# Estimation of Fingertip Contact Force by Measuring Skin Deformation and Posture with Photo-reflective Sensors

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## ABSTRACT

A wearable device for measuring skin deformation of the fingertip—to obtain contact force when the finger touches an object—was prototyped and experimentally evaluated. The device is attached to the fingertip and uses multiple photo-reflective sensors (PRSs) to measures the distance from the PRSs to the side surface of the fingertip. The sensors do not touch the contact surface between the fingertip and the object; as a result, the contact force is obtained without changing the user's tactile sensation. In addition, the accuracy of estimated contact force was improved by determining the posture of the fingertip by measuring the distance between the fingertip and the contact surface. Based on the prototyped device, a system for estimating three-dimensional contact force on the fingertip was implemented.

## CCS CONCEPTS

• **Human-centered computing** → Interaction devices;

## KEYWORDS

wearable device, force sensing, photo-reflective sensor

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## 1 INTRODUCTION

Obtaining the contact force applied by a fingertip when it is touching an object would be useful for various applications. For example, in the case of mobile user interfaces, the contact force input by a user can be used to finely control a target object on the screen. It can also be used to evaluate the interaction of a user with a product, and a more user-friendly product can be designed according to the evaluation results.

Two approaches are commonly taken to obtain fingertip contact force. One approach is to attach a sensor to an object, and use the sensor to measure the contact force between the object and the finger. Since no sensors are attached to the finger, this approach allows the sensor to directly measure the contact force without affecting the natural finger movement. However, the drawback is that a sensor has to be attached to every object to be measured. The other approach is to attach a sensor to a finger or hand. The advantage of this approach is that each target object is not required to have a sensor. However, the tactile sensation of the object may differ when the sensor is attached to the fingertip and when it is not.

In this study, a different approach is proposed: a wearable device that can obtain fingertip contact force without any sensors placed between the surface of the finger and the object. When a finger contacts an object, the skin and subcutaneous tissue of the fingertip deforms. The proposed device measures this skin deformation by using photo-reflective sensors (PRSs) to measure the distance between the side of the fingertip and the sensors. Based on this device, a system for estimating fingertip contact force was implemented.

In addition, the contact area and position of the fingertip can change when fingertip posture changes; therefore, fingertip posture may influence the skin deformation of the fingertip. Fingertip posture was determined by using other PRSs to measure the distance between the fingertip and the contact surface, and those measurements are used to improve accuracy of estimated contact force.

## 2 RELATED WORK

### 2.1 Measuring Skin Deformation with Photo-Reflective Sensors

The proposed system estimates contact force by measuring skin deformation of the fingertip by using PRSs. A method for measuring skin deformation of the forearm with a light sensor was previously proposed by Ogata et al. [16]. A finger-ring device that measures bending angle of a finger and external force applied to the ring was also proposed by Ogata et al. [17]. Utilizing the principle that the skin sinks into the hole drilled in the ring, this ring device obtains various inputs. Moreover, a device that recognizes gestures by measuring the changing shape of an arm with multiple PRSs


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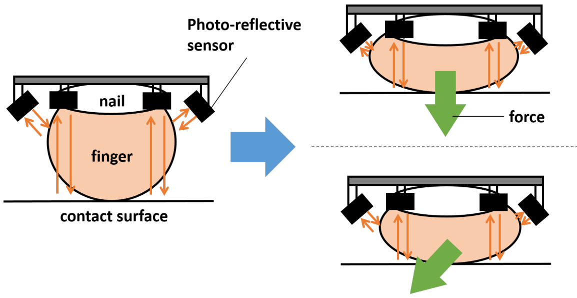


**Figure 1: Principle of estimating fingertip contact force by measuring skin deformation and distance between contact surface and fingertip.**

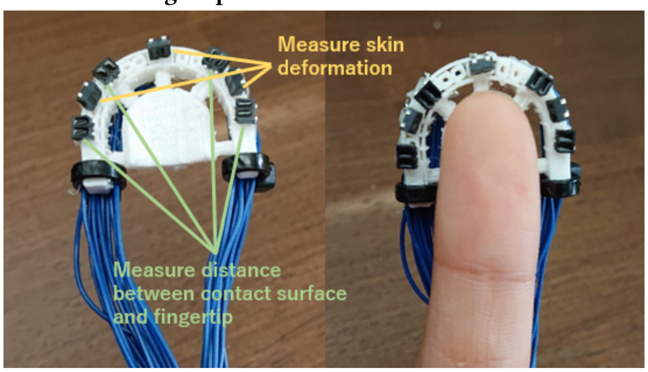


**Figure 2: Appearance of proposed device.**

arranged in a band was developed by Fukui et al. [3]. EarTouch is a device that recognizes gesture input to the ear by using several PRSs attached to the earphone to measure skin deformation inside the ear [9]. AffectiveWear is a device that measures the distance between the skin and the frame of glasses by using an array of PRSs on the frame to recognize facial expressions [11].

