# An Investigation of the Velvet Hand Illusion Using Computational Mechanics and Psychophysics

A doctoral thesis presented

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# 論文要旨

ロボットが人間の住環境や極限環境下で作業を遂行するためには，人間の五感に相当する種々のセンサを備える必要がある．近年内外から注目されているヒューマノイド・ロボットを例にとると，実用化に向けて特に環境と人間への接触によって生じる問題を解決することが急務とされている．　また，遠隔操作型のロボットの場合にも，スレーブとして作業を遂行するロボットの作業現場や作業の様子を臨場感もって操作者に伝達することが必要とされている．このように，近年のロボット工学において触覚センサと触覚ディスプレイへの要求レベルが高まっている．しかしながら，非接触を前提とする視覚や聴覚と異なり，触覚センサや触覚ディスプレイでは物体やヒトへの接触を前提としているために，非接触型のセンサやディスプレイに比べて工学的実現の困難さが際立っている．

本研究では，触覚センサや触覚ディスプレイの研究においてブレイクスルーを期すために，触覚の錯覚現象に一つであるベルベット・ハンド・イリュージョン（VHI）を調査して，その機構を解明することによって新しい触覚センサや触覚ディスプレイを開発する上での重要なヒントを得ることを最終目標としている．このためまず，本触覚の錯覚として本研究で取り上げるVHI から説明する．すなわち，VHI とは両手で金網を挟み両手をこすり合わせると本来存在しないベルベット生地のような布あるいは柔らかい紙のようなものを感じる現象である．片手で金網を触ってもこのような感覚は生じな

い．実際にそこに存在しないものを感じるということは，脳が騙されているということである．脳機能を含めた触覚センシングの機構が解明されれば，本研究の成果は新しい触覚センサの設計思想に繋がると期待される．また，触覚ディスプレイについては，それが物体ハンドリングの仮想現実感によく用いられることから，本研究の成果をより直接的に利用できる．すなわち，仮想現実感では脳を騙してそこに物体があるかのように感じさせることができれば成功であり，VHI の生成機構解明によって操作者に任意の物体を疑似体験させることが可能となると期待される．

VHI の生成機構を解明するために， 本研究では二つの方法論を採用する．まず，一つは心理物理実験法であり，もう一方は計算力学である．前者は， どのような条件のもとで VHI が発生するのか調査するためのものである．感じているか感じていないかは個人的体験であり，一般に外から推し量ることは困難である．そこで，本研究では刺激の物理量と心的変化を関連付けるための実験手法として前者を採用する．また，触覚は皮膚に加えられる力学的刺激により機械受容器が応答することによって生じるために，後者の計算力学は皮膚の変形解析を実施することによって機械受容単位の応答を推測する上で有効に利用される．このため，微小電極を刺入することによって機械受容器の応答を調査するという微小神経電図法に代わって，計算力学を採用する．

本論文は，5 章から構成される．まず 1 章では，前述の本研究の背景と目的を述べている．まず，生物にヒントを得て研究を進める生物模倣の考え方を活用するために，ロボット以外の人工物の設計にこの考え方を利用した

研究開発例について広くサーベイする．その後に，本研究に深く関連する触覚に関して生物模倣の考え方を活用した例について紹介する．その中で，本研究と関連する人間の皮膚・触覚を調査して触覚センサを研究開発した事例について解説する．さらに，人間の触覚機能に基づいて開発された種々の触覚ディスプレイの研究開発事例についても解説する．最後に，新しい触覚センサと触覚ディスプレイを開発することを目指して，人間の触覚認識機構を解明に直接関連する VHI の発生機構について調査研究を進めることを目的としていることを述べる．

続く第 2 章では，VHI に関連する錯覚現象を広く理解するために，視覚と触覚の錯覚現象について文献調査した結果をまとめる．その中で，本研究と関連する触覚の錯覚現象に比べて視覚の錯覚現象の方が報告事例の数が圧倒的に多いことを述べたのちに，代表的な視覚の錯覚現象として Müller-Lyer illusion，Barber pole illusion，Ouchi illusion を取り上げ，現在までに考えられている機構の仮説について紹介する．次に，視覚と触覚の錯覚の間で類似性を議論して，前上述の視覚の錯覚として取り上げた Müller-Lyer illusion，Barber pole illusion，Ouchi illusion が触覚系にも生じることを示す．最後に，触覚系でのみ観察されている Fish bone tactile illusion と VHI について解説する．

第 3 章では，VHI の生じる条件を明らかにするために，Thurstone の一対比較法を用いた一連の心理物理実験について解説する．VHI は金網だけでなく張力を加えた二本の鋼線によっても生じることができる．二本の鋼線をアクリルのフレームに張り，被験者がそれを両手で挟み両手を合わせた状態

でスライド運動させ，そのとき発生するベルベット生地の感触の強さを評価させた．実験条件としては，1)手の方を動かす（能動触），2)試料の方をストローク 60mm，速度 120mm/s の往復運動で動かす（受動触）の二条件を採用した．二本の鋼線が，35，40，45，50，55mm とした 5 つの試料を用意して生じるベルベット生地感の強さを評価した．その結果，能動触と受動触を比較すると，受動触の方が鋼線の間隔変化に対するベルベット生地感の変化が顕著に大きい（約 9 倍）ことがわかった．この結果は，鋼線の移動速度の制御によってベルベット生地感を任意に制御できることを意味しており，触覚ディスプレイにおいてアクチュエータにより VHI を自由に演出できる可能性を示している．また，ストローク 60mm，速度 120mm/s の条件では，二本の鋼線距離 35mm～55mm の範囲で鋼線距離に比例してベルベット生地感が強くなり 55mm で最大値を示すことがわかった．以上の結果から，「圧迫刺激を受けている状態で鋼線の通過を感じるときに VHI が生じる」という従来の知見に加えて，生じる条件をより定量的に定める仮説を提案した．すなわち，鋼線間距離と鋼線移動距離（往復運動のストローク）をそれぞれ $D$ と $r$ とすると　1) $r/D \ll 1$ のとき圧迫刺激のみを受ける領域でも，VHI が誘発される，2) $r/D \fallingdotseq 1$ のとき最大の VHI が生じる，3) $r/D \gg 1$ のとき線の移動刺激が強く VHI が阻害される．

第 4 章では，VHI の生じるメカニズムを明らかにするために，計算力学として有限要素法を用いて VHI が生じているときの触覚受容器に作用している機械刺激を計算・評価する．指を表皮，真皮，皮下組織の三層構造として，それぞれのヤング率をそれぞれ 0.136 MPa、 0.08 MPa および 0.034MPa

とし，ポアッソン比はすべての層について一様に 0.48 とした．微小変形を仮定して，三層構造の材料はすべて線形弾性体とした．鋼線は直径 0.8mm の剛体要素として，平面ひずみ問題として接触変形解析を実施した．なお，過去の研究では表皮の真皮側に形成された畝状の乳頭部が応力集中を生じ，　これにより触覚受容器に作用する刺激を増幅していることが明らかにされている．このため，本研究の有限要素の形状モデルでも乳頭部の内部構造を可能な限り忠実に形成した．解析の条件として，1) 二本の指を腹合わせにした状態で，腹合わせした面に鋼線を通過させる（VHI 発生条件），および 2) 片方の指の表面に鋼線を通過させる（一本指条件），といった二条件でシミュレーションを実施した．触覚の受容単位の内，遅順応機械受容単位 I 型（SA I ）は圧迫刺激を受け取ること，および SA I が獲得する刺激の強さは Mises 応力で評価できることが過去の文献で明らかにされているために，触覚受容器が存在する位置の Mises 応力を計算した．その結果，Mises 応力は鋼線が指に接触する瞬間と指から離れる瞬間に顕著に大きくなることがわかった．VHI 発生条件と一本指条件を比較すると，一本指条件の方が 2 倍大きい値を示していた．このことは，鋼線が通過する刺激は VHI のトリガーとして作用するが，あまりに大きいと VHI を生成する上で阻害要因となってしまうことがわかった．

最後の第 5 章では結論を述べる．本研究で得られた結論を以下に要約する．

・能動触と受動触と比較すると，受動触の方が鋼線間隔に変化に対する生成される VHI の強さの変化が大きいことがわかった．これは，今後触覚ディスプレイで VHI を生じさせる場合に制御可能であることを示している．

・本研究で実施した実験の範囲では，鋼線間隔が広いほど強い VHI 感が生じることがわかった．この結果と前項の結果から，VHI が生じる条件を従来の研究より明確に示すことができた．

・VHI における SA I の反応を調べるために，人間の指を有限要素で模型化して，鋼線との接触変形解析を実施した．その結果，鋼線が通過するときの刺激が小さいほど VHI が発生しやすいことから，SA I は VHI 発生に関して重要な役割を果たしていることがわかった．

・VHI を生成・制御できる触覚ディスプレイを開発するための基礎データを得るために，鋼線に作用させるための力のパターンを垂直力とせん断力について求めることができた．

今後，本研究をさらに進めるために次の課題がある．すなわち，VHI の発生について，能動触と受動触，および鋼線間距離が及ぼす影響について調べたのみであり，まだ十分明らかにできたとは言えない．　今後，鋼線の直径，鋼線の移動速度，鋼線の移動距離などのパラメータについて検討する必要がある．また，本研究の解析は，線形解析に留まっているとともに指の指紋も無視している．さらに掌で触った場合の解析も行っていない．今後，手全体のモデル化も含めて有限要素モデルをより実物の手に近づける必要がある．最後に，本研究の成果に基づいて触覚ディスプレイや触覚センサを設計

製作して，本研究で得られた知見を活用することにより本研究の最終目標を実現したい.

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# Contents

# Chapter 1

# Introduction

Chapter 1 presents an introduction of this thesis. It shows the importance of biological systems as models to imitate and from which we can learn. Several examples of such imitations that yielded successful technologies, methods, and designs are reviewed. Then, this chapter concludes by tackling the human tactile system as a candidate for such imitative techniques, and introducing the necessary components for achieving such a task.

## 1.1 Learning from Nature*

Recognizing that nature's capabilities are superior to many of our technologies, humans have always tried to *imitate* many aspects of its processes and structures. Nature acts as a great model for the development of mechanical tools, computational algorithms, effective materials, as well as novel mechanisms and information technology.

Some examples of nature's technologies include the following:

- Beavers exhibit amazing engineering skills in constructing dams and lodges as their habitats (Figure 1-1).
- Birds make their nests so durably that they last throughout the bird's nesting season. Many nests are hemispherical in the area where the eggs are laid. The nest's size even takes into account the potential number of eggs and chicks, in terms of required space.

* Based on (Bar-Cohen 2006).

Figure 1-1. Beavers build dams on streams and rivers. Such a dam creates a body of water that makes a suitable environment for a beaver family.

- Bats can move their ears in a huge range of directions, localize sound sources, and avoid obstacles, all while flying at relatively high speed.

In addition there are numerous additional examples that have been observed by humans over the centuries. Also humans themselves have amazing capabilities that today's robots, computers, and machines simply do not.

