DISPLAY OF FRICTION IN VIRTUAL ENVIRONMENTS BASED ON HUMAN FINGER PAD CHARACTERISTICS

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ABSTRACT

A friction display system is proposed for virtual environments. Since a user's fingertip is often placed inside a ring or thimble of a haptic interface , the finger pad cannot move relative to the finger structure as freely as it would move in the real world. Thus, it is necessary to imitate the real world movement of the human finger pad in the virtual environment. This paper quantifies the frictional properties of the human finger pad on 9 subjects by simultaneously recording force and movement of the finger pad when it rubs against a rigid plate. Results of such tests and implementation in a virtual environment are reported.

INTRODUCTION

Designers of complex mechanical assemblies typically create physical prototypes to evaluate part interaction, ease of assembly, and functionality. To avoid this time-consuming and costly procedure, virtual prototyping seeks instead to employ realistic simulation and immersive interfaces. Although mechanical CAD systems provide realistic visual displays, they do not permit a designer to manipulate and interact with mechanical elements in a realistic manner. For example, a haptic interface coupled with a visual display would allow a designer to evaluate car dashboard designs [22] and to experience assembly forces [7].

In the real world, we rub on the surfaces of objects to sense their roughness, texture, discontinuity of curvature, etc. Similarly, imposing tangential forces on the users of haptic display systems creates a significant sense of realness in virtual environment. Without imposing friction in the virtual world, all objects are perceived as slippery as an icy surface.

Recently, there have been a number of research works to display friction in the virtual environment. Chen et al. [1] developed a 2-D spring model by using the concept of contact area to unify the forces due to friction and adhesion. Salcudean and Vlaar [16] presented a stick-slip model, which employs a velocity threshold to define sticking, but which only employs a viscous friction during slipping. A stick-slip friction model which uses Coulomb friction in the *slip* phase was employed by Salisbury et al. [17]. However, these works have not included human finger pad frictional characteristics in their friction models. Unlike in the real world, in many haptic interfaces, a fingertip is placed inside a ring or thimble. Thus, the finger pad cannot be displaced relative to the thimble to create the same sense of touch as in the real world. For this reason, a haptic interface must artificially create the displacements and forces as would be created by a real frictional surface. This paper is the first attempt in integrating finger pad characteristics with the virtual friction model.

Although there have been a number of recent works on the normal properties of the finger pad [6, 15, 18, 20, 21], frictional properties of the finger pad have not been explored much. Han et al. [8] investigated human fingers to mimic in making robot fingers. They found that the finger pad coefficient of friction increases significantly for small normal forces (e.g. $< 2N$), and is relatively constant for bigger normal forces. In the field of teleoperation, Edin et al. [2] investigated the effect of slippage on relaying friction to the master operator.

In the next section, a simplified basic stick-slip friction model is explained first. Then finger pad frictional characteristics are explored and incorporated in the basic model. Display of friction in virtual environments using this model is also illustrated.

BASIC STICK-SLIP MODEL

Assume the haptic interface is moving against a surface. In the *slip* phase, the friction force $\mathbf{f}_f$ is:

$$\mathbf{f}_f = \mu_d \,||\, \mathbf{n} \,||\, \frac{\mathbf{v}}{||\, \mathbf{v} \,||} \quad \text{if} \quad ||\, \mathbf{v} \,|| > v_{min} \tag{1}$$

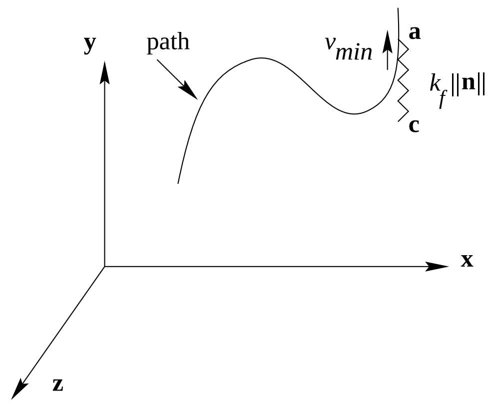

Figure 1. TRANSITION FROM *SLIP* to *STICK* PHASE IN THE SIMPLIFIED MODEL.

