HAPTIC TEXTURE RENDERING AND PERCEPTION USING COIL ARRAY MAGNETIC LEVITATION HAPTIC INTERFACE: EFFECTS OF TORQUE FEEDBACK AND PROBE TYPE ON ROUGHNESS PERCEPTION

A THESIS SUBMITTED TO THE GRADUATE DIVISION OF THE UNIVERSITY OF HAWAI‘I AT MĀNOA IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

IN

MECHANICAL ENGINEERING

MAY 2016

By

Sahba Aghajani Pedram

Thesis Committee:

Peter Berkelman, Chairperson
Brian Bingham
Reza Ghorbani

Keywords: Texture Rendering, Sinusoidal Surfaces, Roughness Perception, Magnetic Levitation Haptic Interface, Torque Feedback, Stylus Shape, Probe Type
With my highest honor, I would love to dedicate my thesis work to my beloved family: my parents, Mehdi and Shahnaz, my sister and brother in law, Marila and Hassan, and my niece and nephew, Medisa and Bardia. Without their unbounded love, hope, and support, this thesis would not have been accomplished.
ACKNOWLEDGMENTS

I would like to express my deepest appreciation to my principal supervisor, Prof. Peter Berkelman, for his unwavering support, guidance and mentorship throughout my masters research. He consistently allowed this research to be my own work, but steered me in the right direction whenever he thought I needed it. His quick mind, openness to new ideas, and excellent technical skills have substantially helped me to grow professional skills in the grad school.

I wish to express my sincere gratitude to my co-supervisor, Prof. Roberta Klatzky at Carnegie Mellon University, who is an outstanding expert in the field of haptics and human perception. I have been more than fortunate and supported to have her alongside of my masters journey, although we have never met in person. Her outstanding solid knowledge, her quick and detailed responses, and her great patience for addressing my questions were extremely precious in my research and added considerably to my technical skills.

I would like to thank Prof. Reza Ghorbani and Prof. Brian Bingham, for taking time out from their busy schedule to read this thesis and serve as my committee. Their insightful comments, invaluable suggestions, and encouragement for this research effort are highly appreciated.

I am deeply grateful for Prof. Mehrdad Nejhad, chair of the Mechanical Engineering Department at UH Manoa, who has always supported and encouraged me during my studies at the University of Hawaii at Manoa.

As a great part of this research involved human experiments, I would like to also thank all of the participants in our experiments who provided very useful comments and spent many hours of their time and effort for realization of this research.
ABSTRACT

A Novel maglev-based haptic platform was deployed to investigate the effects of torque feedback and stylus type on human roughness perception. For this purpose, two haptic probes, fingertip and penhandle, were 3D printed each with one and four embedded magnets respectively.

Three different torque renderings namely No Torque, Slope Torque, and Stiff Torque were developed, in tandem with penetration-based force feedback to render simulated surfaces. The main difference between these conditions was the amount and type of active torque that was generated. Conventional magnitude estimation experiment for data gathering and analysis was performed.

The results of the experiment showed strong effects of wavelength within all torques and probes. Participants rated surfaces rougher in the Slope Torque and with the fingertip compared to penhandle. These results revealed new means of torque-based surface generation that lead to higher roughness perception. The outcomes also highlight the importance of probe type on human roughness perception.
# TABLE OF CONTENTS

Acknowledgments ................................................................. iv

Abstract ................................................................. v

List of tables ................................................................. x

List of figures ................................................................. xiii

List of abbreviations and symbols .......................................... xiv

1 Introduction ............................................................... 1

1.1 The Sense of Touch ..................................................... 1

1.2 Haptics ............................................................... 2

1.3 Haptic Interfaces ....................................................... 3

1.3.1 Impedance Type ..................................................... 4

1.3.2 Admittance Type ..................................................... 5

1.4 Haptic Rendering ....................................................... 7

1.4.1 Rendering Loop ..................................................... 9

1.4.2 Collision Detection .................................................. 9

1.4.3 Force Response Algorithms ..................................... 10

1.5 Thesis Overview ....................................................... 15

2 Literature Review .......................................................... 18

2.1 Roughness Texture Perception ...................................... 18

2.2 Texture Roughness Perception of Real Surfaces ..................... 18

2.2.1 Texture Perception via Bare Hand ................................ 18

2.2.2 Texture Perception via Probe .................................... 20

2.3 Texture Roughness Perception of Simulated Surfaces ................. 21

2.4 Effects of Torque Feedback on Human Perception ..................... 25

2.5 Roles of Probe Type on Human Perception ........................... 28

2.6 Research Questions .................................................... 29

3 Coil Array Magnetic Levitation Haptic Interface ......................... 30

3.1 Motion Tracker (Sensing Unit) ....................................... 31

3.2 Coil Array and Magnets (Actuation Unit) ............................ 31

3.3 Amplifiers and Power Supply (Power Unit) ......................... 33
4 Experimental Setup and Procedure ........................................... 36
  4.1 Experiment Apparatus .................................................... 36
     4.1.1 3D-Printed Haptic Probes .................................. 36
  4.2 Participants .............................................................. 38
  4.3 Surface Rendering Algorithm ........................................ 38
     4.3.1 Force Feedback .................................................... 39
     4.3.2 Torque Feedback .................................................. 40
     4.3.3 Torque Feedback Conditions ................................... 41
  4.4 Roughness Perception Experiment .................................. 45
     4.4.1 Experimental Factors .......................................... 45
     4.4.2 Experiment Procedure .......................................... 45
  4.5 Psychophysical Function of Perceived Roughness (Ψ) .......... 47

5 Results ................................................................................. 49
  5.1 Roughness Estimation Magnitude .................................... 49
     5.1.1 Effects of Wavelength .......................................... 49
     5.1.2 Effects of Torque Feedback .................................... 50
     5.1.3 Effects of Probe Type ............................................ 55
  5.2 REM Sensitivity to Wavelength ....................................... 57
     5.2.1 Effects of Torque Feedback .................................... 57
     5.2.2 Effects of Probe Type ............................................ 58
  5.3 Individual Psychophysical Functions ............................... 59
     5.3.1 Individual Regression Models ................................. 59
     5.3.2 Individual Sensitivity of REM to Wavelength .......... 61

6 Discussion ............................................................................. 65
  6.1 Effects of Wavelength ...................................................... 65
  6.2 Perception with Different Haptic Probes ......................... 67
     6.2.1 No Torque Condition ............................................. 67
     6.2.2 Slope Torque Condition ......................................... 68
     6.2.3 Stiff Torque Condition ........................................... 69
  6.3 Perception with Different Torque Conditions .................... 69
  6.4 Discussion on Grasp Differences in Haptic Probes .......... 71
7 Conclusion and Future Work .................................................. 72
  7.1 Future Work ........................................................................ 73
    7.1.1 Stiffness ...................................................................... 73
    7.1.2 Underlying Reasons for Human Perception Behavior ........ 74

Appendices ................................................................................. 75
3.1 Performance characteristics of planar coil array magnetic levitation haptic interface. 35

4.1 $R_{a(t)}$, $K_{pr}$, and $K_{dr}$ matrices for each of the three torque conditions. 44

5.1 One-way ANOVA results for effects of wavelength of virtual sinusoidal surfaces on perceived roughness. The results show that sinusoidal wavelength has significant affect on perceived roughness within all torque conditions and probes. 49

5.2 Residual ($R^2$) after the linear fit for four different functions of quadratic, power, logarithmic, and exponential along with their associated significance level (P). These results are for the fingertip haptic stylus. 50

5.3 Residual ($R^2$) after the linear fit for four different functions of quadratic, power, logarithmic, and exponential along with their associated significance level (P). These results are for the penhandle haptic stylus. 52

5.4 Slope, y-intercept and goodness of linear fit ($R^2$) for relation between wavelength and perceived roughness. 52

5.5 Within-subject ANOVA results for effects of torque feedback, spatial period, and their interrelation on perceived roughness. All three levels of torque conditions are included. 54

5.6 Within-subject ANOVA results for effects of torque feedback, spatial period, and their interrelation on perceived roughness. Two levels of torque conditions, Stiff Torque and Slope Torque, are included in the analysis. 55

5.7 Within-subject ANOVA results for effects of torque feedback, spatial period, and their interrelation on perceived roughness. Two levels of torque conditions, Slope Torque and No Torque, are included in the analysis. 55

5.8 Within-subject ANOVA results for effects of torque feedback, spatial period, and their interrelation on perceived roughness. Two levels of torque conditions, No Torque and Stiff Torque, are included in the analysis. 55

5.9 Within-subject ANOVA results for effects of probe type, spatial period, and their interrelation on perceived roughness. 57

5.10 Within-subject ANOVA results for impacts of torque feedback conditions on sensitivity of perceived roughness to spatial periods when all three torque conditions were considered in analysis. 58
5.11 Within-subject ANOVA results for effects of torque feedback conditions on the sensitivity of perceived roughness to spatial periods when all three possible combinations of two torque feedback were considered for statistical analysis. 59
5.12 Within-subject ANOVA results for effects of probe type on sensitivity of perceived roughness to spatial periods within three torque feedback conditions. 59
5.13 Sensitivity of magnitude estimate rating to wavelength along with y-intercept and associated goodness of linear fit for each subject when penhandle device was deployed. 64
5.14 Sensitivity of magnitude estimate rating to wavelength along with y-intercept and associated goodness of linear fit for each subject when fingertip device was utilized. 64
# LIST OF FIGURES

1.1 Structure and location of mechanoreceptors in skin [4]. .............................................. 2  
1.2 Commonly used haptic devices with medical, industrial, and (most importantly) scientific applications. ............................................................... 3  
1.3 Impedance-type haptic devices. .............................................................................. 5  
1.4 Admittance-type haptic devices with different application such as bi-manual manipulation and eye surgery. .............................................................. 6  
1.5 Different haptic devices and associated avatars along with different VR environments, a) haptic device is a force feedback scissor, *avatar* is virtual scissor, and the environment simulated as a soft surface. b) haptic device is a force feedback PHANToM omni, *avatar* is a virtual needle, and the virtual environment is a soft tissue. .............................................................................. 7  
1.6 Basic Architecture for typical haptic rendering algorithm. A human operator changes position of the haptic Interface ‘X’. The *Collision Detection* algorithm specifies information regarding contact ‘S’ between avatar and computer-generated environment. *Force Response* algorithm generates the desired forces ‘$F_d$’ to best describe the contact. *Control algorithm* generates the rendering forces ‘$F_r$’ on the human operator, approximating the desired forces based on the devices capabilities [40]. .............................................................. 8  
1.7 Demonstration of the collision detection criteria suggested by [42]. A vertex of object B, $V_b$, lies within the Voronoi region of object A. .......... 10  
1.8 The concept of virtual stiff wall to calculate a 1 DOF geometry-based rendering force. .................................................................................. 11  
1.9 Graphic representation of four sinusoidal textured surfaces with a (a) 6 mm, (b) 2 mm, (c) 0.50 mm and, (d) 0.25 mm periods [44]. ......... 13  
1.10 The prototype of a wireless haptic texture sensor described in [54]. The device is designed for simultaneously measuring contact force and acceleration in a handheld probe. .............................................................................. 14  
2.1 Schematic of the experiment plates used in [65]. .................................................. 19  
2.2 Experiment setup of micro-scale texture used in [71]. ........................................ 20
2.3 The apparatus used to control force (active and passive touch) and speed (passive touch only). 1. tachometer; 2. cam; 3. variable-speed motor; 4. rubber connector; 5. rotating base; 6. balance arm; 7. adjustable wrist support; 8. weight; 9. pivot point about which base rotates (shown as white dotted circle); 10. weight tray; 11. stimulus platform. The inset shows the subject contacting textured surface with a probe (for details on operation, see text). Note that the balance arm is moved sideways by the rotating base, to which it is attached (passive touch only). The balance arm independently moves up or down, whenever the counter-force applied to the textured surface by the subject is less or more, respectively, than the targeted .29N force (both active and passive touch) [77].

2.4 The effects of element spacing on the motion amplitude of probe. The figure is adopted from [44].

2.5 Dithered conical texture models and spherical probe tip. a) Probe Size = 1.5 mm, Spacing = 0.5 mm, b) Probe Size = 1.5 mm, Spacing = 5.5 mm, c) Probe Size = 0.25 mm, Spacing = 0.5 mm, d) Probe Size = 0.25 mm, Spacing = 5.5 mm [44].

2.6 Simple exploration task with a probe generates induced torque signals on the user’s hand (point A).

2.7 Various haptic probes with different grasp types and shapes.

3.1 The entire system of coil array magnetic levitation haptic interface.

3.2 The entire system of coil array magnetic levitation haptic interface.

4.1 Modeled and fabricated haptic styluses.

4.2 Sinusoidal surfaces superimposed onto the maglev system.

4.3 Schematic orientation of the probe in x-z plane in five different time instances for: (a) No torque, (b) Slope torque and (c) Stiff torque.

4.4 Graphical representation of the experiment design with three within-subject experimental factors.

4.5 A subject of the experiment exploring virtual surfaces laterally with the fingertip probe while wearing headphone and blindfold.

5.1 Individual normalized roughness psychophysical functions for 12 subjects superimposed with their cross-subject mean when penhandle probe was deployed.

5.2 Individual normalized roughness psychophysical functions for 12 subjects superimposed with their cross-subject mean when fingertip probe was deployed.
5.3 Cross-subject mean rating of perceived roughness with respect to surface wavelength for each haptic probe within three different torque conditions. For clarity of presentation, vertical SE bars are shown one sided. ........................................ 54

5.4 Cross-subject mean estimate of perceived roughness with respect to surface wavelength for each torque rendering within two haptic styluses. For clarity of presentation, vertical SE bars are shown one sided. ........................................ 56

5.5 Sensitivity of cross-subject mean to spatial periods for three torque renderings within each probe. Two sided error bars are within-subject SE obtained from between-subject standard deviation divided by square root of number of subjects. 58

5.6 Sensitivity of cross-subject mean to spatial periods for two haptic probes within each torque feedback condition. Two sided error bars are within-subject SE obtained from between-subject standard deviation divided by square root of number of subjects. ........................................ 60

5.7 Goodness of fit for five different regressions (linear, quadratic, logarithmic, power, exponential) for each subject when penhandle stylus was utilized. .......................... 62

5.8 Goodness of fit for five different regressions (linear, quadratic, logarithmic, power, exponential) for each subject when fingertip stylus was utilized. .......................... 63
### LIST OF ABBREVIATIONS AND SYMBOLS

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>MLHI</td>
<td>Magnetic Levitation Haptic Interface</td>
</tr>
<tr>
<td>maglev</td>
<td>magnetic levitation</td>
</tr>
<tr>
<td>REM</td>
<td>Roughness Estimation Magnitude</td>
</tr>
<tr>
<td>PSI</td>
<td>Probe Surface Interaction</td>
</tr>
<tr>
<td>SE</td>
<td>Standard Error</td>
</tr>
<tr>
<td>SA</td>
<td>Slowly Adapting</td>
</tr>
<tr>
<td>FA</td>
<td>Fast Adapting</td>
</tr>
<tr>
<td>VR</td>
<td>Virtual Reality</td>
</tr>
<tr>
<td>DoF</td>
<td>Degrees of Freedom</td>
</tr>
<tr>
<td>PSD</td>
<td>Power Spectral Density</td>
</tr>
<tr>
<td>JND</td>
<td>Just Noticeable Difference</td>
</tr>
<tr>
<td>ANOVA</td>
<td>Analysis of Variance</td>
</tr>
</tbody>
</table>
1 INTRODUCTION

1.1 The Sense of Touch

We as humans perceive our surrounding physical environment via five sensory systems which are commonly known as vision, hearing, taste, olfaction (smell), and touch. The information streamed from these five sensory inputs are fused together in our brain which enable us to sense our world and interact with it. Touch, unlike the other four modalities which are located on our head, is distributed throughout our body. Touch is built up from various types of sensation including pressure, temperature, skin stretch, and vibration.

While vision (sight) provides us with various information about the objects such as color and spatial location, it is the sense of touch that helps human to discern the material properties of objects such as texture, hardness, and roughness [1]. In most of our day-to-day manual interactions, our hand receives a wide spectrum of forces and torques which range from almost constant to over one thousand hertz. Mechanoreceptors, which are distributed across skin, muscles, and joints of human body and respond to pressure and/or distortion we receive, are able to detect such force and torque signals and respond to them. As described in [2, 3], there are four primary types of mechanoreceptors in the glabrous skin: Pacinian corpuscles, Meissner corpuscles, Merkel complex, and Ruffini endings. Figure 1.1 shows the structure and location of these four mechanoreceptors in glabrous and hairy skin.

The four types of mechanoreceptors in glabrous skin are different with respect to the characteristics of receptive fields, their rate of adaptation to stimuli, and the physiological characteristics of their endings [2]. When a mechanoreceptor receives a stimulus, it starts to generate impulses in a raised frequency, and the stronger the stimulus, the higher the frequency of the impulse. After creation of this impulse, the cell will adapt to a static stimulus and the pulse will abate to a normal speed. Slowly Adapting (SA) Mechanoreceptors are those that are slow to adapt and return to the speed of normal impulsing. On the other hand, Fast Adapting (FA) mechanoreceptors are those that can return to the normal firing fast [5]. Mechanoreceptors are also divided into two categories based on the size of their receptive fields. Type I mechanoreceptors are those that have a relatively smaller receptive fields and are usually located close to the skin surface. On the contrary, Type II mechanoreceptors are those that have large receptive fields and are located away from the surface of the skin.
1.2 Haptics

The word “haptics” simply means ”sense of touch” and both expressions can be adopted interchangeably. Although in the psychophysical literature the adjectives ”haptic”, ”kinesthetic” and ”tactile” have been used to explain our sense of touch in general [6], these concepts are quite different. Kinesthetic sense is related to sensory information pertain to motions/forces of joints, tendons, and muscles. This sense is involved in various normal human tasks such as walking. Tactile sense, on the other hand, encompasses the sensory information related to skin-surface interaction. As such, tactile feedback allows people to perceive matters such as surface texture and compliance, as well as temperature and vibration. Finally, the word ”haptic” is used to describe the overall sense of touch which incorporates both kinesthetic and tactile information. Manual tasks and interactions generally involve a combination of both kinesthetic and tactile sensation with correspondent weights that are specified based on the type of task being performed [7]. For example, when a person explores a cube to haptically perceive it, these weights are in the way that reflect the cube’s texture, compliance and temperature (tactile) as well as the its spatial characteristics (kinesthetic) such as volume and inertia.

Figure 1.1: Structure and location of mechanoreceptors in skin [4].
1.3 Haptic Interfaces

A haptic interface (or haptic device) is an electromechanical interface that provides haptic communications between the user and the computer. Haptic interfaces are generally very similar to generic robotic systems and consist of various sensors and actuators in variety of configurations and assemblies. Such devices allow users to touch and feel 3D objects in virtual environments which are carefully created by computer programs giving an illusion of feeling real objects. In addition to haptic feedback, the computer sometimes provide additional information such as visual and/or auditory feedback to augment the illusion of perceiving virtual objects as they are real (as examples see [8, 9]). Illustrations of simple haptic interfaces are peripheral devices which are equipped with additional actuators and/or sensors such as smart phones, force feedback joysticks, and UPenn haptography stylus [10]. Haptic devices such as 3D Systems PHANToM haptic device [11], and Magnetic Levitation Haptic Interface (MLHI) [12] from Butterfly Haptics, on the other hand, are more sophisticated platforms. These advanced devices are primarily designed to be deployed in the areas of teleoperation [13], medical application [14], education [15, 16], and most notably, scientific application [17, 18]. For example, haptic researchers have widely used these devices to better understand and characterize the human perception of surfaces/textures ([19–22]), which is also the focus of this thesis as well. MLHI and PHANToM are shown in Figure 1.2.