Specifically, tactile sensing and perception in humans (far superior to those in today's robots) are of a special interest to this study, since its objective is to achieve better understanding of human tactile sensing with the goal of designing a new *tactile display* and a *tactile sensor*.

Toward this goal, an overview of nature's imitation is described in this section. Such imitation serves as a methodology and inspiration for many researchers and within specific scientific subfields has for the last few decades been called *Bionics*.

Bionics (also known as biomimicry, biomimetics, bio-inspiration, bio gnosis, and) is defined as the application of biological methods and systems found in nature to the study and design of engineering systems and modern technology.

The development of technology based on life forms and then applying it to manufacturing is an effective shortcut, because evolutionary pressure typically forces living organisms to become highly optimized, durable and efficient. Even biological materials that are widely used in clothing, such as silk and wool, generally have capabilities that surpass those made by humans. Such bridging can be a key to turning nature's inventions into engineering capabilities, tools, and mechanisms. Toward this end, one can take each aspect of the identified biological characteristics and seek an analogy in terms of an artificial technology.

Some of the commercial implementations of the progress in bionics can be seen in toy stores, where toys seem and behave like living creatures (e.g., dogs, cats, birds, and frogs). More essential benefits of bionics include the development of surprisingly life-like prosthetic implants, and sensory aids that assist in hearing, seeing, or controlling instruments. Bionics increasingly connects emerging themes from various branches of science and engineering.

### 1.1.1 Mimicking vs. Inspiration of Nature

Often, the study of bionics focuses on a implementing a specific function found in nature rather than imitating entire biological structures or systems because those tend to be very complex, and given the limitation of today's technology, attempting to copy nature may not be the most effective approach.

Many examples exist where humans, using nature as inspiration, have used natural principles to invent far more effective solutions. In addition, copying designs, shapes, or mechanisms of simple parts of biological systems is also sometimes possible. For instance, flying machines were inspired by birds using human developed capabilities, whereas the design and function of fins, which divers use, was an imitation of water creatures' legs, such as frogs.

In the following part of this section, notable biological systems, mechanisms, designs and their corresponding bio-inspired counter parts are presented.

### 1.1.2 Bio-inspired Parts and Designs

#### Fins

Fins have been used successfully to enhance humans' swimming and diving. It might not be clear how directly fin design was copied from water creatures, but the similarity to the leg shape of such creatures (frogs, geese, etc.) is apparent. Moreover divers are named frogmen, which is a bio-inspired name.

#### Honeycomb

Honeycombs consist of perfect hexagonal cellular structures (Figure 1-2 a) and they offer an exceptionally efficient packing shape. For the honeybees, the geometry meets their need for a stable structure for storing honey and larvae using the minimum amount of material.

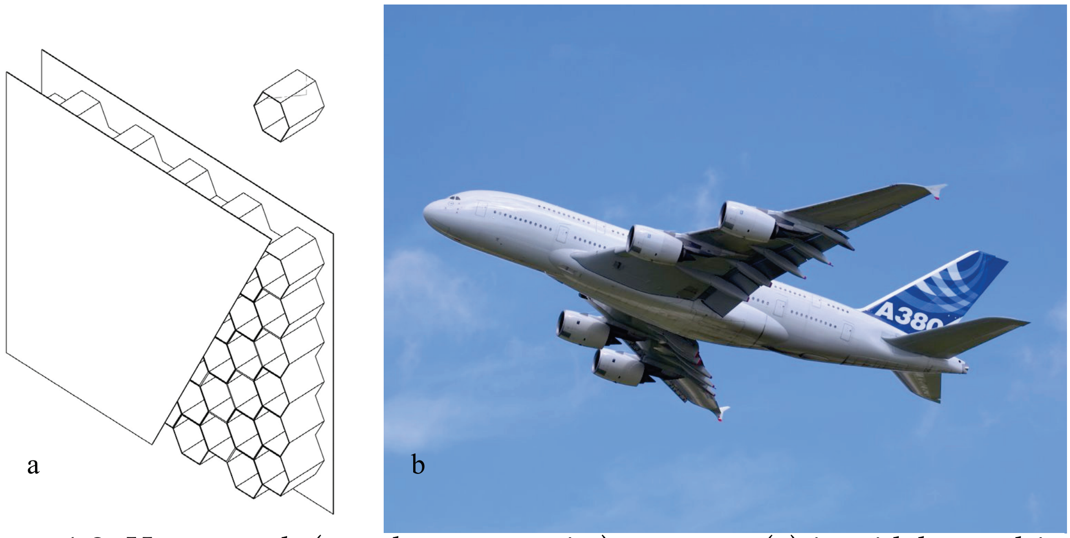


Figure 1-2. Honeycomb (metal or composite) structure (a) is widely used in aerospace industry. The airplane Airbus A380 (b) includes new honeycomb composite which is found from its flooring to interior walls to wing flaps[†].

The honeycomb is, for the same reason, an ideal structure for manufacturing some aircraft structures (Whitener 1986; Atwood 1936) that need to be strong across a wide area, such as the wing and the floor (Figure 1-2 b).

### Hand Fan

A hand fan was for centuries one of the most common ways for people to cool down during the hot summer months. This simple tool used to be made of feathers, which copy the shape of a bird's wing or the tail of the male peacock. The advantage of using feathers is their lightweight structure and their beauty.

[†] DuPont. The miracles of science™. http://www2.dupont.com


Figure 1-3. A Spider web represents an efficient strong low-weight biological structure.

### 1.1.3 Materials in Biology

**Spider Web**

A spider web (Figure 1-3) is an excellent example of a biological structure that uses a special material, which has unique capabilities that serve its intended purpose.

- It is resistant to rain, wind, and sunlight.
- It is made of very strong, continuous, lightweight fibers that are barely visible, which significantly improves its function as an insect trap.
- Although the material is also sticky, because the web is intended to catch prey, the spider itself is able to move freely on it.
- The tensile strength of the radial threads of spider silk is 1154 MPa, while it is 400 MPa for steel.

Recent progress in nanotechnology creates the potential for making fibers that are fine, continuous, and enormously strong. For this purpose, an electrospinning technique was developed (Dzenis 2004) that allows producing 2 μm diameter fibers from polymer solutions and melts in high electric fields. The dynamics of this production process is similar to the bio-chemistry of spider silk production.

### 1.1.4 Mechanisms in Biology

#### Pumping Mechanisms

The human heart is basically a pump that provides a continuous blood circulation through the cardiac cycle. This is performed via *valves* and chambers that change volumes. The use of *one-way valves* is the key to the blood flow inside the veins, where the pressure is lower. Also our lungs pump air in and out via the use of the diaphragm (*tidal pumping*) to enable our breathing.

Similar mechanisms are used in mechanical pumps and valves, which are the main components of hydraulic and pneumatic systems.

#### Inchworm Motors

An *inchworm* (Figure1-4 a) is a caterpillar of a group of moths called *Geomeridae*. They are about 2.5 cm or 1 inch in length, and tend to be green, grey, or brownish. Equipped with appendages at both ends of the body, a caterpillar will clasp with its front legs and draw up the hind end, then clasp with the hind end (prolegs) and reach out for a new front attachment (creating the impression that it is measuring its journey).

This unique way of motion inspired the development of actuators and robots that use this mechanism.

Inchworm mechanisms have many configurations where the unifying drive principle is the use of two brakes (grippers or suction cups depending on the design) and an extender. An example of the operation of an inchworm mechanism is shown in Figure 1-4 b. Actuators are utilized to perform cyclic steps where the first gripper clamps onto the ground and the extender pushes the second gripper forward. Gripper no. 2 then clamps the ground, gripper no. 1 is released, and the extender retracts to move gripper no. 1 forward.

For example, based on the same mechanism illustrated in Figure 1-4 b, Kotay and Rus developed a robot capable of moving flexibly in three-dimensional space, and manipulating objects while moving (Kotay and Rus 2000).

Also, a company called PI[‡] developed non-resonant piezo-stepping nano-positioning (with sub-nanometer resolution) motors using a related mechanism (PiezoWalk®). They generate motion through a succession of coordinated clamping and unclamping of several actuators.

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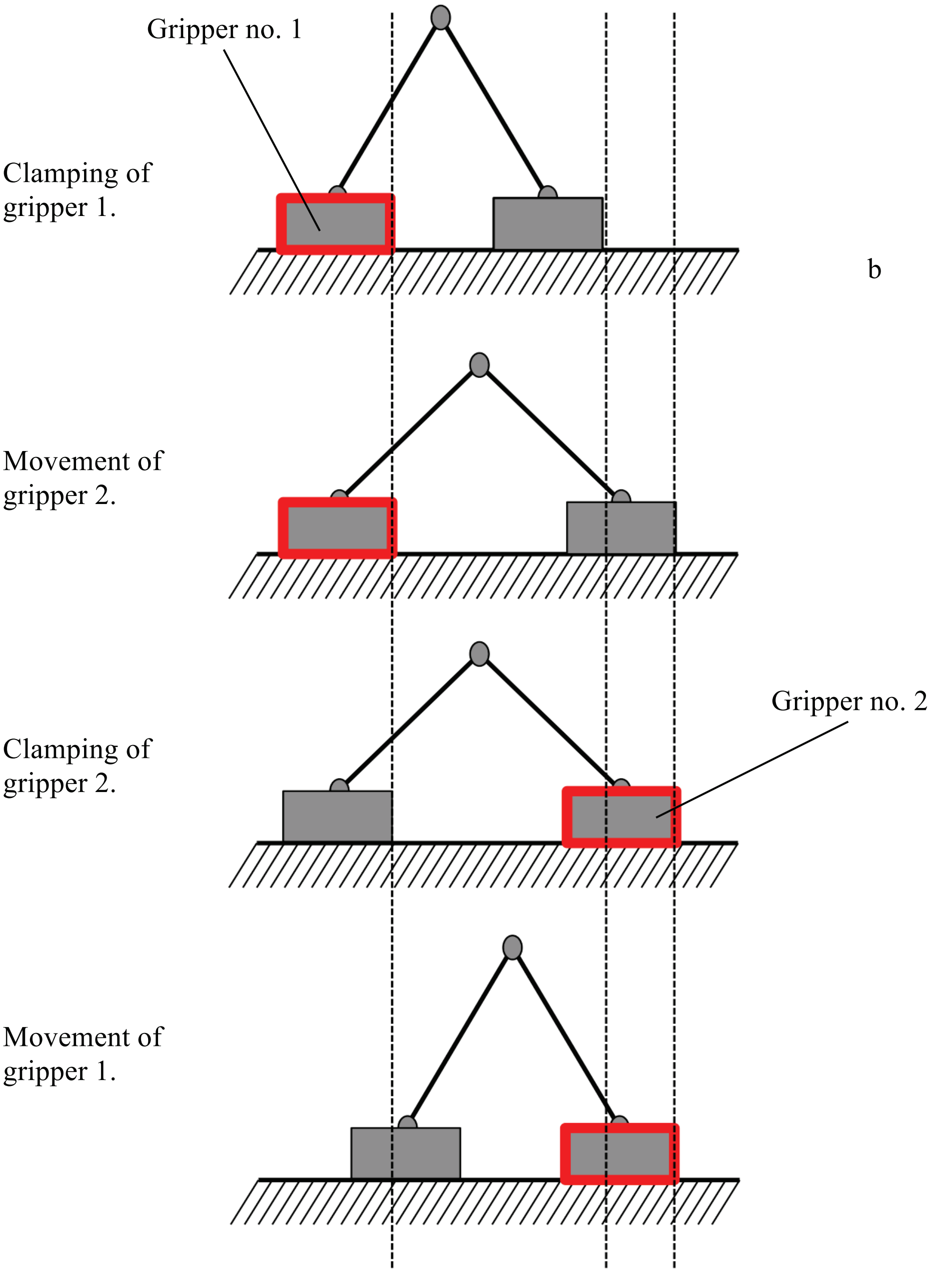
[‡] PhysikInstrumente (PI). http://www.physikinstrumente.com

a




b

Figure 1-4. (a) An inchworm. (b) The mechanism of inchworm motor inspired by the motion of an inchwarm.