### 2.2 Fingertip-Mounted Devices

Several research projects have used devices attached to the fingertip. In one project, a tactile-sensation device that superimposes tactile sensation onto real environments was proposed by Ando [1]. In another, a motion-capture system that measures the bending motion of a finger by sensing the color of the nail was proposed by Mascaro et al. [12]. Moreover, a method of measuring the force applied to a finger pad by measuring the color of the fingertip with a camera was proposed by Grieve et al. [4]. NailO is a device packed with multiple capacitive sensors, and users can input gestures by touching their nails [8]. Acting as a user interface, a system that measures finger movement with a magnet attached to the thumb nail and a magnetic-force sensor attached to the forefinger was proposed by Liwei et al. [2]. NailDisplay, a small device that can be worn on nails, accepts inputs through finger movement [18]. And HapLog can estimate contact force through deformation of a finger pad incorporating a strain gauge [14]. The present study has been greatly influenced by the concept of HapLog. However, in comparison with HapLog, the sensors used in the proposed system are much smaller and in a much larger number, so the proposed system can estimate contact force in three dimensions. In addition, each sensor has a higher durability as it is not physically deformed when the finger touches an object. It also can be used by fingers of different sizes.

### 2.3 Three-Dimensional (3D) Input

Several methods for measuring force input have been proposed. Proposed by Mameno, one of them estimates fingertip contact force with infra-red LEDs and photodiodes [10]. Another method, proposed by Harrison et al., extends interaction by adding a function to measure the shear force on a touch panel [6]. Another method, which measures three-dimensional force by using a large number of force sensors attached to a smartphone case, was proposed by Heo et al. [7].

### 2.4 Fingertip Posture and Measuring Contact Force

In our study, which aimed to improve estimation accuracy of contact force, fingertip posture was determined by measuring the distance between the fingertip and the contact surface. It was reported that the friction coefficient of the fingertip changes according to contact force, contact area, and posture of the fingertip by Han et al. [5]. The relationship between contact angle of the finger and contact area was also reported by Nishimura et al. [15]. Moreover, posture angle of the fingertip was experimentally estimated by using a device that can estimate contact force by measuring blood volume under the fingernail by Mascaro et al. [13]. Since these studies show the relationship between fingertip posture and contact force, in the present study, fingertip posture was also measured, and the measurement results were used to improve the accuracy of estimated contact force.

## 3 PROPOSED HARDWARE DEVICE

A wearable device for estimating fingertip contact force—by measuring skin deformation of a fingertip and distance between the contact surface and the fingertip by using PRSs—was prototyped (Figure 1). A PRS consists of an infrared LED light and a phototransistor for measuring the reflected light. It is generally used for measuring distance and recognizing colors. The proposed system utilizes SG-105 photo-sensors manufactured by Kodenshi Co., Ltd. When a force is applied to a fingertip, the skin on the side of the fingertip deforms. Utilizing that fact, the proposed device measures that deformation by measuring the distance of the device from the side of the finger by using PRSs. Since the skin also deforms by applying force in the shear direction, skin deformation is also caused by three-dimensional contact force. In addition, fingertip posture was determined by measuring the distance between the fingertip and the contact surface by using PRSs attached to the device so that they face the contact surface. In consideration of wearability to the fingertip, 3D printer parts, curved to roughly follow the nail shape, were created. Seven sensors were placed around the edge of the parts so as to surround the fingertip (Figure 2). Three sensors were used to measure skin deformation, and the other four were used to measure the distance between the contact surface and the fingertip. Sensors with different roles were alternately arranged. The proposed device can be attached to a user's finger nail with double-sided tape.

The system consists of a wearable finger device and a laptop PC. The sensors of the device are connected to a microcontroller (Arduino Pro Mini, 3.3 V). The sensor data are transmitted to the PC by serial communication. Based on this system configuration, a system for estimating fingertip contact force was implemented.

