Emergence of lateral softness sensations in surface tactile tele-presentation systems with force feedback

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Received 12 June 2013

Abstract
This paper reveals that lateral softness sensations can emerge in surface tactile tele-presentation systems with force feedback, if the systems have improper displacement measurements and/or stiffness mismatches between a fingertip and tactile sensors. In surface tactile tele-presentation systems, friction force should be reproduced on the master device for high fidelity rendering. If, however, the remote tactile sensor is made of soft material to resemble human fingers, users may experience apparent lateral softness, which does not exist in the remote sample. This work investigates such a phenomenon by using a force-reflecting type master-slave system. The phenomenon is analyzed to provide a simple solution to dissolve the lateral stiffness problem. The experiments reveal that the selection of displacement sensing point is important to prevent emergence of the apparent softness, in addition to the matching of sensor stiffness. The paper also discusses how the force reflecting gain affects the phenomenon.

Key words: Surface haptics, Tactile telepresentation, Lateral compliance, Lateral stiffness, Shear deformation

1. Introduction

Many kinds of tactile displays, or surface haptic displays, have been developed to render surface roughness textures. Surface roughness sensation can be elicited on a fingertip by inducing vibrations. For generating vibrations, reported tactile displays employed many different vibration sources, such as electromagnetic motors (Kontarinis and Howe, 1995; Kron and Schmidt, 2003), piezoelectric vibrators (Ikei et al., 1997; Nara et al., 2001; Okamoto et al., 2009; Wiertlewski et al., 2010), shape memory alloy actuators (Fukuyama et al., 2009), smart fluid (Jansen et al., 2010; Taylor et al., 1998), or electrostatic force (Bau et al., 2010; Tang and Beebe, 1998; Yamamoto et al., 2006). While most of the displays have been used to solely render artificial textures, some of the devices were incorporated in tactile tele-presentation systems to reproduce remote surface textures, combined with tactile sensors that pick up vibrations from remote samples. In most of the reported tactile tele-presentation systems (Kontarinis and Howe, 1995; Kron and Schmidt, 2003; Okamoto et al., 2009; Yamamoto et al., 2006), a user moves his/her fingertip on a master tactile display so as to virtually explore a remote surface, and the exploring motion is measured by a displacement sensor. The measured motion is reproduced at a remote site in real-time and the remote tactile sensor scans a remote surface in the same exploring motion. Then, the resulting vibration measured by the remote sensor is fed back to the master site also in real-time, and is reproduced on the master tactile display. In such a manner, the user can feel remote surface textures by cutaneous sense, as shown in Fig. 1.

Since the tactile sensations depend on the exploring motion, the reproduction of the exploring motion is imperative in such a system; if the sensor moves differently from the user’s exploring motion, completely different vibrations will result. Also important is the physical properties of the tactile sensors. To provide realistic sensations in such a system, the remote tactile sensor should pick up a similar vibration from the sample, as a real human fingertip does. Therefore, many researchers have developed tactile sensors that are composed of soft materials to resemble the vibrational characteristics of human fingertips (Fishel and Loeb, 2012; Hosoda et al., 2006; Kim et al., 2012; Okamoto et al., 2009; Takasaki et al., 2009; Wettels et al., 2008). However, the main design focus is typically paid on the vibrational characteristics, and the lateral stiffness of the soft sensor has not been paid so much attention.
Since most of the reported tactile displays provide vibration stimulus only, tactile tele-presentation systems tend to be designed to feed back only vibration information as well; friction force that accompanies the rubbing has been often ignored. Resulting surface texture feelings tend to be somewhat slippery or monotonous. Obviously, the rubbing friction force should also be measured and reproduced to enhance the reality, but there is not so much work that deals with friction force, in the context of tactile tele-presentation.