### 1.1.5 Artificial life

Artificial life (A-life) is a field of study which examines systems related to life, life processes, and evolution through simulations using computer models, robotics, and biochemistry. A-Life is often described as the effort to understand high-level behavior using low-level rules that are based on the laws of physics. The field itself covers the simulation or emulation of living systems or parts of living systems with the intent to understand their behavior.

Another aspect of this field is the attempt to study emergent properties of living populations, usually by making a simulation of many agents while neglecting the precise details of an individual population's members. The development of *evolutionary programming* needed for such simulations has only been widespread thanks to recent improvements in computational power.

The essence of evolutionary programming consists of a set of equations and operations where the computer software measures how well each program solves a particular problem. Programs with poor results are eliminated and new program codes are generated by recombination, either with or without mutation. The solutions produced by evolutionary programming thereby emulate the solutions in the natural world. In addition, in order to produce effective solutions evolutionary programming may make use of functions that seemingly have no logical relevance to the problem being solved. Such processes are often inspired by biological mechanisms of evolution.

### 1.1.6 Artificial intelligence

Artificial intelligence (AI) is the scientific understanding of the logical mechanisms underlying thought and intelligent behavior and their embodiment in machines. It focuses on tasks often described as necessary elements of an *intelligent* system such as perception, reasoning, and learning, to allow the development of systems that perform these functions so they can also become intelligent.

The field seeks to advance the understanding of human cognition, understand the requirements for intelligence in general, and develop intelligent devices, autonomous agents, and systems that *perceive* their environment, *take actions,* and *cooperate with humans* to enhance their abilities.

The solving of complex nonlinear problems that are beyond the capability of conventional methods has become possible using AI derived tools such as *neural networks* (i.e., networks of artificial brain cells) that can learn, recognize patterns and reach solutions (for an example see (Ohka et al. 2006)). Other AI technologies include fuzzy logic, expert systems, and *genetic algorithms* (for an example see (Ohka et al. 2010)).

Algorithms inspired by social insect behavior have been proposed to solve difficult computational problems such as discrete optimization where the ant colony optimization process was followed. Resulting algorithms were used to solve such problems as vehicle routing and routing in telecommunication networks.

### 1.1.7 Bio-inspired Robotics

Initially, robots were intended to be industrial tools that perform specific tasks quickly and accurately with minimal human supervision. They were considered too bulky and too expensive, requiring excessive amounts of labor to employ, maintain, modify, and upgrade.

Later, advancements in computers (higher computation speeds, larger memory) and control methodologies led to the development of sophisticated robots with increased abilities to emulate biological systems.

Figure 1-5. The humanoid robot NAO has become popular for academic purposes worldwide[§].

Robots that emulate the functions, shape and performance of humans or animals use capabilities of actuators, sensors, and mechanisms that make use of state-of-the-art technology. High-end robots are becoming increasingly sophisticated, allowing them to perform various tasks including *walking, dancing, talking,* and *manipulating objects*, etc.

In order to perform such tasks humanoid robots (for example see Figure 1-5) are equipped with several types of sensors such as vision sensors, tactile sensors, vicinity sensors and encoders.

Recent studies attempt to develop robots that possess *social characteristics*, like those in humans and animals. These robots are capable of autonomous

[§] Aldebaran Robotics. http://www.aldebaran-robotics.com operation, the ability to communicate feelings in the form of facial expressions and voices, and to react to feelings expressed by humans (happiness, sorrow).

Also, scientists are developing the use of multiple small robots that can operate in *colonies* like the ants. Such robots are capable of operating both as individuals in cooperative systems, and as inter-connected parts of a large system.

### 1.1.8 Bio-inspired Sensing

For creatures to be able to adapt to their environment, interaction between themselves and the environment requires them to acquire information using their sensory organs. This action of collecting data about their surrounding is called sensing.

In humans, sensing describes two integrated processes:

- The ability to detect various features or cues of the environment (colors for vision, textures for touch, etc.) using specialized sensing organs (eyes, skin, etc.), which provide input to the central nervous system.
- The ability of the central nervous system to interpret the received information as a combined perception of these features. Examples include recognizing different objects within a scene using vision, and recognizing an object's contours using touch, etc.

Imitating sensing organs and mechanisms in humans can lead to developing sensors that possess excellent sensing characteristics (which can be used to enhance robots' capabilities as shown in Section 1.1.7). In addition, understanding those sensing mechanisms is essential for designing virtual reality devices like 3D TVs and haptic displays. Although this is applied for all senses, in the scope of this thesis examples for only vision and touch are presented.

### Bio-inspired Vision

The act of seeing in humans can be briefly described by the following mechanism (Najarian, Dargahi and Mehrizi 2009):

1. The eye lens *focuses* the light emitted by objects in the outside world onto a light-sensitive membrane in the back of the eye, called the *retina*.
2. The retina membrane is a multilayered sensory tissue containing millions of photoreceptor cells, serving as a transducer for the conversion of patterns of light into neuronal signals. These cells detect the photons of light and respond by producing neural impulses.
3. A network of neurons collects these impulses and transmits them down the optic nerve to the primary and secondary visual cortex of the brain. The brain then interprets these impulses into vision.

It is by this mechanism that we can explore a variety of apparent characteristics of surrounding objects. These characteristics include shape, color, quantity, and more.

Several principles in cameras' design are adapted from eyes. For instance, just like that the iris of the eye controls the diameter of the pupil depending on the light intensity, the diaphragm/iris of a camera stops the passage of light except for that passing thought the aperture (opening in the center of the iris), which controls the brightness of the resulting image (Smith 1997).

The retina inspired the development of anthropomorphic visual sensors with variable resolution that increases towards the center of the visual field. The advantage of such sensor is that a considerable reduction in the data requirement is obtained by utilizing nonuniform sampling in conjunction with a high-resolution central focal point (Shin, Inokuchi and Kim 1997).

Silicon retina, which exhibits almost a constant response to variation in illumination, was designed based on the neural architecture and functionality of biological retina. Such device is expected to be useful as a vision sensor for autonomous mobile robots due to its power efficiency, compactness, and real-time processing ability (Shimonomura and Yagi 2008).

### Bio-inspired Touch (or Tactile Sensing)

The process of touch in humans can be described by the following mechanism:

1. It originates with a physical contact between the skin (the touch sensory organ) and an object, which plays the rule of an external stimulus.
2. There are four types of mechanoreceptors (respond to mechanical stimuli) embedded all over the human skin throughout the body. These detect the mechanical deformation of the skin caused by the stimuli and respond by emitting neural impulses (Najarian, Dargahi and Mehrizi 2009).
3. A network of neurons collects these impulses and transmits them to the brain. The brain then interprets these pulses into the perception of touch.

By this mechanism we receive various kinds of information such as surface roughness, hardness, vibration and the convex and concave shapes of Braille dots. It also enables us to manipulate objects with different shapes without any excessive force or slippage.

Providing robots with tactile sensing capabilities is very important to make them interact effectively with their environment. From tactile information, a robot can recognize objects' shape and hardness, and prevent injury to human beings in a domestic environment.

Mimicking the sense of touch by producing artificial tactile skin or sensor is a challenging process due to several problems (Dargahi and Najarian 2004):

- Contrary to the visual sense, the tactile sensing does not possess any localized sensory organ. In fact, the sense of touch operates all over the skin like a distributed phenomenon. In addition, the transduction of tactile signals is distributed over a considerably wider surface than in a single localized sensory organ such as eyes.
- Tactile sensing has a complex nature and to find suitable technological analogies in science or engineering is not an easy task.
- Tactile sensing is not related only to the mechanical deformation of the artificial tactile sensor, but also to the object being handled.
- The relation between different aspects of the tactile features (such as texture, shape, force, friction.) is not clearly understood.

To simplify the problem researchers tried to focus on a single tactile capability of human sensing (such as recognizing textures) and designed sensors that own it.

For example, Mukaibo et al. developed a texture sensor emulating the major features of a human finger. It has a layered structure, and elements like bone and nail. It detects different textures in a way similar to the way humans do (Mukaibo et al. 2005).

Along with tactile sensors, in this paper we are particularly interested in addressing the difficult robotics problem of generating artificial tactile sensation using tactile displays.

There are many kinds of experimental tactile displays such as mechanical vibratory pin arrays, surface acoustic waves, pin arrays driven by pneumatic actuators and piezoelectric actuator arrays to stimulate the mechanoreceptive units. All of these generate pressure distribution to deliver the tactile sensation to an operator's fingers to emulate touching a virtual object. Even given these many varieties of tactile display, as yet there is no best way to produce the tactile sensation.

Since none of these tactile displays generate relative motion between the finger surface and the display pad, the operator cannot feel a real sense of touching. In order to overcome this shortcoming of tactile displays, a bio-inspired method may provide a promising solution.

## 1.2 Objectives of This Research

From the example of human tactile systems, we can infer from Section 1.1.8 that biological systems have many advantageous characteristics that attract much attention from researchers in many fields.

The primary research problem addressed in this paper is "to achieve better understanding of how human tactile systems work by studying a special tactile phenomenon called the velvet hand illusion (VHI)" (which will be described in Chapter 2).

The main objectives of this research are given as follows:

- Investigate the human sensory mechanism underlying the perception of the VHI.
- Clarify the degree to which the VHI mechanism is related to the sensing organ (the skin) and its receptors and/or to a complex cognitive process in the brain.
- Discuss the specifications of a tactile display that could utilize the sensory mechanism of the VHI.

## 1.3 Methodology of This Research

In order to accomplish these research objectives, the following procedures were followed:

- A literature review of the current work on sensory illusions (focusing on optical and tactile experiments) was conducted to gain the in depth understanding necessary to work with the VHI (presented in Chapter 2 of this thesis).
- The basic tactile aspects of the VHI were examined using psychophysical experiments (presented in Chapter 3).
- A series of CAE analyses was performed to predict nerve activity during the tactile illusion (presented in Chapter 4).