# 4 ESTIMATION OF 3D FINGERTIP CONTACT FORCE

The proposed device estimates three-dimensional contact force applied to the fingertip. Since each person's skin deforms in a different manner, a multivariate regression model for each person is generated and used for estimating contact force. A multivariate regression model is a statistical method for estimating a relational expression between two certain continuous variables. It can estimate the value of one variable from the other. Accordingly, contact force was estimated from skin deformation of the fingertip by using the regression model to obtain the relation between skin deformation and contact force. In addition, the contact force was estimated from skin deformation of the fingertip and the distance between the contact surface and the fingertip by obtaining the relation between skin deformation, distance, and contact force with a regression model (Figure 3).

The proposed method involves two phases: a learning phase and an estimation phase. First, during the learning phase, skin deformation of the fingertip, distance between the contact surface and the fingertip, and contact force are simultaneously measured to determine the relationship between these three acquired parameters by using a regression model. Next, during the estimation phase, only skin deformation of the fingertip and distance between the contact surface and the fingertip are measured, and the regression model used in the learning phase is utilized to estimate three-dimensional contact force.

## 4.1 Measuring Fingertip Skin Deformation and Contact Force

Fingertip contact force was measured as three-dimensional data with a USL06-H5-50N load cell, manufactured by Tec Gihan Co., Ltd. Skin deformation of the fingertip and distance between the contact surface and the fingertip were measured with the proposed device as seven-dimensional data.

Sensors such as PRSs and load cells have a high-frequency and minute fluctuation, so they obtain sensor values with noise. To remove the noise, sensor values were therefore acquired five times and averaged. In addition, a thin flat plate (with size of 5 × 5cm) was placed on the load cell so that the distance between the contact surface and the fingertip could be accurately measured (Figure 4).

## 4.2 Selecting Regression Model

In preliminary experiments, several regression models, namely, kernel-ridge regression, support-vector regression, Gaussian-process regression, random-forest regression (RFR), and gradient-boosting regression, were investigated. On the basis of the results of the experiments, RFR was chosen since it had the highest coefficient of determination.

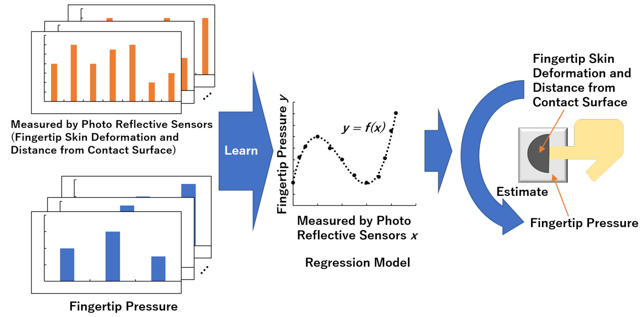


**Figure 3: Overview of estimation of 3D contact force of fingertip.**

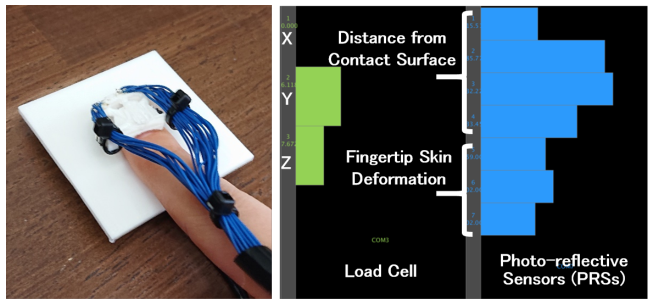


**Figure 4: Data acquired by the proposed device (seven PRSs) and load cell**

The determination coefficients of RFR and gradient-boosting regression are higher than in kernel-ridge regression and Gaussian-process regression because RFR and gradient-boosting regression both perform dimension reduction by selecting feature quantities at the time of model construction. The determination coefficient of RFR is higher than that of gradient-boosting regression, because RFR is less affected by changes in hyperparameters than gradient-boosting regression is.

By using RFR, 64 sets of sub-samples were generated from the dataset through random sampling, and 64 decision trees were created as weak learners, where each decision tree learns from each sub-sample. The decision trees randomly select $M/3$ variables from $M$ explanatory variables of the sub-sample ($M = 3$ for fingertip contact force and $M = 7$ for fingertip skin deformation and the distance between the contact surface and the fingertip) and calculate the best split function among all variables. The split function splits the sub-samples to obtain a statistical relationship between explanatory variables and dependent variables. To estimate contact force, the average of the estimated results of all learners is calculated.