Haptic Interfaces can be categorized with respect to different characteristics. For example, one factor that differentiates these devices is the type of the actuators being used in their design. MLHI utilizes a combination of magnets and coils to generate desired forces and torques while devices such as PHANToM and Novint Falcon [23] deploy DC motors and mechanical linkages. Each of these systems have advantages and disadvantages. Magnetic levitation systems have many advantages over traditional motorized linkage systems for haptic interaction, including the elimination of friction and hysteresis from the motion dynamics and the full 6 DOF in rigid-body motion plus

![Sensible PHANToM omni](image1.png) ![Magnetic Levitation Haptic Interface](image2.png)

Figure 1.2: Commonly used haptic devices with medical, industrial, and (most importantly) scientific applications.
force and torque feedback from a single moving part. On the other hand, MLHIs have relatively much smaller range of motion (order of 5%) and are more expensive in comparison with linkage and motor based devices such as PHANToM.

A more general distinction to divide haptic devices is the relationship of motion and force at the user’s hand. Based on this factor, haptic devices are divided into two groups, impedance type and admittance type which will be further elaborated in Sections 1.3.1 and 1.3.2. For our research, the novel coil array magnetic levitation haptic interface developed by Berkelman et. al [24] at Human Robot Interaction Laboratory has deployed. This Interface is an impedance-type haptic device.

1.3.1 Impedance Type

Mechanical impedance is a matrix quantity in which specifies how much a structure and/or a point on a structure resists force when a motion is applied [25–27]. In impedance-type haptic interfaces, the device captures (usually through combination of sensing unit data and estimation algorithms) the motion of the user’s hand which is somehow attached to the device handle and outputs desired forces and/or torques. The location of these forces and torques might be different from where the handle is held. Lightweight, back-drivable mechanisms with DC motors are generally used for designing these type of haptic interfaces. In these devices, the following force-motion dynamic relationship is presented to the user:

\[
\vec{F} = Z_{\text{environment}} \vec{x}
\]  

(1.1)

In this equation, \( \vec{F} \) is the force vector applied to the user’s hand, \( Z_{\text{environment}} \) is the impedance of the virtual or remote environment, \( x \) is the position (and possibly orientation) of the haptic interaction tool in which the user grasps and \( \vec{x} \) is the outputted velocity vector.

PHANToM omni (see 1.2a) is likely the most well known impedance-type haptic interface which has been broadly used in the haptic research community [20, 28–30]. Although most impedance-type haptic devices are mechanism and motor driven including the master manipulator of the Da Vinci Surgical System [31, 32] (Figure 1.3a), and the Novint Falcon haptic device (Figure 1.3c), there are other impedance-type haptic platforms with novel actuation systems such as pneumatically actuated haptic device [33] or magnetic levitation haptic interfaces [12, 24] (see Figure 1.2b and Figure 1.3b). This magnetic levitation (maglev) based haptic platform was used for the research presented in this thesis.

Impedance-type haptic interfaces are generally able to sufficiently simulate virtual environments that let the user to move his/her hand freely (\( Z_{\text{environment}} \approx 0 \)). However, these devices encounter problems for creating very stiff environments (\( Z_{\text{environment}} \gg 0 \)) due to several reasons such as actuator saturations and/or nonlinearities in the systems dynamics. As an example, these
devices are usually not capable of generating very stiff contacts such as walls or bones. One solution to solve this problem, however, is to use these devices and providing high-frequency vibrations for a very first short period of contact which was suggested by Kuchenbecker [34].

### 1.3.2 Admittance Type

Mechanical admittance is a matrix quantity in which specifies how much a structure and/or a point on a structure resists motion when a force is applied [35]. For an Admittance type haptic interface, the mode of control is admittance control [25–27, 36] which means that force from the user is first being measured usually at the endpoint of the device (typically through combination of data from force sensing unit and estimation algorithms), and then position and/or velocity information is calculated from this force data and is exerted on the user’s hand. The position and force relationship of these devices can be presented as follows:

\[
\vec{x} = Y_{\text{environment}} \vec{F}
\]  

(1.2)

In this equation, \(x\) is the position (and possibly orientation) of the haptic interaction tool in which the user grasps and \(\vec{x}\) is the outputted velocity, \(Y_{\text{environment}}\) is the admittance of the virtual or remote environment, and \(\vec{F}\) is the estimated force/torque vector.

![Images of haptic devices](a) Master manipulator of Da Vinci System  
(b) Coil array magnetic levitation haptic interface  
(c) Novint Falcon haptic device

Figure 1.3: Impedance-type haptic devices.
Examples of admittance-type haptic interfaces are novel admittance-type haptic interface for bimanual manipulations [37] (Figure 1.4a), the HapticMaster from FCS Control Systems [38] (Figure 1.4b), and the Jonhs Hopkins University Steady-Hand robot [39] (Figure 1.4c).

Admittance control scheme for haptic interaction is particularly suitable for devices with high dynamics and nonlinearities. Such nonlinearity and complex dynamics which are due to friction, hysteresis, etc. available in actuators, gears, sensors, and other electromechanical parts can be eliminated with high control gains. For simulating free space ($Y_{environment} \gg 0$) with these haptic devices, however, these high gains of control loop possibly increase systems instability, and actuator saturation which limit the more widespread use of this type of haptic interfaces.

(a) Novel admittance-type haptic interface  
(b) HapticMaster from FCS Control Systems  
(c) The Jonhs Hopkins University  
Steady-Hand robot

Figure 1.4: Admittance-type haptic devices with different application such as bi-manual manipulation and eye surgery.
1.4 Haptic Rendering

In the context of haptics, *Haptic Rendering* refers to the process of generating forces/torques and motion by the haptic interface to provide kinesthetic and/or cutaneous feedback to the user. Haptic rendering algorithms compute the correct interaction forces/torques to create realistic contacts between representation of the haptic device inside of the virtual reality (VR) environment and other simulated objects. Further, haptic rendering algorithms assure that the haptic platform successfully generates these computed forces/torques on the human operator [40].

An *avatar* is the virtual representation of the haptic device (or at least part of it such as handle) in the VR (see Figure 1.5). Choosing proper shape and geometry of an avatar depends on the modality of the simulation as well as capabilities of the haptic device. The location, that is the position and/or orientation, of the avatar is actively controlled by the operator. It is type of the contact between avatar and simulated environment that specifies action and reaction forces/torques. The avatar can be presented as only a single point (or a sphere) exchanging forces and motion (translation) with the user in only 3D space, or more advanced, can be modeled as a volumetric object with 6D forces/torque and motions (both translation and rotation) exchange.

A typical haptic rendering process is composed of three main components: *Collision Detection*, *Force Response*, and *Control Algorithm* [40]. Figure 1.6 shows the graphical representation of a generic haptic rendering algorithm.

![Figure 1.5: Different haptic devices and associated avatars along with different VR environments, a) haptic device is a force feedback scissor, *avatar* is virtual scissor, and the environment simulated as a soft surface. b) haptic device is a force feedback PHANToM omni, *avatar* is a virtual needle, and the virtual environment is a soft tissue.](image-url)
Figure 1.6: Basic Architecture for typical haptic rendering algorithm. A human operator changes position of the haptic Interface ‘X’. The Collision Detection algorithm specifies information regarding contact ‘S’ between avatar and computer-generated environment. Force Response algorithm generates the desired forces ‘\( F_d \)’ to best describe the contact. Control algorithm generates the rendering forces ‘\( F_r \)’ on the human operator, approximating the desired forces based on the devices capabilities [40].

Collision Detection algorithms serve the role of detecting collisions between avatar and virtual objects. Such algorithms also provide information about when, where, and what kind of collision (point, area contact, etc.) has happened.

Force Response algorithms compute desired interaction forces/torques between avatar and simulated objects after collision. These forces/torques typically are in a way that resemble actual interaction among real objects and generally computed as a function of avatar’s position.

Control Algorithms generate rendering forces/torques in a way that minimizes the error between desired forces/torques and the ones that the device can actually produce. Inputs of the control algorithms are desired forces/torques computed by force response algorithms and outputs are rendering forces/torques commanded to the haptic devices, based on its capabilities and limitations. As a result, one source of unrealistic haptic feedback could be hardware and/or software limitations of haptic devices that limit their ability to provide the exact desired forces/torques on the user.
1.4.1 Rendering Loop

Haptic rendering is a discrete-time manner in its nature and haptic control loop is being updated several hundred times a second. If simulation engine incorporates both haptics and graphics, usually they are processed in parallel (multi threaded) with dissimilar update rates. For a high fidelity, compelling haptic interaction, an update rate of near 1000 Hz for haptics loop and close to 60 Hz for the graphics thread is recommended. Update rate of haptics thread is primarily bounded by the resolutions and update frequencies of actuation/sensing units of the device. A typical haptic thread loop is composed of the following sequential components:

- As user moves the handle, the low-level control algorithm records the location of the device at the frequency up to the maximum update rate of sensor.

- Based on this information, software calculates locations of the end effector that is being represented as an avatar inside of VR (forward kinematics for linkage-based haptic devices). Generally the movements of the virtual avatar and the device handle are very analogous, in terms of direction and magnitude. This helps to create a simulated environment with realistic feelings.

- Collision Detection algorithms use this information along with the virtual objects definitions/boundaries and specify whether and to what extent, penetration or indentation, the collision has occurred. Virtual objects shapes can be 1D (such as a point), 2D (such as a curved line), and 3D entities (such as a cylinder or a cube).

- Force Response algorithms calculate the desired haptic stimuli based on collision information to best represent contacts that would feel natural.

- Finally, Control Algorithms transfer the desired haptic stimuli to the human operator via haptic platform considering device limitations and overall stability of the system.

As mentioned earlier, for a high fidelity, natural, and compelling haptic interaction, the total time for processing all of these five sequential events should be around 0.001 seconds. Collision detection algorithms are typically the most complex and computationally expensive components amongst all.

1.4.2 Collision Detection

Collision detection algorithms are an essential entity of haptic rendering and can potentially be computationally expensive. As such, various algorithms have been developed to reduce their costs.
Simpler algorithms require less computation time and hardware sophistication to render while reducing degree of accuracy. More complicated solutions require more advanced software/hardware to capture detailed and complex collisions of objects. Lin et al. in [41] provides a comprehensive review on various collision detection algorithms deployed in haptics. Amongst all of different methods, the technique suggested by Lin and Canny [42] is one of the first collision detection techniques used in haptic rendering, yet effective and accurate. In this method, Voronoi region of various geometric features such as nodes, edge, and faces are pre-calculated. In each loop, a pair of these computed features is selected and software checks if they are the closest features based on whether they are in each other’s Voronoi region.

The simulated objects (virtual surfaces) and avatar used in this thesis are quite plain and do not require complicated algorithms such as the one mentioned earlier [42]. Detailed explanations of our collision detection algorithm are provided in chapter 4.

### 1.4.3 Force Response Algorithms

Once the collision is detected, the desired forces/torques must be calculated to best reflect the contact of virtual objects. Such computed haptic stimuli depend on various parameters including compliance and rigidity of objects, the nature of contacts (point, line, area, etc.) and so forth. In the context of this thesis, the simulated surfaces and avatars are all rigid objects with limited stiffness and surfaces have macro-scale textures.

![Figure 1.7: Demonstration of the collision detection criteria suggested by [42]. A vertex of object B, \( V_b \), lies within the Voronoi region of object A.](image)
Interaction stimuli of rigid contacts include two different types of forces/torques: The ones from virtual objects geometry (geometry-dependent) and the ones from surface characteristics of simulated object such as texture and roughness (surface-dependent).

**Geometry-dependent Force Rendering Algorithms**

For this type of rendering algorithm, the computed haptic stimuli is dependent on the object stiffness, and geometry. The feedback forces/torques assume the avatar is colliding with a frictionless and texture-less virtual objects. A typical way to render such haptic feedback is performed using penetration depth of the avatar into the virtual object. For example, as shown in Figure 1.8, considering a 1 degrees of freedom (DoF) avatar that can only move in the $x$ direction. Also, there is a virtual wall that is located at the origin. When human operator moves the avatar in virtual free space ($x > 0$), shown by green color in Figure 1.8, s/he feels no forces/torques. However, if the user pushes to enter the constrained space ($x < 0$), featured by red color in Figure 1.8, s/he will feel a reaction force proportional to the penetration depth of the avatar inside of constrained space. Following equations summarize the virtual wall concept for calculating the rendering forces:

$$F_x = \begin{cases} 
0 & \text{if } x \geq x_{wall} \\
-K_{wall}(x_{avatar} - x_{wall}) = -K_{wall}(x_{PD}) & \text{if } x < x_{wall} 
\end{cases} \quad (1.3)$$

In this equation, $F_x$ is the reaction force in $x$ direction, $K_{wall}$ is the wall stiffness represented by a spring-like notion, $x_{avatar}$ is the actual position of avatar which is controlled by the user, $x_{wall}$ is position of the virtual wall on the $x$ axis, and $x_{PD}$ is the penetration depth of the avatar inside of virtual wall (Figure 1.8).

![Figure 1.8: The concept of virtual stiff wall to calculate a 1 DOF geometry-based rendering force.](image-url)
In Equation 1.3, the force feedback is proportional to the wall stiffness \(K_{wall}\) and avatar penetration depth \(x_{PD}\). The stronger the user tries to enter the constrained space, or the more stiffness the wall is, reaction forces will be higher.

In many cases, especially for high stiffness virtual walls (e.g. \(K_{wall} > 5 \text{ N/mm}\)), representing the wall with merely a virtual spring will result in undesirable vibrations and instability of the system. Hence, a virtual damper is usually added in parallel with the virtual spring to damp high frequency noises and improving the stability of the system. In this case, the equations will be updates as follow:

\[
F_x = \begin{cases} 
0 & \text{if } x \geq x_{wall} \\
-K_{wall}(x_{avatar} - x_{wall}) - D_{wall}(\dot{x}_{avatar}) & \text{if } x < x_{wall}
\end{cases} 
\] (1.4)

In Equation 1.4, \(D_{wall}\) is the damping coefficient associated with the virtual wall and all of the other parameters are the same as Equation 1.3.

For rendering stable virtual walls, the proper choice of \(K_{wall}\) and \(D_{wall}\) is highly important and pertain to the device capabilities and limitations. For example, the PHANToM omni [11] can handle stable virtual walls up to around 3 N/mm while magnetic levitation haptic interface [12] is capable of rendering virtual walls up to 15 N/mm. For the coil array maglev system that we have in the lab, the maximum stiffness (compliance) for rendering virtual surfaces is around 1.5 N/mm. The main reason for this limitation is that, currently our sensing estimation of the avatar’s velocity \(\dot{x}_{avatar}\) is noisy. Since increasing \(K_{wall}\) usually requires increasing \(D_{wall}\), increasing stiffness of the wall will amplify such noisy data, resulting in instability and high frequency vibrations of the system.

This simple yet effective virtual wall concept is not the only algorithm for rendering virtual stiff contacts. For instance, Kuchenbecker in [34] proposed a method for rendering high stiff rigid contacts by generating high frequency force vibrations for only a first short period of contact. In the context of this thesis however, we deploy virtual wall concept to render simulated surfaces due to its simplicity and efficiency. The rendered surfaces for our research include textures/roughness associated with them as well which will be discussed in the next section.

**Surface-dependent Force Rendering Algorithms**

All of the real surfaces contain, at some extent and scale, irregularities (textures) and indentations. Most of these irregularities are not even perceivable by human eyes yet can be detected by our sense of touch. Simulating these fine textures, especially the ones in order of \(\mu m\) (micron-scale textures), is cumbersome. For example, observing/recording such fine shapes and geometry, which is stochastic in its nature, is very complicated. Estimating surface properties based on its interaction with an external probe could be another method for capturing fine textures. However, the
mechanics of handle-surface contact would require that both of the motion and force (could be very low resolution) be measured at the same time to build accurate models, which is not easily achievable as well. Even if the texture of real surfaces can be precisely specified, the micro-modeling of such highly complicated irregularities would be computationally prohibitive for real time applications [43]. Also, almost all of haptic devices are capable of generating textures down to a certain scale (tenth or hundredth of mm) due to their limited position and force bandwidth [44]. Nonetheless, different researchers have developed various micro- and macro-scale textured surfaces models to best describe real textured surfaces. Such models usually are superimposed to virtual surfaces with various range of stiffness which was discussed in the previous section.

Many haptic researchers have deployed periodic mathematical functions to generate textures for simulating surfaces. These deterministic models are generally simple to generate and allow for manipulating surface parameters quite easily. For example, sinusoidal function with different wavelengths and amplitudes is probably the most deployed function as the basis for rendering virtual textured surfaces [18,22,28,29,44–48]. Figure 1.9 (adopted from [44]) shows four graphical representations of sinusoidal surfaces with the same amplitude and various wavelengths. In the context of this thesis, the words ‘wavelength’, ‘interelement spacing’, ‘groove width’ and ’spatial period’ have been used interchangeably.

Figure 1.9: Graphic representation of four sinusoidal textured surfaces with a (a) 6 mm, (b) 2 mm, (c) 0.50 mm and, (d) 0.25 mm periods [44].
Other mathematical functions that have been deployed to model surface textures are trapezoidal and dithered conical textures [44], triangular gratings [49], and square-wave functions [50]. In addition to these deterministic models, some researchers developed stochastic methods for virtual texture modeling [43, 51]. For example, Siira et al. [43] proposed a fast algorithm to synthesize haptic textured surfaces based on the statistical properties of the surface.

The priori model design methods discussed so far demonstrate feed forward behavior, meaning they do not simulate textures based on any given feedback from real environments. In theory, such classical spring-damper texture rendering should be able to produce both low and high frequency accelerations for surface rendering. In reality, however, due to the factors mentioned earlier haptic devices are not capable of rendering contacts with high stiffness and damping coefficients. This results in merely low frequency force vibrations feedback from most of haptic platforms. Many articles such as [52, 53] have proposed that the lack of high frequency vibrational feedback in these classical spring-damper algorithms might be the primary reason that such simulated surfaces feel unrealistic. Consequently, there has been a body of research, usually referred to as “data-driven” haptic textures modeling (e.g. [52, 54, 55]), in which virtual textures are simulated based upon recording and playing back the high frequency data obtained from real surfaces. In this category, the haptic stylus is usually equipped with a sensing/actuating peripherals to record vibrations from textures of real surfaces and then play back these high frequency signals. Figure 1.10 depicts a wireless haptic texture sensor developed by Pai et al. [54]. The sensor is well suited for measurement of real textures.

Kuchenbecker et al. in [56] described a new texture modeling and synthesis algorithm based on linear prediction of acceleration data recorded from real tool-surface interactions. For playing back these signals, they have also demonstrated a new handle prototype which can be integrated into the PHANToM device and enables users to feel fine surface textures.