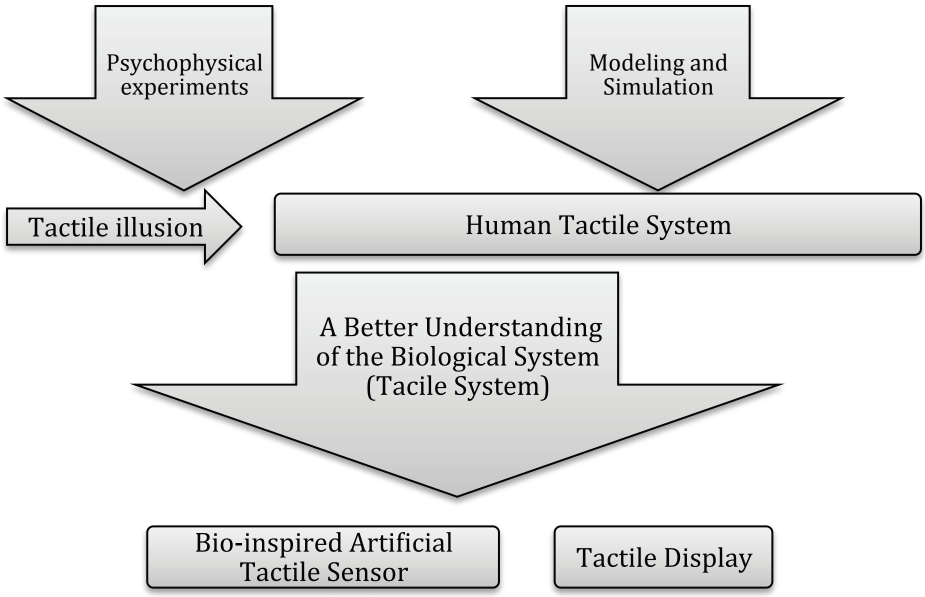


Figure 1-6. The methodology followed for this research.

- A discussion is offered of the present study's results, which includes a description of the VHI mechanism, and recommendations for the design of future tactile displays and sensors based on the findings described in Chapters 3 and 4 (presented in Chapter 5).

# Chapter 2

# Sensory Illusions

Chapter 2 introduces the concept of sensory illusions, and presents descriptions and up-to-date explanations of the most studied ones. It starts with some optical illusions that may be familiar to the reader, and then tackles some of the relatively less known tactile illusions. It also sheds light on the differences and similarities between the optical illusions presented, and their tactile versions.

## 2.1 Introduction

A sensory illusion is the perception of a stimulus by one sense of the five human senses, which does not agree with that of another sense or with objective tests[**].

It also has been defined as a percept arising from a specific stimulus delivered under specific conditions that gives a different conscious experience when the conditions are changed, as explained below. In other words, the information available to the perceiver should be separable into a *constant part* and a *variable part*, and the percept produced by the constant part should be contingent on the variable part which can include endogenous neural states. In addition, the change should be *surprising, unexpected,* even *amusing* when the perceiver becomes aware of it (Hayward 2008).

** http://science.howstuffworks.com/illusion-info.htm

Today some illusions might not be interesting or surprising if their mechanisms are well known. For example, a straight stick half submerged in a glass of water appears to be bent at the water line, but if the observer runs a finger along it, the stick will feel straight. The bent appearance is called an *optical illusion*, and its reason is the refraction of light as it passes from water into air.

Another example of a physical-phenomenon-based illusion is the *Doppler effect* (first described by the Austrian physicist Christian Doppler (1803-1853) in 1842), which is basically the change in frequency of a sound wave for an observer moving relative to the source of the wave. It is commonly heard when a vehicle sounding a siren or horn approaches, passes, and recedes from an observer. The perceived frequency is higher (compared to the emitted frequency) during the approach, it is identical at the instant of passing by, and it is lower during the recession.

So, for the Doppler effect, the constant part (see Hayward's definition above) is hearing a specified sound, and the variable part is moving the sound source either toward the observer or away from him, and the percept is hearing a sound with a varying frequency. John Scott Russell made one of the first experimental observations of the Doppler effect and reported his observations in a famous paper by Russell (1848).

Other illusions may depend wholly or in part upon the characteristics of the *sensing organs* (ear, eye, …etc.), the sensory information delivered by sensory neurons (a part of the *peripheral nervous system* (PNS)), or the interpretation of this information by the *central nervous system* (CNS) (Figure 2-1).

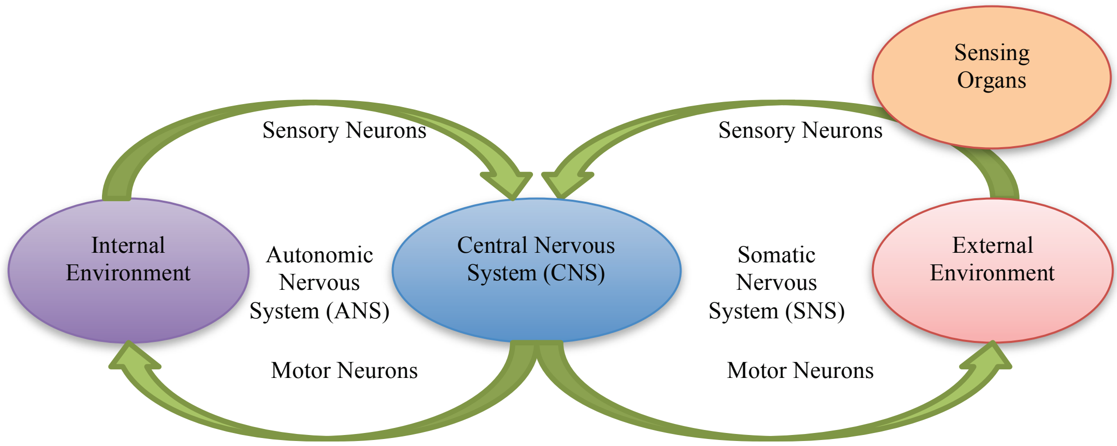



Figure 2-1. A schematic representation of the nervous system. The peripheral nervous system (PNS) consists of the somatic and the autonomic nervous systems. The sensing organs collects information about the external environment.

## 2.2 Background

Studying the underlying mechanisms of sensory illusions and investigating the reasons behind them, can provide us with two important perspectives. First is a great deal of understanding of how the sensory organs and the nervous system work. Second is an understanding of how both systems integrate to obtain and process the sensory data which causes the *perception* of the applied illusion (or stimulus in general).

Among the established body of research on sensory illusions, we can make a distinction between studies which are primarily descriptive and those that are quantitative. The former include observational reports in which the illusion is described, and the necessary conditions for it to happen are experimentally investigated (for example see (Mochiyama et al. 2005)).

The quantitative studies are usually more in depth and performed using *psychophysical experiments*, which essentially analyze the relationship between stimulus and sensation using experimental procedures (for example see (Fisher and Zanker 2001)). The target of such experiments is to determine whether the subject can detect a stimulus, identify it, differentiate between it and another stimulus, and describe the magnitude or nature of this difference (Gescheider 1997). Various kinds of experiments exist according to: their stimulus; task; method; analysis; and measure (Kingdom and Prins 2009).

Analyzing the results of these psychophysical experiments can reveal the mechanism behind sensory illusions. Some questions that can be formulated in this context are:

- Is the illusion related to: a) the sensory organ or to the b) processing in the nervous system?
- If the answer is b), is it limited to PNS or CNS?
- And in the case of more complex illusions, is the illusion a result of the order or the priority in which the cognitive processing of different parts of a stimulus take place?

In recent years researchers have achieved a better understanding of how the nervous system works, which explained some nervous system-dependent illusions (by answering questions like the ones proposed above), such as the following. In the *size–weight illusion*, when a person simultaneously picks up a large box in one hand and a much smaller one of the same weight in the other, the larger box will seem the lighter. The illusion persists if the boxes where lifted subsequently using the same hand.

During the 20th century, different explanations of the mechanism of this illusion were proposed, including the mismatch between expected and required lifting forces (Koseleff 1957), and the mismatch between proprioceptive information generated by the two objects (Ross 1966). Those explanations were later proved wrong by contradictory experimental evidence, and recently the following explanation was proposed:

> The central nervous system integrates prior expectations with proprioceptive information in a sub-optimal (Anti-Bayesian) way, leading to this illusory perception (Brayanov and Smith 2010).

In the next part of this chapter, several sensory illusions, their descriptions, and the theories proposed to explain them are reviewed. Only examples of optical and tactile illusions are included.

## 2.3 Optical Illusions

Optical (or visual) illusions are probably the most well known, and most studied compared to other types of illusions (particularly tactile or auditory), though this is not to say that the number of other types of illusions is small. A contributing factor to this is the fact that optical illusions are easy to re-create (all it takes is a pencil and a paper) (Hayward 2008).

Moreover with the wide use of computers and the Internet, one can generate them without being an artist, and a lot of web sites provide access to a huge repository of such figures. This ease of access is also true to a lesser extent for auditory illusions. On the other hand, illustrating tactile illusions usually requires equipment and preparation. Some examples of the most studied optical illusions with the theories proposed to explain their mechanisms are as follows.

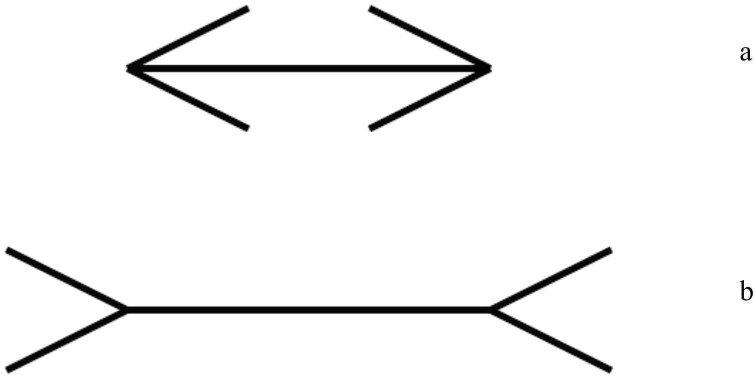



Figure 2-2. The standard Müller-Lyer illusion. Which line is longer? See the text for answer.

## 2.3.1 Müller-Lyer Illusion

The Müller-Lyer illusion (in its basic or standard version) is an optical illusion in which two identical lines appear different in length if “arrowheads” (Figure 2-2 a) or “arrow tails” (Figure 2-2 b) are attached to their ends. This illusion was named after the German psychiatrist and sociologist Franz Carl Müller-Lyer (1857–1916). Although there is considerable variation in the reported magnitude of the effect (presumably due to the different experimental conditions in various studies), the line terminated by the arrowheads always appears shorter than the line of equal length terminated by arrow tails (Howe and Purves 2005).

An interesting experiment related to this illusion is one in which, two groups of subjects were instructed to draw lines with the same lengths as the ones in the illusion figure (with one line visually presented to the subject each trial) using a stylus. One group of subjects was instructed to ignore the illusion while the other was told nothing. Subjects in both groups produced lines longer or shorter according the illusion, and no difference in responses between the two groups was detected (Anii and Kudo 1997).

