force exerted position T, the measured foot tip force $\boldsymbol{F}$ is converted into joint torque $\boldsymbol{T}$ by (4).

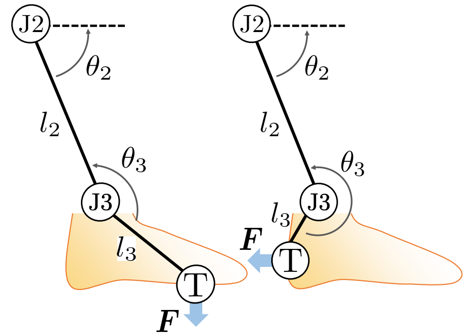

Fig. 6: Setting parameters l_3 and θ_3 according to the force exertion position T which varies depending on the direction of force exertion

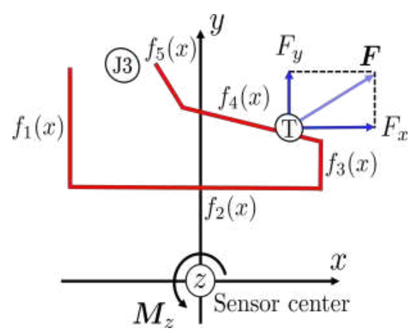

Fig. 7: The moment around the z-axis generated by the shape function $y = f(x)$ inside the boot and the foot tip force $\boldsymbol{F}$ is defined as M_z

3) Drawing OFD by measured joint torque: The joint torque $\boldsymbol{T}$ calculated in section III-B2 is plotted on the torque plane as the joint torque measurement point p as shown in Fig. 8. Furthermore, the OFD based on the measured values is obtained by drawing a line segment with the slope described in section II-B where the distance D_{i} from the origin O passing the measurement point $p_{\mathrm{max\_i}}$ (i = AB, BC, CD, DE, EF, FA) is maximum [6].

However, this OFD based on the measurements does not satisfy the property of OFD that the lengths of the opposite sides are equal. Therefore, we draw the OFD with equal lengths of the opposite sides by optimizing the following equation.

$$\min_{d_{\mathrm{i}}} J = \sum_{\mathrm{i}} (D_{\mathrm{max\_i}} - d_{\mathrm{i}})^2 \quad (6)$$

$$\text{subject to BC} = \text{EF} \quad (7)$$

This is calculated to minimize the sum of the squares of the error between the distance $D_{\mathrm{max\_i}}$ between the origin and each side of the OFD based on the measurements and the distance d_i between the origin and each side of the newly drawn OFD with equal opposite sides. In this case, a hexagon with equal lengths of all the opposite sides is obtained by applying the constraint condition that the lengths of one set of opposite sides are equal as in (7).

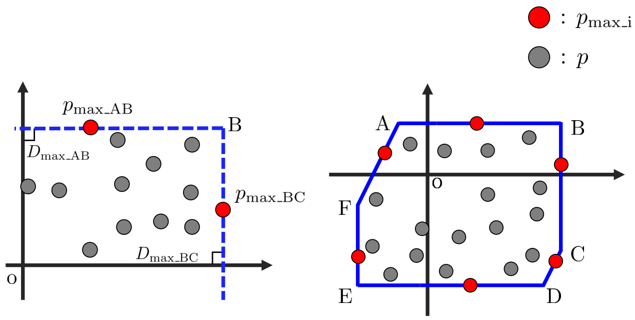

Fig. 8: How to draw OFD by joint torque by measurement

4) Estimation of muscle group torque: Since there is no antagonistic muscle e5 to the bi-articular muscle f5, the sides AF and CD of the OFD are $\boldsymbol{T}_{\mathrm{f5}}$, and $\boldsymbol{T}_{\mathrm{f5}}$ is uniquely determined from the OFD. Furthermore, by drawing a line parallel to each side from the tip of $\boldsymbol{T}_{\mathrm{f5}}$ as shown by the dashed line in Fig.3, all other muscle group torques $\boldsymbol{T}_{\mathrm{s}}$ can be uniquely determined from the OFD.

