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A Tendon Skeletal Finger Model for Evaluation of Pinching Effort

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Abstract— **In this paper, we propose a tendon skeletal finger model and discuss which finger postures the human feels easy to pinch based on the tendon forces and the human experimental results. The finger model mimics a human tendon skeletal structure. The tendon forces during the pinching motion were simulated using the finger model. Simulation results show that the tendon forces closely mirror the human muscle activity. Sensory evaluation of subjective pinching effort was conducted with five subjects. The subject pinched five kinds of cylinders, from 20 [mm] to 100 [mm]. The pinching force and the surface EMGs were simultaneously measured in the experiment. Based on the human questionnaire tests, we investigated which finger postures the human feels easy to pinch a cylinder. The results show that the pattern of the EMGs measured by the experiment is very similar to that of the tendon forces calculated by the finger model simulation. This indicates that the tendon force is a useful index of the subjective pinching effort and it can be used for the quantitative evaluation instead of EMGs.**

I. Introduction

The quantitative evaluation of product usability is important for product design. A questionnaire survey using a semantic differential method is commonly used for such an evaluation of subjective usability. In recent years, quantitative evaluation methods have been proposed based on physical data that are measurable by sensors. Radhakrishnan *et al.* analyzed the force distribution during tube grasping motions [1]. Kong *et al.* measured the maximum pulling force, the surface EMGs, and the contact force when pulling seven different meat hooks. They developed a biomechanical hand model to estimate the tendon force [2]. These research addressed the quantitative evaluation of a power grasp using the whole hand (palm and fingers).

On the other hand, some research work in biomechanics has proposed an accurate musculoskeletal model of the human hand and fingers; An *et al.* established a three-dimensional normative hand model based on X-ray image analysis [3], Holzbaur *et al.* developed a biomechanical model of the upper extremity [4], Flanagan *et al.* discussed control strategies of the human fingertips [5], and Valero-Cuevas proposed a precise model of the human finger, including neuro-musculo-skeletal interactions [6]. However, their research were not discussed about the quantitative evaluation of pinching effort.

It is well known that humans obtain tactile and tension information through receptors in their skin and muscles. There has been much research related to tactile sensing in the robotics field. For example, Shimojo *et al.* developed a high-speed tactile sensor sheet that can cover a free-form surface [7]. However, their techniques were not applied to the quantitative evaluation of subjective usability. A goal of this research is to propose an evaluation system of product usability using a robot hand that equips multiple sensors, such as contact sensors, pressure sensors, and force sensors. Fig. 1 shows the concept of the evaluation system, which is designed to correlate the obtained sensor data with human sensory information. We have presented the concept of the evaluation of the pinching effort by comparing the sensor data from the sensing hand with the human muscle activity[8].

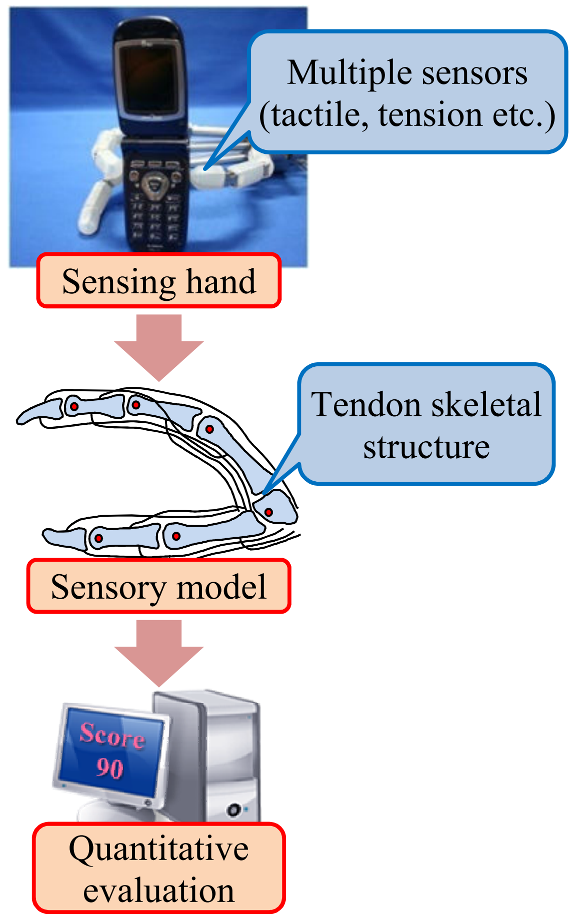

Fig. 1. Concept of evaluation system

In this paper, we improve the tendon skeletal finger model and discuss which finger postures the human feels easy to pinch based on the tendon forces and the human experimental results. First, the model of the index finger and the thumb which mimics human tendon skeletal structure are developed.