## 4.3 Implementation

The proposed contact-force-estimation system was implemented by using the software Processing and programming language Python. Processing is used to record and visualize (as in Figure 4) fingertip skin deformation and the distance between the contact surface and the fingertip acquired by the proposed device and fingertip contact force acquired by the load cell. Python is used to generate a regression model and estimate fingertip contact force. During the learning phase, Processing records fingertip skin deformation, distance between the contact surface and the fingertip, and contact force and sends the recorded data to Python, which generates a RFR model from the received data. During the estimation phase, Processing sends sensor values to Python, which estimates fingertip contact force with the RFR model. The sampling rate of the sensors was set to 60 fps. The RFR implementation from the scikit-learn library was used.

## 4.4 Accuracy of Estimated Contact Force (in Pre-defined Condition)

Accuracy of the contact force estimated by the proposed system was evaluated by a user experiment. In the experiment, the participants were three Japanese men and six Japanese women in their twenties. During the experiment, each participant attached the proposed device on the index finger of their dominant hand. As shown in Figure 5, they then placed the finger on the load cell to apply a force to the load cell in four directions. Fingertip skin deformation of the index finger and distance between the fingertip and the contact surface were measured by the device, and contact force of the fingertip was measured by the load cell. Before the experiment, the participants practiced applying force twice in four directions and confirmed that an appropriate force was applied in each case. After completing the practices, ten sets of measurements (fingertip skin deformation, distance, and contact force) in each direction for each participant were acquired over about 12,000 frames (i.e., 60 fps × about 20 seconds × 10 trials). The participants applied force in the order of right, diagonally forward, forward and perpendicular for about five seconds in each direction, and they repeated this procedure ten times. During the experiments, the participants were able to see the visualized data (Figure 4) in real time. During the preliminary experiments, it was observed that the device was incapable of estimating forces over 10 N on the load cell since skin deformation did not occur. Therefore, when more than 10 N was applied in the z-axis direction, the sensor values were considered as 10 N.

On the basis of the data obtained from each participant, we performed ten-fold cross-validations, and the absolute value of the difference between the contact force measured by the load cell and that estimated by the proposed method was calculated, to evaluate the accuracy of estimated contact force. Since the shape of the finger skin depends on the participant, it was necessary to perform learning on each participant. Average estimation error of contact force for all participants was then calculated. Furthermore, to compare the estimation errors in the cases including or not including posture of the fingertip in the estimation, ten-fold cross-validation was performed without using the distance from the fingertip to the contact surface.

The result of the experiment for evaluating estimation accuracy (Figure 6) shows that the errors in the case including posture of the fingertip were 0.661 N (SD of 0.276 N) in the x-axis direction, 1.002 N (SD of 0.270 N) in the y-axis direction, and 1.071 N (SD of 0.200 N) in the z-axis direction. And in case posture of the fingertip was not included, the corresponding values were 0.865 N (SD of 0.327 N) in the x-axis direction, 1.077 N (SD of 0.268 N) in the y-axis direction, and 1.294 N (SD of 0.148 N) in the z-axis direction. In order to compare errors between cases with and without fingertip pose, a paired t-test was performed on each axis; a difference was considered to be significant if it was observed at a significance level of 5 %. An example of the temporal transition of estimation value of three-dimensional contact force for one participant is shown in Figure 7. In the figure, especially in the case of the x-axis, the estimation value in the case including posture is closer to the true value (i.e., contact force measured by the load cell) than the estimation value obtained by measuring only skin deformation of the fingertip. It is possible that that the participants tilting their finger to the right when applying forces in the x-axis direction significantly influences estimation error. On the other hand, the difference between two estimation values on the y-axis is smaller than that on the x-axis. This result is possibly due to the fact that the angle of tilting the finger was smaller when the participants applied forces in the y-axis direction than when they applied it in the x-axis direction. The cause of estimation error was likely to be improper force applied to the load cell since we put a thin plate on the load cell. Another cause is assumed to be the influence of ambient light during the experiment.

