31st Annual International Conference of the IEEE EMBS
Minneapolis, Minnesota, USA, September 2-6, 2009

Biomechanical Analysis of Subjective Pinching Effort Based on Tendon-Skeletal Model

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***Abstract*— In this paper, the influence of the finger posture on the subjective effort during pinching motion is investigated by using a tendon-skeletal finger model. The experimental results show that the subjective effort human feels is affected by the size of the object he/she pinches, and the subjective effort correlates with the finger length. The simulation results show that the pattern of the tendon forces is similar to that of the EMG activity measured in the experiment, and the positive correlation was observed between the finger length and the object size where the summation of the tendon forces becomes the minimum. These results suggest that the reason why subjective pinching effort is influenced by the finger posture is the difference in the efficiency of the force transmission from the muscles.**

I. INTRODUCTION

The quantitative evaluation of product usability is important for product designs. 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 various sensors. Radhakrishnan *et al.* measured a force distribution during tube grasping motions [1]. Yong *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 researches addressed the quantitative evaluation of a power grasp using the whole hand (palm and fingers). On the other hand, some works in biomechanics have proposed accurate musculoskeletal models of the human hand and fingers: An *et al.* established a three-dimensional normative hand model based on X-ray image analysis [3], and Valero-Cuevas proposed a precise model of a human finger including neuro-musculo-skeletal interactions [4]. However, their biomechanical analysis based researches have not been applied to the evaluation of the product usability.

We have presented the concept of the evaluation of the pinching effort by comparing the sensor data obtained from a human-like robot hand with the human muscle activity [5]. In the study, the surface EMG and the pinching force when pinching an object were simultaneously measured for the quantification of the human's sensory evaluation. The results show the subjective pinching effort are correlated with the tendon force of fingers. In this paper, the influence of the finger posture on the subjective effort during pinching motion is discussed. Even if the target fingertip force is same, the tendon force to exert the fingertip force varies according to the finger posture because the joint moment arms of human fingers vary depending on the posture. This implies that the subjective pinching effort human feels would also vary according to the finger posture. The approach in this paper is shown in Fig. 1. We investigate the influence of the finger posture by comparing experimental results of humans with simulation results by using a tendon-skeletal finger model. In the experiment, a questionnaire survey is conducted and the surface EMGs of subjects who have various hand sizes are measured. The experimental results show that the subjective effort human feels is affected by the size of the object he/she pinches, and the subjective effort correlates with the finger length. In the simulation, the tendon force to exert the fingertip force is calculated by using a biomechanical model that mimics the variation of human's joint moment arms. The simulation results show that the pattern of the tendon forces is similar to that of the EMG activity measured in the experiment, and positive correlation is observed between the finger length and the object size where the summation of the tendon forces becomes the minimum. These results suggest that the reason why subjective pinching effort is influenced by the finger posture is the difference in the efficiency of the force transmission from the muscles.

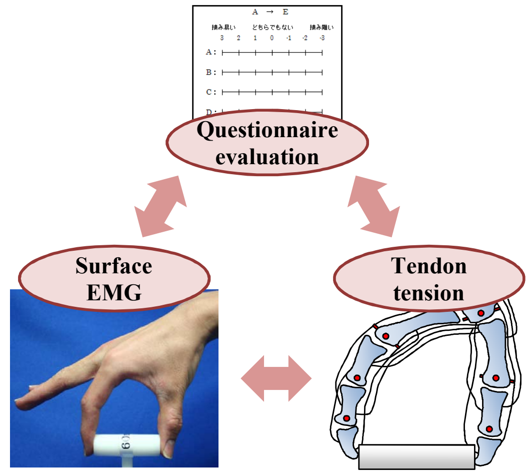

Fig. 1. Approach of this paper

This work was supported by KAKENHI (20700161).