### Explanation

Being probably the most famous of all the optical illusions, it is surprising that the perceptual mechanism behind the Müller-Lyer illusion is not exactly clear, but many explanations have been suggested. Some of the most popular are presented here.

The most well-known theory explaining this illusion is *the perspective theory*. In general, a picture is itself two-dimensional, but it represents objects lying in three dimensions. So "pictures are essentially ambiguous in depth" (Gregory 1965) which requires the brain to try to account for the missing dimension. Because we are accustomed to perceiving three dimensions out of flat pictures, some 2D illustrations may be thought of as flat projections of typical views of objects in 3D world and as such might be interpreted wrongly. So, the arrow tail case of the Müller-Lyer figure (Figure 2-2 b) is a

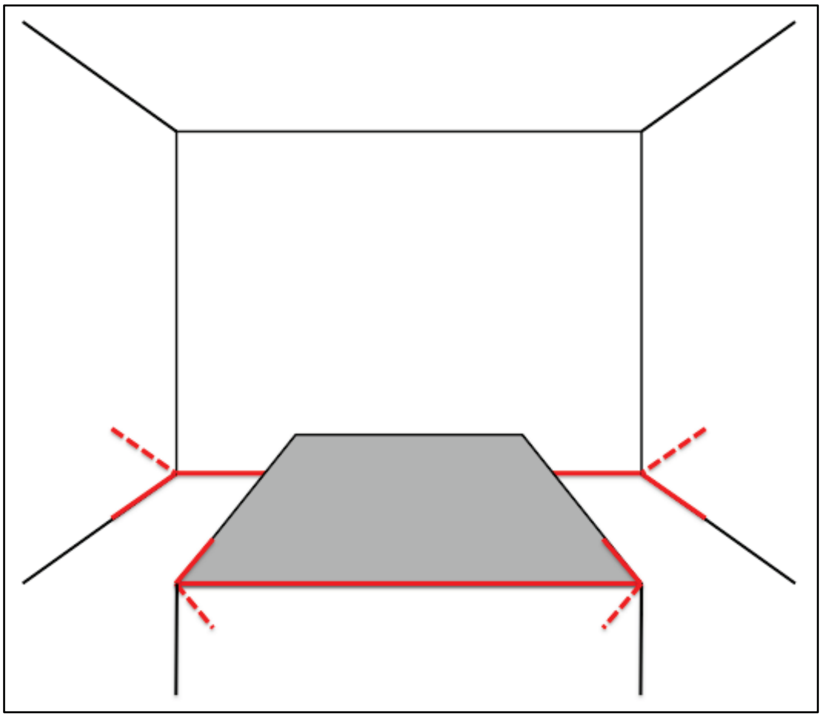


Figure 2-3. The perspective theory as an explanation for the Müller-Lyer illusion. We tend to underestimate the length of lines if they belong to a pattern, which resembles an outside corner in 3D world, and vice versa. Adapted from http://www.newworldencyclopedia.org/entry/Muller-Lyer_illusion

typical projection of, say, the corner of a room (the tails representing the intersections of the walls with the ceiling and floor) while the arrowhead case (Figure 2-2 a) is a typical projection of an outside corner of a house or a box (Figure 2-3). The parts corresponding to nearer objects are typically underestimated in length (Gregory 1963). The perspective theory has been supported by studies which compared the perception of this illusion by people of different cultural backgrounds. Stewart reported that American children were more affected by the illusion than rural Zambian children, who are much less exposed to "rectangular structures"(Stewart 1973). However this theory cannot explain why the illusion persists if arrowheads and arrow tails are replaced with circles or squares (Howe and Purves 2005) (shown in Figure 2-4).

Another theory that explains this illusion is, *the assimilation theory*, which proposes the possibility that our visual system is not able to separate the lines from the whole figure. So according to this theory, the overestimation of the line length of the arrow tail case in the Müller-Lyer illusion is due to the fact that the combination of the line and the arrow tail is actually longer. This

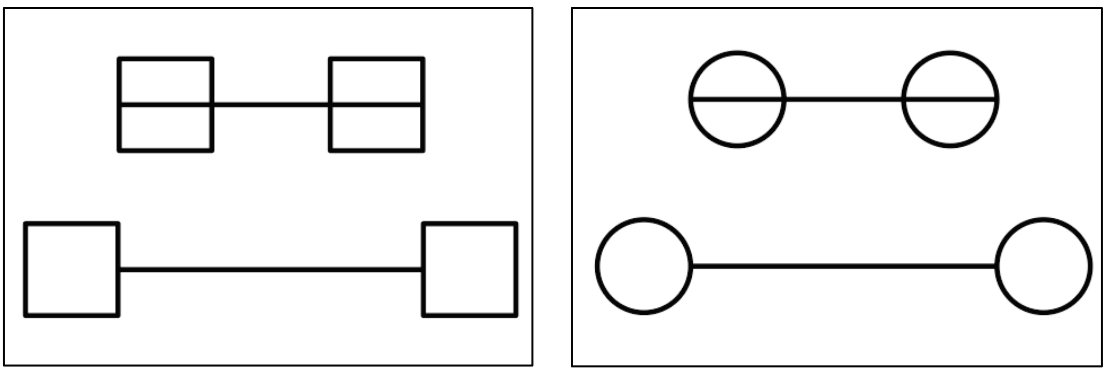


Figure 2-4. Other variations of the Müller-Lyer illusion. The perspective theory cannot explain the illusion for variations in which the line does not end with an arrowhead or an arrow tail.

description also holds for other variations such as the ones shown in Figure 2-4. This theory, though, was discarded (Howe and Purves 2005).

Recently, Howe and Purves analyzed a large database of pictures of natural scenes using image processing to get the distribution of lines and angles positions that matched those of the Müller-Lyer illusion. Their findings suggested that the perceptual effects elicited by the Müller-Lyer stimulus and its major variants are correctly predicted by the *probability distributions* of the possible physical sources underlying the relevant retinal images (Howe and Purves 2005). Simply stated, some patterns of lines appear more than others in the environment surrounding us. This study asserts that both our visual processing and the related, subsequent spatial judgments of line lengths is to some degree probabilistic according to these *statistical regularities*. This was later supported experimentally (Blessing and Svetlik 2007).

### 2.3.2 Barber Pole Illusion

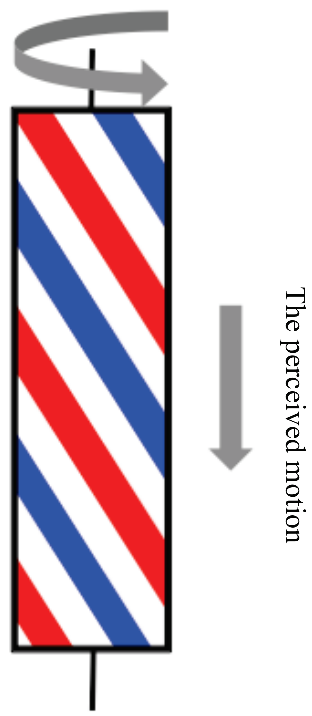



Figure 2-5. Barber pole illusion. The pole is rotating around its axis but an illusory motion of the stripes along the pole is perceived.

The Baber pole illusion is an optical illusion, which shows how the human visual system processes motion. The illusion happens when a diagonally striped pole is rotated around its axis, the stripes appear like they are moving in the direction of the axis (Figure 2-5). Guilford attempts to describe the situation where the perceiver may or may not experience the illusion. He noted that an observer of the barber's pole might see (depending on the intensity of the experienced illusion) the following:

- the actual motion of the pole, which is the rotation around its axis and see the strips for what they actually are (helixes), in other words, the observer does not feel the illusion at all;
- only the vertical motion of the strips as if they were moving (downwards for the case of Figure 2-5), so basically the observer fully experiences the illusion;
- or, a combination of the two (vertical and horizontal) movements with one component prevailing to a greater or lesser degree (Guilford 1929).

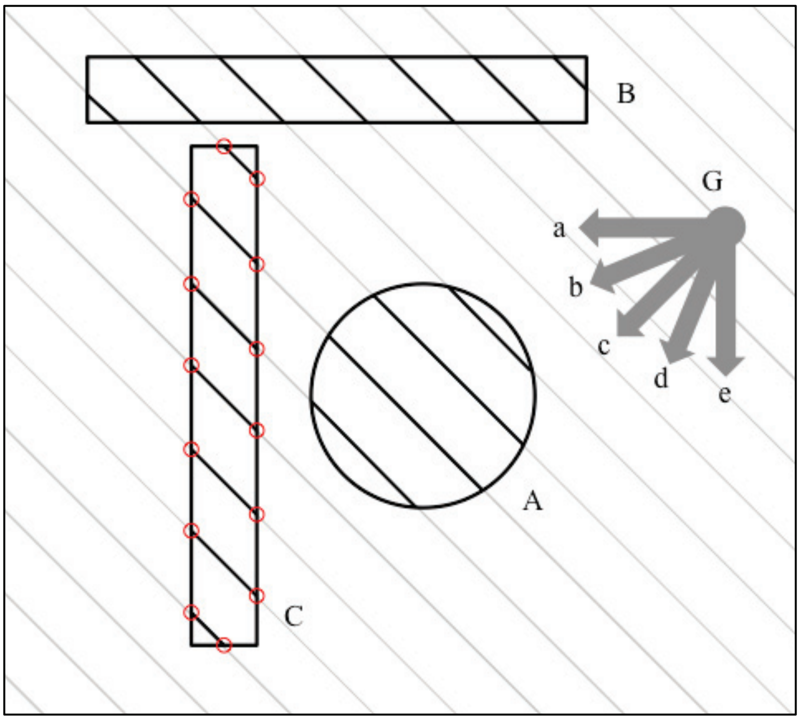



Figure 2-6. It is impossible to determine whether the actual direction of motion of the grating G is a,b,c,d or e when looking at it though a small aperture A. Adapted from (Mussap and Crassini 1993)

### Explanation

It is well established that the reason behind this illusion can be understood in terms of the *aperture problem*[††].

The aperture problem: if the motion of oriented elements (lines or bars) is detected through an opening (an aperture) that is small compared to the moving elements, the only information that can be extracted (whatever the direction of the motion) is the component of the motion perpendicular to the local orientation of the elements as motion parallel to the elements causes no detectable change in the stimulus. Looking at the moving *grating* G through a small aperture A, it is impossible to determine whether the actual motion is in

[††] For an Explanatory video see: http://www.sandlotscience.com/Ambiguous/Barberpole_Illusion.htm

the direction of "a" or that of "d" (see Figure 2.6) (Wallach 1935; Marr and Ullman 1981; Adelson and Movshon 1982; Wuerger, Shapley and Rubin 1996).

If the grating in Figure 2.6 is moving in the direction "a" (horizontally to the left), it is seen to move downward in the vertical rectangular aperture C, leftward (same as the actual movement) in the horizontal aperture B, and in the circular aperture A the perceived direction of motion varies from person to person. This relation between the aperture shape and the perceived motion direction was experimentally studied in (Mussap and Crassini 1993).