Another possible method for rendering virtual surfaces with high frequency accelerations was developed by Kontarinis and Howe [57]. In this method, an existing haptic device was augmented

Figure 1.10: The prototype of a wireless haptic texture sensor described in [54]. The device is designed for simultaneously measuring contact force and acceleration in a hand-held probe.
with an axillary actuator that induces accelerations on the user’s hand. Also, ‘inverted’ audio speakers were mounted to the custom haptic device near the user’s fingertips. The recorded accelerations from a teleoperated slave system were amplified by constant gains and drove the speakers. The results from human experiment showed improved performance in some tasks with this device. Participants also noted that they felt the haptic display more realistic with high frequency vibrations compared to only a haptic display.

The haptic surface rendering method deployed in the context of this thesis is virtual wall concept presented by Equation 1.4. For rendering textures, the commonly used sinusoidal function with constant amplitude and variable wavelengths was adopted. This is mainly due to the simplicity of these rendering methods as well as the possibility of comparing our first user trial with the system against other research in the literature.

1.5 Thesis Overview

This thesis provides new insights on the effects of incorporating various torque feedback methodologies and haptic probe types into the virtual environment, in terms of texture simulation and human perception.

In Chapter 1, high level explanations of commonly used terms/concepts in the context of haptics were given. Various haptic devices were discussed and two broad categories of such systems, impedance- and admittance-type, were analyzed. The concept of haptic rendering along with its three main elements: Collision Detection, Force Response, and Control Algorithms were extensively explained. Force rendering algorithms (both geometry-based and surface-based) were discussed. The concept of virtual wall for geometry-based was introduced. Deterministic and stochastic, and data-driven models for surface-based force rendering along with number of examples were provided. This chapter provides a rich foundation to better explain underlying reasons behind different parts of this thesis.

In Chapter 2, the literature in the area of surface, especially roughness, perception is reviewed. Studies are generally divided into two main groups depending on whether they deployed real or simulated surfaces. For real surfaces, studies in which subjects explored surfaces with bare hand as well as investigations that users felt surfaces via an intermediate median (e.g. pen-like probe) were extensively explained. For simulated textures, advantages of using virtual surfaces (vs. real ones) are mentioned and results from different experiments were compared against each other. Since the psychometric function obtained from these surfaces generally were unable to replicate their real counterparts, possible reasons for such disparities are discussed. In terms of torque feedback in texture perception, the literature of using torque in haptics is reviewed and the potential affects of
this component on texture perception is discussed. Finally, different types of haptic probes/devices are explained and possible influence of probe type on roughness perception is analyzed.

In Chapter 3, the coil array magnetic levitation haptic interface which was used in our human experiments is discussed. Different components of this platform including sensing and actuation units, power supply, and control software are explained. For sensing, Certus OptoTrak motion tracker from Northern Digital Inc. with an update rate of 860 Hz and resolution of 0.01 mm is deployed. For actuation, 27 cylindrical coils arranged in a planar array generate magnetic fields. With proper manipulation of these fields, the system provides full 6 DoF motion for any platform with two or more embedded magnets. Four power supplies and 27 current amplifiers are deployed to generate coil currents. Control software of the platform runs on a Linux operating system with 1.8 GHz Intel processor and have an update rate of 860 Hz. Overall system characteristics is reported in the last part of this Chapter.

The general set up and procedure of the human perception experiment is explained in Chapter 4. Design and fabrication of two different haptic probes namely, fingertip (thimble) and penhandle, is provided. Surface rendering algorithms, spring-damper method for geometry-based and 2D sinusoidal functions for surface-based force rendering are extensively discussed. For torque feedback, PD control scheme in the form of matrices is given. Different torque conditions namely No Torque, Slope Torque and Stiff Torque are described in details. The experiment design including three within-subject experiment factors (Torque, Wavelength, and Probe) along with the general experiment procedure are explained. Finally, the formulations for transforming raw data to psychophysical function of roughness are provided.

Comprehensive results of the human experiment is reported in Chapter 5. Repeated measure analysis of variance (ANOVA) test was used for all statistical analysis in this Chapter. First, the effects of wavelengths on perceived roughness is examined which found to statistically be very strong, within all torques and probes. The effects of torque feedback on roughness percept within each probe and the impacts of probes on perceived roughness within each torque condition are investigated. It was shown that the roughness data for three torque conditions were essentially equivalent for the penhandle probe, while Slope Torque condition felt more rough than the other two with the same level of perceived roughness. The effects of probes and torque conditions on the sensitivity of roughness rating to spatial periods are also studied. The results suggested that penhandle had less sensitivity than the fingertip in No Torque condition, while the probes showed the same level of sensitivity in the other two conditions. In the last part of the Chapter, individual roughness data and sensitivity were discussed.

In Chapter 6, a general discussion on the experimental results are provided and the outcomes are compared against previous studies in this area. Discussion on the effects of wavelength obtained from our experiments and comparisons against earlier investigations with real and virtual
surface are stated. The effects of probe type across different torque conditions and impact of torque renderings within different probe are explained. Finally, essential differences between type of pen-like and finger grasp such impedance and/or area of contacts are mentioned. Although they need to be verified in the future studies, it is hypothesized that these differences would play, to some extent, some role on different responses across the probes and torque conditions.

In Chapter 7, a general conclusion for this research is stated and some possible research extensions for future are suggested. One of such work could be to improve the velocity estimation of the system through adoption of new algorithms such as EKF and/or additional hardware including gyro. This can open up a new path to investigate impacts of stiffness on perception of virtual roughness, a topic that has attained little to no attention in the literature, yet very important (suggested by research) on human roughness. Another suggestion for future work would help us to better understand outcomes obtained from this research, e.g., variabilities across probes and torque conditions. This includes, but not limited to, analyzing force/torque signals in the frequency domain through FFT and PSD, experimentally obtaining/comparing impedance of pen-like and finger grasp active DoFs, or sensing force/torque signals directly from human finger/hand rather than at the probe tip. Such analyses would definitely help to better confirm and understand outcomes of this thesis effort.
2 LITERATURE REVIEW

2.1 Roughness Texture Perception

Texture of an object is counted as one of the paramount material properties which specifies its nature. A substantial body of research has performed to better understand the important elements of textures along with their relations to the complex human neural processes that perceives them [58–62]. Different investigators have proposed that the texture of a surface constitutes of various independent components. For example, Hollins et al. [58] suggested that four factors of vibration, stickiness, roughness, and hardness have the most effects on describing texture. Between all of these components, roughness has gained the most attention amongst haptic and psychophysical researchers.

2.2 Texture Roughness Perception of Real Surfaces

2.2.1 Texture Perception via Bare Hand

Early studies on texture perception roughly commenced in 1920’s by Katz who proved that subjects, during the task of writing, are able to differentiate between dissimilar papers [63]. Such psychological investigations further developed in subsequent decades (e.g. in 1960’s and 1970’s) by others, for instance, Stevens and Harris [64] and Lederman et al. [65, 66]. In all of these early studies for human roughness perception, subjects, via bare hand, explored real surfaces that had different macro-scale geometry. For example, in a study by Lederman et al. [65], users actively explored grooved metal plates with macro scale textures (spatial period $\geq 200 \mu m$, see Figure 2.1). The authors proposed that between various parameters of ”days”, ”runs”, ”groove width (ridge)”, and ”fingertip force”, only the last two played the most important roles in roughness perception. They also found out that the relative affects of groove width on users perception of roughness was more significant than the ridge. It was also proposed that the perceived roughness was increased as the groove width and fingertip force increased, and was descended when the groove ridge increased. Later experiments by Lederman et al. [67, 68] suggested that neither spatial periods (see Figure 2.1) nor vibrations that are produced during interaction of skin with surface measurably contributed to roughness perception of macro-scale textures. In a different research, Taylor et al. [66] proposed that three parameters of cross sectional area of the fingertip within the groove, cross sectional area of skin deviation from its resting position, and penetration depth of the finger into

18
the grooves predict roughness perception. It was based on this and similar studies that researchers begun to reason that the roughness perception is mainly affected by spatial deformations of skin of the finger and that the temporal effects, e.g. vibrations, did not influence roughness perception of macro-scale textures.

In contrast to macro-scale textures, research [69–72] suggest that vibration cues from skin-surface interaction may play significant role in human percept of surface roughness in micro-scale textures (spatial periods $\leq 200\mu m$). For example authors in [70, 71] suggested that the roughness (and most likely stickiness as well) of fine textures (micro-scale textures) is the function of Pacinian weighted power of the vibrations it educes. Figure 2.2 shows the experiment setup used in [71]. Hence, Although the roughness percept via direct touch is largely mediated by spatial effects, it is obvious that some part of the experience is mediated by vibration. The portion in which vibrational cues affect human roughness perception is primarily dependent on the type of the textures (whether marco- or micro-scale textures) in which subjects are experiencing through bare hand.

After well understanding the roughness percept of human from relatively simple surface texture models, e.g. rectangular texture models, psychological researchers sought to investigate the texture parameters of more sophisticated and complex surface representations and stimuli. The research (e.g. [73, 74]) involving such stimuli, which are usually created through photoengraving techniques [75], have expanded our knowledge from the underlying neural processes and surface texture parameters that affect human percept of textural surface roughness via direct touch.
2.2.2 Texture Perception via Probe

As mentioned in the previous section, when human explores surfaces through bare hand, it was spatial cues (e.g. skin deformation among grooves) that mainly contribute to human roughness perception. When feeling surfaces through an intermediate probe, since the availability of spatial cues is removed, it seems at a first glance that no roughness would be felt by subjects. In contrast, an extensive psychological research on human roughness perception [21, 75, 76] confirmed that human actually perceives roughness via intermediate probes. Researchers proposed that it is, in fact, the vibratory (temporal) texture coding cues that mediate human percept of roughness when using a probe. [21,75,76]. For example, Lederman et al. [77] claimed that the perceived roughness function is strongly affected by the exploration speed (temporal cues) when subjects felt surfaces through a rigid probe. This finding is, however, in contrast with the results that Lederman suggested earlier for the roughness perception via bare hand. In [68], she found out that the relative speed of motion between the surface and subjects’ bare finger provided a relatively small to negligible effect on roughness percept.

Roughness variations with respect to groove width were found to be different between using a probe or a bare finger. In case of bare finger, the perceived roughness typically was described with a linear increasing function of log(magnitude) to log(spacing), up to a certain spacing that roughness elements are so spaced apart resulting in no feeling of textures any more [78]. When using a probe, however, Klatzky et al. [76] described the relation of log(spatial periods) to log(roughness) with an inverted U shape (quadratic) function. This means that the perceived roughness increases first as the groove spacing (spatial period) increases until it reaches a point that the perception starts showing a descending trend with the increase in groove spacing. The authors mentioned that such quadratic relationship (vs. linear function for bare hand) most likely stems from the relation between the probe size (interaction area) and the groove width. They proposed that the perceived roughness reached its maximum value when the distance between subsequent roughness elements exceeds the diameter of the probe tip. In other words, when the diameter of the probe tip is less...
Figure 2.3: The apparatus used to control force (active and passive touch) and speed (passive touch only). 1. tachometer; 2. cam; 3. variable-speed motor; 4. rubber connector; 5. rotating base; 6. balance arm; 7. adjustable wrist support; 8. weight; 9. pivot point about which base rotates (shown as white dotted circle); 10. weight tray; 11. stimulus platform. The inset shows the subject contacting textured surface with a probe (for details on operation, see text). Note that the balance arm is moved sideways by the rotating base, to which it is attached (passive touch only). The balance arm independently moves up or down, whenever the counter-force applied to the textured surface by the subject is less or more, respectively, than the targeted .29N force (both active and passive touch) [77].

that spatial periods, the probe will only ride the upper surfaces of the elements. As the space between spatial elements increases, the probe will fall between spaces and will ride the surface in different manner. The authors named this transient situation, so-called drop point. They also suggested that this point is affected by various parameters of element spacing, diameter of probe tip, height of elements, and exploration speed. Figure 2.4 shows how a probe penetration changes the mechanics of the probe-surface interaction (PSI).

### 2.3 Texture Roughness Perception of Simulated Surfaces

In the last three decades, considerable advancements in technology have opened up its path into many research fields including haptics. First introduced in 1990’s, the PHANToM device [11]...
is the most deployed platform in the haptic research community. With this introduction of haptic devices, human perception research studies were no longer limited to using merely real surfaces which were hard, expensive, and time consuming to create. Utilizing haptic platforms, especially in the area of surface and texture perception, has introduced many advantages. These advantages include the ease of manipulating surface parameters and stimuli in a much shorter period of time with higher accuracy. Moreover, effects of various surface parameters could be investigated, otherwise impossible or very cumbersome with real surfaces. For instance, impacts of various torque feedback on human perception which is one of the main focus of this thesis is only possible to carefully study through haptic platforms. Such advantages has enabled investigators to more accurately study the human texture percept within a broader range of textures and more physical attributes of textures. On the other hand, when feeling textures through simulated surfaces, several important concerns need to be carefully addressed. For example, how accurately simulated surfaces can represent their real counterparts? What are the capabilities of haptic interfaces for simulating both micro- and macro-scale textures? How these device capabilities affect human perception? What are the differences between perceived roughness for virtual vs. real surfaces?
As mentioned earlier, the correlation between element spacing, among all parameters, and roughness has attained the most attention in the literature. Surprisingly, most research with haptic interfaces [20, 22, 29, 45] have been unable to replicate the psychometric function obtained from real surfaces [76]. In [76], Klatzky et al. obtained a quadratic function (inverted U shaped) to describe roughness with respect to the spatial periods. On the contrary, human perceptual research with haptic devices generally acquired a linear descending function between roughness (log roughness) and element spacing (log element spacing). The exact reason for such discrepancy between real and simulated surfaces is not clear, researchers have hypothesized different reasons to explain it. For example, Unger et al. hypothesize that the main reason is that investigators use infinitesimal point to simulate probe tip contacting virtual textures [19]. When the interaction point of contact is described in this way, the handle moves with a frequency/height almost equal to the frequency/height of the surface, all the time (for comparison with real surfaces see Figure 2.4). This causes the frequency of handle motion/force be higher for smaller element spacings and lower for bigger spacing, without any transition point. Since temporal cues primarily mediate roughness perception through a probe, the linearly decreasing frequency of handle motion/force will most likely result in a monotonically decreasing human roughness function. This might explain how imperfect model of virtual handle tip has affected monotonic results from simulated surface.

Another factor that might explain the disparities when feeling real and simulated surfaces is the limitations associated with haptic devices. Most devices deployed in the haptic research are impedance type which are insufficient for rendering highly stiff virtual surfaces. As suggested in [79], factors such as finite position resolution of sensors/actuators and the limited computational speeds in the control loop software, bound the rendered stiffness to approximately 1 N/mm. In contrast, the stiffness of typical stiff objects we feel every day, such as wood or wall, is around 10 N/mm and higher. Consequently, most simulated surfaces in the literature have been very compliant compared to real surfaces. Unger [44] proposed that the compliance (stiffness) of the virtual surfaces affect the magnitude of roughness percept. He suggested that stiffness seems to amplify the surface geometry and stiffer surfaces would feel rougher providing that all the other parameters stay the same. This is probably due to the fact that users will feel force signals with higher amplitude for stiffer surfaces. Most importantly, he stated that in order to render surfaces as stiff as wood or metal, a haptic device capable of rendering surfaces with 5,000-10,000 (N/m) of stiffness should be deployed. If a haptic device with less rendered stiffness be used, the results of the experiment will have large margins of error on estimation of roughness. The range of stiffness that Unger used for surface rendering was between 3,000 to 15,000 (N/m) with MLHI (see Figure 1.2b). When he rendered Dithered Conical Textures (see Figure 2.5), used virtual spherical probes with various but finite radii (instead of infinitesimal probe) and rendered high stiffness (10 N/mm)
surfaces, the results of roughness rating was an inverted U shaped function, an identical trend found in studies with real surfaces [76].

Another disagreement in roughness perception literature is whether researchers should use a group function or individual data to present human roughness perception. For instance, Kornbrot et al. [29] performed a set of simulated textured experiments on 23 participants using sinusoidal virtual textured surface and PHANToM omni device. She witnessed that although the psychometric function presenting group roughness percept was a quadratic trend, there were 13 with linearly decreasing psychometric functions, 3 with anomalous trends, and only 7 with quadratic functions. She made a conclusion that even though the group function showed the trend of real surface, it did not reflect most of the individual trends actually. She further stated that in fact it is not the infinitesimal nature of virtual probe that caused discrepancies between real and virtual surfaces, which is in contrast with claims by Klatzky et al. in [19, 76].

Figure 2.5: Dithered conical texture models and spherical probe tip. a) Probe Size = 1.5 mm, Spacing = 0.5 mm, b) Probe Size = 1.5 mm, Spacing = 5.5 mm, c) Probe Size = 0.25 mm, Spacing = 0.5 mm, d) Probe Size = 0.25 mm, Spacing = 5.5 mm [44].
2.4 Effects of Torque Feedback on Human Perception

The body of research conducted for examining the role of torque feedback on human perception is so little compared to force feedback. One possible reason could be that most of the commonly used haptic devices, e.g. 3D PHANToM, cannot provide active torque rendering. Providing force and torque feedback in every DoF of a haptic device can be both expensive and complex. Another factor is the computational cost associated with 6 DoF haptic rendering. In addition to these hardware- and software-related limitations, behavioral studies of torque may be neglected since it is a difficult variable to isolate from a psychological perspective; experiments suggest that forces and torques are perceived inter-dependently rather than processed separately [80]. Finally, the coupled nature of force and torque in tasks such as surface exploration with a probe, which is a common convention in human perception studies, further impedes isolating the impacts of torque feedback on human percept.

Virtually all of the rendering algorithms in the literature have focused on various force feedback to simulate different surfaces. This concentration on just force signals is despite the fact that these forces (that come from interaction of probe with surfaces) generally generate some coupled torque on the users’ hands in different directions. Figure 2.6 shows a simple case of such induced in-plane torques where a human operator is moving a probe against a 2D sinusoidal surface. Equation 2.1 describes magnitude/direction of the induced torque acting on the grasping point (point A).

\[
\beta = \alpha + \frac{l_2}{l_1} \tan \theta
\]

Figure 2.6: Simple exploration task with a probe generates induced torque signals on the user’s hand (point A).
\[ T_A = mg \cos(\beta)l_2 + (F_t \sin(\alpha + \beta) - F_n \cos(\alpha + \beta))(l_1 + l_2) \]
\[ = mg \cos(\beta)l_2 + \sqrt{F_t^2 + F_n^2}(l_1 + l_2) \sin(\alpha + \beta - \tan^{-1}(F_n/F_t)) \]  

(2.1)

In this equation, \( m \) is mass of the probe, \( g \) is gravity, \( \beta \) is the angle between the probe and horizontal axis, \( l_1 \) is the distance between the probe tip and center of probe’s inertia, \( l_2 \) is the distance between center of probe’s inertia and the user’s grasping point (A), \( F_t \) and \( F_n \) are lateral and normal forces exerted on the probe tip, and \( \alpha \) is the surface slope angle (with respect to negative horizontal axis)

Equation 2.1 implies that the induced torque is the function of probe geometry and inertia \((l_1, l_2, m)\), the user’s speed and force in which the surface is explored \((F_t, F_n)\), the angle between the probe and horizontal axis \( (\beta) \) which depends on the user, and finally \( \alpha \) which is the instantaneous surface slope. Note that this equation is periodic and depends on \( \alpha \) which is changing along the surface. Although Equation 2.1 may not be applied for any surface, a very similar time-varying torque signal that is a function of instantaneous slope of the surface is generated for all textures in general.