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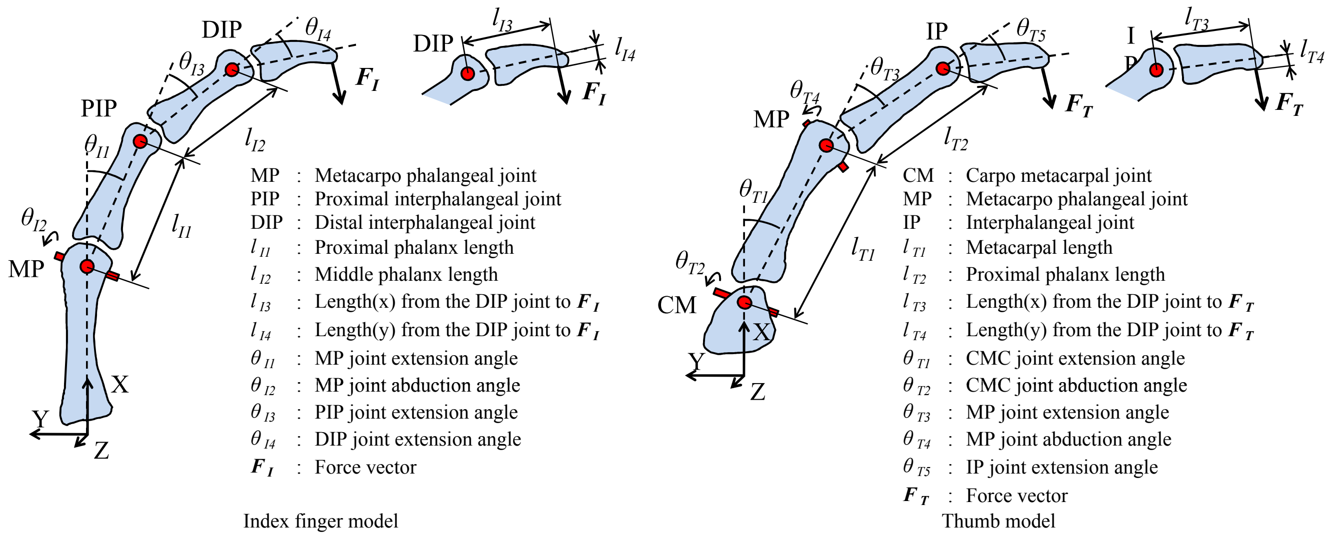

Fig. 2. Finger models

The tendon forces during the pinching motion are simulated using the finger model. The finger model has variable moment arms based on human data. Simulation results show that the tendon forces closely mirror the human muscle activity. Second, sensory evaluation of subjective pinching effort is conducted for five subjects. The subject pinched five kinds of cylinders, from 20 [mm] to 100 [mm]. The pinching force and the surface EMGs are simultaneously measured in the experiment. The results show that the surface EMG closely reflects the pinching effort. It is known that there is the linear relationship between a surface EMG and a tendon force during static motions. Based on the human questionnaire tests, we investigated which finger postures the human feels easy to pinch a cylinder. The results show that the pattern of the EMGs measured by the experiment is very similar to that of the tendon forces calculated by the finger model simulation. This indicates that the tendon force is a useful index of the subjective pinching effort and it can be used for the quantitative evaluation instead of EMGs.

II. Pinching simulation

A. Finger model

In this section, the tendon forces during a pinching motion are simulated using finger models. The model mimics human index finger and thumb.