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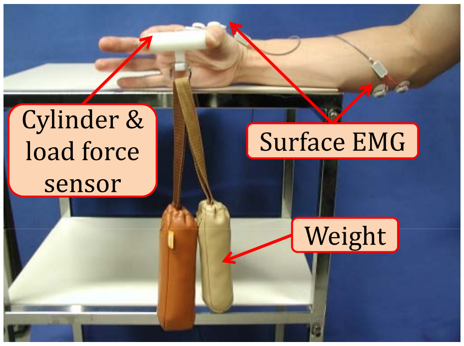


Fig. 2. Pinching experiment by subjects

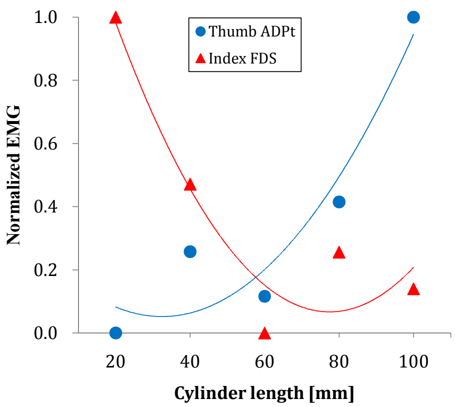


Fig. 3. Normalized integrated EMG when pinching cylinders with various length

II. Measurement of Human Pinching Motion

A. Experimental setup

Fig. 2 shows an overview of the experiment. Disposable radiolucent electrodes (F-150S, Nihon Kohden) were put on the skin of the hand and arm of the subject to measure the surface EMGs of the flexor digitorum superficialis (FDS) muscle and the adductor pollicis (ADP) muscle.

Eight healthy male subjects aged from 22 to 24 years old volunteered for the experiment. All subjects were given the experimental protocol information and they gave their consent to participate. In the experiment, the subjects pinched nine cylinders whose length are $20, 30, 40 \sim 100$[mm] with the weight of 300[g]. After trials, we asked the subjects which length is the easiest to pinch.

TABLE I
Subject's finger length

Subject	Index finger [mm]	Thumb [mm]
A	185	120
B	190	127
C	192	129
D	193	137
E	201	145
F	205	141
G	222	147

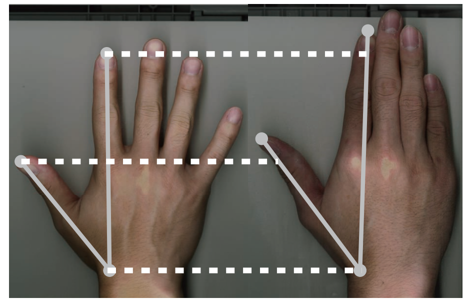
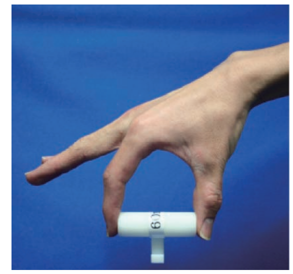


Fig. 4. Hand size of Subject A and Subject G

(a) Small hand



(b) Large hand

Fig. 5. Finger postures with different hand size

B. Results

Fig. 3 shows the normalized integrated EMGs related to the index finger (FDS) and thumb (ADP). The curves shown in the figure are given by the least square regression curve fitting. The EMG activity of the thumb becomes higher according to the cylinder length. On the other hand, the EMG activity of the index finger becomes lower. A possible reason of these patterns of the muscle activities is the change in the finger posture during pinching the cylinder. The examples of the hand size are shown in Fig. 4. Table I shows the finger length of the subjects. The subjects have variety of hand size; Subject G have 20% longer fingers than Subject A.

The difference in the hand size influences the finger posture during pinching as shown in Fig. 5. Fig. 6 shows the correlation between the finger length and the cylinder length that the subjects feel the easiest to pinch. The lines shown in the figure are the least square regression line. The positive correlation can be observed between the finger length and the cylinder length; a larger cylinder is easier to pinch for the subjects with a large hand. This is a clue to investigate the influence of the finger posture on the subjective pinching effort. In the next session, we build finger models with a tendon-skeletal structure and investigate the influence of the finger posture.

III. Pinching Simulation

A. Finger model

Fig. 7 shows the finger models built for the simulation. The index finger 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

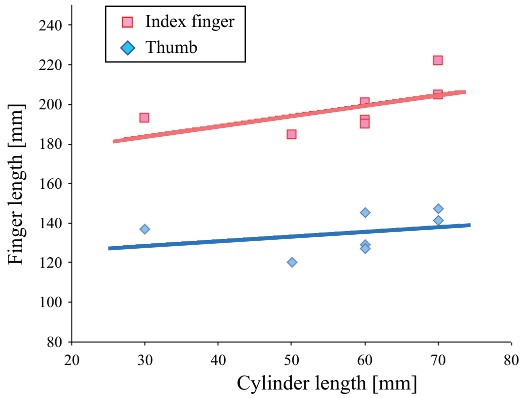


Fig. 6. Correlation between the finger length and the cylinder length that subjects feel the easiest to pinch