Although this induced torque is not active in its nature, it may have measurable influence on human roughness perception. In fact, the effects of torque feedback on human perception (not roughness) have already been studied by other studies. Wu et al. [80] performed a set of experiments to investigate the effects of force and torque feedback on haptic discrimination of force, torque and stiffness. Such study suggested that torques and forces are coupled in human perception rather than processed separately by the brain. Also, this study revealed facilitation of stiffness discrimination by correlated torque and force.

The sensitivity of human perception to torque has also been studied psychophysically in the literature. For instance, studies such as [81,82] claimed that the just noticeable difference (JND) for torque is around 13 %, compared to force which is around 6-8 % [83, 84]. Jandura and Srinivasan [81] investigated JND in pinch motion and reported a JND of 12.7 % at the reference torque of 60 mN.m. Wu et al. [80] used a maglev haptic interface to generate both torque and force and measured JND of 29.9% and 7.7 % for torque discrimination with constant force and force discrimination with constant torque, respectively. While the 7.7% JND was comparable to other studies [83, 84], they claimed that the higher value of 29.9%, compared to [81], could be because of the presence of the constant force and/or different reference torque which was 200 mN.m. The sensitivity of human to torque has been realized to be intrinsically dependent on the context of task and type of the interaction. Woodruff and Helson [82] suggested that when the reference torque decreased from 0.98 to 0.082 N.m, the torque sensitivity changed from 4.4 to 12.6 %.
Other researchers have studied the effectiveness of torque feedback for haptic rendering. For example, Ho et al. in [85] developed a novel rendering algorithm, with a combination of both force and torque feedback, for the perception of 3D objects in VRs. The results suggested that subjects were able to recognize 3D objects faster with this novel rendering algorithm compared to using only force feedback rendering. In [86], Wang et al. investigated the role of torque feedback in haptic perception of virtual object location. They concluded for some applications, e.g., virtual sculpting in which the user is free to move the probe, force feedback solely is sufficient for locating the object without any significant improvement from providing torque feedback. On the other hand, for applications such as laparoscopic surgical simulator, where environment imposes some constraints on the probe, both force and torque feedback would be necessary to obtain the best judgment of the object distance within the simulated environment. Verner et al. examined the effects of both torque feedback for simple tasks such as virtual drawing and/or tracing [87]. They stated that for such tasks the user’s performance with a 3 DoF haptic device (force feedback only) approximates the subject’s performance with a 6 DoF haptic device (both force and torque feedback). Similarly, Santos-Carreras et al. [88] noted that additional torque feedback did not significantly facilitate the performance of subjects in suturing task experiment. Conversely, Weller and Zachmann [89] showed that both of user perception and performance in object collection game with 6-DoF haptic platform and torque feedback outperformed both performance and perception of users that utilized a 3-DOF haptic device. Moreover, Lee et al. [90] suggested that for successful tele-drilling of screw in spinal fusion surgery, both force and torque feedback are necessitated to be applied on the subjects’ hand. These results generally suggest that the effectiveness of additional torque feedback highly depends on the type of the task that is being performed.

While the role of torque feedback has been suggested for haptic discrimination of different surface properties such as stiffness [80], and hardness [91], little is known about the role of torque feedback in perception of texture roughness. When surfaces, real or virtual, are explored via an intermediate median such as a probe, any probe-surface interaction (PSI) force that is in a direction not directly towards or away from the grasping point produces an additional torque on the grasping point. It is unknown how human brain perceives this additional torque feedback to discern roughness. For example, would surfaces feel less rough when coupled torque feedback is not available?

Although most studies described in this Chapter are concerned with torque that is coupled with force, the role of uncorrelated torque rendering on human percept has been proposed by literature. For instance, results from [92] recommended that the presence of uncorrelated torque facilitated the perception of object location in the task of rocking. Also, authors in [80] stated the highest JNDs for force discrimination when uncorrelated torque feedback was provided, compared to when correlated or constant torque feedback was given. Since decoupled torque feedback is not
designed specifically to reflect real world interactions and dynamics, it can be computationally less expensive, specifically when interaction involves complex dynamics. As a result, decoupled torque feedback can be a good alternative for full torque feedback when performance rather than realism is desirable. Studying decoupled torque feedback in the context of human perception of surfaces would have further implications for developing haptic VEs and platforms. For example, high frequency noises in rotational DoF of the haptic device can be considered as random, uncorrelated torques. Information on how users perceive uncorrelated torques would then be valuable for selecting/developing proper haptic devices for simulating textures. To the best of the present authors’ knowledge, no previous research studies address these questions about the role of coupled and uncoupled torque feedback in tandem with different probes on human texture perception.

2.5 Roles of Probe Type on Human Perception

Investigating the role of probe type, fingertip (Figure 4.1a) and pen shape (Figure 4.1d), on human texture perception is the other primary goal of this thesis effort. As medians between users’ hand and haptic stimulus, it is possible that different haptic probes would transfer signals in dissimilar manner resulting in different human perception of virtual textures.

Since most of the probes used in the human roughness perception are either in the shape of thimble or pen-shaped, it is reasonable to ask if and/or how deployment of different probes would affect roughness perception of computer-generated textures. Surprisingly, the role of probe on human perception has only attained little attention in the literature. Most of the researchers have focused on developing more sophisticated algorithms to simulate textures/probes in virtual environments without considering actual probe with different types. In an important study, however, Kornbrot et al. [29] performed a set of experiments using Phantom haptic device (see Figure 2.7)

![Various haptic probes with different grasp types and shapes.](image)

Figure 2.7: Various haptic probes with different grasp types and shapes.
and sinusoidal haptic textures. They investigated the role of various factors, including different probes, on human perception. The results of magnitude ratings were similar for both probes, thimble and pen-shaped while a few participants did have statistically significant different functions. Although such results have been obtained in the literature, we are interested in examining the roles of different probes on human texture perception in a deeper way and within various torque feedback conditions. Our system, which will be detailed discussed in the next chapter, permits forces and torques to be generated on a magnet embedded device which can be worn directly on the finger or be grasped by hand. Moreover, Our haptic device provides an opportunity to readily integrate various haptic styluses with minimal software and hardware update. In contrast, other devices such as PHANToM and/or other existing magnetic levitation haptic interfaces are usually constrained, in terms of the shape of their device handle. This limitation may be one important factor explaining the fact that haptic probes have been confined to merely thimble and pen-like types.

2.6 Research Questions

The main research questions to be answered within the context of this thesis are:

- Would subjects feel virtual texture rougher with thimble or penhandle probe?
- How does psychometric function of human judgments with respect virtual textures change within different styluses?
- How does human receive surface roughness within different torque conditions?
- How does (active or passive) torque affect human texture perception?
3 COIL ARRAY MAGNETIC LEVITATION HAPTIC INTERFACE

The advantages of magnetic levitation systems rather than motorized linkages for haptic interaction are that friction and hysteresis are eliminated from the motion dynamics, and all 6 degrees of freedom in rigid-body motion and force and torque feedback are obtained from a single moving part. Therefore the precision and response speed of the magnetic levitation system depend only on the sensors and actuators and are not limited by the dynamics of any mechanical mechanism. The spatial nonlinearity and complexity of extended magnetic fields produce challenges in magnetic levitation device modeling, design, and control, however.

In our sets of user trials for roughness texture perception, a novel coil array magnetic levitation haptic interface developed by Berkelman et al. at the University of Hawaii at Manoa [8, 24, 93, 94] have been deployed. Figure 3.1 depicts the entire platform along with different parts.

The device consists of the following subsystems: motion tracker, array of 27 of wounded coils, magnet embedded objects, current amplifier, and a PC control system. Each subsystem will be explained in details in the following sections.

Figure 3.1: The entire system of coil array magnetic levitation haptic interface.
3.1 Motion Tracker (Sensing Unit)

An optical motion tracking system from Northern Digital Inc. is utilized to detect and provide both position and orientation (6 DoF) of the levitated object in real-time. The size of this measurement unit is 1126 mm $\times$ 200 mm $\times$ 161 mm with the total mass of 18 kg. When smart LEDs are utilized, the update rate of tracking is at the maximum of 860 Hz, accuracy up to 0.1 mm, and resolution of 0.01 mm.

The motion tracker is securely fixed to a rigid frame above the coil array and facing down (see Figure 3.1) to detect the location of multiple LEDs placed on levitated items. For the two haptic probes used in our experiments (one of them is shown in Figure 3.1c), three wireless LED markers along with the wireless strober are deployed. The use of wireless markers eliminate any additional/undesirable forces on the levitated object from electrical wiring and allow a levitation system with minimal contact.

3.2 Coil Array and Magnets (Actuation Unit)

In our magnetic levitation haptic interface, forces and torques are generated due to the electromagnetic interaction between the currents in the coil array and permanent magnets which are embedded in haptic probes. As shown in Figure 3.1b, the coil array consists of 27 cylindrical coils which are arranged in the planar array, 6 rows of multiple (from 3 to 6) coils, each in hexagonal shape with 35 mm spacing between coil centers. The distance between each rows of coils is 30 mm.

Each cylindrical coil is made of copper to avoid magnetization and to maximize the dissipation of heat generated by currents. They have the inner and outer diameter of 12.5 and 25.4 mm with the height of approximately 30 mm. Figure 3.2 depicts the coil array along with its assigned coordinate system, and distances mentioned above. $R_x$ (roll), $R_y$ (pitch), and $R_z$ (yaw) are rotational directions around $x$, $y$, and $z$ axes respectively.

To generate magnetic fields over top of the coil array, the currents are sent to the magnet wire with 1000 turns around each cylindrical coils. Magnet wires have a diameter of 0.402 mm (AWG 26), a resistance of approximately 9 $\Omega$, and thermal grade of 155 $^\circ$C. The coil currents are limited to a maximum of 3.0 A in the system software to avoid overheating.

When a single magnet is placed in the generated magnetic field, three electromagnetic forces (in all directions) and two torques (in $R_x$ and $R_y$ directions) are generated, allowing active control in 5 DoFs of the system. The electromagnetic forces and torques depend on the coil currents and the relative positions/orientations of the coils and magnets with respect to each other. In [94], authors
explained three methods to calculate and model these forces and torques. A short description of this calculation is mentioned here.

As described in [94, 95], if \( N \) coils (in the most recent version of our system \( N \) is equal to 27) are utilized in our system, the forces and torques can be calculated as follows:

\[
F = A \times I
\]  
(3.1)

Where \( F \) is the \( 6 \times 1 \) force/torque matrix, \( A \) is the \( 6 \times N \) transformation matrix and is a function of relative positions and orientations of coils and magnets, and \( I \) is the \( N \times 1 \) current matrix. Equation 3.1 can be described in a more detailed form as:

\[
\begin{bmatrix}
F_x \\
F_y \\
F_z \\
T_x \\
T_y \\
T_z
\end{bmatrix} = \begin{bmatrix}
a_{f_x}(r_1,z,\theta_1,\phi,\psi_1) & \cdots & a_{f_x}(r_N,z,\theta_N,\phi,\psi_N) \\
a_{f_y}(r_1,z,\theta_1,\phi,\psi_1) & \cdots & a_{f_y}(r_N,z,\theta_N,\phi,\psi_N) \\
a_{f_z}(r_1,z,\theta_1,\phi,\psi_1) & \cdots & a_{f_z}(r_N,z,\theta_N,\phi,\psi_N) \\
a_{t_x}(r_1,z,\theta_1,\phi,\psi_1) & \cdots & a_{t_x}(r_N,z,\theta_N,\phi,\psi_N) \\
a_{t_y}(r_1,z,\theta_1,\phi,\psi_1) & \cdots & a_{t_y}(r_N,z,\theta_N,\phi,\psi_N) \\
a_{t_z}(r_1,z,\theta_1,\phi,\psi_1) & \cdots & a_{t_z}(r_N,z,\theta_N,\phi,\psi_N)
\end{bmatrix} \begin{bmatrix}
I_1 \\
I_2 \\
I_3 \\
I_4 \\
\vdots \\
I_N
\end{bmatrix}
\]  
(3.2)

In this equation, \( F_x, F_y, \) and \( F_z \) are generated forces in the \( x, y, \) and \( z \) directions and \( T_x, T_y, T_z \) are generated torques in the \( R_x, R_y, \) and \( R_z \) directions (see Figure 3.2).
In matrix $A$, $z$ is the vertical distance between magnets and coils array, and $r_i (i = 1, 2, ..., N)$ is the radial offset distances between the vertical axes of the magnet and $i^{th}$ coil and is given by:

$$r_i = \sqrt{(m_x - c_{ix})^2 + (m_y - c_{iy})^2} \quad (3.3)$$

In Equation 3.3, $m_x$ and $m_y$ are the horizontal and vertical position of the magnet. $c_{ix}$ and $c_{iy}$ are the horizontal and vertical position of the $i^{th}$ coil.

In Equation 3.1, $\theta_i$ are the rotation angles to separate radial horizontal forces and torques into $x$ and $y$ components:

$$\theta_i = \text{atan}2(m_y - c_{iy}, m_x - c_{ix}) \quad (3.4)$$

Furthermore, in Equation 3.1 $\phi$ is the tilt angle of the magnet and $\psi_i$ is the angle from $i^{th}$ coil center to the magnet center in the horizontal plane.

The A matrix described above is for the case when one magnet is placed in a magnetic field from $N$ coils. In this case, only 5 DoF (all directions except $R_z$) of the magnet can be actively controlled. If $m (m > 1)$ magnets being utilized in the levitation system all of the 6 DOF of the magnets combination can be controlled [94]. In this situation, if $A_j$ be the transformation matrix for the combination of the $j^{th}$ magnet and $N$ coils, the total transformation matrix of the levitation system can be described as:

$$A = \sum_{j=1}^{m} A_j \quad (3.5)$$

In each control loop, the A matrix for the combination of $m$ magnets and $N$ coils is calculated. This rectangular A matrix is kinematically redundant, that is the number of actuators are more than DOFs to be actively controlled. Since this A matrix is not square in general, it is not invertible and $I = A^{-1}F$ cannot be utilized for coil current calculation and control commands. In this case, the Moore-Penrose pseudoinverse [96, 97] $A^+$ of $A$ is used to calculate the coil currents ($I = A^+F$) which minimizes the sum of current squares for levitation control. More detailed calculations of transformation matrices of $A$ and $A^+$ can be found in [94].

### 3.3 Amplifiers and Power Supply (Power Unit)

After calculation of coil currents using the transformation matrices of $A$ and $A^+$, they should be sent to the coils. Since the calculated currents in the system software are digital and the actual coil currents are analog signals, a 32-channel analog output PCI board (United Electronic Industries PD2-AO-32-16) in the controller PC is utilized to convert control signals to analog. These signals
will be sent to the Pulse-width Modulation current amplifiers (Copley Controls Z2112) where the actual coil currents are generated and sent to the coils. In the most recent set up of the system, four power supplies and 27 current amplifiers are utilized to generate coil currents. The coil currents are confined, in software, to a maximum of 3.0 A to avoid overheating.

3.4 PC and Control Software (Control Unit)

For controlling the location (position and orientation) of a magnet embedded levitated object (see Figure 3.1c) in real-time, conventional PD feedback control algorithm is deployed. The system utilizes a Linux 2.7 operating system kernel running on 1.8 GHz Intel core 2 duo processor PC with real time, multithreaded, and multipriority programming for real-time feedback control. The system software is developed using C/C++ programming language and is responsible for many tasks including communication with motion tracker and PCI board; calculation of transformation matrix and its pseudoinverse, and feedback control laws, among others. The software update rate primary depends on the motion tracker frequency as well as the number and type of emitters being used on the levitated object. For the probes with three smart LEDs that we deployed in our experiments, the control update rate is 860 Hz.

3.5 System Characteristics

One of the primary limitations of previous maglev haptic devices for haptic interaction was small range of motion they allowed. Our novel magnetic levitation haptic interface, on the other hand, provides a relatively large range of motion which is nearly comparable to the workspace of haptic devices such as PHANToM. The translational motion range of the device is $80 \text{ mm} \times 80 \text{ mm} \times 25 \text{ mm}$ in $x$, $y$, and $z$ directions. The rotational range of motion of the system depends on magnet arrangement. For the present pen and fingertip platforms rotational range is approximately $\pm 40^\circ$ in roll, $\pm 40^\circ$ in pitch, with unlimited motion in yaw.

The other novel characteristics of our planar coil array magnetic levitation haptic interface is its expandable horizontal motion range without any limitation (in $x$ and $y$ directions), and the use of redundant kinematics methods for controlling levitated objects which provides more system controllability and less power consumption. The performance characteristics of the system is summarized in the Table 4.1.

One of the main reasons for using this platform to study perception with different probes is the fact that integration of new haptic styluses is straightforward, requiring only minimal changes on system’s software. For most of other haptic devices, however, developing new probes usually requires changing some parts of the system’s hardware or building probes on top of each other.
<table>
<thead>
<tr>
<th>parameter</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Translational range ($x \times y \times z$)</td>
<td>$100 \times 100 \times 40$ mm</td>
</tr>
<tr>
<td>Rotational range (roll, pitch, yaw)</td>
<td>$\pm 40^\circ, \pm 40^\circ, \text{unlimited}$</td>
</tr>
<tr>
<td>Motion resolution</td>
<td>$10 \ \mu m$</td>
</tr>
<tr>
<td>Motion accuracy</td>
<td>$100 \ \mu m$</td>
</tr>
<tr>
<td>Control update frequency</td>
<td>$860 \ Hz$</td>
</tr>
<tr>
<td>Haptic probe mass</td>
<td>$100-500 \ gr$</td>
</tr>
<tr>
<td>Maximum force</td>
<td>$20 \ N$</td>
</tr>
<tr>
<td>Maximum torque</td>
<td>$3 \ N.m$</td>
</tr>
<tr>
<td>Maximum translational stiffness</td>
<td>$1.5 \ N/mm$</td>
</tr>
<tr>
<td>Maximum rotational stiffness</td>
<td>$10 \ N.m/rad$</td>
</tr>
</tbody>
</table>

Table 3.1: Performance characteristics of planar coil array magnetic levitation haptic interface.

These changes would include additional complexity to the system’s dynamics and possibly change the way of transmitting signals from the device to the hand in an unrealistic way.

The system also allows active motion control in 6 DoFs which provides further advantage for including torque, in addition to force feedback, in simulating virtual surfaces. This opens up new paths towards more realistic VRs where a full DoFs dynamics of interaction is realized. This would also help researchers to understand how a 6 DoF PSI, instead of interaction based on force feedback only, would mediate human perception of virtual textures.

Due to all of these characteristics and advantages, this novel haptic system is suitable for exploring the impacts of different torque feedback algorithms and probe shapes, two parameters that have given little to no attention in the literature, on human perception. In the next chapter, the experiment setup and procedure will be discussed in details.
4 EXPERIMENTAL SETUP AND PROCEDURE

The roughness perception experiment will be discussed in this Chapter. General experimental procedure and data analyses are similar to those deployed in studies such as [44, 76] with a different haptic platforms and other parameters of interest.