where μ_d is the dynamic coefficient of friction, $|| \mathbf{n} ||$ is the magnitude of normal force, $\mathbf{v}$ is the tangential velocity of the haptic interface, and v_{min} is a small threshold velocity. As soon as $|| \mathbf{v} ||$ becomes smaller than v_{min}, the *stick* phase begins.

It is more intuitive to explain the *stick* phase in a simplified form first. Later, the incorporation of pulp frictional behavior into this simplified model will be explained.

Figure 1 shows the transition from *slip* to *stick* phase. Point **a** represents the transition point where the velocity reaches a threshold of v_{min}. During this transition, a virtual spring is formed whose stiffness $k_f \; || \mathbf{n} ||$ is proportional to the normal force. It pulls the haptic interface towards **c** (stick center). The spring force at this moment is:

$$\mathbf{f}_f = k_f \; || \mathbf{n} || \; (\mathbf{a} - \mathbf{c}) = \mu_d \; || \mathbf{n} || \; \frac{\mathbf{v}}{|| \mathbf{v} ||} \tag{2}$$

As long as the spring force is less than the static friction limit $\mu_s \, || \mathbf{n} ||$, the *stick* phase holds. In other words, the haptic interface is trapped in a circle of radius $\mu_s/\mu_d \; ||$ **a-c** $||$ centered at **c**. **c** is found by:

$$\mathbf{c} = \mathbf{a} - \frac{\mu_d \, || \mathbf{n} ||}{k_f \; || \mathbf{n} ||} \frac{\mathbf{v}}{|| \mathbf{v} ||} = \mathbf{a} - \frac{\mu_d}{k_f} \frac{\mathbf{v}}{|| \mathbf{v} ||} \tag{3}$$

where $\mathbf{v}$ is the velocity just before transition. It can be easily shown that the maximum stick radius is μ_s/k_f. The harder the contact materials of surface and haptic interface, the bigger k_f. The *slip* phase begins when the haptic interface is μ_s/k_f or equally $\mu_s/\mu_d \; || \mathbf{a} - \mathbf{c} ||$ away from **c**. We can imagine that the virtual spring has a rupture limit of $\mu_s \; || \mathbf{n} ||$.

Figure 2 shows a one-dimensional simulation of position, velocity, and friction force of a haptic interface moving tangentially against a wall. It is assumed that normal force is constant and there is a sinusoidal tangential motion. It shows that when velocity becomes as slow as v_{min}, the *stick* phase (dotted) begins. The dashed line in Figure 2(i) shows stick center position. A slight increase in y after the onset of the *stick* phase at point **a**, causes a slight increase in virtual spring force $\mathbf{f}_f$. Then y decreases until the force in the virtual spring is $\mu_s \; || \mathbf{n} ||$. At this point, friction suddenly changes to $\mu_d \; || \mathbf{n} ||$ of the *slip* phase. Note that the change of force is continuous in transition from the *slip* to the *stick* phase, and discontinuous in transition from the *stick* to the *slip* phase.