IV. Measurement results of knee and foot joint muscle strength

In this chapter, the validity of the developed system is tested by measuring joint torques using the Cybex (Cybex Norm) joint torque measuring device and comparing them with the measurement results of the developed MSES for the five muscles of knee and ankle joints.

A. Measurement condition

The subjects are two adult men, and their link lengths and measurement postures are shown in TABLE I. Note that l_1 is the link length between the hip joint and the knee joint, θ_1 is the hip flexion angle, and both Cybex and the developed system are measured in the same posture.

TABLE II shows moment arms of the bi-articular muscle f5, i, e. the gastrocnemius muscle. They are obtained from the leg6dof9musc model (height: 1.80[m], weight: 75.16[kg]) in OpenSim4.1.

TABLE I: Subject's link length and measurement posture

	Subject 1	Subject 2
l_1[m]	0.43	0.46
l_2[m]	0.39	0.43
θ_1[deg]	90	90
θ_2[deg]	80	80

TABLE II: Moment arms of the gastrocnemius, at θ_1=90 deg and θ_2=80 deg obtained from the leg6dof9musc model in OpenSim4.1

A_{f5knee}[m]	0.018
A_{f5ankle}[m]	0.061

In the MSES three sets of force exertion in five directions are performed as one set. The maximum torque of each muscle group in the three sets of measurements is used as the comparison value.

In Cybex, the joint torques are measured in four directions of isometric motion of knee extension, knee flexion, foot dorsiflexion, and foot plantar flexion in the postures as shown in Fig.9 and Fig.10. In Cybex, the maximum force is exerted three times for three seconds, and the maximum torque in the three exertions is used.

Fig. 9: Measurement of knee joint torque in Cybex

Fig. 10: Measurement of ankle joint torque in Cybex

B. Measurement results and discussion

The measurement results of subject 1 with the developed MSES for the five muscles of knee and ankle joints are shown in Fig. 11.

TABLE III shows the five muscle group torques by the MSES, the joint torques derived from them, and the joint torques measured by Cybex. As a result, the knee joint torques are equal for both subjects 1 and 2. However, the ankle joint torques showed large errors in the foot plantar flexion torque. The reasons for the measurement errors are the difference in the method of holding the ankle joints and the difference in the posture of the trunk. Therefore, it is considered necessary to reconsider the measurement instructions and the optimal direction of force exertion for the developed MSES for the five muscles of knee and ankle joints.

TABLE III: Muscle group torques obtained from the developed MSES for the five muscles of knee and ankle joints, joint torques obtained from them, and joint torques of Cybex [N·m]

<table>
<tr><th rowspan="2"></th><th colspan="3">Subject 1</th><th colspan="3">Subject 2</th><th rowspan="2"></th></tr>
<tr><th colspan="2">MSES</th><th>Cybex</th><th colspan="2">MSES</th><th>Cybex</th></tr>
<tr><td>$\boldsymbol{T}_{\mathrm{e2}}$</td><td colspan="2">213</td><td>222</td><td colspan="2">178</td><td>193</td><td>Knee extension torque</td></tr>
<tr><td>$\boldsymbol{T}_{\mathrm{e4}}$</td><td colspan="2">35</td><td>31</td><td colspan="2">44</td><td>43</td><td>Foot dorsiflexion torque</td></tr>
<tr><td>$\boldsymbol{T}_{\mathrm{f2}}$</td><td>123</td><td rowspan="2">144</td><td rowspan="2">122</td><td>92</td><td rowspan="2">106</td><td rowspan="2">122</td><td rowspan="2">Knee flexion torque</td></tr>
<tr><td>$\boldsymbol{T}_{\mathrm{f5}}$</td><td>78</td><td>59</td></tr>
<tr><td>$\boldsymbol{T}_{\mathrm{f4}}$</td><td>48</td><td>121</td><td>95</td><td>62</td><td>101</td><td>77</td><td>Foot plantar flexion torque</td></tr>
</table>

V. Conclusion

In this study, we described a newly developed MSES in a five muscle model including bi-articular muscle of the knee and ankle joints based on the functionally effective muscle theory.