Shimojo et al. suggested that the misleading motion of the *line terminators* (the closest parts of the grating lines to the edges of the aperture, see the red circles in Figure 2.6) determines the perceived motion of the whole grating (Shimojo, Silverman and Nakayama 1989; Mussap and Crassini 1993).

For example, in the case of the grating moving in the direction "a" and seen through aperture C (in Figure 2.6), the line terminators on the edges parallel to the longer axis of C (12 of them) will move downward, and those on edges parallel to the short axis (only 2 of them) will move leftward. So generalizing the motions of the line terminators is the cause of the ambiguous perceived downward motion.

Recently, further investigations were also performed of the parameters affecting this illusion like the difference in contrast and orientation between the grating inside the aperture, the grating surrounding it (Mussap and Grotenhuis 1997), the orientation of the grating, and also the aspect ratio of the rectangular aperture (Fisher and Zanker 2001).

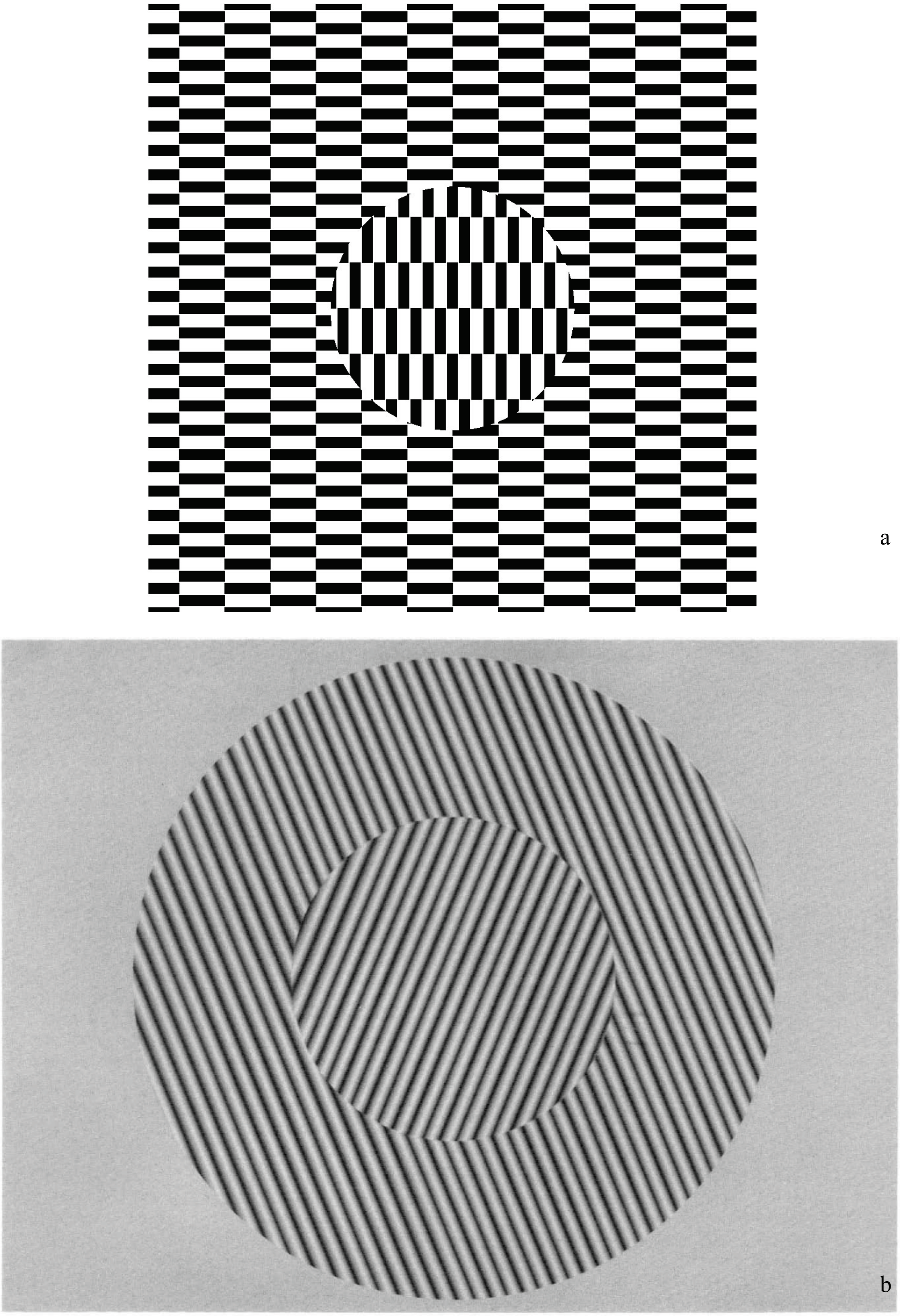



Figure 2-7. Ouchi illusion. a) The original version. Adapted from (Ouchi 1977). b) The harmonic version. Adapted from (Hine, Cook and Rogers 1995).

### 2.3.3 Ouchi Illusion

Ouchi illusion is an amazing optical illusion named after its inventor Hajime Ouchi. Basically a disk with a rectangular checkerboard pattern superimposed on another checkerboard can appear to move (Figure 2-7 a) (Ouchi 1977; Hine, Cook and Rogers 1995). When the central pattern is orthogonal (though the angle does not need to be 90 degrees for the illusion to be perceived, see below) to its background, it may appear to slide or wiggle in front or behind the surrounding pattern. The perceived motion is certainly an illusion because a stationary two-dimensional picture generates it (Khang and Essock 1997).

Hine et al. found that the checkerboard pattern is not necessary for the illusion to occur, but rather the components of lower spatial frequency. They used two sinusoidally-modulated (haromic) contrast gratings of different orientations for the surrounding and the inner disk (Figure 2-7 b). They reported that the illusion was strongest for angles between the gratings of less than 60°. Also, the apparent motion can be cancelled by physically moving the inner disk grating in the opposite direction to the illusory movement (Hine, Cook and Rogers 1995).

Kang and Essock used a composite pattern made up of the sum of the fundamental (checkerboard) and harmonic components. The composite pattern exhibited a stronger illusion than either the fundamental or the harmonic pattern. They also noted that adding a blurry boundary between the inner disk and the surrounding did not reduce the illusion (Khang and Essock 1997).

Ashida experimentally found that the optimal size (which exhibits the strongest illusion) of the inner pattern increased proportionally with the size of the blocks in the checkerboard pattern. The optimal fundamental spatial frequency was lower for a larger stimulus (larger image) both for checkerboard patterns and simpler sinusoidal grating patterns (Ashida 2002).

### Explanation

It was observed that the illusion persisted in *dichoptic viewing* in which the two parts, the inner disk and background, were presented separately to each of the two eyes. This seems to suggest that *the illusion is not of peripheral but of central origin* (Khang and Essock 1997).

Hine et al. suggested that the illusion occurs because of a failure to integrate two motion signals into single motion vectors (Hine, Cook and Rogers 1995).

The illusion seems to disappear when the subject is instructed to hold the eyes steady on a spot. This implies that the occurrence of the illusion may begin with retinal-image motion as typically caused by *eye movements*. Although, others claimed that eye movements are not necessarily required to generate the effects because image motion alone can yield apparent relative motion.

There are several kinds of eye movements that might be involved when the patterns are presented in free viewing (where the subject is given no instructions). These include flicks (micro saccades), high-frequency tremors, slow drifts, saccades, smooth pursuits, or vergence movements. It was suggested that flicks could play a role in the generation of this illusion (Khang and Essock 1997).

The theory of eye movement as an explanation of this illusion was supported by recent studies (Ölveczky, Baccus and Meister 2003; Zanker, Hermens and Walker 2010). Ölveczky et al. argued that the retinal motion of the pattern (Figure 2-7 a) is mainly governed by vertical eye movements in the periphery part of the eye, and by horizontal eye movements in the center part of the eye. Because the eye executes horizontal and vertical eye movements independently, the neurons stimulated by the disk convey the signal that the disk jitters due to the horizontal component of the eye movements, while the neurons stimulated by the bakgound convey the signal that movements are due to the independent vertical component. This triggers the object motion sensitive cells in the retina to signal an apparent movement of the disk (Ölveczky, Baccus and Meister 2003).

## 2.4 From Optical to Tactile Illusions[‡‡]

### 2.4.1 Similarities between Touch and Vision Senses

Because of the development of research concerned with the sense of vision, scientists are trying to check if the same principles and mechanisms can be utilized for the sense of touch. Such an approach is supported by the similarities between both senses. These similarities include the following (Scilingo, Sgambelluri and Bicchi 2008).

- For both systems, regions of high and low acuity exist in the sensing organ surfaces. The high acuity region for vision is the

[‡‡] Based on (Scilingo, Sgambelluri and Bicchi 2008)

fovea of the retina. For touch, high acuity regions are the fingers, lips and tongue.

- Both systems code different features of the applied stimuli using *neural channels.* For vision, neural channels code information related to hue, saturation of color and intensity of light, while for touch, channels give information about intensity of pressure, and change of pressure.
- Using brain-mapping techniques, it was reported that when a touch stimulus is presented to a blind person, the pathways to the visual cortex are activated as well as the normal pathways. If a normal person with eyes closed performs the same task, the visual cortex does not display such activity. This means that in blind people the touch sense provides surrogate sensations for vision. This confirms that information in both senses is codified in a similar way.

### 2.4.2 Tactile Flow

Scilingo et al. proposed that there might exist a tactile analogy of a widely used concept in vision research called *optical flow*. They referred to it as *tactile flow* (Scilingo, Sgambelluri and Bicchi 2008). Due to its importance in explaining certain tactile illusions, a description is provided here starting with defining the vision version.

The Optical flow is the distribution of apparent velocities of movement of *brightness patterns* in an image. It can arise from relative motion between object and viewer or from changes in light sources (Horn and Schunck 1981).

It describes the apparent motion of objects, surfaces, and edges in a visual scene. The human brain extracts several pieces of information about the external environment by analyzing this flow field. This was supported by an experiment in which physiological recordings of the middle temporal superior (MST) area of monkeys' brains proved that the neurons in this area are selective for optical flow components (Orban et al. 1992).

Note: the aperture problem defined in Section 2.3.2 can also be described in terms of optical flow. It occurs when the tangential component of the velocities becomes mathematically undefined which results in ambiguity in determining the direction of motion, hence the relationship with Barber Pole Illusion.