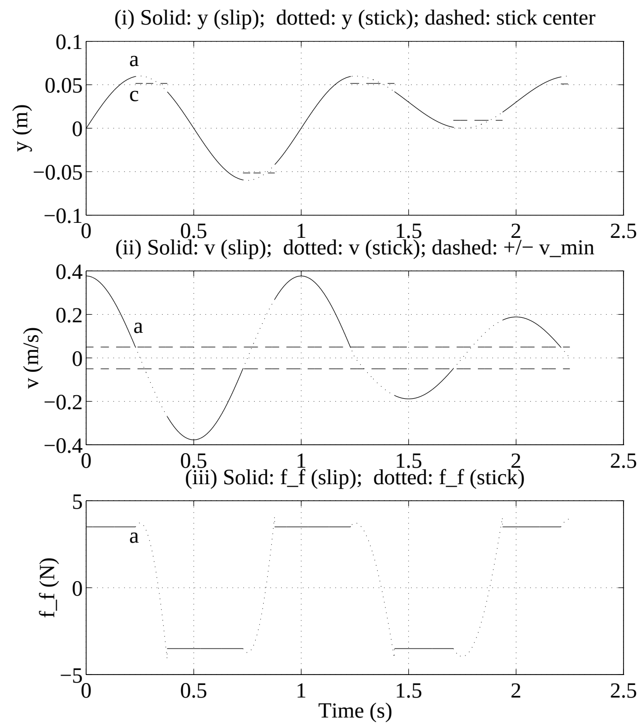

Figure 2. SIMULATION OF STICK-SLIP FRICTION FORCE IN THE BASIC MODEL.

FINGERTIP FRICTIONAL CHARACTERISTICS

In order to have a realistic model of the stick-slip friction, we need to incorporate the frictional properties of the pulp into our model. Skin is thick, glabrous, and rich in sweat glands. Nerve endings are found in abundance in the skin [4]. Soft subcutaneous adipose tissue forms an almost continuous layer beneath skin. Blood vessels and lymphatics form a rich network throughout the adipose tissue. This tissue can be distorted readily and it slowly resumes its original shape [12]. An abundance of nerves also run through this tissue.

Stick Ellipse

The stick region of the pulp should be evaluated. 9 subjects were asked to press on a paper-coated, flat, and rigid plate with

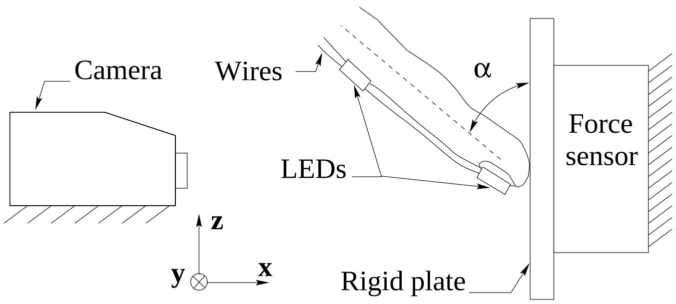

Figure 3. THE EXPERIMENTAL SETUP FOR MEASURING FINGER PAD FRICTIONAL CHARACTERISTICS.

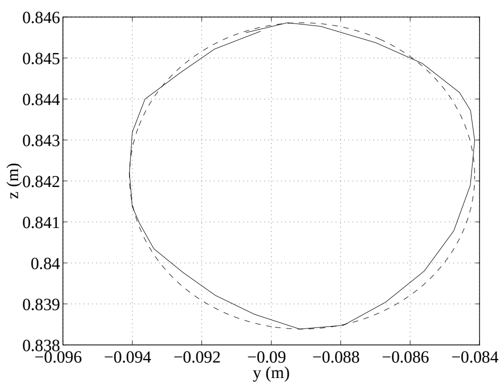

Figure 4. THE STICK ELLIPSE OF THE PULP. SOLID: EXPERIMENTAL DATA; DASHED: FITTED ELLIPSE.

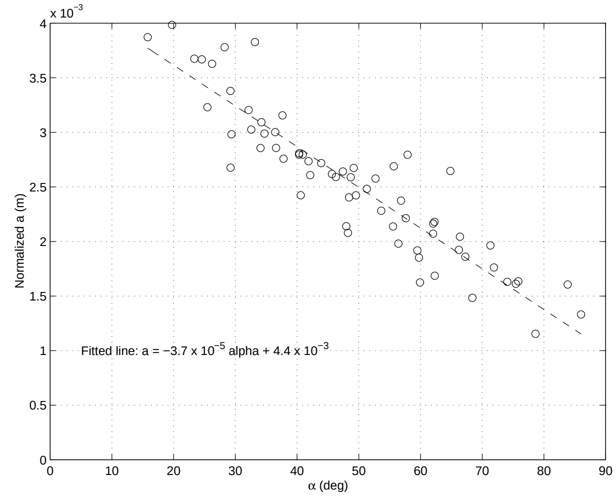

Figure 5. MAJOR AXIS OF THE NORMALIZED STICK ELLIPSE (IN LATERAL DIRECTION) VERSUS THE FINGER ANGLE.