For the experiments performed in this body of research, virtual surfaces are deterministically modeled with sinusoidal gratings ranging from 0.7 to 6 mm while the virtual avatar is modeled as an infinitesimal point. Many earlier studies [20, 28, 44] used a sinusoidal surface modeling as their basis. As discussed in Section 2.3, considerable discrepancies have been found between various studies, however. The primary purpose of our experiments is not to explain the underlying reasons behind these discrepancies nor proposing a sophisticated virtual surface model, but rather to characterize the effects of two parameters, torque feedback algorithms and stylus type, on human perception which has not been well studied by haptic researchers.

Sinusoidal surfaces and point-based probe tip are easy to generate, manipulate and well suited for studies where the main focus is not on surface and contact model sophistication. As a result of this simplicity yet sufficiency of this model, it has been deployed throughout our experiments.

4.1 Experiment Apparatus

The novel coil array magnetic levitation haptic interface described in Chapter 3 was deployed in our human trials. In the following sections, design, fabrication, and control of two haptic probes deployed in our experiments are explained.

4.1.1 3D-Printed Haptic Probes

Design and Fabrication

Since one of the goals of this research was to specify the effects of probe type on human percept of virtual textures, a pen handle and a fingertip haptic styluses (shown in Figure 4.1) were designed in Solidworks software and then 3D printed using the uPrint 3D printer by dimention Inc. The use of 3D printing technology provided a unique opportunity for fast and cheap prototyping of light weight haptic probes which minimizes coil currents needed for running haptic simulations. This is particularly critical in our system, since it cannot be continuously running for more than approximately two minutes without heat compromising the coils and wires.

While fingertip haptic probe surrounds the fingertip and the nail of only index finger, the pen-handle probe is grasped with thumb, index and middle fingers, and very similar to a real pen.
Since the type of grasp, part of hands/skin involved, and the shape of each probe is different, it is interesting to investigate how these might mediate human perception.

Each probe had three infrared LEDs on top, which allowed the optical motion tracker to provide position and orientation feedback in real time. Due to the use of three smart markers, the update rate of the motion tracker and haptic control can be at the maximum of 860 Hz, which is virtually sufficient for generating high fidelity, stable haptic interaction. The fingertip haptic probe is embedded with a single magnet with 25.40 mm diameter, 9.53 mm thickness, and has a total mass of 100 grams. The penhandle probe weighs 150 grams and has 4 embedded magnets, three of which are 45 degree tilted and symmetrically arranged around the probe shaft axis, each with radius and thickness of 11.11 mm and 3.175 mm. The fourth magnet is in the direction of probe’s shaft and has radius and thickness of 19.05 mm and 12.7 mm. Since the penhandle is essentially more prone to vibrations than the fingertip, a damping tape is attached to the its shaft to reduce vibrations of the probe and enable rendering virtual surfaces with higher stiffness.
Control

Since the number and configuration of magnets that are embedded into each probe are different, a separate control software was utilized for each. For the penhandle probe, the control software developed by Berkelman and Miyasaka [95] was deployed in which forces/torques from each of four magnets were superimposed to generate net forces/torques onto the penhandle body. Control software for the fingertip was separately developed based on the calculations presented in Section 3.2. and involved less computation as only a single magnet was used.

4.2 Participants

Twelve subjects, nine males and three females, with an average age of 29.3 years old and age range of 22 to 36 years old, participated in this study. All participants received both written and verbal instructions about the experiment procedure which will be described later. All subjects were right-handed by self-report with no known manual sensory abnormalities. The subjects were also advised not to push hard on the virtual surfaces as this may cause the system to be shut down. Three participants had prior experience with haptic devices. Subjects were graduate and undergraduate students from College of Engineering at the University of Hawaii and received money compensation for their time and effort to participate. All experiments were performed with IRB approval from the University.

4.3 Surface Rendering Algorithm

To avoid computational complexity and noise susceptibility from sophisticated rendering algorithms such as the Dithered Conical Texture [19] and to focus on the role of torque feedback on human perception, simple 2D (e.g. $x'$-$z'$ plane in Figure 4.2) sinusoidal surfaces are used. The contact between virtual surfaces and probes was simulated as a single point. The amplitude of surfaces was 0.4 mm peak to peak for all surfaces, similar to the amplitude used in other studies such as [19, 22, 98]. The spatial periods ranged from 0.70 mm to 6.00 mm in eleven equally spaced increments of 0.48 mm. The 0.70 mm was the minimum spatial period in which the maglev haptic device was capable of generating stable sinusoidal surfaces. These sinusoidal surfaces can be described as:

$$\begin{align*}
Z_{surf} &= A \sin\left(\frac{2\pi}{D_{surf}} X_{surf}\right) + B \\
-20 &\leq Y_{surf} \leq 60 \text{ mm}
\end{align*}$$

(4.1)
In this equation, $B$ is the constant distance of surfaces from coils, $X_{surf}$, $Y_{surf}$, and $Z_{surf}$ are the components of each point (P) of the virtual surface in the x, y and z direction, and $A$ and $D$ are the amplitude and spatial period of the surfaces respectively. Figure 4.2 shows the superimposition of virtual surfaces (e.g. $Y_{surf} = 20 \text{ mm}$) onto the maglev system. In this Figure, the yellow and blue frames are for maglev and virtual surfaces respectively ($x$ and $x'$, $y$ and $y'$, $z$ and $z'$ are parallel).

### 4.3.1 Force Feedback

To provide subjects with proper force feedback in z direction, the conventional spring-damper algorithm is used. This algorithm is based on the penetration depth of the infinitesimal end point of the stylus into the virtual surfaces. For x and y directions, only damping forces (stiffness coefficients set to zero) are provided to avoid a slippery sensation. Simulating surface with force in z direction only (rather than 2D forces that are normal to the surface) further simplifies our rendering and avoids undesirable source of possible instability such as ones reported in [99].

The position of the center of mass of the haptic probe, penhandle or fingertip, is sensed by the motion tracker at each time step of $t$ which can be expressed as $P_{hp}(t) = [x(t), y(t), z(t)]^T$. The generated force feedback on the users’ hand can then be formulated as:

$$F(t) = \begin{cases} 
K_p(P_{surf}(t) - P_{hp}(t)) + 
\frac{f_{imp}K_d}{x_p}(P_{hp}(t) - P_{hp}(t - 1)) & \text{if } z(t) \leq Z_{surf} \\
0, & \text{if } z(t) > Z_{surf}
\end{cases}$$

(4.2)
\[
K_p = \begin{bmatrix}
0 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 1.5
\end{bmatrix} \text{ (N/mm)}, \quad K_d = \begin{bmatrix}
10 & 0 & 0 \\
0 & 10 & 0 \\
0 & 0 & 10
\end{bmatrix} \text{ (N/mm/s)}
\]

In this equation, \( F(t) \) is the electromagnetic force vector to be generated on the haptic probe at time \( t \), \( K_p \) and \( K_d \) are proportional and derivative error gains matrices, \( P_{hp}(t) \) and \( P_{hp}(t-1) \) are position vectors of the probe’s center of mass at time \( t \) and \( t-1 \), \( P_{surf}(t) \) is the position vector of the virtual surface where \( X_{surf} = x(t) \), \( Y_{surf} = y(t) \) and \( Z_{surf} \) is obtained from Equation 4.1, and \( f_{samp} \) is the sampling frequency of the motion tracker which is equal to 860 Hz.

### 4.3.2 Torque Feedback

Since virtual surfaces in our experiments are 2D and for further simplicity in surface rendering and data analysis, only torque feedback in the pitch \((R_y)\) direction, active or passive, are considered for analysis. The general method for active torque feedback calculation is similar to force feedback except that the computation involves more matrix calculation. This is due to the fact that we use rotation matrices provided by motion tracker, rather than angles, for specifying the orientation of levitated object. Presenting the orientation in this way, rather than the vector-based Euler angle or roll-pitch-yaw representations, avoids various potential disadvantages for rotational control such as kinematic singularities (or "gimbal lock"), nonisometric distortion of angular measurements for large angles, and ambiguity regarding the sequence of rotations about \( \hat{x} \), \( \hat{y} \), or \( \hat{z} \) fixed or rigid-body axes. Orientation of the haptic probe, in the form of rotation matrix, is denoted by \( R_{hp}(t) \) at each time step \( t \). After obtaining the orientation, a torque feedback is generated on the haptic probe in a way that it brings the current orientation of the probe \( (R_{hp}(t)) \) into a desired orientation. This desired orientation \((y\text{-axis rotation matrix for our 2D surfaces})\) at each time step \( t \) is denoted by \( R_d(t) \) and can be expressed as follow:

\[
R_d(t) = \begin{bmatrix}
\cos(\alpha(t)) & 0 & \sin(\alpha(t)) \\
0 & 1 & 0 \\
-\sin(\alpha(t)) & 0 & \cos(\alpha(t))
\end{bmatrix}
\]

(4.3)

In this equation, \( \alpha(t) \) is the desired angle of the haptic probe with respect to the y axis of the maglev coordinate frame.
Given the rotation matrix $R_{hp}(t)$ specified by the motion tracker and $R_d(t)$ be calculated based on some criteria at each time step $t$, angular velocity and the angular error can be then calculated as described in [100]:

$$E = (R_d(t) - R_{hp}(t))R_{hp}^T(t) = \begin{bmatrix}
0 & -e_z(t) & e_y(t) \\
e_z(t) & 0 & -e_x(t) \\
-e_y(t) & e_x(t) & 0
\end{bmatrix} \quad (4.4)$$

In this equation, $e(t) = [e_x(t), e_y(t), e_z(t)]^T$ is rotational error vector at the time step $t$ which is calculated from the skew-symmetric difference matrix $E$.

To decrease the effects of errors rising from sensor and floating-point calculation, the error vector $e(t)$, which is used for feedback control, can be obtained by the backward-difference approximation from $E$ as:

$$e_x(t) = \frac{E_{32} - E_{23}}{2}, \quad e_y(t) = \frac{E_{13} - E_{31}}{2}, \quad e_z(t) = \frac{E_{21} - E_{12}}{2} \quad (4.5)$$

In a similar way, the rotational velocity vector, $\omega(t) = [\omega_x(t), \omega_y(t), \omega_z(t)]^T$, can be calculated from the skew-symmetric difference matrix $\Omega$ as

$$\omega_x(t) = \frac{\Omega_{32} - \Omega_{23}}{2}, \quad \omega_y(t) = \frac{\Omega_{13} - \Omega_{31}}{2}, \quad \omega_z(t) = \frac{\Omega_{21} - \Omega_{12}}{2} \quad (4.6)$$

where

$$\Omega = f_{smp}(R_{hp}(t) - R_{hp}(t-1))R_{hp}^T(t) \quad (4.7)$$

and finally the active torque vector $T(t)$ in the x-z plane can be calculated as:

$$T(t) = K_{pr}e(t) + K_{dr}\omega(t) \quad (4.8)$$

In this equation, $e(t)$ and $\omega(t)$ are the angular error and velocity calculated from Equation 4.5 and Equation 4.6 and $K_{pr}$ and $K_{dr}$ are proportional and derivative gain matrices with units of Nm/radian and Nm/radian/s respectively.

### 4.3.3 Torque Feedback Conditions

Three different torque feedback conditions were investigated in this study. We refer to these torque feedback conditions as No Torque, Slope Torque, and Stiff Torque. The main differentiation among these conditions is the magnitude and type of active torque feedback applied on the probe in pitch motion, which leads to dissimilar probe orientation at each time step (see Figure 4.3). In
all three conditions there is no active torque feedback in yaw motion (z axis). This is due to the fact that this DoF of the fingertip probe is not controllable since it is embedded with a single magnet only [101]. Dissimilar to different torques, an identical penetration-based algorithm explained earlier is used to generate force feedback within all conditions.

**No Torque**

In this torque condition, no active torque feedback in the pitch motion is generated on the user’s hand. Subjects perceive only torques that are coupled with the z-axis forces from PSI calculated in Equation 4.2. This type of torque feedback has been deployed in the texture perception literature by studies such as [29] where the haptic platform (e.g. PHANTOM omni shown in Figure 1.2a) is capable of generating force feedback only.

The orientation of the haptic probe (shown in Figure 4.3a) at each time step $t$ is dependent on four parameters: 1) orientation in which the probe is being held, 2) angle of the probe relative to the PSI force, 3) magnitude of the coupled force from PSI acting on the probe, and 4) other effects such as gravity, etc. Since most of these parameters are determined by the user during the experiment in real time, the orientation of the probe cannot be specified off-line and is depicted in Figure 4.3a in a random manner.

![Figure 4.3: Schematic orientation of the probe in x-z plane in five different time instances for: (a) No torque, (b) Slope torque and (c) Stiff torque.](image)

42
With this torque feedback condition, subjects perceive higher coupled torque when holding the penhandle compared to fingertip, given identical PSI force for both probes. This is due to the fact that the distance between the grasp point and PSI force is larger for the penhandle probe compared to the fingertip.

**Slope Torque**

In the second torque condition, *Slope Torque*, active torque feedback is provided on the probe in such a way that the probe always remains perpendicular to the sinusoidal surface in the x-z plane (see Figure 4.3b). In this situation, subjects received torque feedback from two different sources, a passive (coupled) torque feedback from PSI (similar to No torque condition) and an active torque feedback based on calculations in Section 4.3.2.

Since the probe is orthogonal to the sinusoidal surface at each contact point, the $R_d(t)$ (or $\alpha(t)$) can be described as:

$$\alpha(t) = \tan^{-1}\left(\frac{\partial Z_{surf}(t)}{\partial X_{surf}(t)}\right) = \tan^{-1}(A(\frac{2\pi}{D}) \cos(\frac{2\pi}{D} X_{surf}(t)))$$  \hspace{1cm} (4.9)

and the desired rotation matrix (y-axis rotation matrix) corresponding to this angle is:

$$R_d(\alpha(t)) = \begin{bmatrix}
\cos(\alpha(t)) & 0 & \sin(\alpha(t)) \\
0 & 1 & 0 \\
-\sin(\alpha(t)) & 0 & \cos(\alpha(t))
\end{bmatrix}$$  \hspace{1cm} (4.10)

and the generated torque ($T(t)$) can be presented as:

$$T(t) = \begin{cases}
K_{pr}e(t) + K_{dr}\omega(t) & \text{if } z(t) \leq Z_{surf} \\
0, & \text{if } z(t) > Z_{surf}
\end{cases}$$  \hspace{1cm} (4.11)

with

$$K_{pr} = \begin{bmatrix} 10 & 0 & 0 \\ 0 & 2 & 0 \\ 0 & 0 & 0 \end{bmatrix}, K_{dr} = \begin{bmatrix} 150 & 0 & 0 \\ 0 & 200 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

It can be seen from $K_{pr}$ and $K_{dr}$ matrices along with Equation 4.11, active torque feedback in roll motion ($K_{pr}(1, 1) = 10, K_{dr}(1, 1) = 150$) prevents any rotation out of the x-z plane, active
torque feedback in pitch direction \((K_{pr}(2, 2) = 2, K_{dr}(2, 2) = 200)\) ensures the haptic probe to be always perpendicular to the virtual surface in the x-z plane, and absence of any active torque in yaw direction \((K_{pr}(3, 3) = 0, K_{dr}(3, 3) = 0)\) is due to the fact that this DoF is not controllable for the fingertip probe. This torque formulation and matrices coefficients are identical for both fingertip and penhandle.

**Stiff Torque**

In the third condition, *Stiff Torque* feedback, the rotational motion of the probe in both of x-z and z-y planes are constrained, while the probe is free to rotate in yaw motion. In fact, the probe will always stay upright in this torque condition (see Figure 4.3c) In this situation, users perceive torque from the constrained active torque only and the coupled torque from PSI force, which was available for the other two torque conditions, is negligible. This is due to the fact that the PSI force vector is, almost, in the z direction and passes through the haptic probe shaft. However, the coupled torque from friction forces (x direction) are available. The major difference between this torque condition and previous one is that in the later \(\alpha(t)\) changes at each time instance based on the slope of the surface, where as in the former \(\alpha(t)\) is always constant and equal to zero. This type of torque feedback has been deployed in studies such as [19] to prevent the probe from rotational motion which confines experiment variables and facilitates investigation of parameters of interest on human texture perception.

Figure 4.3 demonstrates the rotation movement of the probe in five different time instances for each of the three torque conditions. Table 4.1 also summarizes the values of \(R_{\alpha(t)}, K_{pr}, K_{dr}\) matrices which are needed at each time step \(t\) to calculate \(T(t)\) for each of the three torque conditions.

<table>
<thead>
<tr>
<th>Torque Condition</th>
<th>(R_{\alpha(t)})</th>
<th>(K_{pr})</th>
<th>(K_{dr})</th>
</tr>
</thead>
</table>
| No torque        | \[
\begin{bmatrix}
0 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 0
\end{bmatrix}
\] | \[
\begin{bmatrix}
0 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 0
\end{bmatrix}
\] | \[
\begin{bmatrix}
0 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 0
\end{bmatrix}
\] |
| Slope torque     | \[
\begin{bmatrix}
\cos(\alpha(t)) & 0 & \sin(\alpha(t)) \\
0 & 1 & 0 \\
-\sin(\alpha(t)) & 0 & \cos(\alpha(t))
\end{bmatrix}
\] | \[
\begin{bmatrix}
10 & 0 & 0 \\
0 & 2 & 0 \\
0 & 0 & 0
\end{bmatrix}
\] | \[
\begin{bmatrix}
150 & 0 & 0 \\
0 & 200 & 0 \\
0 & 0 & 0
\end{bmatrix}
\] |
| Stiff torque     | \[
\begin{bmatrix}
1 & 0 & 0 \\
0 & 1 & 0 \\
0 & 0 & 1
\end{bmatrix}
\] | \[
\begin{bmatrix}
10 & 0 & 0 \\
0 & 10 & 0 \\
0 & 0 & 0
\end{bmatrix}
\] | \[
\begin{bmatrix}
150 & 0 & 0 \\
0 & 150 & 0 \\
0 & 0 & 0
\end{bmatrix}
\] |
4.4 Roughness Perception Experiment

4.4.1 Experimental Factors

In our experiments, subjects explored a series of virtual surfaces (variable wavelengths) with both penhandle and fingertip probes. The effects of three within-subject experimental factors (spatial period, torque condition, and probe type) along with their mutual interactions on the human roughness perception were investigated. Within one set of trials for each subject, the factor of spatial period consisted of 12 values, which were equally spaced in the range of 0.7 to 6 mm. Each of these values were repeated 3 times for reducing statistical noise and acquiring more reliable estimates of performance. The full set of trials (12 spatial periods × 3 repetitions = 36) were presented to each participant in a random order, for removing possible effects of learning. The factors of torque feedback with 3 different conditions of No torque, Slope torque, and Stiff torque along with the factor of probe type with two different types of fingertip and penhandle, were blocked for each user, so that each individual explored three different blocks of torque condition separately for each probe (6 blocks for two probes), each with 36 virtual surfaces. The factor of probe was nested under subjects followed by torque feedback nested under probe. The sequences in which the three torque conditions and two haptic probes were allocated to different subjects were randomized separately to eliminate possible bias from any specific sequence. With three conditions of torque feedback and two types of haptic probes, a minimum number of (3! × 2! = 12) subjects was required to present all possible sequence of torque condition and probe type to all users. Figure 4.4 depicts a graphical representation of these three experimental factors and how they are nested. In total, 2592 (12 spatial periods × 3 repetitions × 2 probe types × 12 subjects) data points were collected for the whole experiment.