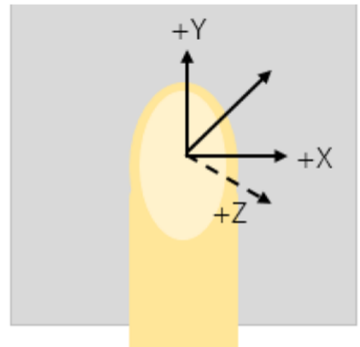


**Figure 5: Participants place their index finger on the load cell and apply force four direction: to the right (x-axis), diagonally forward, forward (y-axis), and perpendicular to the load cell (z-axis).**

## 4.5 Accuracy of Estimated Contact Force (in Random Condition)

To determine the accuracy of estimated contact force (in random condition), another user experiment was conducted. The participants (the same ones who participated in the first experiment) were three Japanese men and six Japanese women in their twenties. During the experiment, they attached the proposed device on their index finger of their dominant hand and placed the finger on the load cell to apply force to the load cell in positive directions shown in Figure 5 because the load cell used in the experiment cannot measure forces in the negative direction. The participants were told to apply force in any positive direction and change the direction in which they applied it every 2 seconds. Fingertip-skin deformation of the index finger and distance between the fingertip and the contact surface were measured with the proposed device, and contact force of the fingertip was measured with the load cell.

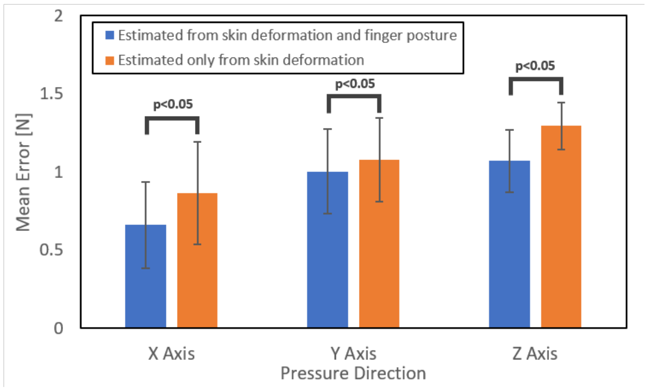


**Figure 6: Mean error of contact-force estimation (average of the absolute value of the difference between the contact force measured by the load cell and that estimated by the proposed method) under a pre-defined condition.**

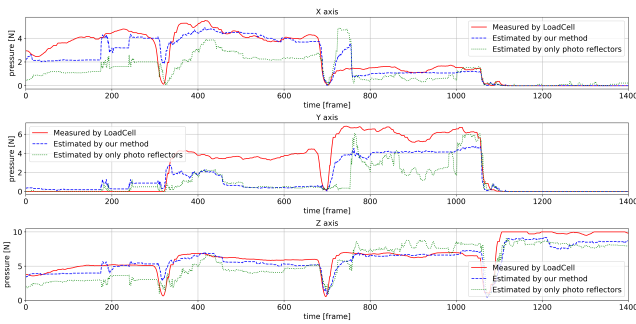


**Figure 7: Example estimation value of fingertip contact force under a pre-defined condition.**

The participants took a short break to rest their finger between the first experiment and the second experiment. Ten sets of the above-mentioned variables were measured for each participant; that is, about 12,000 frames (i.e., 60 fps $\times$ about 20 seconds $\times$ 10 trials) were acquired. When more than 10 N was applied in the z-axis direction, the sensor values were considered as 10 N.

On the basis of the data obtained from each participant, we performed ten-fold cross-validations, and the absolute value of the difference between the contact force measured by the load cell and that estimated by the proposed method was calculated, to evaluate the accuracy of estimated contact force. Since the shape of the finger skin depends on the participant, it was necessary to perform learning on each participant. Average estimation error of contact force for all participants was then calculated. Furthermore, to compare the estimation errors in the cases including or not including posture of the fingertip in the estimation, ten-fold cross-validation was performed without using the distance from the fingertip to the contact surface.

The result of the experiment for evaluating estimation accuracy (Figure 8) shows that the errors in the case including posture of the fingertip were 0.657 N (SD of 0.367 N) in the x-axis direction, 0.943 N (SD of 0.449 N) in the y-axis direction, and 1.179 N (SD of 0.248 N) in the z-axis direction. And in the case not including posture of