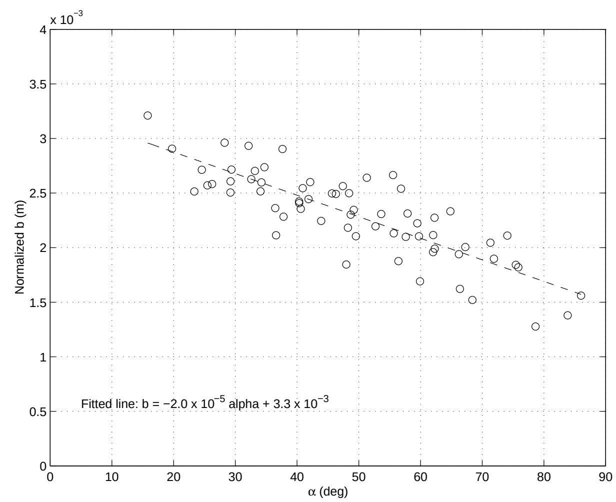

Figure 6. MINOR AXIS OF THE NORMALIZED STICK ELLIPSE (IN LONGITUDINAL DIRECTION) VERSUS THE FINGER ANGLE.

their index finger and exert both normal and tangential forces as far as no slip occurred. Subjects were between 23 and 51 years old (mean = 32.5, standard deviation = 7.8). 8 were males and 1 was female. 3 had relatively callous finger pads and 6 had relatively soft finger pads. As shown in Figure 3, the fingertip position and inclination angle of the finger relative to the plate were determined by two IRED markers attached on top of proximal and distal segments of the finger. Three-dimensional locations of IREDs were determined by an optoelectronic tracking device called Optotrak 3020 (Northern Digital, Ltd., Waterloo, Ontario, Canada) which has a stated accuracy of 0.1 - 0.15 *mm* in a 2.5 *m* distance. The contact force was measured by a six-axis force and torque sensor JR3 model 67M25 (JR3, Inc., Woodland, California) which was placed under the flat plate. Position and force signals were recorded synchronously.

Figure 4 shows a typical result of this experiment where a subject tried to move along the largest possible curve in the **yz** plane, while the center of his fingertip remained almost fixed. It shows an ellipse rather than a circle. Figures 5 and 6 show the normalized axes of this ellipse for all subjects. It shows that both major and minor axes shorten as finger angle with contact plane α increases. All subjects showed a similar linear trend of decreasing axes versus α. However, the length of axes were different for each subject. The value of axes at $\alpha = 45$ deg was used to normalize axes lengths for all subjects. Two lines were fitted for axes a and b as displayed in Figures 5 and 6. Since it was not possible to collect equal number of samples for all subjects, the least squares error vector was multiplied by a weight matrix so that all subjects have equal role in the final fitted lines [13]. Figure 7 combines Figures 5 and 6 into a single figure and shows the stick ellipse for different angles of finger.