Fig. 2 shows the finger model constructed for the pinching simulation. The index finger model consists of a fixed metacarpal and three phalanges. The DIP and the PIP joints have 1 DOF (degree of freedom) for flexion/extension, and the MP joint has 2 DOF for flexion/extension and ad/abduction. The index finger model is driven by seven independent muscles; flexor digitorum profundus muscle (FDP), flexor digitorum superficialis muscle (FDS), extensor indicis proprius muscle (EIP), extensor digitorum proprius muscle (EDC), lumbricalis muscle (LUM), dorsal interosseous muscle (DI), and palmar interosseous muscle (PI). The thumb model contains a fixed trapezium bone and three phalanges. The IP joint has 1 DOF for flexion/extension, and the MP and the CM joints have 2 DOF for flexion/extension and ad/abduction. The thumb model is driven by nine independent muscles; flexor pollicis longus muscle (FPL), flexor pollicis brevis muscle (FPB), extensor pollicis longus muscle (EPL), extensor pollicis brevis muscle (EPB), abductor pollicis longus muscle (APL), abductor pollicis brevis muscle (APB), the transverse head of the adductor pollicis muscle (ADPt), the oblique head of the adductor pollicis muscle (ADPo), and opponents pollicis muscle (OPP).

It is difficult to construct an anatomically accurate finger model because the human hand structure is very complicated. Some research discussed the importance between the finger posture and the moment arm when exerting the fingertip force[9] [10]. The joint torques $\boldsymbol{\tau}_I$ and $\boldsymbol{\tau}_T$ were calculated from the following equations:

$$\boldsymbol{\tau}_I = \mathbf{M_I F_{tendonI}} \tag{1}$$

$$\boldsymbol{\tau}_T = \mathbf{M_T F_{tendonT}} \tag{2}$$

where $\boldsymbol{\tau}_I = \left\{ \tau_{DIP} \quad \tau_{PIP} \quad \tau_{MPa} \quad \tau_{MPf} \right\}^T$ is the vector of the index finger joint torques, $\mathbf{M_I}$ is the vector of the index finger moment arms at each joint, $\mathbf{F_{tendonI}} = \left\{ f_{FDP} \quad f_{FDS} \quad f_{EIP} \quad f_{EDC} \quad f_{LUM} \quad f_{DI} \quad f_{PI} \right\}^T$ is the vector of the index finger tendon forces, $\boldsymbol{\tau}_T = \left\{ \tau_{IP} \quad \tau_{MPa} \quad \tau_{MPf} \quad \tau_{CMa} \quad \tau_{CMf} \right\}^T$ is the vector of the thumb joint torques, $\mathbf{M_T}$ is the vector of the thumb moment arms at each joint, and $\mathbf{F_{tendonT}} = \left\{ f_{FPL} \quad f_{FPB} \quad f_{EPL} \quad f_{EPB} \quad f_{APL} \quad f_{APB} \quad f_{ADPt} \quad f_{ADPo} \quad f_{OPP} \right\}^T$ is the vector of the thumb tendon forces.

It is well known that the moment arm of each joint changes according to the joint angle. In this paper, the moment arms $\mathbf{M_I}$ and $\mathbf{M_T}$ are calculated by the quartic approximation which are shown in fig.3 and fig.4. These profile are given by the quartic approximation based on the row cadavers data that were measured by An *et al.* and Smutz *et al.* [11][12].