4.4.2 Experiment Procedure

Subjects were seated at a distance of (about) 40 cm from the maglev system that was comfortable for each individual. The maglev system was at the height of (around) 55 cm from the ground. Subjects were instructed on how to perform each trial and the whole experiment for about 15-20 minutes. On each trial, subject actively explored a virtual texture, for a maximum of 7 seconds, by moving his or her hand with the haptic probe above the coils laterally in x direction of maglev coordinate system (see Figure 3.2 and Figure 4.5) back and forth. Then s/he verbally specified a number representing the magnitude of the surface roughness they felt. Since research has shown that visual [102] and auditory [103] cues have measurable influence on textural information, all subjects were blindfolded while listening to white noise through headphones (see Figure 4.5) to restrict the perception to touch only. The task was free magnitude estimation. Subjects were asked
Figure 4.4: Graphical representation of the experiment design with three within-subject experimental factors

to use positive numbers (> 0) to specify the roughness of sinusoidal textures with higher numbers indicating rougher surfaces. No specific definition of roughness was given and participants were requested to judge the roughness with their knowledge from daily interaction with real items. After exploring the surface and specifying the roughness magnitude associated with it, the user could take a break of up to 5 seconds. At any point in which they verbally expressed they were ready for the next trial, the experimenter would hit the 'Enter' button and a new surface would be generated.

Figure 4.5: A subject of the experiment exploring virtual surfaces laterally with the fingertip probe while wearing headphone and blindfold.
by the maglev system. Experiment software was programmed in a way that subjects would feel up to 8 virtual surfaces (around 90 seconds) and the platform would be shut down automatically afterwards (duration of 30-60 seconds) to avoid coils overheating and system damage. Subjects were instructed not to move their hands in the y direction since there would be only friction and no texture to feel. They were also asked not to push hard into the surfaces in the z direction, which could result in high current generation (> 3 A) and system shut down. Prior to each block of 36 trials, a set of six initial demonstrations which spanned the whole range of 12 surface textures and its extreme was provided to participants in a random order. The demonstration allowed users to get an understanding of the haptic system as well as the range of surface textures they are about to explore, within each specific combination of a haptic probe and torque condition. If subjects decided that they were familiar ”enough” with the system and textures, the initial demonstration stage for later blocks could be skipped. A typical duration of the experiment for each subject was around three hours.

4.5 Psychophysical Function of Perceived Roughness ($\Psi$)

To calculate a psychometric function which represents roughness rating with respect to the three experimental factors mentioned earlier, a methodology analogous to studies such as [19, 98] was used. Each individual roughness number which was obtained from each individual trial in the experiment can be expressed as $\Omega(i, j, k, h, l)$, where $i = 1, 2, ..., n_{subj}$ is the $i^{th}$ subject and $n_{subj}$ is equal to 12, $j = 1, ..., n_{prob}$ is the $j^{th}$ probe and $n_{prob}$ is equal to 2, $k = 1, ..., n_{torq}$ is the $k^{th}$ torque condition and $n_{torq}$ is equal to 3, $h = 1, 2, ..., n_{wave}$ is the $h^{th}$ wavelength and $n_{wave}$ is equal to 12, and finally $l = 1, ..., n_{repe}$ is the $l^{th}$ repetition where $n_{repe}$ is 3. This raw data is then transformed, via four steps, to acquire reliable data points for developing the psychological function.

First, the three iterations of each wavelength within all users, probe types and torque conditions were averaged. This averaged data set is denoted by $\Lambda(i, j, k, h)$, and can be obtained as:

$$\Lambda(i, j, k, h) = \frac{\sum_l \Omega(i, j, k, h, l)}{n_{repe}} \quad (4.12)$$

Second, since each subject used their own scale, a normalization of the $\Lambda(i, j, k, h)$ data set must be performed. To do this, each averaged data point is divided by the mean of all estimates by subject $i$, and a normalized averaged data set for that subject, denoted by $\Theta(i, j, k, h)$ is acquired. This data set is expressed as:

$$\Theta(i, j, k, h) = \frac{\Lambda(i, j, k, h)}{\sum_{i,j,k,h} \Lambda(i, j, k, h)} \quad (4.13)$$
Next, the normalized averaged data for each subject, $\Theta(i, j, k, h)$, is rescaled, to show the overall magnitude estimation, by multiplying by the grand mean of all estimates from all participants, conditions, and trials. This *rescaled normalized averaged* data set is denoted by $\Xi(i, j, k, h)$ and expressed as:

$$\Xi(i, j, k, h) = \Theta(i, j, k, h) \frac{\sum_i \Theta(i, j, k, h)}{n_{subj}}$$ (4.14)

Finally, for calculating the cross-subject psychophysical function, denoted by $\Psi(j, k, h)$, each point that is associated with the $j^{th}$ probe, $k^{th}$ torque condition, and $h^{th}$ spatial period can be obtained as:

$$\Psi(j, k, h) = \frac{\sum_i \Xi(i, j, k, h)}{n_{subj}}$$ (4.15)

The standard error (SE) of the cross-subject mean, $\Psi(j, k, h)$, within each combination of wavelength, torque feedback and probe type, can be obtained via dividing the between-subject standard deviation by square root of number of subjects (as suggested in [104]):

$$\sigma_w(j, k, h) = \sqrt{\frac{\sigma_s(j, k, h)^2}{n_{subj}}}$$ (4.16)

In this equation, $\sigma_w(j, k, h)$ is within-subject SE which has been calculated based on between-subject standard deviation, $\sigma_s(j, k, h)$. The calculation of within-subject SE is based on the assumption that since between-subject variance usually has no effects in statistical analyses of within-subject designs, it legitimately could be ignored [104].
5 RESULTS

Based on the procedure explained in the previous chapter, the human roughness estimation experiment was conducted and roughness estimation magnitude (REM) data were collected. The position/torque and force/torque of the haptic probes were also collected digitally by the maglev system at the 860 Hz sampling rate.

For each subject, 216 positive numbers were recorded, one magnitude estimation for each of the textures encountered. The psychophysical function was then calculated for each subject and the cross-subject trend was found by averaging the normalized individual functions based on the techniques outlined in Section 4.5. Five data points that fell outside of the three standard deviation interval of rescaled normalized averaged data set, \( \Xi(i, j, k, h) \), were discarded as outliers. The data points averaged from all other subjects within the same experimental factors were substituted for each outlier. Individual psychophysical function of roughness estimation, \( \Xi(i, j, k, h) \) where \( i = 1, 2, ..., 12 \) is the \( i^{th} \) subject, as well as the cross-subject mean roughness estimation, \( \Psi(i, j, k) \), are plotted in Figure 5.1 and Figure 5.2 for the penhandle and fingertip probe respectively.

IBM SPSS Statistics software v23 (IBM Corporation, 1 New Orchard Road Armonk, New York, United States) was utilized for all of statistical analyses in this chapter. Also, statistical \( \alpha \) (significance level) has been set to 0.05 (95% confidence level) in all of statistical analyses.

5.1 Roughness Estimation Magnitude

5.1.1 Effects of Wavelength

Although the shape of the estimated roughness with respect to wavelength (across different torque conditions and probes) is dissimilar between subjects, Figures 5.1 and Figure 5.2, most

<table>
<thead>
<tr>
<th></th>
<th>Fingertip</th>
<th>Penhandle</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( F )</td>
<td>( P ) value</td>
</tr>
<tr>
<td>No Torque</td>
<td>F(3.35,36.82) = 44.32</td>
<td>&lt; 0.000</td>
</tr>
<tr>
<td>Slope Torque</td>
<td>F(2.44,26.88) = 24.70</td>
<td>&lt; 0.000</td>
</tr>
<tr>
<td>Stiff Torque</td>
<td>F(2.44,26.88) = 34.44</td>
<td>&lt; 0.000</td>
</tr>
</tbody>
</table>

Table 5.1: One-way ANOVA results for effects of wavelength of virtual sinusoidal surfaces on perceived roughness. The results show that sinusoidal wavelength has significant affect on perceived roughness within all torque conditions and probes.
follow a decreasing trend of the roughness as the wavelength increases. A within-subject analysis of variance (ANOVA) test signifies that element spacing (wavelength) has measurable effects on perceived roughness within all torque conditions and probes. The $p$ value of one-way ANOVA test along with other statistical parameters can be found in Table 5.1. This table clearly confirms that wavelength, as an independent variable, mediates perceived roughness in a significant way, no matter what probe or torque condition were presented to users.

Since spatial periods affect perceived roughness in a measurable way, it is interesting to investigate the shape of the relationship as well. The shape of the psychophysical trend (in all of the six plots) follows neither a power nor an exponential trend and hence is not linearized by a log transform of either the ordinate or both axes. For the penhandle probe, the linear fit accounts for 94.94%, 93.11%, and 93.7% of the variance for Stiff, Slope, and No torque conditions respectively. For the fingertips probe, the linear fit accounts for 98.5%, 99.33%, and 98.93% of the variance for Stiff, Slope, and No torque conditions. Table 5.2 (fingertip) and Table 5.3 (penhandle) demonstrate the residual after the linear fit for four different functions of quadratic, power, logarithmic, and exponential along with their associated level of significance. Since the linear fit does account for the most of the variance within all torque conditions and probes, it may be safe to suggest that the relationship between cross-subject REM and wavelength can be mostly described with a linear trend, when subjects deployed our maglev haptic system to explore virtual textures. The slope, y-intercept, and goodness of fit ($R^2$) of this linear trend for different combination of the probes and torques can be found in Table 5.4.

5.1.2 Effects of Torque Feedback

To investigate the impact of different torque rendering algorithms within various haptic probes, the mean magnitude ratings were submitted to a within-subject ANOVA with factors of spatial period (12) and torque condition (3) for each probe. Greenhouse-Giesser were utilized for corrections of degrees of freedom. For fingertips probe, the statistical analysis revealed the effects of

<table>
<thead>
<tr>
<th></th>
<th>Quadratic</th>
<th>Power</th>
<th>Logarithmic</th>
<th>Exponential</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$R^2$</td>
<td>$P$</td>
<td>$R^2$</td>
<td>$P$</td>
</tr>
<tr>
<td>No Torque</td>
<td>0.64</td>
<td>0.00</td>
<td>0.14</td>
<td>0.23</td>
</tr>
<tr>
<td>Slope Torque</td>
<td>0.44</td>
<td>0.02</td>
<td>0.09</td>
<td>0.35</td>
</tr>
<tr>
<td>Stiff Torque</td>
<td>0.35</td>
<td>0.04</td>
<td>0.00</td>
<td>0.86</td>
</tr>
</tbody>
</table>

Table 5.2: Residual ($R^2$) after the linear fit for four different functions of quadratic, power, logarithmic, and exponential along with their associated significance level ($P$). These results are for the fingertip haptic stylus.
Figure 5.1: Individual normalized roughness psychophysical functions for 12 subjects superimposed with their cross-subject mean when penhandle probe was deployed.
torque condition was significant, F(1.63, 17.91) = 9.19, p < 0.005, partial-eta-squared (η²) = 0.46, reflecting the higher perceived roughness for the Slope Torque condition compared to the other two torque renderings, which essentially resulted in equivalent magnitudes. When similar analysis was implemented without Slope Torque condition, the effect of torque feedback was not measurable (F(1.00, 11.00) = 0.29, p = 0.603, η² = 0.025). For these two torque conditions, however, the effects of spatial period was significant (F(2.13, 23.47) = 52.08, p < 0.0001, η² = 0.826). These results mark that the Stiff Torque and No Torque conditions were both perceived equally by participants. The interrelation of torque feedback condition and wavelength was not noticeable (F(6.06, 66.65) = 1.105, p = 0.37, η² = 0.091).

Dissimilar to the fingertip stylus, the AVONA test did not reflect significance of torque feedback condition (F(1.86, 20.41) = 1.69, p = 0.207, η² = 0.133) for the penhandle probe. This implies that all three torque conditions were statistically identical in terms of perceived roughness. Similar to the fingertip, on the other hand, the effects of spatial period was measurable (F(2.55, 28.06) = 76.38, p < 0.0001, η² = 0.874). Also, the interaction of spatial period and torque renderings was not significant (F(6.84, 75.28) = 1.57, p = 0.16, η² = 0.13). A complete output of a within-subject ANOVA test which specifies the effects of torque feedback, wavelength, and their mutual interrelation are summarized in Table 5.5. This table includes results of the statistical analysis when all of three torque rendering conditions are compared against each other. Table 5.6, Table 5.7, Table 5.8 are similar tables except that only two torque levels (3 possible combinations) are compared against each other.

Table 5.3: Residual (R²) after the linear fit for four different functions of quadratic, power, logarithmic, and exponential along with their associated significance level (P). These results are for the penhandle haptic stylus.

<table>
<thead>
<tr>
<th></th>
<th>Quadratic</th>
<th>Power</th>
<th>Logarithmic</th>
<th>Exponential</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R²</td>
<td>P</td>
<td>R²</td>
<td>P</td>
</tr>
<tr>
<td>No Torque</td>
<td>0.76</td>
<td>0.00</td>
<td>0.02</td>
<td>0.66</td>
</tr>
<tr>
<td>Slope Torque</td>
<td>0.75</td>
<td>0.00</td>
<td>0.12</td>
<td>0.28</td>
</tr>
<tr>
<td>Stiff Torque</td>
<td>0.63</td>
<td>0.00</td>
<td>0.07</td>
<td>0.40</td>
</tr>
</tbody>
</table>

Table 5.4: Slope, y-intercept and goodness of linear fit (R²) for relation between wavelength and perceived roughness.

<table>
<thead>
<tr>
<th></th>
<th>Fingertip</th>
<th>Penhandle</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Slope</td>
<td>Y-intercept</td>
</tr>
<tr>
<td>No Torque</td>
<td>-7.63</td>
<td>66.72</td>
</tr>
<tr>
<td>Slope Torque</td>
<td>-6.35</td>
<td>69.37</td>
</tr>
<tr>
<td>Stiff Torque</td>
<td>-7.72</td>
<td>67.82</td>
</tr>
</tbody>
</table>
Figure 5.2: Individual normalized roughness psychophysical functions for 12 subjects superimposed with their cross-subject mean when fingertip probe was deployed.
Figure 5.3: Cross-subject mean rating of perceived roughness with respect to surface wavelength for each haptic probe within three different torque conditions. For clarity of presentation, vertical SE bars are shown one sided.

Figure 5.3 depicts the cross-subject mean data within each of haptic probes for three torque rendering conditions. The vertical error bars are shown for each wavelength and computed based on Equation 4.16. For clarity of presentation, they are shown one sided.

Table 5.5: Within-subject ANOVA results for effects of torque feedback, spatial period, and their interrelation on perceived roughness. All three levels of torque conditions are included.

<table>
<thead>
<tr>
<th></th>
<th>Torque</th>
<th>Wavelength</th>
<th>Torque × Wavelength</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fingertip</td>
<td>$F(1.63, 17.91) = 9.19$</td>
<td>$F(1.79, 19.76) = 50.71$</td>
<td>$F(6.06, 66.06) = 1.11$</td>
</tr>
<tr>
<td>Penhandle</td>
<td>$F(1.86, 20.41) = 1.69$</td>
<td>$F(2.55, 28.06) = 76.38$</td>
<td>$F(6.84, 75.28) = 1.57$</td>
</tr>
</tbody>
</table>
5.1.3 Effects of Probe Type

A very similar statistical analysis procedure was implemented to examine the effects of probe type within various torque conditions. The cross-subject mean magnitude ratings were submitted to a within-subject ANOVA with factors of spatial period (12) and probe type (2, penhandle and fingertip) for each of the three torque conditions. Again, Greenhouse-Giesser were utilized for corrections of degrees of freedom. For No Torque condition, the ANOVA test showed that REM for both of penhandle and fingertip haptic styluses are statistically identical (F(1.00, 11.00) = 0.075, p = 0.789, \(\eta^2 = 0.007\)). In a similar way, the test proved that there is no measurable perceived roughness difference between two probes in Stiff Torque (F(1.00, 11.00) = 0.865, p = 0.372, \(\eta^2 = 0.073\)). For the Slope Torque condition, on the other hand, the ANOVA results indicated that there is a significant distinction between REM data of fingertip and penhandle devices (F(1.00, 11.00) = 10.2, p < 0.01, \(\eta^2 = 0.48\)). This reflects that subjects, on average, perceived surfaces rougher with the fingertip probe compared to when they deployed penhandle device. A comprehensive statistical output which shows the effects of probe type, wavelength and their mutual interaction on REM is reported in Table 5.9. As it can be seen from this Table, the effects of interrelation of probe type and wavelength (Probe \(\times\) Wavelength) on the roughness estimate is not significant, regardless of torque feedback condition.

Table 5.6: Within-subject ANOVA results for effects of torque feedback, spatial period, and their interrelation on perceived roughness. Two levels of torque conditions, Stiff Torque and Slope Torque, are included in the analysis.

<table>
<thead>
<tr>
<th>Torque Wavelength</th>
<th>Torque (\times) Wavelength</th>
</tr>
</thead>
<tbody>
<tr>
<td>F</td>
<td>F(^2)</td>
</tr>
<tr>
<td>F(1.00, 11.00) = 8.19</td>
<td>0.02, 0.43</td>
</tr>
<tr>
<td>F(1.84, 20.23) = 39.21</td>
<td>&lt; 0.00, 0.78</td>
</tr>
<tr>
<td>F(4.43, 48.70) = 1.49</td>
<td>0.22, 0.12</td>
</tr>
</tbody>
</table>

Table 5.7: Within-subject ANOVA results for effects of torque feedback, spatial period, and their interrelation on perceived roughness. Two levels of torque conditions, Slope Torque and No Torque, are included in the analysis.

<table>
<thead>
<tr>
<th>Torque Wavelength</th>
<th>Torque (\times) Wavelength</th>
</tr>
</thead>
<tbody>
<tr>
<td>F</td>
<td>F(^2)</td>
</tr>
<tr>
<td>F(1.00, 11.00) = 8.19</td>
<td>0.02, 0.43</td>
</tr>
<tr>
<td>F(1.84, 20.23) = 39.21</td>
<td>&lt; 0.00, 0.78</td>
</tr>
<tr>
<td>F(4.43, 48.70) = 1.49</td>
<td>0.22, 0.12</td>
</tr>
</tbody>
</table>

Table 5.8: Within-subject ANOVA results for effects of torque feedback, spatial period, and their interrelation on perceived roughness. Two levels of torque conditions, No Torque and Stiff Torque, are included in the analysis.

<table>
<thead>
<tr>
<th>Torque Wavelength</th>
<th>Torque (\times) Wavelength</th>
</tr>
</thead>
<tbody>
<tr>
<td>F</td>
<td>F(^2)</td>
</tr>
<tr>
<td>F(1.00, 11.00) = 8.19</td>
<td>0.02, 0.43</td>
</tr>
<tr>
<td>F(1.84, 20.23) = 39.21</td>
<td>&lt; 0.00, 0.78</td>
</tr>
<tr>
<td>F(4.43, 48.70) = 1.49</td>
<td>0.22, 0.12</td>
</tr>
</tbody>
</table>

55
Figure 5.4: Cross-subject mean estimate of perceived roughness with respect to surface wavelength for each torque rendering within two haptic styluses. For clarity of presentation, vertical SE bars are shown one sided.
Table 5.9: Within-subject ANOVA results for effects of probe type, spatial period, and their interrelation on perceived roughness.