As for the validation of the developed system by comparing the results with those measured by Cybex, the results showed that the knee joint torques are equal for both Subjects 1 and 2. However, the ankle joint torques show large errors except for the foot dorsiflexion torque of subject 1. Therefore, it is necessary to reconsider the measurement instructions and the optimal direction of force exertion for the developed MSES.

In the future, we plan to continue improving the developed system and to test it on a larger number of subjects.

Acknowledgment

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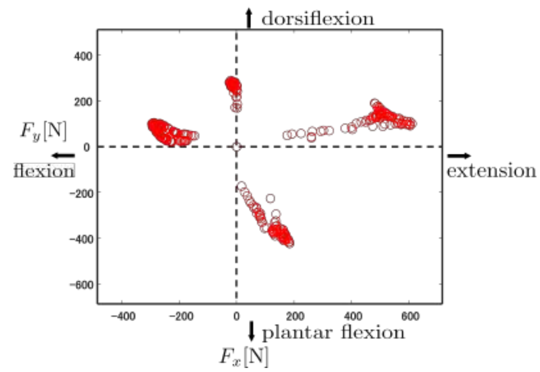
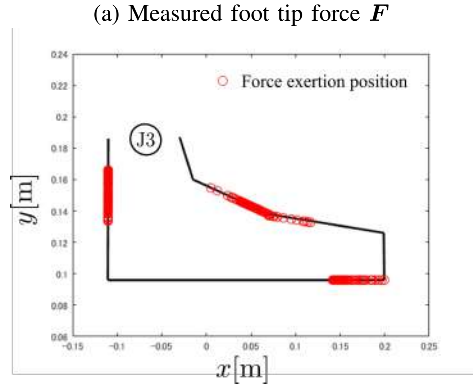
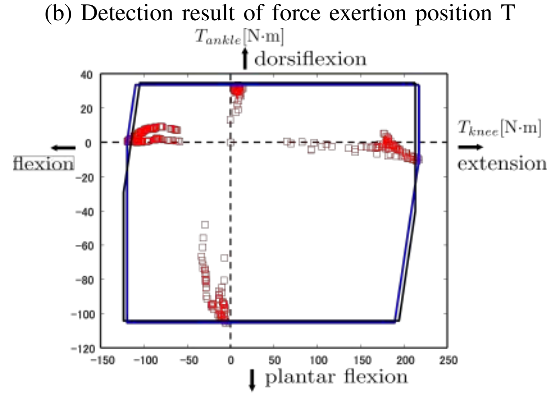


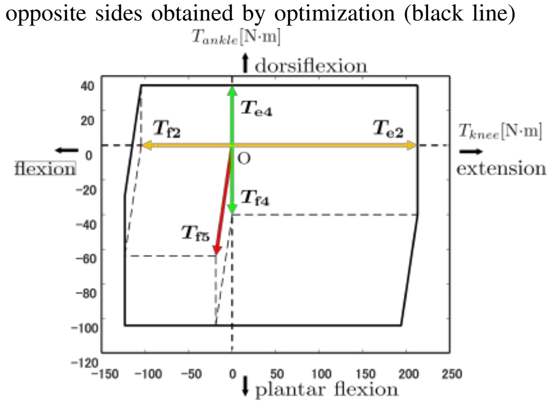
(a) Measured foot tip force $\boldsymbol{F}$



(b) Detection result of force exertion position T



(c) OFD of joint torque with unequal opposite sides obtained from the measurement results (blue line) and OFD of joint torque with equal opposite sides obtained by optimization (black line)



(d) OFD of joint torque with equal opposite sides and each muscle group torque $\boldsymbol{T}_s$

Fig. 11: Measurement results of subject 1 by the developed MSES for the five muscles of knee and ankle joints