1.1. Effect of lateral force on tactile tele-presentation

The rubbing friction force creates lateral shear deformation on a fingertip. The role of the shear deformation in terms of tactile cutaneous sensation has been discussed in many literatures (Gleeson et al., 2010; Levesque and Hayward, 2003). It has also been pointed out by a recent study (Matsui et al., 2011) that the shear deformation affects the exploring motions of the human hand. Some devices that reproduce shear deformations have also been reported (Drewing et al., 2005; Matsui et al., 2011; Saga and Deguchi, 2012; Solazzi et al., 2011). But the effect of the shear deformation in the context of tactile tele-presentation has not been well studied.

Considering the findings reported in the above literatures, it is expected that users’ experience in tactile tele-presentation systems will become more realistic by feeding back finger deformation caused by friction, in addition to the texture-oriented vibrations. However, due to the absence of practices, practical problems in realizing such a system have not been made clear, which motivated us to carry out this work. In this work, we have tried to reveal a practical problem that can arise when the rubbing frictional force and corresponding shear deformation are reproduced in tactile tele-presentation systems. As the first step, the work developed a simple tele-presentation system that reproduces finger shear deformations. The experimental system is based on force-reflecting type master-slave architecture, which has been extensively studied for haptic tele-operation (Anderson and Spong, 1989; Hannaford and Anderson, 1988; Sheridan, 1989). In some studies, such as (Kontarinis and Howe, 1995), force-reflecting type master-slave was used together with vibratory tactile display for tactile tele-operation, as well. However, as those studies rather focus on how tactile feedback can improve haptic operations, not on the quality of tactile sensations, the effect of lateral force feedback on tactile sensations has not been discussed. In other typical haptic tele-operation studies, force sensors in the remote site has a rigid structure as it is solely used for force sensing. Therefore, although there are a number of studies on the force transparency or stability of haptic master-slave systems (Hannaford, 1989; Hokayem and Spong, 2006; Lawrence, 1993; Yokokohji and Yoshikawa, 1994), the effect of using soft sensors, especially its effect on the perceived tactile sensations, has not been paid attention.

1.2. Scope of this work

Through our experiments using the developed prototype system, we found an interesting phenomenon that is emergence of lateral softness sensations. If a soft tactile sensor is employed in the system, a user may feel lateral softness as the user changes the scanning direction, even though the remote surface sample is rigid. The paper reveals the cause of the phenomenon through simple experiments and provides a guideline to prevent the emergence of the lateral softness.

The remainder of the paper is structured as follows. In the next section, the paper describes the overview of the tele-presentation system that feeds back friction force. The third section describes the phenomenon: emergence of apparent lateral softness. The fourth section formulates this phenomenon and discusses a solution to prevent the emergence. The proposed solution is verified in the fifth section experimentally. The last section summarizes the work and provides a simple design guideline for the future developments.
2. Experimental setup

This section describes the experimental setup that was developed to investigate the apparent lateral softness that emerges due to improper displacement measurement and/or stiffness mismatch between a fingertip and a tactile sensor. The system consists of two major parts, a master device and a remote tactile sensor. A user virtually rubs a remote surface sample by moving a contact pad in the master site. The motion of the contact pad is reproduced in the remote site to scan the remote sample in the same motion. The remote tactile sensor measures friction force coming from the remote sample that is fed back to the master device in real time. The resultant system architecture is same as a typical force-reflecting-type master-slave system. The system, however, is unique in that it is designed for direct touch. Typical force reflecting systems utilize styluses for their operations and therefore users’ experience is limited to force sensation only (Anderson and Spong, 1989; Hannaford and Anderson, 1988; Sheridan, 1989). Conversely, this system allows users to experience a kind of surface tactile sensations due to the flat interacting plate employed in the master device (although tactile rendering was not implemented in this particular work). Differently from typical work on master-slave systems, this work focuses on the cutaneous sensations elicited by the system. The following subsections describe the details of each part, the master device and the remote tactile sensor.