<table>
<thead>
<tr>
<th>Probe Type</th>
<th>F(1.00, 11.00)</th>
<th>F value</th>
<th>η²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stiff Torque</td>
<td>0.87</td>
<td>0.07</td>
<td></td>
</tr>
<tr>
<td>Slope Torque</td>
<td>10.20</td>
<td>0.48</td>
<td></td>
</tr>
<tr>
<td>No Torque</td>
<td>0.08</td>
<td>0.01</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Wavelength</th>
<th>F(2.05, 22.59)</th>
<th>F value</th>
<th>η²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stiff Torque</td>
<td>62.71</td>
<td>&lt; 0.000</td>
<td>0.85</td>
</tr>
<tr>
<td>Slope Torque</td>
<td>54.72</td>
<td>&lt; 0.000</td>
<td>0.83</td>
</tr>
<tr>
<td>No Torque</td>
<td>64.16</td>
<td>&lt; 0.000</td>
<td>0.85</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Probe × Wavelength</th>
<th>F(4.15, 45.69)</th>
<th>F value</th>
<th>η²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stiff Torque</td>
<td>1.31</td>
<td>0.28</td>
<td>0.11</td>
</tr>
<tr>
<td>Slope Torque</td>
<td>0.95</td>
<td>0.45</td>
<td>0.08</td>
</tr>
<tr>
<td>No Torque</td>
<td>1.45</td>
<td>0.24</td>
<td>0.12</td>
</tr>
</tbody>
</table>

Figure 5.4 shows mean REM data relative to wavelengths for each haptic probe within different torque conditions. One sided vertical data error bars are calculated according to Equation 4.16.

5.2 REM Sensitivity to Wavelength

In addition to magnitude of estimates, sensitivity of roughness data to wavelength changes is important to investigate, e.g. how this sensitivity might be influenced under different torques and/or various probes? Our results, which are from our new haptic platform and relatively compliant virtual surfaces, show that such sensitivity is constant (linear trend) over the range of 0.7-6 mm of wavelengths, within all probes and torque renderings. Table 5.4 summarizes the slope of the linear approximation between roughness and interelement spacing.

5.2.1 Effects of Torque Feedback

For each subject, the slope of the linear function was obtained for all probes and torque conditions and then were submitted to a within-subject ANOVA with factor of torque feedback condition (3). For fingertip probe, the test reveals that the distinction between slopes within different torque condition is significant (F(1.90, 20.91) = 4.21, p = 0.03, η² = 0.28). Further investigation suggested this distinction is due to the slope of linear function in Slope Torque condition which is statically lower that the other two. For penhandle, on the other hand, the impact of various torque feedback was not significant (F(1.86, 20.43) = 3.21, p = 0.07, η² = 0.23). This indicates that the sensitivity of REM to wavelength was statistically equivalent for all torque conditions. A complete list of outputs of ANOVA is reported in Table 5.10 and Table 5.11. In Table 5.10, all three torque conditions are considered in the analysis while Table 5.11 reports the results when combinations of two torque rendering feedback (total of three) are tested in SPSS. Figure 5.5a and Figure 5.5b depict the slope of cross-subject linear relation for different torque rendering conditions when fingertip and penhandle probes were deployed respectively. Two sided vertical error bars in both figures are showing within-subject SEs mentioned earlier.
5.2.2 Effects of Probe Type

Similarly, the slopes of the linear function for each subject, as mentioned earlier, were submitted to a within-subject ANOVA with factor of probe type (2) to investigate effects of probe type.

Table 5.10: Within-subject ANOVA results for impacts of torque feedback conditions on sensitivity of perceived roughness to spatial periods when all three torque conditions were considered in analysis.

<table>
<thead>
<tr>
<th>Probe Type</th>
<th>F</th>
<th>P value</th>
<th>$\eta^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fingertip</td>
<td>$F(1.90, 20.91) = 4.21$</td>
<td>0.03</td>
<td>0.28</td>
</tr>
<tr>
<td>Penhandle</td>
<td>$F(1.86, 20.43) = 3.21$</td>
<td>0.07</td>
<td>0.23</td>
</tr>
</tbody>
</table>
For No Torque condition (see Figure 5.6a), statistical analysis shows that the slope differentiation between two probes was significant ($F(1.00, 11.00) = 5.33, p = 0.04, \eta^2 = 0.33$). For Slope Torque condition (see Figure 5.6b), on the other hand, the difference between slopes of the linear approximation for two styluses was not statistically measurable ($F(1.00, 11.00) = 0.12, p = 0.74, \eta^2 = 0.01$). Similarly, the slopes of the linear trend for both probes were statically equivalent for the Stiff Torque condition ($F(1.00, 11.00) = 0.90, p = 0.36, \eta^2 = 0.08$). Figure 5.6c shows the slope along with within-subject SE bars when Stiff Torque condition was presented to subjects. All statistical results discussed in Section 5.2.2 is summarized in Table 5.12.

5.3 Individual Psychophysical Functions

In addition to cross-subject (group) REM and sensitivity, individual roughness data provide valuable information regarding human perception of virtual surfaces. Individual mean REM data within different probes and torque conditions are plotted earlier in Figure 5.1 and Figure 5.2. Although in human experiments similar to ours individual variations are usually treated as noise (unless they are really extreme), Kornbrot et al. recommended that both group and individual data should be analyzed and reported since group data might not closely reflect the behavior of majority of subjects [29].

5.3.1 Individual Regression Models

As mentioned earlier, linear regression model was used to describe the relationship between cross-subject perceived roughness and spatial periods. In addition to these group analyses, it is worthwhile to understand the effectiveness of linear models to capture the trend of each individuals

Table 5.11: Within-subject ANOVA results for effects of torque feedback conditions on the sensitivity of perceived roughness to spatial periods when all three possible combinations of two torque feedback were considered for statistical analysis.

<table>
<thead>
<tr>
<th></th>
<th>F(1, 11)</th>
<th>$P$ value</th>
<th>$\eta^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fingertip</td>
<td>$F(1, 11) = 6.25$</td>
<td>0.03</td>
<td>0.36</td>
</tr>
<tr>
<td>Penhandle</td>
<td>$F(1, 11) = 5.48$</td>
<td>0.04</td>
<td>0.33</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>F(1, 11)</th>
<th>$P$ value</th>
<th>$\eta^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fingertip</td>
<td>$F(1, 11) = 5.10$</td>
<td>0.05</td>
<td>0.32</td>
</tr>
<tr>
<td>Penhandle</td>
<td>$F(1, 11) = 3.62$</td>
<td>0.08</td>
<td>0.25</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>F(1, 11)</th>
<th>$P$ value</th>
<th>$\eta^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fingertip</td>
<td>$F(1, 11) = 0.04$</td>
<td>0.84</td>
<td>0.00</td>
</tr>
<tr>
<td>Penhandle</td>
<td>$F(1, 11) = 0.68$</td>
<td>0.43</td>
<td>0.06</td>
</tr>
</tbody>
</table>

Table 5.12: Within-subject ANOVA results for effects of probe type on sensitivity of perceived roughness to spatial periods within three torque feedback conditions.

<table>
<thead>
<tr>
<th>Torque Condition</th>
<th>F(1, 11)</th>
<th>$P$ value</th>
<th>$\eta^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stiff Torque</td>
<td>$F(1.00, 11.00) = 0.90$</td>
<td>0.36</td>
<td>0.08</td>
</tr>
<tr>
<td>Slope Torque</td>
<td>$F(1.00, 11.00) = 0.12$</td>
<td>0.74</td>
<td>0.01</td>
</tr>
<tr>
<td>No Torque</td>
<td>$F(1.00, 11.00) = 5.33$</td>
<td>0.04</td>
<td>0.33</td>
</tr>
</tbody>
</table>

59
Figure 5.6: Sensitivity of cross-subject mean to spatial periods for two haptic probes within each torque feedback condition. Two sided error bars are within-subject SE obtained from between-subject standard deviation divided by square root of number of subjects.
as well. Figure 5.7 (penhandle) and Figure 5.8 (fingertip) graphically illustrate the goodness of fit of five different linear, quadratic, exponential, logarithmic, and power functions for each subject and torque condition. As it can be qualitatively witnessed, most of the relationship is accounted for by linear trend for most subjects, a very similar outcome to the group mean rating. There are, however, very few subjects within torque/probe conditions (e.g. subject 4 in Figure 5.8b) that a residual significant amount of variance is accounted further by other trends (in this case quadratic trend). Table 5.13 and Table 5.14 report the goodness of linear fit ($R^2$) quantitatively.

### 5.3.2 Individual Sensitivity of REM to Wavelength

The sensitivity of the cross-subject roughness rating with respect to spatial periods within different probes and torques was reported in Table 5.4. Table 5.13 and Table 5.14 are very analogous but contain sensitivity information for each user. According to these tables, all participants showed negative sensitivity (descending function) between roughness rating and wavelength with all renderings and probes. For penhandle stylus, the goodness of linear fit is greater than 0.70 ($R^2 \geq 0.70$) for 89% of the 36 reported slopes within all torque conditions. For fingertip, this number decreases to 78%. In total, within three torque conditions and two probe types, 83% of the 72 reported slopes have goodness of linear fit greater than 0.70. The linear average of $R^2$ for the twelve subjects within all torque conditions is 0.81 for penhandle probe and 0.80 for the fingertip probe. On the other hand, The average of $R^2$ of the linear fit for group data within all torque conditions is 0.94 for penhandle and 0.99 for fingertip.

From torque rendering point of view, for each of torque rendering conditions, the goodness of linear fit is greater than 0.70 for 83% of the 24 reported slopes within two haptic styluses. The linear average of $R^2$ for the twelve subjects within two probes is 0.82 for No Torque, 0.77 for Slope Torque, and 0.83 for Stiff Torque. The linear average of $R^2$ for group data within two haptic probes is 0.96, 0.96, and 0.97, for No Torque, Slope Torque, and Stiff Torque respectively.
Figure 5.7: Goodness of fit for five different regressions (linear, quadratic, logarithmic, power, exponential) for each subject when penhandle stylus was utilized.
Figure 5.8: Goodness of fit for five different regressions (linear, quadratic, logarithmic, power, exponential) for each subject when fingertip stylus was utilized.
Table 5.13: Sensitivity of magnitude estimate rating to wavelength along with y-intercept and associated goodness of linear fit for each subject when penhandle device was deployed.

<table>
<thead>
<tr>
<th></th>
<th>No Torque</th>
<th></th>
<th>Slope Torque</th>
<th></th>
<th>Stiff Torque</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Slope</td>
<td>Y-intercept</td>
<td>$R^2$</td>
<td>Slope</td>
<td>Y-intercept</td>
<td>$R^2$</td>
</tr>
<tr>
<td>Subject 1</td>
<td>-6.48</td>
<td>65.15</td>
<td>0.65</td>
<td>-6.73</td>
<td>64.75</td>
<td>0.89</td>
</tr>
<tr>
<td>Subject 2</td>
<td>-8.04</td>
<td>70.32</td>
<td>0.85</td>
<td>-7.27</td>
<td>69.47</td>
<td>0.77</td>
</tr>
<tr>
<td>Subject 3</td>
<td>-9.11</td>
<td>72.51</td>
<td>0.92</td>
<td>-7.97</td>
<td>72.71</td>
<td>0.86</td>
</tr>
<tr>
<td>Subject 4</td>
<td>-4.53</td>
<td>55.59</td>
<td>0.82</td>
<td>-2.96</td>
<td>65.55</td>
<td>0.70</td>
</tr>
<tr>
<td>Subject 5</td>
<td>-5.38</td>
<td>61.83</td>
<td>0.86</td>
<td>-5.99</td>
<td>58.55</td>
<td>0.78</td>
</tr>
<tr>
<td>Subject 6</td>
<td>-2.33</td>
<td>53.50</td>
<td>0.23</td>
<td>-3.20</td>
<td>52.14</td>
<td>0.56</td>
</tr>
<tr>
<td>Subject 7</td>
<td>-7.11</td>
<td>63.26</td>
<td>0.93</td>
<td>-7.08</td>
<td>64.76</td>
<td>0.95</td>
</tr>
<tr>
<td>Subject 8</td>
<td>-8.60</td>
<td>72.84</td>
<td>0.76</td>
<td>-5.92</td>
<td>62.01</td>
<td>0.70</td>
</tr>
<tr>
<td>Subject 9</td>
<td>-5.71</td>
<td>58.58</td>
<td>0.88</td>
<td>-6.59</td>
<td>63.45</td>
<td>0.94</td>
</tr>
<tr>
<td>Subject 10</td>
<td>-7.49</td>
<td>63.99</td>
<td>0.72</td>
<td>-6.59</td>
<td>65.64</td>
<td>0.88</td>
</tr>
<tr>
<td>Subject 11</td>
<td>-5.99</td>
<td>64.22</td>
<td>0.89</td>
<td>-4.78</td>
<td>58.96</td>
<td>0.86</td>
</tr>
<tr>
<td>Subject 12</td>
<td>-10.12</td>
<td>67.72</td>
<td>0.89</td>
<td>-8.22</td>
<td>67.62</td>
<td>0.86</td>
</tr>
</tbody>
</table>

Table 5.14: Sensitivity of magnitude estimate rating to wavelength along with y-intercept and associated goodness of linear fit for each subject when fingertip device was utilized.

<table>
<thead>
<tr>
<th></th>
<th>No Torque</th>
<th></th>
<th>Slope Torque</th>
<th></th>
<th>Stiff Torque</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Slope</td>
<td>Y-intercept</td>
<td>$R^2$</td>
<td>Slope</td>
<td>Y-intercept</td>
<td>$R^2$</td>
</tr>
<tr>
<td>Subject 1</td>
<td>-6.75</td>
<td>65.85</td>
<td>0.63</td>
<td>-5.00</td>
<td>60.84</td>
<td>0.71</td>
</tr>
<tr>
<td>Subject 2</td>
<td>-7.57</td>
<td>66.43</td>
<td>0.89</td>
<td>-7.64</td>
<td>68.31</td>
<td>0.94</td>
</tr>
<tr>
<td>Subject 3</td>
<td>-11.45</td>
<td>79.19</td>
<td>0.93</td>
<td>-10.93</td>
<td>79.64</td>
<td>0.93</td>
</tr>
<tr>
<td>Subject 4</td>
<td>-3.68</td>
<td>47.76</td>
<td>0.85</td>
<td>-0.43</td>
<td>53.71</td>
<td>0.06</td>
</tr>
<tr>
<td>Subject 5</td>
<td>-4.80</td>
<td>53.82</td>
<td>0.61</td>
<td>-3.90</td>
<td>61.92</td>
<td>0.65</td>
</tr>
<tr>
<td>Subject 6</td>
<td>-4.86</td>
<td>56.58</td>
<td>0.89</td>
<td>-5.04</td>
<td>59.30</td>
<td>0.90</td>
</tr>
<tr>
<td>Subject 7</td>
<td>-9.71</td>
<td>74.09</td>
<td>0.90</td>
<td>-8.37</td>
<td>77.93</td>
<td>0.92</td>
</tr>
<tr>
<td>Subject 8</td>
<td>-8.67</td>
<td>74.11</td>
<td>0.86</td>
<td>-8.81</td>
<td>80.55</td>
<td>0.91</td>
</tr>
<tr>
<td>Subject 9</td>
<td>-7.67</td>
<td>70.73</td>
<td>0.88</td>
<td>-6.48</td>
<td>68.41</td>
<td>0.84</td>
</tr>
<tr>
<td>Subject 10</td>
<td>-8.86</td>
<td>72.58</td>
<td>0.95</td>
<td>-2.26</td>
<td>65.49</td>
<td>0.28</td>
</tr>
<tr>
<td>Subject 11</td>
<td>-5.63</td>
<td>58.08</td>
<td>0.90</td>
<td>-5.66</td>
<td>63.77</td>
<td>0.77</td>
</tr>
<tr>
<td>Subject 12</td>
<td>-11.85</td>
<td>81.43</td>
<td>0.96</td>
<td>-11.70</td>
<td>92.51</td>
<td>0.90</td>
</tr>
</tbody>
</table>

64
6 DISCUSSION

This research make several important contributions in the area of virtual surface and roughness perception. In this chapter, these contributions are reviewed and comparisons against previous research is provided. Also, more insights into the results along with possible explanations for the obtained data are stated which would help to better understand claims proposed by this research.

6.1 Effects of Wavelength

Although studying the impacts of spatial period on roughness perception was not the main purpose of this research effort, it is useful to compare our results with previous research. Our study confirm strong influence of surface wavelength on roughness, within all probe types and torque conditions (see Table 5.1, Table 5.2, Table 5.3, and Table 5.4). The relation was best described by linear function with negative slope within all conditions, although there is a residual significant amount of variance that is accounted further by quadratic functions (see Table 5.2 and Table 5.3).

Comparison against simulated surface literature

Our results verify the outcomes from previous virtual roughness perception studies [18, 19, 29, 45, 105] in a sense that there is strong impact of wavelength on perceived roughness. However, the shape of psychophysical function relating REM to spatial period might be different. Authors in [29] suggested a linear trend between log-log transform of REM data to spatial periods. Unger et al. in [18] obtained a function consisted of a long initial plateau of high roughness, followed by a linear decline between log(perceived roughness) and log(wavelengths). In [106], investigators reported a linear relation between ln(roughness) and spatial periods. Although there might be dissimilarities between these studies, what is common amongst most is the suggestion of linear decreasing trend between log-log of roughness and spatial periods after wavelength of 2 mm with a slope close to -0.8. Such a linear trend is also witnessed in our data with the only difference that, neither REM nor wavelengths were not log transformed.

Our results from ANOVA test did not signify any difference in the psychophysical function before and after 2 mm, although roughness was only measured at three spatial periods smaller than 2 mm (0.70 mm, 1.18 mm, 1.66 mm, 25 % of the whole range). Consequently, there is a research need for more populated wavelengths smaller than 2 mm to test the hypothesis in the literature, using our novel system.

The reason for clear disparities of REM-wavelength relation across different research with simulated surfaces (especially when wavelength < 2 mm) is not clear. Similar to [107] which
suggested the effects of virtual surface stiffness on human percept, Unger et al. [19] proposed that dissimilarities might be related to different surface stiffness among studies. [19] deployed surfaces with stiffness of 10 N/mm, while studies such as [29, 106] utilized PHANToM device that is capable of generating virtual surfaces up to 2 N/mm stiffness. For our experiments, virtual surfaces with stiffness of 1.5 N/mm were rendered, which is close to the stiffness used in [29]. Since our results also show more similarities to [29] than [19], it might be legitimate to suggest that stiffness may play some role in terms of the shape and possibly magnitude of psychometric function. For instance, it might be the case that up to a certain stiffness, the trend is most likely to be linear, but as surfaces become stiffer, shape of the psychophysical function changes to an inverted U shaped. This hypothesis must be tested through another set of experiments with the main focus on studying relation between roughness and wavelength within a wide range of surface stiffness (e.g. 0.1 to 15 N/mm).

Another major difference between previous studies that might contribute to their disagreement is using dissimilar torque feedback conditions. Studies such as [19] used MLHI and did not allow any rotation of the probe in any direction, the situation that is very analogous to our Stiff Torque condition. On the other hand, [29] did not block rotation of the stylus since they deployed only 3 DoF haptic platform. This is also identical to our No Torque condition. Our results revealed that, however, the difference between the shape, magnitude, and slope of psychometric roughness-wavelength functions were not significantly different among No Torque and Stiff Torque condition, with both fingertip and penhandle. Consequently, one can conclude that the differences in Stiff Torque and No Torque conditions, most likely, do not play significant role on human perception of virtual textures, especially regarding the characteristics of psychophysical function.