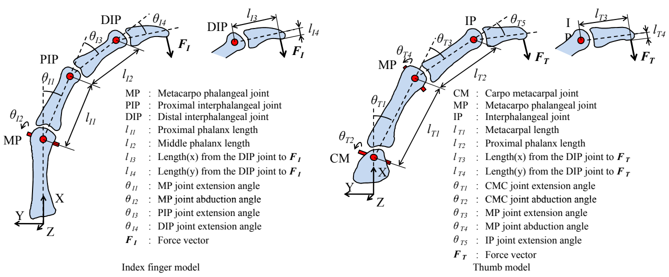


Fig. 7. Finger models

model is driven by seven independent muscles: flexor digitorum profundus (FDP), flexor digitorum superficialis (FDS), extensor indicis proprius (EIP), extensor digitorum proprius (EDC), lumbricalis (LUM), dorsal interosseous (DI), and palmar interosseous (PI). The thumb consists of 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 (FPL), flexor pollicis brevis (FPB), extensor pollicis longus (EPL), extensor pollicis brevis (EPB), abductor pollicis longus (APL), abductor pollicis brevis (APB), the transverse head of the adductor pollicis (ADPt), the oblique head of the adductor pollicis (ADPo), and opponents pollicis (OPP).

In this model, the joint torques $\boldsymbol{\tau}_I$ and $\boldsymbol{\tau}_T$ are 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 $\boldsymbol{\tau}_I$ is the vector of the index finger joint torques, $\mathbf{M_I}$ is the vector of the index finger moment arms, $\mathbf{F_{tendonI}} = \{\, f_{FDP} \;\; f_{FDS} \;\; f_{EIP} \;\; f_{EDC} \;\; f_{LUM} \;\; f_{DI} \;\; f_{PI} \,\}^T$ is the vector of the index finger tendon forces, $\boldsymbol{\tau}_T$ is the vector of the thumb joint torques, $\mathbf{M_T}$ is the vector of the thumb moment arms, and $\mathbf{F_{tendonT}} = \{\, f_{FPL} \;\; f_{FPB} \;\; f_{EPL} \;\; f_{EPB} \;\; f_{APL} \;\; f_{APB} \;\; f_{ADPt} \;\; f_{ADPo} \;\; f_{OPP} \,\}^T$ is the vector of the thumb tendon

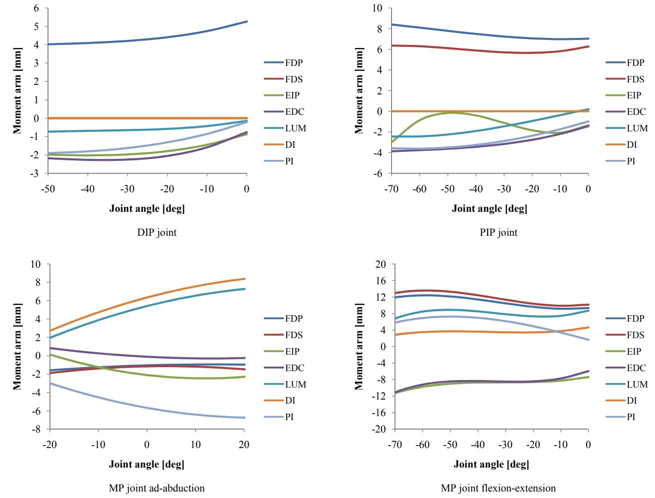


Fig. 8. Joint moment arms of the index finger used in our simulation

forces.

It is well known that the joint moment arms vary according to the finger posture. In this paper, we use the joint moment arm data that were measured from row cadavers by An *et al.* and Smutz *et al.* [6], [7]. In our simulation, the joint moment arms are given by the quadratic approximation of the An and Smutz data. Fig. 8 shows the examples of the joint moment arms used.