2.1. Master device

Figure 2 shows an appearance of the master device. Main components of the device are a contact pad, a linear voice coil motor (VCM), a load-cell, and two laser displacement sensors. The contact pad is a rigid acrylic plate with a flat surface. The pad is guided by a linear guide that is arranged on the load-cell (LUR-A-50NSA1, Kyowa Electronic Instruments) to facilitate measurement of the vertical contact force. A user puts his/her index fingertip on the contact pad and moves it laterally to virtually explore a remote surface. The finger and the contact pad always move together and do not slip against each other. The VCM (AVM30-15, Technohands) is connected to the contact pad to provide lateral force, $F_m$, which simulates the friction force measured at the remote site. One laser displacement sensor (ZX-LD40, Omron) measures displacement of the contact pad, $x_p$.

During the operation, the user rests his palm on a palm rest. The palm rest is guided by a linear guide that can freely move with negligibly small friction so that it does not disturb the exploring motion of the finger. The palm rest is equipped with a finger supporter that gently fixes the position of the finger against the palm rest. The displacement of the palm rest, $x_f$, is measured by the other laser displacement sensor (ZX-LD100, Omron). We assumed that the displacement of the palm rest represents the position of the finger bone, and this displacement is hereafter simply referred to as “finger displacement”. On the other hand, the displacement of the contact pad, $x_p$, represents the position of the fingertip surface. When the VCM generates friction force, the fingertip deforms laterally, which creates a difference in the two displacements.

Although the system is equipped with two displacement sensors, this is solely for investigation of the phenomenon. We assume that future practical systems will use only one displacement sensor, considering the cost and the simplicity of the system.
2.2. Remote tactile sensor

Figure 3 shows an appearance of the remote tactile sensor. The sensor body is made of silicone resin to roughly resemble the softness of a fingertip and is fixed to a rigid sensor base. Lateral stiffness of the sensor was roughly matched to the stiffness of a fingertip. The sensor body is wrapped by a PVDF (polyvinylidene fluoride) film to facilitate tactile vibration measurement (Yamamoto et al., 2006). In this particular work, however, the system does not use PVDF signals because this work focuses on friction force; effects of texture vibration transmission will be addressed in our future work.

The sensor base is held by an acrylic beam, on which two strain gauges (KFP-2-120-C1, Kyowa Electronic Instruments) are glued to measure lateral friction force, $F_r$, between the sensor and a surface sample. Beneath the tactile sensor, a sample stage is arranged to reproduce the user’s motion in the master site. The stage is actuated by a VCM (AVM30-15, Technohands) and a linear slider (EZS3-20, Oriental motor). The VCM, which is located beneath the sample stage, vertically pushes up the sample against the tactile sensor. The linear slider that is located at the bottom actuates the stage in a lateral direction and reproduces the finger lateral motion at the master site.

2.3. Control architecture

Figure 4 is a schematic diagram that overviews the signal flow of the system. The fundamental control architecture used in the system is same as a typical force-reflecting type master-slave system; the master device measures displacement, which is sent to the remote site, whereas the remote system measures resulting force, which is fed back to the master. The whole controller is implemented on a DSP board (DS1104, dSPACE). The controller reads all the measured signals and drives all the actuators based on the measured signals. No communication delay was assumed. The controller sends positioning pulse sequences to the driving unit of the linear slider in the remote system (that accepts CW/CCW positioning pulses) to reproduce the motion of the master device. The positioning pulse sequence is calculated based either on contact pad (fingertip surface) displacement $x_p$, or finger (palm rest) displacement $x_f$. For force reproduction, the controller reads friction force, $F_r$, from the remote site which is reproduced at the master site by using current-controlled VCM in an open-loop control.

Although reproduction of vertical contact force would be also important in this kind of systems, this particular work fixed the contact force at the remote site and the user in the master site tried to keep the constant contact force during the experiments. This is partially because that the data will be contaminated by contact force fluctuation if the vertical force is simply reproduced.