Comparison against real surface literature

Studies such as [98] which deployed real surface proposed that interelement spacing is an influential factor in human perception of surface roughness. Consequently, regarding significance of spatial periods on roughness perception, our results are also in agreement with real surface studies, so were they with virtual textures. As mentioned earlier, studies on real surfaces also suggested that the shape of the function relating log-log roughness to wavelength is an inverted U shape, within different probes they examined. Unfortunately, most of studies that deployed computer-generated surfaces, including this research, have failed to replicate this inverted U trend. Although the exact reason is unclear, several hypotheses for this considerable controversy have suggested. For example, [29] claimed that such function that obtained for real surfaces was the result of mathematical summation of substantially variable individual psychometric functions that were different from their U shaped group trend. So it is likely that this U shaped function does not accurately reflect the behavior of each participant and cannot be generalized. On the other hand, Unger et al.
in [19] obtained virtually identical (to real surfaces) results when they simulated the probe tip with some finite geometry and deployed dithered cones virtual surfaces. As such, they stated that it is, in fact, the infinitesimal nature of the virtual probe tip (used in many studies including [29]) that is unrealistic and causes most of the results to diverge from real textures outcomes, rather than some inherent differences in data analyses. A similar claim was also suggested by earlier studies [46]. This might also explain the linear results of our experiment, as we deployed the same infinitesimal paradigm for simulating probe tip in tandem with only simple 2D sinusoidal functions for virtual surfaces. Another possible factor for these different results could be low stiffness surfaces (1-2 N/mm) that have been widely used in the literature, which was explained in previous section.

6.2 Perception with Different Haptic Probes

Differences in roughness magnitude and its sensitivity to wavelength between fingertip and penhandle was investigated in this research. These two probes are commonly used type of medians that previous researchers have deployed. The exact geometry and dimension of similar probes might be different across other studies, especially when dissimilar haptic platform is used (MLHI or PHANToM). Nevertheless, we assume that, since the general configuration of hand and fingers along with their relation to the probe is similar, the results of these experiments are comparable. For example, our penhandle probe is very similar to the pen-like haptic stylus of studies such as [18, 20, 29, 76] and our fingertip probe is very analogous to the thimble device of studies like [29, 105, 108].

Our results show that the subjects’ rating of virtual surface roughness (its magnitude and sensitivity) could be similar or different for these two probes, it highly depends on the type of torque feedback that is being rendered.

6.2.1 No Torque Condition

This is the most commonly used torque condition in previous studies as it does not require 6 DoF haptic platforms. When subjects encountered virtual surfaces with this rendering condition, only coupled torques from PSI forces, along with active force in z axis were available to the users. The rotational configuration of the probe, that is the angle of probe with respect to the x axis of the maglev frame, is indeterministic and a function of variables such as how hard the probe is being pushed. This is different from the other two torque conditions where this angle is deterministically known at each time step. The personal observation of the experimenter is that, although this angle is not known in this condition, users were likely to hold probes closely aligned with z axis.

In terms of the magnitude of the roughness, both fingertip and penhandle showed statistically similar results for cross-subject data in No Torque condition. This conclusion is supported by the
outcomes of earlier studies [29, 105, 106] which deployed a different haptic platform with the same No Torque condition and reported identical results for penhandle and thimble styluses.

Regarding the sensitivity of roughness rating to interelement spacing, our results revealed people with fingertip probe had greater sensitivity (-7.63 l/mm) than penhandle stylus (-6.74 l/mm). The effect size ($\eta^2$), however, was not very large (0.33) relative to effect size of wavelength, which was 0.85 in the No Torque condition. These sensitivity results were also qualitatively verified by previous studies [29, 105] which reported higher negative exponent factor (or sensitivity) for thimble than penhandle. One should note that our results obtained from direct comparison between subjects sensitivities rather then considering the cross-subject interaction of probe and wavelength (probe $\times$ wavelength) as the basis of sensitivity. When considering the latter approach, the ANOVA did not signify ($p = 0.24$, see Table 5.9) any difference between the sensitivity of two probes in the No Torque condition. In fact, it is not uncommon that an omnibus ANOVA will be insensitive to sensitivity differences this small. It is testing for a 3 way interaction, which is hard to obtain. Consequently, analyzing the slopes directly, as we did, is a perfectly legitimate subsidiary analysis. Although, one reason for this slope difference between probes could be differences in the amplitudes of the coupled torque signal, investigation of underlying reasons for variance between probes require further investigation and is out of the scope of this thesis.

Our results can also be compared against the research performed by Klatzky et al. in [98], but at the very high level. They investigated the percept of texture roughness using real surfaces and a pen-like probe, which produced passive torque on the fingers, and compared it to a "zero-moment probe". In the latter case, participants held a tool (spool-shaped) between their thumb and the index finger, in a way that resulted in total of zero moment on the users’ hand. With this probe, they illustrated that the relation between perceived roughness and interelement spacing was still a U shaped function, similar to pen-like probes [76]. However, the zero-moment probe generated higher curvature and a later peak on the spacing continuum than the pen-shaped probe. These results implicitly suggest that the shape of the psychophysical function did not change within different probes (and dissimilar torque conditions), while characteristics of the function (curvature and peak) was influenced by probe types. Our outcome also shows that the shape of the linear trend did not change across probes, but the slope (function’s characteristics) was different between probes. As mentioned earlier, the amount of passive torque feedback received by fingertip probe was less compared to penhandle. This creates a condition analogous to [76] with different probes and dissimilar torque, which is a good basis for results comparison.

6.2.2 Slope Torque Condition

In this research, we have introduced a novel torque feedback paradigm, which is based on the instantaneous slope of sinusoidal surface. With this rendering condition, participants were
exploring surfaces while receiving force and torque signals from three different channels: a coupled torque signal from PSI force(s), z-axis PSI force, and a decoupled torque signal. The magnitude of this decoupled torque is proportional to the differences between current and desired (instantaneous slope of surface) angles of haptic probe. Since this is a new idea developed in this research, there exists no previous results that we could compare our outcomes with.

For this novel torque feedback condition, ANOVA test suggested that the cross-subject magnitude of roughness rating was higher for fingertip probe than penhandle. The effect size for this difference is moderate ($\eta^2 = 0.48$), compared to strong effect size of wavelength parameter which is 0.83 for the Slope Torque condition. This suggest that, different probes might transfer temporal cues from active torque differently and the reason might be related to dissimilar areas of skin that are involved in each probe, different number of fingers grasped, or variant probe’s impedances. This issue will be further discussed (qualitatively) later in this chapter.

Unlike roughness magnitude, both probes essentially yielded similar results for sensitivity of REM data to spatial periods. In this case, both group sensitivity analysis (probe × wavelength) and individual sensitivity outcomes suggested statistically identical slopes for both of fingertip (-6.35 1/mm) and penhandle (-6.11 1/mm).

### 6.2.3 Stiff Torque Condition

This torque rendering condition was extensively used by Unger et al. in their studies [18, 19]. With this torque condition, participants were receiving two active signals while exploring surfaces: one from PSI forces in z axis and another from active torque algorithm which held the probe upright. The main similarity between this and No Torque condition is that in both cases, the amplitude of torque signal, passive in one and active in another one, increases as the angle between the probe and y axis (maglev frame) increases. On the other hand, the primary difference between this torque rendering and Slope Torque condition is that, at each time instance, the angle of probe is known and constant in the former while known and non-constant in the latter.

Our results suggested that there is no statistically significant difference of the magnitude and sensitivity of roughness data between probes. The slope of REM-wavelength was -7.72 1/mm for the fingertip and -7.08 1/mm for penhandle. These results might implicitly suggest that different probes result in a very similar psychometric function (in terms of shape, magnitude, and sensitivity) provided that the rotation of haptic probe be blocked.

### 6.3 Perception with Different Torque Conditions

The use of dissimilar torque feedback conditions by previous studies was one of the main motivations to investigate whether (and to what extent) these torque differences are important. As
mentioned earlier in this chapter, our results, for both fingertip and penhandle, suggest that the adoption of two different torque condition by the literature, No Torque and Stiff Torque, did not contribute to discrepancies found between roughness functions in these studies.

The outcome for the data of Slope Torque condition tell a different story. When people actively felt surfaces with fingertip probe, the magnitude of roughness rating was significantly higher for the Slope Torque condition, compared to the other two statistically identical torque renderings. This difference in magnitude was also witnessed in the sensitivity as well. The cross-subject slope of psychophysical function was shallower for the Slope Torque condition than the other two torque renderings which had identical slopes. The underlying explanation for these dissimilarities (in both magnitude and sensitivity) within different torque renderings is unclear but it might be linked to the additional vibration cues (3 channels for Slope Torque, while two channels for either of Stiff Torque and No Torque) that are available in Slope Torque. In fact, Unger et al. in [18] recommends that perceived roughness is highly correlated to the power spectral density (PSD) of the z axis force signal. While three conditions had similar z axis force signals, with additional active torque feedback cues in Slope Torque condition, it might be the case that, not only the power of active force feedback, but also the power (or other characteristics) of active torque feedback be an attribute of roughness. Studying this hypothesis is subjected to the future studies.

Another important implication of our results from our novel torque-based surface rendering suggest that for generating rougher surfaces with the same force feedback algorithm, 6 DoF haptic devices will be superior. This is due to the fact that such haptic devices can generate rotational vibrations by the slope torque feedback method used in our experiment. This method of generating rougher surfaces is particularly of interest when there are some limitations on the maximum force generation of the haptic device.

The results for penhandle probe show that this additional active torque signal available in Slope Torque condition, does not necessarily yield to higher perceived roughness, within all haptic probes. In fact, subjects felt similar level of roughness within all three torque feedback conditions, when penhandle probe was used. Similar is true regarding the roughness sensitivity to wavelength, that is the slope of roughness function was statistically equivalent within all torque conditions. One point that should be mentioned here that even though the sensitivity data suggest similar values within all three torque conditions, further investigations of such sensitivity within three combinations of two torque conditions did not show similar results. In other words, one would expect that the results from comparing sensitivity among each of two torque renderings (No Torque & Slope Torque, Slope Torque & Stiff Torque, Stiff Torque & No Torque) show no statistical significance, as all three conditions were equivalent, but this was not the case. As it can be seen in Table 5.11, the $P$ value for Stiff Torque & Slope Torque is 0.04 which is a suggestion of statistical difference of slope values between these two conditions. To explain this it should be noted that it is, in fact, not
uncommon to find that in a comparison of three values, there is *non-transitivity*, two of them differ, but the second one does not differ from one or both. This is often just a matter of experimental power.

### 6.4 Discussion on Grasp Differences in Haptic Probes

We found out that the use of different haptic probes is important for perceived roughness. Now we want to take a closer look at the possible reasons for this issue. When people explored surfaces through either of penhandle or fingertip, the type of the grasp, number of fingers, and area of the skin were different for each probe. For example, for the thimble stylus, only the fingertip part of the index finger was inside the probe, and consequently, it was the main receivers of the total of forces and torques from PSI. On the other hand, users grasped penhandle probe in a pen-like manner, that is the probe is held within three fingers of thumb, index, and middle with with a common area between fingertip parts of each finger. In this case, force/torque signals from PSI had a totally different receptors than the fingertip probe. This might be an important factor in terms of how human brain interprets roughness and could be one of the reasons that led to differences in perception within different probes.

Another paramount distinction between the two probes is the structure of fingers that are involved for grasping each one. For the fingertip probe, only the single index finger is included and the grasp configuration is serial. On the other hand, with the involvement of three fingers, the grip configuration of the penhandle is a parallel structure. Parallel structure manipulators are generally characterized by high stiffness, but low damping and inertia [109]. In [110], characteristics (e.g. stiffness) of the two configurations, pen grasp and single index finger grip (similar to our probes) have been quantified and compared against each other. In their experiments, the task was 2D and subjects were asked to ground the wrist of their hand on the flat surface. This was primary to eliminate the dynamics effect on their arm from measurements. A very similar situation was available in our experiments as the subjects moving their hands in 2D and tended to have very small motion in their arm during exploring surfaces. The results of their experiments suggested that the average (in all directions) stiffness of the pen grasp was 3-5 times the index grasp. They also showed that the disturbance rejection performance of the pen grasp is 2 times the index finger. Higher impedance for the penhandle simply means that the fingertip motions will be smaller, on average, through penhandle than fingertip if similar force/torque signals are applied. Also, higher disturbance rejection associated with pen-like grasp might have some affects on which force/torque signals being transformed through fingertip(s). Consequently, differences in grasp impedance might play some role on transferred temporal sues and perceived roughness. This requires to be validated through separate analysis of force/torque signals and grasp impedances in the future.
7 CONCLUSION AND FUTURE WORK

In this thesis, the 6 DoF coil array magnetic levitation haptic interface was deployed to study human perception of virtual roughness. The nature of the system allowed integration and control, with only a minimal software and hardware adaptation, of two commonly used haptic probes namely fingertip and penhandle. The impacts of three torque feedback conditions, two of which were frequently used in previous studies, on roughness rating of subjects were investigated across different probes. In the No Torque condition, no active torque feedback were generated and only users felt torques from PSI forces. The Slope Torque condition, which was developed for the first time in this research, presented users with a combination of active and passive torques. Active torques were generated to rotate the handle to be orthogonal to sinusoidal surfaces and passive torques were from PSI. In the Stiff Torque condition, active torques were generated on the handle to restrict it rotation in two directions. Sinusoidal surfaces along with a PD controller based on the penetration depth of the probe’s tip were chosen as the basis of virtual surface rendering. A relatively wide range of 12 surfaces (0.7 \leq \text{wavelength} \leq 6 \text{ mm}) with constant amplitude of 0.4 mm were virtually generated. 12 subjects participated in the experiment and raw data was transformed based on a method explained earlier.

Our results drew some important relations between factors of torque, wavelength, and probe with roughness. First of all, our outcomes confirmed strong effects of spatial period on roughness rating. The trend was found to be linearly decreasing function within all torque conditions and probes. This result confirmed earlier studies that suggest strong effects of spatial periods on roughness, whether real or virtual surfaces were explored. The shape of the function was somehow different, however, from previous studies. For real surfaces, the psychometric function found to be an inverted U shaped function. The reason for deviation of results of virtual surface from real surface outcomes is unclear, but literature has suggested that the infinitesimal nature of virtual probes to be probably playing the rolling factor. For virtual surface, different trends such as linear and U shaped like trends have proposed by previous studies. Despite disparities in trends especially for wavelength \leq 2 \text{ mm}, a linear trend for wavelength \geq 2 \text{ mm} between log(roughness) to log(wavelength) with an exponent factor of -0.8 has been suggested in the literature. Our findings also support this notion except that we did not log transformed either of roughness or wavelength. We found out that the slope for the No Torque feedback were -7.63, and -6.74 for fingertip and penhandle. Similarly for the Stiff Torque feedback, the slopes were -7.72 and -7.08 for fingertip and penhandle respectively.
Our experiment also revealed interesting results about the effects of torque feedback and probe types as well. For the fingertip, surfaces with Slope Torque feedback rated to be the most rough ones, and textures with the other two torque conditions were felt with the same level of roughness. The sensitivity of roughness-to-wavelength was found to be negatively smaller in the Slope torque condition compared to the other two which had the same level of sensitivity. The story is totally different for the penhandle probe. The magnitude rating and sensitivity of roughness were found to be equivalent within all three torque conditions. These results explicitly suggest that subjects ratings in Stiff Torque and No Torque conditions did not have any significant differences in shape and magnitude of function, using either of probe. This is very important since various researchers have previously deployed these two conditions separately without explicitly acknowledging whether these different conditions affect perception or not. Our results show that they statistically yield to the same results.

In the No Torque condition, the magnitude of roughness was identical for each probe while the panhandle probe had shallower negative slope. In the Slop Torque condition, the fingertip had higher roughness magnitude with the same level of sensitivity to the penhandle. In the Stiff Torque condition, both of the magnitude and sensitivity were equivalent across probes. Although the exact reasons for these human perception behaviors within different torque renderings and probes is not clear, factors such as lower impedance of the fingertip grasp, higher shear forces in pen-like grasp, different areas of skin contact, and availability of various force/torque signals with dissimilar PSDs, are candidates that might be attributing to our roughness perception. These proposals need to be tested in the future and are out of the scope of this thesis.

7.1 Future Work

This research effort was the first human haptic test using the novel haptic platform developed at the Human-Robot Interaction Laboratory in the University of Hawaii at Manoa. Several research paths can be envisioned to be pursued in the future based on the results and lessons learned from this research.

7.1.1 Stiffness

One research area for future study could be to develop necessary hardware and software enabling the system to render surfaces with (one order of magnitude) higher stiffness. As stated in [19], one of the main reasons that results from virtual surfaces does not match the real ones, might be the relatively low stiffness (order of 2.0 N/mm) of the virtual surfaces being used while real stiff surfaces have stiffness around 10.0 N/mm or higher. With the current set up, surfaces with stiffness up to 1.5 N/mm, which is one order of magnitude less than what being suggested, can be
stably rendered. Currently, the main limitation for rendering high stiffness is the relatively noisy estimation of the velocity, which is calculated from simple backward difference of the position. In fact, this simple method amplifies any error in the position by the factor of haptic update rate (860). Possible solutions for this could be either through use of more sophisticated estimation algorithms such as EKF, or integrating another sensor such as an accelerometer/gyro and estimating the state of the system through sensor fusion. Upon running much stiffer surfaces, some research work that has not been done in the literature can be imagined. For example, the effects of stiffness on roughness has only been studied for stiffness up to 1-2 N/mm [107] and there has been found strong correlation between stiffness and perceived roughness. So a possible work extension would be to study the effects of stiffness on roughness percept within a broader range of surface stiffness (e.g. 0.1 to 10 N/mm). Other possible extension could be investigating shape of the psychometric function relating roughness to wavelength across a wide range of stiffness values. Since different studies with dissimilar levels of stiffness have reported dissimilar trends, this would be really valuable for explaining disagreements in the literature. For instance, it might be the case that human, up to a certain stiffness, shows one trend, and as the surface becomes stiffer, human roughness function changes. This can have further implications in designs of haptic devices with special requirements on the minimum stiffness they should be capable of rendering for generating surfaces with natural feeling.

7.1.2 Underlying Reasons for Human Perception Behavior

Although some suggestions were made, one important issue that has not been addressed by this research is in-depth qualitative and quantitative reasons of why various torques and probes affect our roughness perception in this way. For example, one possible future work could be to look at the force/torque signals in different torque renderings and, for example, to study signals total PSD (or other characteristics), which has been suggested by other research to be correlated to roughness. Another possible work for the future could be to experimentally obtain the mechanical impedance of the pen grasp and index finger in all DoFs of probes. Having this information along with the force/torque signals, the positional information of the probe can be specified. This might be important information as [18] has suggested that the acceleration of the probe in the z axis is partially correlated to perceived roughness. Another possible future work could be to use force/torque sensors at different parts of the finger/hand and to directly measure and analyze these perceived force/torque signals and their relations to roughness percept, rather than signals generated by the haptic platform.
REFERENCES


[21] Roberta L Klatzky. Sensing and displaying spatially distributed fingertip forces in haptic interfaces for teleoperator and virtual environment systems.