Therefore, we must deviate from our basic stick-slip model in two ways:

1. We need to have a stick ellipse rather than a circle.

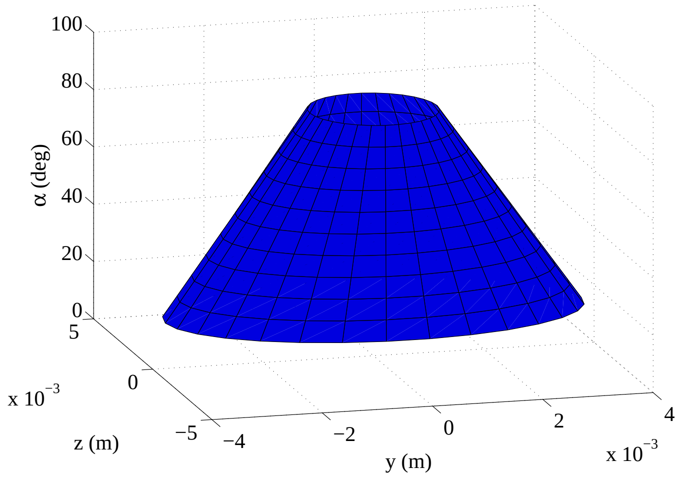

Figure 7. THE NORMALIZED STICK ELLIPSE FOR DIFFERENT FINGER ANGLES.

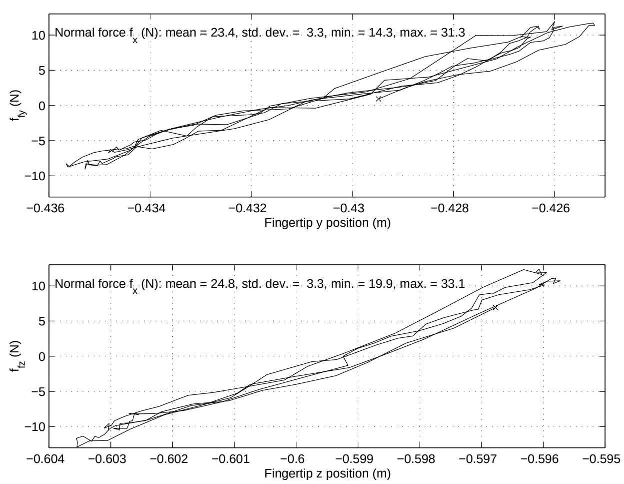

Figure 8. THE LINEAR RELATIONSHIP BETWEEN FRICTION FORCE AND FINGER PAD DISPLACEMENT.

2. Stick ellipse gets smaller as α increases.

Force-Displacement Relationship in *Stick* Phase

The relationship between the tangential force and displacement of the pulp should be obtained. 11 subjects were asked to push back and forth along two perpendicular directions sequentially along lateral (**y**) and longitudinal (**z**) directions without slippage. The angle between finger and plate remained fixed at a convenient angle, e.g. 45 deg. Figure 8 shows the typical results for one subject. It shows a linear relationship between friction and displacement. Therefore, we can keep our earlier assumption of a linear spring as outlined in Section 2.

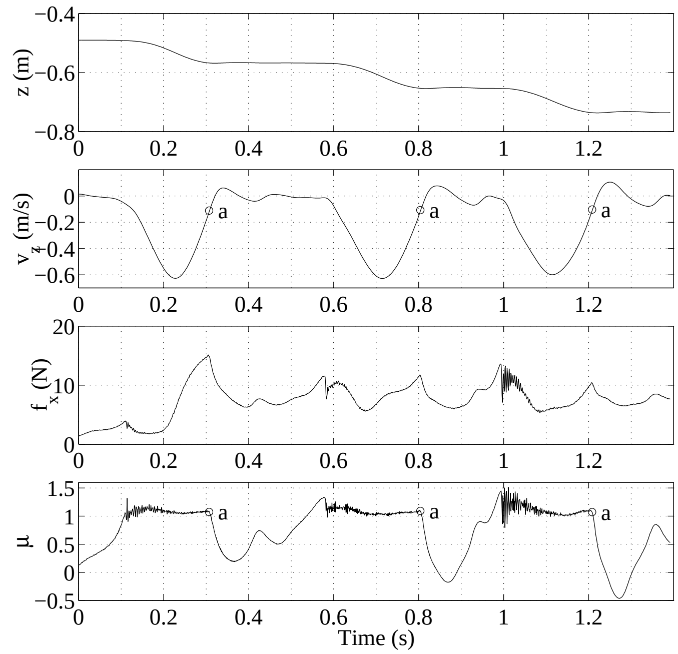

Figure 9. CHANGE OF PHASE FROM *SLIP* TO *STICK*.