3. Emergence of softness in turnover

This section explains the softness emergence phenomenon using results of simple experiments. As the remote surface sample, a flat acrylic plate without any surface texture feature was chosen, to focus on the shear deformation of the fingertip. The vertical contact force in the remote site was set to a fixed nominal value, 2 N, and a user in the master site was directed to operate the device with approximately 2 N contact force. The value was selected so that it can create enough friction force for the lateral deformations, within the range of typical contact force that users produce during rubbing exploring motions. To keep the contact force at the nominal value, the user trained himself to produce a constant force by monitoring the output of the load-cell on the master site, before carrying out the experiments. Also during the experiments, the output of the load-cell was shown to the user for reference.
3.1. Improper displacement measurement generates apparent lateral softness

In the following experiments, the remote stage followed either the contact pad displacement or the finger displacement. The comparison of these two experiments shows that finger displacement should be measured for proper reproduction of lateral stiffness of a remote sample.

3.1.1. Contact pad displacement as the reference

Typical force-reflecting type master-slave systems measure displacement of their styluses (which is in this case the contact pad) in the master site. This first experiment was, thus, carried out to resemble such typical situations; the pad displacement was used as the reference for the remote stage motion. With that setup, we found that a kind of softness sensation can be felt during motion turnovers, although the remote object was a rigid acrylic plate.

Figure 5 graphically shows the situation. This situation appears in the initial start-up and in every motion turnover, but the following explanation focuses on the initial motion when a user just starts rubbing motion from the initial rest. When a fingertip rubs a real surface, the fingertip experiences lateral shear deformation before it starts slipping. If the surface is compliant in lateral rubbing direction, the surface also deforms in the lateral direction, which makes the finger displaces without slipping (Fig. 5 (A)(i)). In case of the master-slave system, if the contact pad displaces before the tactile sensor starts slipping (Fig. 5 (B)(i)), users feel as if the remote surface is compliant in lateral direction, since this situation is virtually the same as the above real situation. (Here, it should be noted that users can feel the start of slipping of the remote sensor by a sudden drop of friction force due to friction states change from static to dynamic, or by the tactile vibration signal if vibration feedback is implemented, which is not the case for this work.)

In the master-slave system, the forces on the master and the remote sites are always in balance. Therefore, when the fingertip laterally deforms, the remote sensor also deforms to produce the same lateral restoring force as the fingertip does. To have the remote sensor deform, the remote stage must displace that requires the reference displacement signal from the master site also changes by the same amount. Since, in the case considered here, the reference signal is the contact pad displacement, the contact pad must move before the sensor starts slipping. Thus, even when a remote sample...
is rigid and has no lateral deformation, the contact pad in the master site moves laterally before the start of slipping. This results in the situation illustrated in Fig. 5 (B)(i), which is felt as lateral softness by the user.

Figure 6 shows the experimental results that graphically explain the behavior. Figure 6 (A) shows time-course measurement results of the two master displacements and friction force measured at the remote site; finger displacement is shown only for reference. The plot for the vertical contact force shows the measured vertical force in the master site. Although there is a little fluctuation, it can be confirmed that the vertical contact force in the master site was kept near the nominal value (2 N) during the experiment. Figure 6 (B) shows the relationship between the contact pad displacement and friction force at a turnover (the shaded area in Fig. 6 (A)). As explained above, the pad displacement is related with the perceived lateral deformation of the remote sample, the ratio (or the gradient in the plot) between the force and the pad displacement corresponds to the lateral stiffness. The plot in (B) clearly shows that apparent lateral softness emerged in this case.

3.1.2. Finger displacement as the reference

If the system has the apparent lateral softness, the system cannot render the correct cutaneous sensations any more, and thus the emergence of the apparent softness should be avoided. As one can easily imagine from the above explanation, the lateral softness emerged because of the wrong choice of the point of displacement measurement. In the above experiment, the displacement of the contact pad, which represents the fingertip surface, was measured in the master site and was reproduced in the remote site as the relative displacement of the sensor base (which is equivalent to the bone of the finger) against the target sample. This means that the emergence of the lateral softness can be avoided by using finger displacement as the reference for the remote stage control.