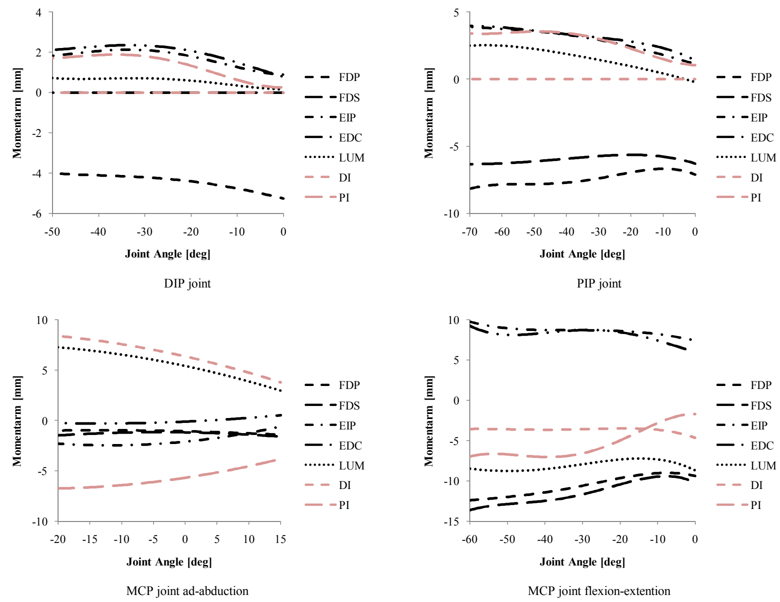

Fig. 3. Index finger moment arms

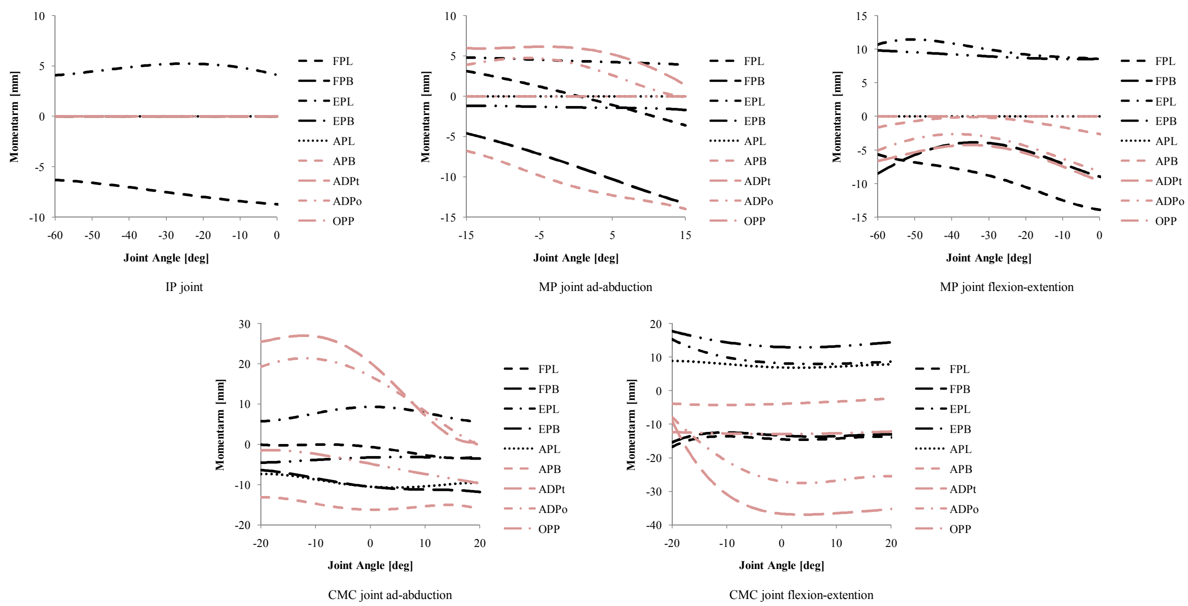

Fig. 4. Thumb moment arms

The tendon forces are calculated accurately using the variable moment arms.

The joint torques $\boldsymbol{\tau}_I$ and $\boldsymbol{\tau}_T$ can be calculated by using Jacobian matrices:

$$\boldsymbol{\tau}_I = \mathbf{J_I^T F_I} \tag{3}$$
$$\boldsymbol{\tau}_T = \mathbf{J_T^T F_T} \tag{4}$$

where $\boldsymbol{J}_I$ is the index finger Jacobian matrix, $\boldsymbol{J}_T$ is the thumb Jacobian matrix, $\mathbf{F_I} = \left\{ f_{Ix} \quad f_{Iy} \quad f_{Iz} \quad \tau_{Ix} \quad \tau_{Iy} \quad \tau_{Iz} \right\}^T$ is the index fingertip force and torques, and $\mathbf{F_T} = \left\{ f_{Tx} \quad f_{Ty} \quad f_{Tz} \quad \tau_{Tx} \quad \tau_{Ty} \quad \tau_{Tz} \right\}^T$ is the thumb fingertip force and torques. The following equations were obtained by substituting Eq. 1 to Eq. 4:

$$\mathbf{F_I} = \left(\mathbf{J_I J_I^T}\right)^{-1} \mathbf{J_I M_I F_{tendonI}} \tag{5}$$
$$\mathbf{F_T} = \left(\mathbf{J_T J_T^T}\right)^{-1} \mathbf{J_T M_T F_{tendonT}}. \tag{6}$$

The tendon forces can be calculated from the fingertip forces based on Eq. 5 and Eq. 6. However, it is a redundant problem because 6 DOFs of the finger are driven by 7 tendons for the index finger, and 6 DOFs are driven by 9 tendons for the thumb. Therefore, the tendon forces are derived from the optimization calculation of the following