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 $\mathbf{J_I}, \mathbf{J_T}$ are Jacobian matrices, $\mathbf{F_I}, \mathbf{F_T}$ are the fingertip forces and torques of the index finger and thumb, respectively. The following equations are 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 axis forces at the fingertip are driven by seven and nine tendons for the index finger and thumb, respectively. Therefore, the tendon forces are derived from the optimization calculation of the following equation [8]:

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

$$0 \leq f_i \leq f_{imax} \tag{8}$$

where $PCSA$ is a physiological cross sectional area of each muscle and f_{max} is the maximal force of each muscle that is determined by $PCSA$ and the maximal muscle stress [9]. In this paper, we used the $PCSA$ values of Cuevas *et al.* research [10], [11].

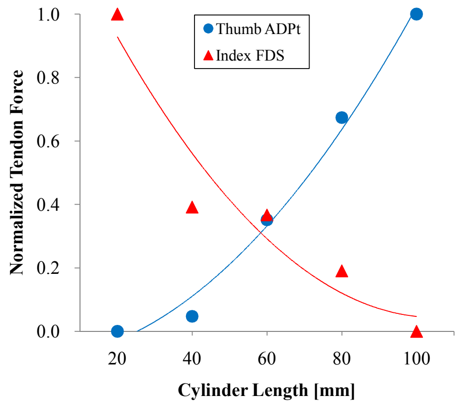


Fig. 9. Normalized summation of all the tendon forces when pinching cylinders with various length

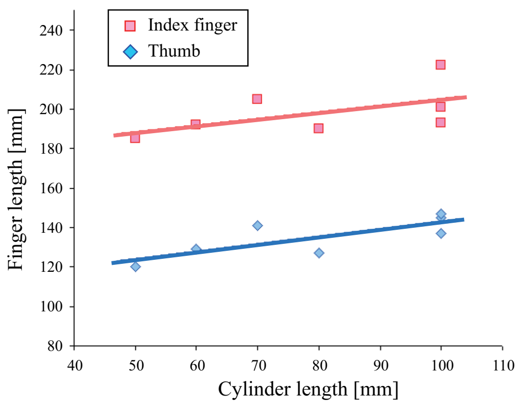


Fig. 10. Correlation between the finger length and the cylinder length where the summation of the simulated tendon forces becomes the minimum

B. Results

The link length ($l_{I1} \sim l_{I4}, l_{T1} \sim l_{T4}$) and posture ($\theta_{I1} \sim \theta_{I4}, \theta_{T1} \sim \theta_{T5}$) of the fingers were determined based on the subject data.

Fig. 9 shows the normalized tendon forces when pinching cylinders. This pattern of the tendon forces is similar to that of the human EMG activities shown in Fig. 3. Fig. 10 shows the correlation between the finger length and the cylinder length where the summation of all the tendon forces becomes the minimum. The lines in the figure are the least square regression line. The positive correlation can be observed between the finger length and the cylinder length: a larger cylinder is easier to pinch for a larger hand. This pattern is also similar to that of human results shown in Fig. 6. This indicates that the tendon force is a useful index for the evaluation of the subjective pinching effort and it can be used for the quantitative evaluation instead of EMGs.

The finger posture during pinching an object varies depending on the finger length even if a same object is pinched, and thus the tendon force to exert the fingertip force varies because the joint moment arms of human fingers vary depending on the finger posture. Our results imply that the reason why the subjective pinching effort is influenced by the finger length is the difference in the force transmission efficiency from the muscles.

IV. CONCLUSION

This paper investigated the influence of the finger posture on the subjective pinching effort by comparing experimental results of humans with simulation results by using a tendon-skeletal finger model. In the experiment, a questionnaire survey was done and surface EMGs of the subjects with various hand sizes were measured. The experimental results show that the EMG activity varies according to the object size he/she pinches, and the subjective effort correlates with the finger length. In the simulation, the tendon force to exert the fingertip force was calculated by using a biomechanical model that mimics the variation of human's joint moment arms. The simulation results show that the pattern of the tendon forces is similar to that of the EMGs measured in the experiment, and the positive correlation was observed between the finger length and the object size where the summation of the tendon forces becomes the minimum. These results imply that the reason why the subjective pinching effort is influenced by the finger length is the difference in the force transmission efficiency from the muscles.

Our results also suggest that the tendon force is a useful index for the evaluation of the subjective pinching effort, and it can be used for the quantitative evaluation instead of EMGs. We plan to make a robot hand with various sensors, which can quantitatively evaluate the usability and safeness of products instead of humans in the future work.

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