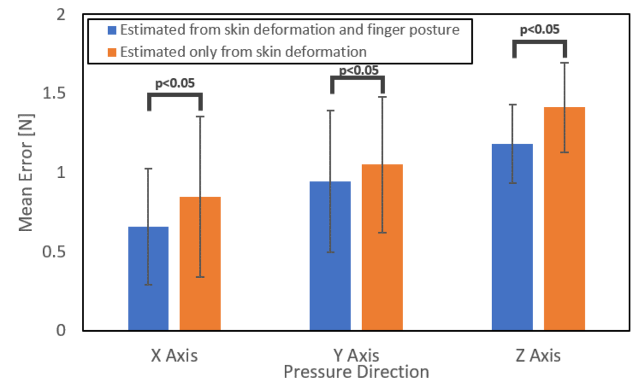


**Figure 8: Mean error of estimated contact force (average of the absolute value of the difference between the contact force measured by the load cell and that estimated by the proposed method) under a random condition.**

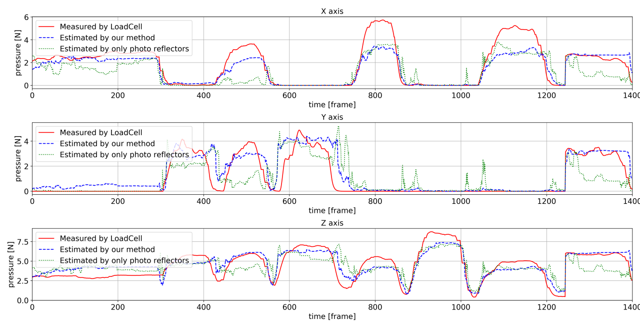


**Figure 9: Example estimation value of fingertip contact force under a random condition.**

the fingertip, the corresponding values were 0.847 N (SD of 0.507 N) in the x-axis direction, 1.050 N (SD of 0.430 N) in the y-axis direction, and 1.411 N (SD of 0.282 N) in the z-axis direction. In order to compare errors between cases with and without fingertip pose, a paired t-test was performed on each axis; a difference was considered to be significant if it was observed at a significance level of 5 %. An example of the temporal transition of estimation value of three-dimensional contact force for one participant is shown in Figure 9. In the Figure, when 0 N was applied in the x-axis or y-axis direction to the load cell, estimation value varied from 1 to 2 N in the case not including posture; however, the estimation value was about 0 N in the case including posture. When the participant applied force in the z-axis direction, estimation value varied from 1 to 2 N in the case not including posture. It is possible that it is easier to estimate contact force in the x-, y-, or z-direction by including posture than by not including it.

## 5 LIMITATIONS AND FUTURE WORK

The proposed fingertip-contact-force-measurement device utilizes PRSs to estimate contact force on the fingertip. However, as PRSs are easily affected by ambient light, the device malfunctions frequently in an environment with direct sunlight. In future work, to solve that problem, we will work on carrying out modulation control.

Another limitation of the device is that users with extremely large or small fingers may have difficulty using it. This problem can be solved by adding variations to the device size or by developing a device that can be adjusted according to the size of user's finger. In this study, the proposed device measured skin deformation of the fingertip. However, as size and shape of each user's fingertip differ, it is difficult to share a similar regression model for all users. Therefore, the contact-force-estimation system needs to be able to generate a regression model for individual users. Even if the same user wears the device, accuracy of estimated contact force decreases due to misalignment of the device during use or different mounting positions when re-attaching the device. Therefore, the system always needs to be able to generate a model when a user re-fits the device. We believe that these problems can be solved by calibrating the sensor values of the device.

## 6 CONCLUSION

A wearable device for measuring skin deformation of the fingertip was proposed. The device can estimate contact force without having a sensor on the contact surface between the fingertip and the object. It utilizes PRSs to measure the skin deformation by measuring the distance from the PRSs to the side of the fingertip to estimate the contact force. In addition, estimation accuracy was improved by determining posture of the fingertip by measuring the distance between the fingertip and the contact surface. A regression model was used to obtain the statistical relationship between skin deformation of the fingertip, distance between the fingertip and the contact surface, and three-dimensional contact force. The model was utilized to further estimate three-dimensional contact forces with other skin-deformation data. To evaluate accuracy of estimated contact force, a user experiment in which participants applied forces in a pre-defined condition was conducted. From the results of the experiment, mean estimation errors are 0.661 N in the x-axis direction, 1.002 N in the y-axis direction, and 1.071 N in the z-axis direction in case including posture. To evaluate accuracy of estimated contact force, a user experiment that the participants applied forces in a random condition was conducted. From the results of the experiment, the mean estimation errors are 0.657 N in the x-axis direction, 0.943 N in the y-axis direction, and 1.179 N in the z-axis direction in case including posture. The calculation of the t-test showed that the errors in case including and not including posture of the fingertip were significant on each axis.

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