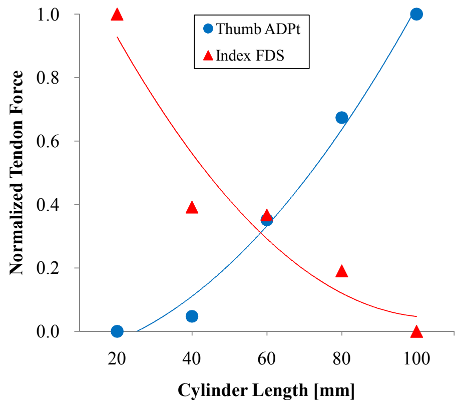

Fig. 5. Simulation results

equation [13]:

$$u(F_{tendon}) \triangleq \sum_{i=1}^{n} \left(\frac{f_i}{PCSA_i} \right)^2 \rightarrow \min \quad (7)$$

$$0 \leq f_i \leq f_{imax} \quad (8)$$

where $PCSA$ is a physiological cross sectional area of each muscle and f_{max} is a maximal force of each muscle that is determined by $PCSA$ and maximal muscle stress [14]. In this paper, we used the $PCSA$ values of Cuevas *et al.* research [15][16].

B. Simulation results

Fig. 5 shows the results of the simulation when $F_{Itip} = F_{Ttip} = \{ 0.0 \quad 10.0 \quad 0.0 \quad 0.0 \quad 0.0 \quad 0.0 \}^T$. Table I shows the link sizes of each model and Table II shows the joint angles that are determined based on the human finger posture during the pinching motion. The human finger posture was measured by a motion capture system (MAC 3D, Motion Analysis, Co.). In this figure, the tendon forces are normalized based on the minimum and maximum values of the tendon forces during the simulation. The curves in the figure are the approximate quadratic curves of each tendon force.

TABLE I
LINK SIZES

l_{I1} [mm]	l_{I2} [mm]	l_{I3} [mm]	l_{I4} [mm]
39.0	25.0	10.0	5.0

l_{T1} [mm]	l_{T2} [mm]	l_{T3} [mm]	l_{T4} [mm]
45.0	32.0	17.0	5.0

TABLE II
JOINT ANGLE

Cylinder length [mm]	θ_{I1} [degree]	θ_{I2} [degree]	θ_{I3} [degree]	θ_{I4} [degree]
20	60.0	0.0	18.5	11.9
40	51.2	0.0	24.3	17.0
60	37.8	0.0	20.7	21.5
80	19.5	0.0	25.6	26.5
100	2.3	0.0	19.4	29.7

Cylinder length [mm]	θ_{T1} [degree]	θ_{T2} [degree]	θ_{T3} [degree]	θ_{T4} [degree]	θ_{T5} [degree]
20	2.8	0.0	0.0	0.0	0.1
40	3.0	0.0	-0.1	0.0	0.1
60	3.1	0.0	-0.1	0.0	0.0
80	3.3	0.0	-0.1	0.0	0.1
100	3.4	0.0	-0.1	0.0	0.0

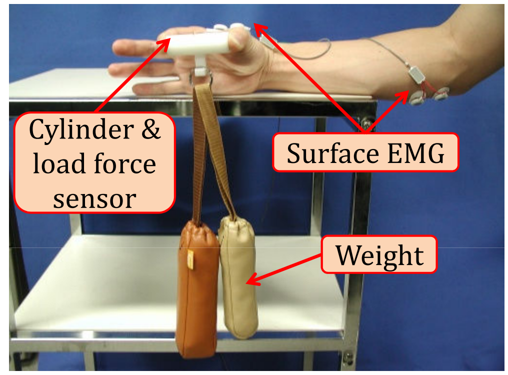

Fig. 6. Experiment with human

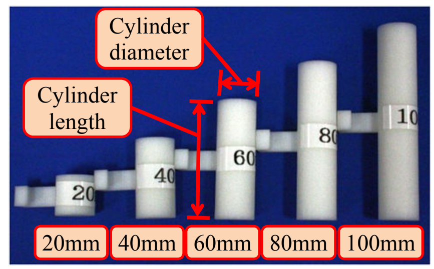

Fig. 7. Cylinder dimensions

The tendon forces of the thumb ADPt becomes higher according to the cylinder length. On the other hand, the tendon forces of the index finger FDS becomes lower according to the cylinder length. This result indicates a possibility that the quantitative evaluation using the tendon force.