The measurement result, when the finger displacement, \( x_f \), is used as the reference, is shown in Fig. 7 (A). The relationship between the friction and the pad displacement during a turnover is shown in Fig. 8 as (ii). The plot in Fig. 8 shows the relationship between the displacement of the contact pad \( x_p \) and the reproduced friction force \( F_m \) during a turnover, as same as Fig. 6 (B). The curve (ii) in the plot is almost vertical, which means that the lateral softness did not emerge in this case and that subjects could feel the correct lateral stiffness of the remote surface.

3.2. Effect of sensor stiffness

The previous set of experiments compared two different measurements of displacement in the master site. The results insisted that the finger displacement should be measured to reproduce the lateral stiffness correctly. However, even if the fingertip displacement is measured, the lateral stiffness can still emerge if the sensor lateral stiffness is not appropriate.

The next experiment shows such a situation by using a softer tactile sensor body. Another tactile sensor was fabricated for this experiment using softer resin. The lateral stiffness of the softer sensor is smaller than that of human fingertips. In this case, subjects could feel apparent softness, which can be explained by using Fig. 9. If stiffness of the tactile sensor is smaller than that of the fingertip, the tactile sensor deforms more than the fingertip under the same lateral force (friction force), which resulted in additional displacement in the master site. The time-course results using the soft sensor is shown
in Fig. 7 (B), and the relationship between the pad displacement and the friction is shown in Fig. 8 as (iii). The curve (iii) shows different gradients for positive and negative friction. This would be because of the non-linearity of the sensor stiffness, which was not prominent in the harder sensor. In the softer sensor, as the sensor is vertically compressed, the spring characteristics would be different for the motion recovering the original sensor shape and for the opposite motion that increases the sensor deformation. Thus, the curve completely flips when the sensor turns in the opposite direction. That can be confirmed by the curve (iii') in Fig. 8, which was extracted from another turnover for the opposite direction; the curves (iii) and (iii') are symmetric.

4. Mathematical expression

For mathematical formulation of the phenomenon, the situation is modelled as in Fig. 10. Generally, rubbing motions can be divided into two phases, sticking phase and slipping phase, and this analysis focuses on the sticking phase, since the apparent lateral softness appears in this phase. (Since the finger is always sticking to the contact pad in our setup, the sticking and slipping should be discriminated by the state of the remote sensor.) The sticking phase appears in two different conditions; one is the initial start-up, and the other is motion turnover. In the initial start-up, the finger and the sensor are first resting at an un-deformed state, and then start deforming as the finger moves. The first resting state is hereinafter referred to as the “natural state”. During the motion turnovers, the natural state also appears at the middle of the motion (see. Fig. 10). Therefore, we analyze the behavior of the fingertip and the sensor for the period starting from the natural state until the end of the sticking motion. In the following analysis, all the displacements were measured from the natural state.

4.1. Case I: contact pad displacement as the reference

When the pad displacement, \( x_p \), is used as the reference, the displacement of the remote stage, \( x_r \), coincides with \( x_p \).
In sticking phases, $x_r$ is also equal to the sum of sensor deformation $\delta_s$ and the target sample deformation $\delta_t$.

$$x_r = \delta_s + \delta_t = x_p$$  \hspace{1cm} (1)

Due to the nature of the force-reflecting type master-slave system, the forces for both sites balance as,

$$F_m = F_r$$  \hspace{1cm} (2)

In sticking phases, if we assume linear spring behavior for all the lateral deformations, the forces have the following linear relationships against the deformations.