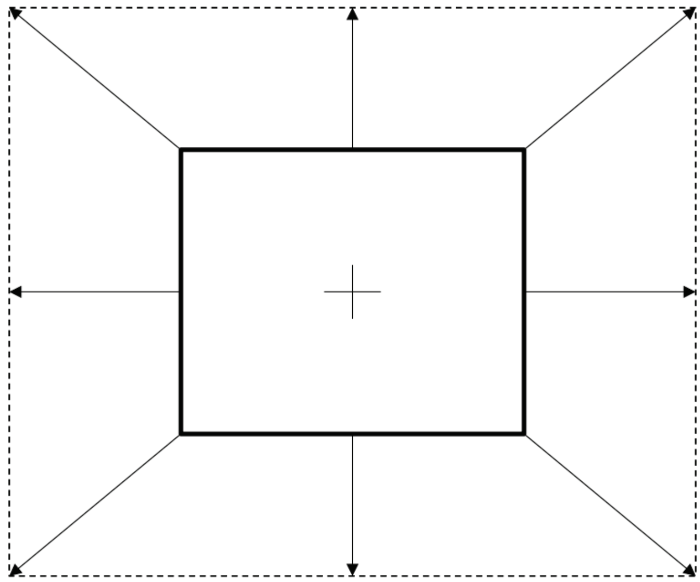
Optical flow techniques such as motion detection, object segmentation, time-to-collision, motion compensated encoding, are utilized in computer vision and video file compression.

To simply illustrate researchers use an application called time-to-collision (or time-to-contact). When an object at a distance $D$ from a camera moves with a constant velocity $V$ toward it, it will crash at time $T=D/V$, called time-to-collision. If the relative motion occurs along the line of sight, the optical flow field has a simple radial form (Figure 2-8 a) and the center of the radial flow pattern is called Focus of Expansion (FoE). In other words, the image of an approaching object expands. In this case, only using optical measurements based on the optic flow and without knowing the velocity or distance from the surface it is possible to determine when the crash will occur. In fact, it is sufficient to pick a point in the image and divide its distance from the FoE by its divergence from the FoE. In the time to contact paradigm the iso-brightness contours of move in a radial direction.

For touch, during a tactile indentation task (Figure 2-8 b) the *contact area* between the fingertip and an object changes with relative motion. The iso-strain contours in the contact area form concentric circles or ellipses with their centers at *the initial contact point*. These contours move radially with the relative motion described. Compare this with the expansion of the image, and the iso-brightness contours in the optical flow example (time-to-collision) above.

Accordingly, Scilingo et al. suggested that tactile flow as an analogy to optical flow can be formulated as the distribution of apparent velocities of movement of *strain* patterns, and they used the related *strain energy density* (SED) instead of strain because of the convenience of managing SED which is a scalar compared with managing strain tensor.

A related technique was used to relate the rate of contact area change with object softness (or compliance) discrimination (Bicchi, Scilingo and De Rossi 2000).



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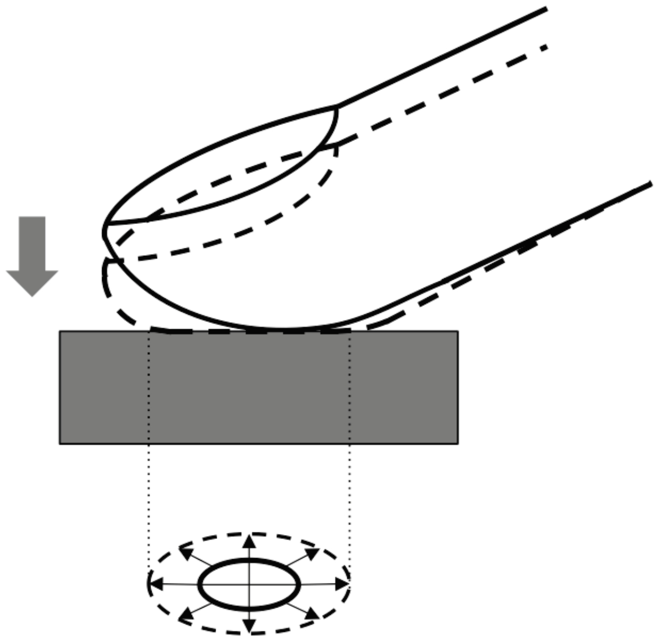

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Figure 2-8. The concept of tactile flow as an analogy to optical flow.

## 2.5 Tactile Illusions

We have already pointed out some of the difficulties facing research concerned with tactile sensing (see Section 1.1.8), and the reasons behind the unfamiliarity of tactile illusions compared to their optical counter parts (see Section 2.3). Due to these two reasons many of them remain not understood, although the recent attention to tactile (or *haptic*) virtual reality and its applications necessitates achieving a better understanding of these illusions because of the unique and exciting perceptions they elicit.

The following is a brief discussion of tactile illusion research to date, with the illusions considered divided into two categories:

- tactile versions of optical illusions, and
- pure tactile illusions.

For a comprehensive review of tactile illusions see Hayward's excellent paper (2008).

### 2.5.1 Tactile Versions of Optical illusions

#### The tactile Müller-Lyer Illusion

The existence of a tactile version of the Müller-Lyer Illusion was confirmed experimentally in many reports. Suzuki & Ashida found no significant difference between the illusory perception of Müller-Lyer Illusion for both vision and touch using a simple experiment. They reported that lines ending with arrow tails appear 1.3 times longer than lines ending with arrowheads for both cases (Suzuki and Arashida 1992).

Several parameters affecting this illusion were investigated such as exploration mode, orientation of the figure (horizontal or vertical), and experiment configurations (Heller et al. 2005). Notably, contrary to its optical version, instructions to ignore the arrowheads and arrow tails reduced the tactile illusion especially for the vertical figure (Millar and Al-Attar 2002).

The perception of the tactile Müller-Lyer Illusion was explained in early research in terms of visual experience, which relates the judgment of line lengths based on the sense of touch to past visual perception of edges/lines. However that was contradicted by Heller et al. (2002), who found no effect of the visual status (being blind-folded-sighted, late blind, congenitally blind (blind from birth), and low-vision subjects) of the subject on the illusion.

### The tactile Barber Pole Illusion

Scilingo et al. checked the existence of a tactile version of the barber pole illusion described in Section 2.3.2 experimentally. They used an apparatus, in which the subject's fingertip contacts a moving textured pad with ridges through a small opening of about the size of a human forefinger (compare with the concept of an aperture in Section 2.3.2). The pad can be fixed at any angle on a linear motorized slide, which also has the capability to change orientation (Figure 2-9). The experiment consisted of keeping the finger still while the pad was moved slowly by the slide in a direction unknown to the subject, with the pad being fixed on the slide at an angle also unknown.

Their results show the direction of the texture motion perceived by the subjects is almost perpendicular to that of the actual motion direction, which agrees with the principle of the optical barber pole illusion. It was suggested

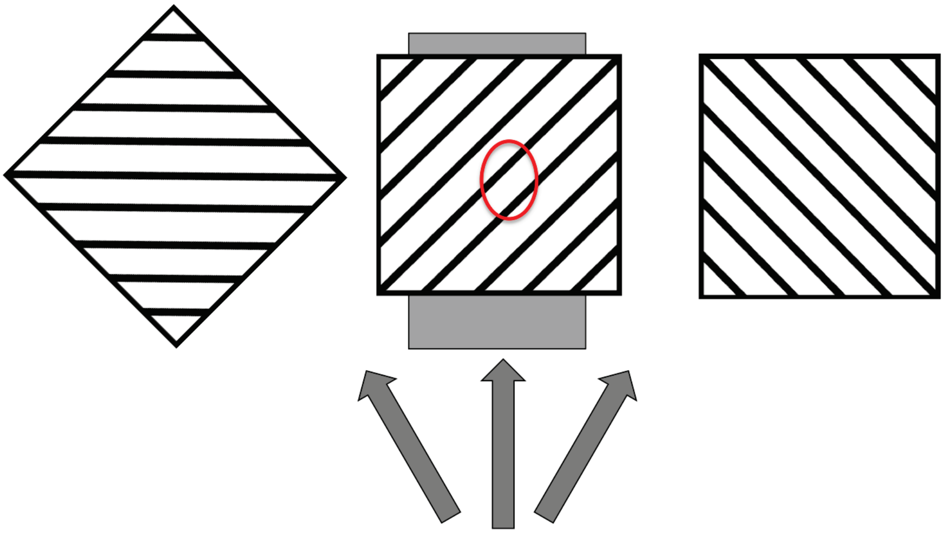

Figure 2-9. The principle of the apparatus used for experiments on the tactile barber pole illusion. Both, the direction of the motion of the linear motorized slide, and the orientation of the textured pad can be changed. The red oval represents the opening though which the subject's forefinger touches the pad. Adapted from (Scilingo, Sgambelluri and Bicchi 2008).

that there might be an analogy to the optical aperture problem (Scilingo, Sgambelluri and Bicchi 2008), which can explain the reason of this illusion (see also Section 2.4.2).

### The Tactile Ouchi Illusion

Scilingo et al. checked the existence of a tactile version of the Ouchi illusion described in Section 2.3.3. They used an apparatus in which a subject can place his/her finger on a metallic plane endowed with a small opening through which he/she could touch a moving pad (with the forefinger).

The pad has a simplified 3D model of the Ouchi pattern that was manufactured using a technique of microprinting in a nylon structure (Figure 2-10). The pad was placed on an end-effector, which was controlled by a personal computer. The motion imposed on the pad (by the end-effector) was a vibration in a random direction of a frequency of 4Hz. This frequency was chosen in order to maximize the response of *Meissner corpuscles* (one of the four types of mechanoreceptors in the skin which is highly sensitive to low frequency vibrations). Compare the motion imposed in this experiment with the eye's retina motion, which is related to the optical Ouchi illusion as shown in Section 2.3.3.

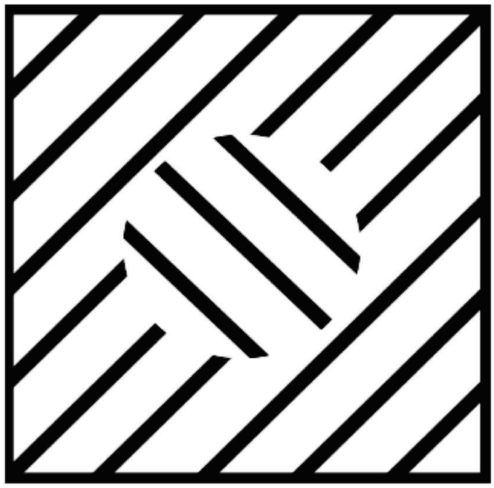

Figure 2-10. The textured pad used for the tactile Ouchi illusion. Adapted from (Scilingo, Sgambelluri and Bicchi 2008).

They reported that 45% of the subjects felt an illusion. The description of the feeling was that the circle felt like it is raised against the surrounding area, or vice versa. This is similar to the feeling that the disk is in front of or behind the background that was reported for the optical version of this illusion. The finding of 45% implies that for such a perception the tactile system's resolution is poor compared to that of the optic system. It was suggested that this illusion's mechanism is similar to its optical version (Scilingo, Sgambelluri and Bicchi 2008).

### 2.5.2 Pure Tactile Illusions

#### Fishbone tactile illusion

The Fishbone tactile illusion is a tactile illusion in which the convex and concave shape of objects with certain patterns (resembles the shape of fish spine, hence the name) cannot be distinguished through rubbing by the fingertip. The shape consists of a set of parallel flat ridges a few mm wide,

Figure 2-11. The pattern used in the fishbone illusion. When the centerline is stroked with the fingertip, a subject feels that the center is concave.

separated by a few mm, a fraction of a mm high, and oriented perpendicular to the direction of fingertip motion (Figure 2-11).