III. MEASUREMENT OF HUMAN PINCHING MOTION

A. Measurement system

In this section, the subjective pinching effort and the human EMGs during a pinching motion are measured. We show that the human EMGs reflect the subjective pinching effort and the quantitative evaluation of product usability could be achieved by estimating muscle activities.

Fig. 6 shows an overview of the experiment to measure human pinching motion. A capacitance triaxial kinesthetic sensor (PD3-32-05-80, Nitta) was built into the cylinders to measure pinching force. Disposable radiolucent electrodes (F-150S, Nihon Kohden) were put on the hand and the arm of the subject to measure the surface EMGs of the flexor digitorum superficialis muscle, which flexes the index finger, and the adductor pollicis muscle, which flexes the thumb. The surface EMGs were amplified by an EMG amplifier (EMG-021, Harada Electronics Industry) and stored in a PC through an A/D board.

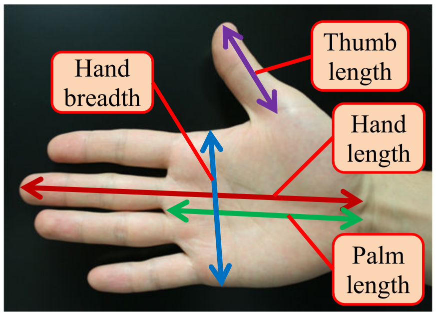

Fig. 8. Measurement dimensions

Fig. 7 shows the cylinders used in the experiment. These cylinders have lengths of 20, 40, 60, 80 and 100 [mm] and a diameter of 20 [mm]. Subjects pinched in the length direction of the cylinder by using the index finger and thumb.

B. Method

In our experiment, 300 [g] and 600 [g] weights are used. Five healthy male subjects, aged 22 to 24 years old, volunteered for the experiment. All subjects were given the experimental protocol information and they gave their consent to participate. The pinching motion was conducted by their stronger arm, depending on whether they were right- or left-handed. The arm of the subject was placed on a desk, and the middle, ring, and little fingers were kept open so as not to influence the pinching motion. Table III shows the average and standard deviation of the subjects' hand sizes. Fig. 8 shows the measured parts of the hand. The subjects' hand sizes were similar to the standard Japanese hand size.

Before beginning the experiment, we explained its purpose to the subjects. In the experiment, the subjects pinched each cylinder and scored the effort level of the cylinder. The score had seven levels from -3: "very difficult to pinch" to +3: "very easy to pinch." The first trial was done from 20 [mm] to 100 [mm], and the second trial was done from 100 [mm] to 20 [mm]. A two-minute interval was kept between each trial.

C. Questionnaire survey results

Fig. 9 shows the average and standard deviation of the scores. The curves in the figure are the approximate quadratic curves of the 300 [g] and 600 [g] weights. We can see that the score of the 300 [g] weight object is higher than that of the 600 [g] weight object, indicating that the light object is easier to pinch than the heavy object. The positive score is observed when the cylinder length is 40, 60 and 80 [mm] for both the 300 [g] and 600 [g] weights. On the other hand, the negative score is observed when the cylinder length is 20 and 100 [mm] for both the 300 [g] and 600 [g] weights. A possible reason is that the finger posture when pinching the middle length cylinder makes it easy to exert pinching force.

TABLE III

AVERAGE AND STANDARD DEVIATION OF HAND SIZE

	Ave.	SD
Hand length [mm]	184.4	5.5
Palm length [mm]	104.6	4.7
Hand breadth [mm]	82.6	5.3
Thumb length [mm]	61.6	2.8