Switching from *Slip* Phase to *Stick* Phase

In Section 2, it was stated that when velocity becomes smaller than a threshold v_{min}, *slip* phase ends and *stick* phase begins. We need to determine v_{min} based on behavior of the human finger pad. 11 subjects were asked to frequently slip and stick on the plate along a tangential axis **z** as shown in Figure 9 for one subject. In the figure, velocity v_z, normal force f_x, and $\mu = f_{fz}/f_x$ are also shown. Points a show the end of *slip* phase which is accompanied by a distinct change in μ. It is seen that phase change occurs at an absolute velocity of $v_{min} = 0.1 m/s$.

High Frequency Oscillation in *Slip* Phase

When we rub on a dry surface, a high-frequency vibration is produced as we move on the surface. This has to be incorporated into the *slip* phase model. The lack of such an oscillation in virtual environments creates a feeling of moving in a fluid rather than rubbing on a dry surface. An experiment was performed to obtain the vibrational behavior of the pulp in the *slip* phase. A subject was asked to move his fingers tangentially on a flat plate in the **z** direction, while pressing gently on it in the normal **x** direction. Figure 10 show the results for position and force of the fingertip in **x** and **z** directions. The oscillation of position and force signals are evident in those figures. The sampling rate for both position and force was 1000 Hz. Figure 11 shows the power spectrum density for tangential and normal forces. The peak of vibration is at 89 Hz for this test. Stochastic models [3, 5, 19] are appropriate to create such an oscillation in virtual environments. Howe and Cutkosky [10] have also reported experimental results

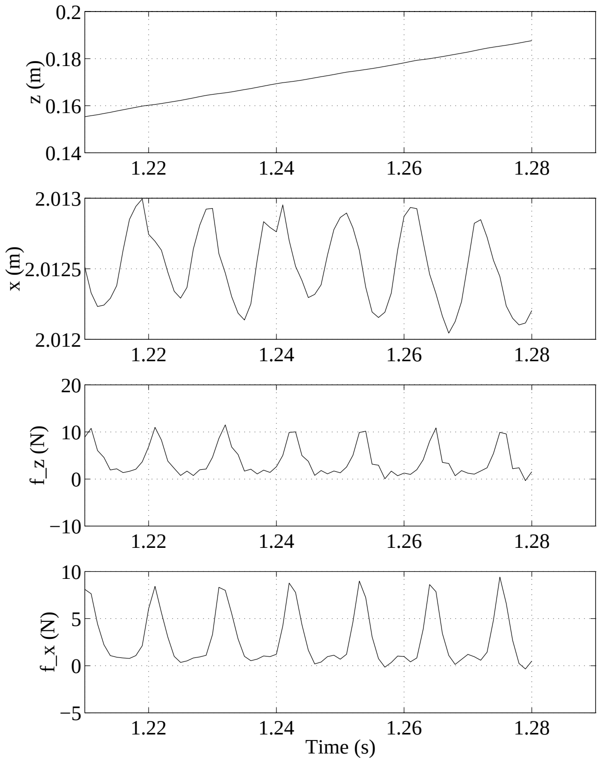

Figure 10. x and z COMPONENTS OF THE FINGERTIP POSITION AND FORCE.