$$F_m = \frac{\delta_f}{c_f}$$  \hspace{1cm} (3)

$$F_r = \frac{\delta_s}{c_s} = \frac{\delta_t}{c_t}$$  \hspace{1cm} (4)

where $\delta_f$ is the deformation of the fingertip and $c_f$, $c_s$, and $c_t$ are the lateral compliances (inverse of the stiffnesses) of the fingertip, the remote sensor, and the remote target sample, respectively. From the above equations, the apparent lateral compliance that emerges in the master site, $c_a$, is calculated as

$$c_a = \frac{x_p}{F_m} = c_s + c_t$$  \hspace{1cm} (5)

This means that the user feels the serial combination of the two springs, which represent the sensor and the target sample. If the target sample is rigid, as the example shown in §3, the user simply feels the softness of the remote sensor. The correct reproduction is possible only when sensor is rigid ($c_s = 0$). However, tactile vibration sensing normally requires soft sensor body and thus this condition is not practical.

### 4.2. Case II: finger displacement as the reference

When the finger displacement, $x_f$, is used as the reference, Eq. (1) needs to be modified as

$$x_r = \delta_s + \delta_t = x_f = x_p + \delta_f$$  \hspace{1cm} (6)

The other Eqs. (2) to (5) still hold for this case. Finding apparent lateral compliance from these equations results as

$$c_a = \frac{x_p}{F_m} = c_s + c_t - c_f$$  \hspace{1cm} (7)

In this case, if the sensor compliance is same as the finger compliance, the user experiences the correct compliance, $c_t$, on the master device.
4.3. With force/displacement scaling

Master-slave systems are sometimes employed for manipulation of different-sized worlds, such as microscopic worlds under microscopes. In such a case, the force and the displacement exchanged between the master and the remote sites are scaled to match the size of the target world. Here, we would like to discuss if we can keep the correct lateral stiffness in such a case.

When the displacement (from master to remote) and the force (from remote to master) are scaled by factors of $g_x$ and $g_f$, respectively, the following equations hold, instead of (1), (6), and (2)

$$x_r = \delta_s + \delta_t = \begin{cases} g_x x_p & \text{(for case I)} \\ g_x (x_p + \delta_f) & \text{(for case II)} \end{cases}$$

(8)

$$F_m = g_f F_r$$

(9)

Resulting lateral compliance is

$$c_a = \begin{cases} c_s + c_t & \text{(for case I)} \\ \frac{c_s + c_t}{g_f g_x} & \text{(for case II)} \end{cases}$$

(10)

Here we consider two situations. In one situation, we know, in advance, that the target sample is a rigid body, that is $c_t = 0$. In the other situation, we do not have any information on the compliance of the target body; in this case $c_t$ can have an arbitrary value. For case I, if $c_t = 0$, there is a solution that matches the apparent lateral compliance with that of the target sample; the solution is $c_s = 0$. However, this solution requires the sensor to have a rigid body, which is not appropriate for the tactile tele-presentation system. If $c_t$ takes an arbitrary value, on the other hand, there is no solution for case I that holds for arbitrary $c_t$.

For case II, a solution is found only for the situation $c_t = 0$. When $c_t = 0$, which means the target surface is rigid, the apparent stiffness matches with the target stiffness if the following condition is fulfilled

$$c_s = g_f g_x c_f$$

(11)
Unfortunately, for the second situation where the target sample has arbitrary stiffness, correct reproduction of the lateral stiffness cannot be guaranteed regardless of the choice of the scaling factors and the sensor stiffness.

Equation (11) also suggests that if scaling is allowed, we can compensate the inappropriate stiffness of the remote sensor by force or displacement scaling (again, for the case $c_t = 0$). This possibility is verified in the following experimental section.

5. Experimental evaluation

A set of experiments was carried out using the softer sensor as the remote sensor. A pilot experiment identified that the lateral stiffness of the softer sensor was almost 6 times smaller (softer) than that of a fingertip. Through the following experiments, we confirmed if this inappropriate lateral stiffness of the sensor can be compensated by appropriate force scaling. Displacement scaling was not used as the system specifications, such as motion strokes and displacement sensor resolutions, did not allow significant displacement scalings.