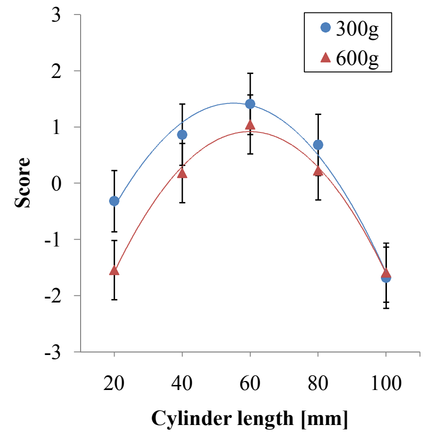

Fig. 9. Questionnaire results

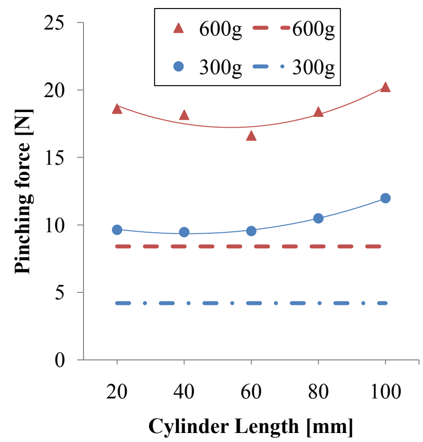

Fig. 10. Pinching force

D. Measurement results of pinching force and surface EMGs

Fig. 10 to Fig. 12 show the typical pinching force and the integrated surface EMGs during the pinching motion. The integrated surface EMGs were normalized using the minimum and maximum values of the integrated surface EMGs during the experiment. The curves in the figures are the approximate quadratic curves of the 300 [g] and 600 [g] weight.

The dash line and the dot-dash line in Fig. 10 mean the necessary theoretical force to pinch the cylinders with 300 [g] and 600 [g] weight, respectively. The necessary theoretical forces are calculated based on the friction coefficient between the finger and the cylinder. The measured pinching force is larger than the necessary theoretical force because a human applies a safety margin when grasping an object tightly. The lowest value of the pinching force is observed in the vicinity of the 60 [mm] cylinder for both weights.

Fig. 11 shows the normalized EMGs related to the index finger and thumb when the cylinder weight is 300 [g], and

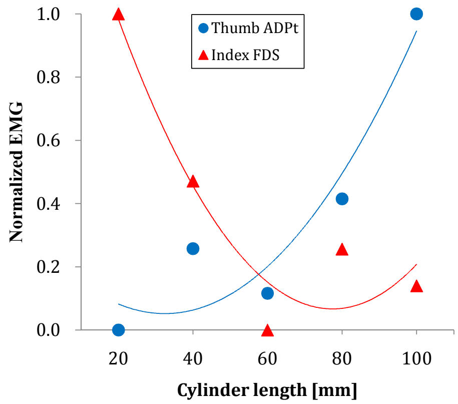

Fig. 11. Integrated EMG (300[g])

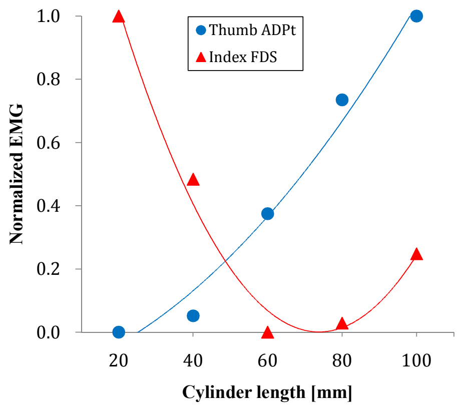

Fig. 12. Integrated EMG (600[g])

Fig. 12 shows the normalized EMGs when the cylinder weight is 600 [g]. The normalized EMGs of the index finger FDS becomes lower according to the cylinder length, and the normalized EMGs of the thumb ADPt becomes higher according to the cylinder length. A possible reason is that the finger posture when pinching a short cylinder makes it hard for the index finger to exert pinching force. On the other hand, when pinching a long cylinder, a large antagonist force is necessary to open the thumb widely, and thus the muscle activity of the thumb increases. This pattern of the EMGs is very similar to that of the tendon force calculated by the finger model simulation (shown in Fig. 5). This indicates that the tendon force is a useful index of the subjective pinching effort and it can be used for the quantitative evaluation instead of EMGs.

IV. Conclusion

This research aimed the quantification of pinching effort by measuring and estimating the tendon force during the pinching motion. We proposed the tendon skeletal finger model and discussed the classification of pinching effort by simulation and human experiment.

The finger model has variable moment arms based on the quartic approximation of An and Smutz data. Based on the human questionnaire tests, we investigated which finger postures the human feels easy to pinch a cylinder. The results show that the pattern of the EMGs measured by the experiment is very similar to that of the tendon forces calculated by the finger model simulation. This indicates that the tendon force is a useful index of the subjective pinching effort and it can be used for the quantitative evaluation instead of EMGs.

In this paper, we focused only on tendon force, but tactile sensation takes also very important rolls to judging the pinching effort for humans. Future work includes developing a sensing hand that can measure both tendon force and tactile information.

V. Acknowledgment

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