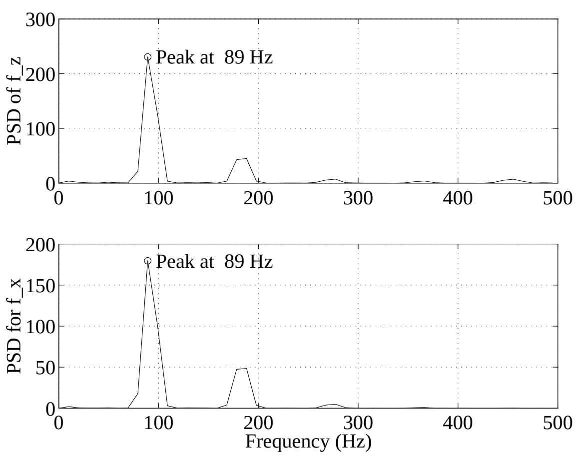

Figure 11. POWER SPECTRUM DENSITY OF THE TANGENTIAL AND NORMAL FORCES.

of oscillations of fingers of a manipulators. Since those fingers did not have sweat glands, their results are not comparable with the results reported here.

EXPERIMENTAL RESULTS IN VIRTUAL ENVIRONMENTS

We have so far implemented the stick-slip model on a flat virtual surface and asked users to touch it by the Sarcos Dextrous Arm Master, an advanced hydraulic force-reflecting exoskeleton [11, 9, 23]. Figure 12 shows the preliminary experimental results of friction in a tangential **y** direction on a flat plane with coefficients of friction $\mu_s = 0.3$ and $\mu_d = 0.2$. The data were recorded at 500 Hz. Regions of relatively constant coefficient of friction represent *slip* phase and the transient regions represent *stick* phase. The users reported a feeling of moving a rubber eraser against a paper.

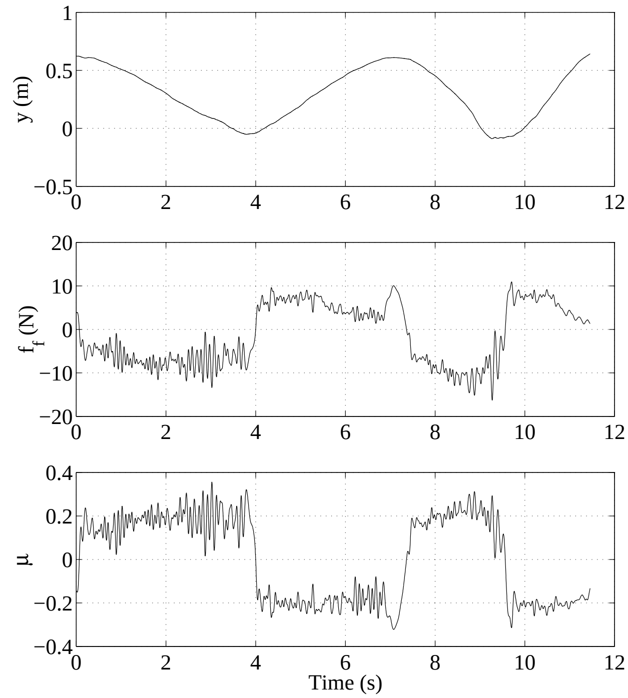

Figure 12. FRICTION ON A VIRTUAL PLANE IN THE y DIRECTION. POSITION, FRICTION FORCE, AND COEFFICIENT OF FRICTION ARE SHOWN.

DISCUSSION

This paper has presented a friction model for virtual environments based on characteristics of human finger pads. The frictional behavior of the human finger pad is a complex phenomenon which cannot be emulated accurately in virtual environment. However, our experiments showed that we can "reasonably" approximate finger pad behavior for implementation in a virtual environment.

We assumed that friction is proportional to the normal force in *stick* phase. Although there is some approximation in this assumption, we believe it is an acceptable assumption for virtual environments. Another source of error is hysteresis which is more significant for some subjects than results show in Figure 8. Also, a third order spring is more appropriate for some subjects than a linear spring in *stick* phase. Since it is not practical to determine the appropriate spring for any individual subject *a pri-*

ori, it is argued that a linear spring can be applied for all subjects [13].

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