The finger displacement, $x_f$, was used as the motion reference for the remote site. Force scaling gain $g_f$ was set either to 1, 2, 4, or 6. The vertical contact force on the master site was kept at 2 N by the user’s effort. In the remote site, the vertical contact force was set to $1/g_f$ of the nominal contact force of 2 N, to keep the magnitude of the reproduced force at the master site within an appropriate level.

We evaluated the apparent stiffness from the slopes that relates the displacement and the force during turnovers (as in Fig. 6 (B)). The results are plotted in Fig. 11 and their corresponding time-course plots, together with force-displacement relations, are provided for reference in Fig. 12. Horizontal axis in Fig. 11 represents inverse of force scaling $1/g_f$, whereas vertical axis indicates the apparent compliance ($x_p/F_m$). The dashed line in the plot is the theoretical estimation obtained from Eq. (10) for case II, with the following condition: $c_f = 0.8$ (which is calculated from Fig. 6 with an assumption that the original sensor has almost the same lateral stiffness as the fingertip), $c_t = 0$, $c_s = 6c_f$, and $g_x = 1$. It was confirmed that the apparent stiffness did not emerge when the force-reflecting gain was set to the ratio of the stiffnesses, that is $g_f = 6$. This result confirms that the compliance can be compensated using Eq. (11).

For the force scaling factor $g_f = 6$, we also tested different scalings for vertical contact force. The plot in Fig. 11 also shows the results for vertical scaling factors of $1/4$, $1/3$, and $1/2$ against the nominal contact force of 2 N. Regardless of the vertical force scaling, the correct lateral compliance was rendered on the master site. If we assume Coulomb’s law of friction, changing the vertical contact force is equivalent to changing the friction coefficient. Therefore, the results imply that the emergence of the lateral softness is not affected by the friction coefficients of the sensor surface.

6. Conclusions

Force-reflecting type master-slave control is a common architecture for bilateral force feedback. If the architecture is applied to surface tactile displays, however, it can exhibit strange phenomenon in terms of cutaneous sense. The phenomenon is emergence of apparent lateral softness sensations. This paper reported how the lateral softness emerges within such a system through a set of simple experiments and formulated it. What was revealed in the paper may sound rather natural and obvious, but is quite important for designing tele-tactile system with force feedback, since the apparent lateral stiffness deteriorates the quality of reproduced sensations.
Fig. 12  Time-course results and the relation between the pad displacement and the friction force, for the experiments using the lateral force scaling: (A) \( g_f = 1 \), (B) \( g_f = 2 \), (C) \( g_f = 4 \), and (D) \( g_f = 6 \).

The paper revealed that the apparent lateral softness emerges in two cases. One case is inappropriate displacement measurement in the master site. The other case is mismatch of lateral stiffness between a fingertip and a tactile sensor. From the results of the experiments, the following guideline can be derived:

i. The motion of the remote tactile sensor should be controlled in reference to the finger (bone) displacement, not the device (contact pad) displacement.

ii. The lateral stiffness of the remote tactile sensor should be adjusted to that of a human finger.

iii. If the guideline ii. cannot be satisfied, tuning of force reflecting gain may prevent the emergence of lateral stiffness, if force scaling is applied in the application and the target sample is rigid.

The experiments of this work did not pay much attention to the vertical contact force and kept it at a constant value. Although the final experiment implied that the vertical force does not significantly affect the emergence of the lateral stiffness, it should affect other aspects of the perceived sensations. Therefore, the effect of vertical force should be investigated in the future study.

Acknowledgements

This work was supported by Funding Program for Next Generation World-Leading Researchers (#LR013) from JSPS and Grant-in-Aid for JSPS Fellows (24-8552).

References