If a fingertip is freely stroked back and forth along the centerline of the pattern (the fish's "spine"), the adjacent ridges generate an illusory perception that the center of the pattern is concave, i.e. the central strip is lower than the ridge height, whether this central strip is in fact higher, lower, or the same height as the ridges (Nakatani, Howe and Tachi 2006).

Nakatani, Howe and Tachi (2006) suggested that this illusion might be explained by one of the following two mechanisms.

- Using a microscope and high-speed camera (120 frames/s), they found little difference in the finger print deformation when rubbing either a concave or a convex fishbone patterns machined on a transparent acrylic plate. Although this could explain the illusion, it does not explain why subjects always feel the pattern as concave.

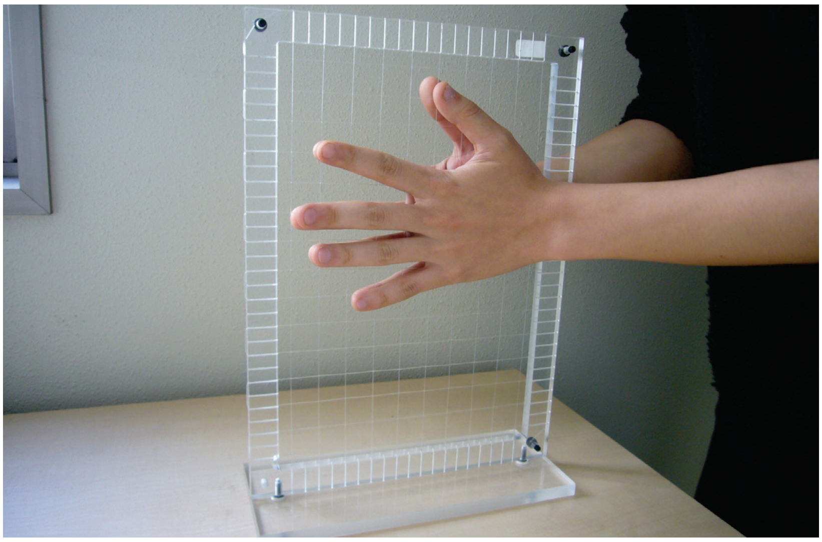

Figure 2-12. The wire mesh used for the velvet hand illusion. When the mesh is rubbed with both hands, a slippery sensation (velvet-like hence the name) is felt by the subject.

- The second potential mechanism is based on the processing of the tactile signal in the central nervous system. In particular, tactile stimulus may be interpreted as both confirming the presence of a surface texture and the presence of the surface itself. In other words, the absence of tactile sensations in the smooth central strip and the presence of tactile sensations in the adjacent regions may be interpreted as the absence of a surface in the center, i.e., a concave shape.

### Velvet hand illusion

Velvet hand illusion (VHI) is an illusion in which a subject can feel a strange velvety, slippery or oily sensation when he/she lightly rubs a wire mesh between hands, keeping them pressed gently together (Figure 2-12).

Mochiyama et al. (2005) showed that a rigid mesh is not a necessary condition; instead, two wires are sufficient for the illusion to happen, no remarkable difference between active and passive touch was detected.

On the contrary, Kawabe et al. (2010) found out, experimentally, that the illusion is considerably stronger when caused by passive touch compared with active touch. They also related the intensity of the perceived illusion with wire distance.

Although the mechanism of this illusion is not clear yet, it was suggested, based on FEM simulation of the illusion, that Merkel's disks (the mechanoreceptor sensitive to edges and curvature) play a role in the perception of this illusion (Chami et al. 2010).

For further details on psychophysical experiments and FEM modeling of this illusion refer to Chapter 3 and Chapter 4 respectively.

# Chapter 3

# Psychophysical Experiments on Velvet Hand Illusion

In this chapter we focus on VHI (described in Chapter 2) to determine the specifications of an actuator for a tactile display enhanced by VHI. We investigate the relationship between wire distance and intensity of illusionary sensation using a series of psychophysical experiments (using Thurstone's Paired Comparison) under active and passive touch.

## 3.1 Introduction

In virtual reality, there are many kinds of experimental tactile displays such as mechanical vibratory pin arrays (Ikei, Yamada and Fukuda 1999), surface acoustic waves (Takasaki et al. 2000), pin arrays driven by pneumatic actuators (Tanaka, Yamauchi and Amemiya 2002) and piezoelectric actuator arrays (Ohka et al. 2007); however, all of these generate pressure distribution to emulate the tactile sensation of an operator's fingers touching a virtual object. Since the tactile display does not generate relative motion between the finger surface and the display pad, the operator cannot feel a real sense of touching. If our brain believes the virtual object to be a real object in spite of no relative motion on the tactile display, we can improve the above ordinary tactile displays. In this chapter, we adopt a tactile illusion to trick an operator's brain into believing the operator is touching a real object.

In Chapter 2 a review of the most studied sensory illusions showed that several explanations of various optical illusions, like the Müller-Lyer and barber pole, have been proposed, and the mechanisms of some of those illusions have been determined. On the other hand fewer tactile illusions, like fishbone and VHI, have been studied and the mechanism of such tactile illusions are still unknown

Since the VHI causes the sensation of contacting a given material, i.e. velvet (material-feeling, hereafter), we concentrate on this illusion and apply it to a new tactile display design.

VHI is caused by such a wire mesh as shown in Figure 2-12. A person rubs his/her hands together on either side of wires strung through a frame, producing the sensation of rubbing a very smooth and soft texture like velvet. This tactile illusion is caused by brain activity. In another report, we began to study a tactile display utilizing the comb illusion to emulate relative motion between a tactile display and a finger surface (Ohka 2010). Since we focus on VHI, which has the possibility to generate material-feeling, this study, in combination with the above study, we will introduce guidelines for a new tactile display.

In this chapter, using a series of psychophysical experiments, VHI is investigated to obtain requirements for an actuator array of a tactile display. For the psychophysical experiments, we developed equipment composed of a pair of parallel wires and a frame because VHI was caused not only by wire mesh but also by two parallel wires. We prepared six sets of equipment with different distances between the two wires to obtain the optimum distance for causing maximum VHI. In the active touch condition, human subjects bring their hands together on opposite sides of the two wires and move their hands to feel VHI. To compare the active touch condition with passive touch, the equipment is put on a motorized x-table and moved with reciprocating motion to cause the subject to feel VHI passively. According to the experiments using *Thurstone's Paired Comparison*, we evaluated variation in VHI strength with different distances between two adjacent wires, and the difference between passive and active touch in VHI.

## 3.2 Basic Characteristics of Mechanoreceptive Unit in Vibrotactile Stimuli

Basic characteristics of mechanoreceptive units are important for designing a tactile display using VHI. Many studies have been conducted to measure detection thresholds presenting vibrotactile stimuli on the skin (Verrillo 1966; Verrillo 1968; Mountcastle, LaMotte and Carli 1972; Gescheider 1976; Bolanowski et al. 1988). Some of these studies investigated the relations between threshold curves and neural mechanisms that determined the shapes of the curves.

All of these studies used normal vibrations to the skin surface as stimuli. Miyaoka obtained human psychophysical thresholds for normal and tangential vibrations on the hand in previous studies (Miyaoka 2004; Miyaoka 2005). Since these results are used in this chapter to obtain the requirements for design, let us review them briefly in this section.

Miyaoka measured the vibrotactile thresholds at the distal pad of the left index finger by transmitting tangential-sinusoidal vibrations onto the skin surface with a small contactor. Seven subjects took part in this experiment.

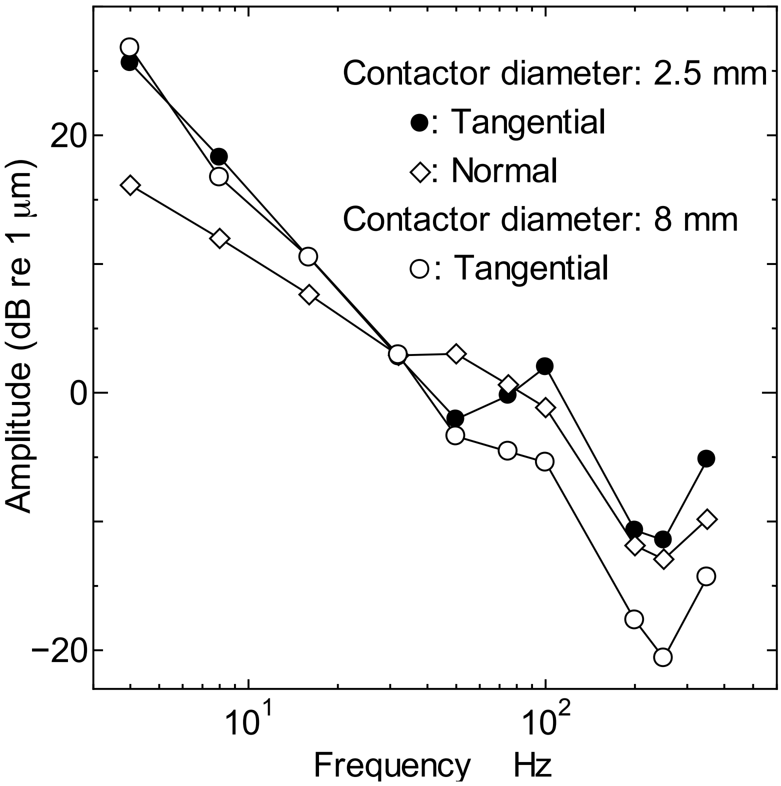

Figure 3-1. Tangential and normal threshold curves (Miyaoka 2004; Miyaoka 2005)

The tangential stimuli were transmitted with a contactor 2.5 mm in diameter. The contactor was attached to a vibrator (AKASHI, MEE-025) that was assembled to produce tangential vibrations.

The subject sat down, and then placed his/her left hand on the contactor. Tangential vibrations were transmitted to the distal pad of the subject's left index finger. The stimuli amplitudes were changed using the Parameter Estimation Sequential Testing (PEST) procedure (Taylor and Creelman 1967). For each subject, four measurements were taken for each stimulus frequency.

Miyaoka calculated the average tangential thresholds obtained for the seven subjects with a 2.5-mm contactor. The average tangential-threshold curve is shown in Figure 3-1. The solid circles in the figure denote the average thresholds. The threshold curve decreased linearly from 4 to 50 Hz, increased gently until 100 Hz, and decreased again above 100 Hz. A U-shaped curve was observed between 100 and 350 Hz. The shape of the tangential-threshold curve indicates that at least two types of mechanoreceptors determine the shape of the curve.

The tangential-threshold curves obtained with an 8-mm contactor are shown in Figure 3-1. Open circles denote the tangential thresholds obtained with an 8-mm contactor. The two threshold curves of solid and open circles overlapped between 4 and 50 Hz and were U-shaped, but they did not overlap between 100 and 350 Hz. Since this spatial summation effect is one of the characteristics of FA II (Verrillo 1966; Verrillo 1968; Mountcastle, LaMotte and Carli 1972; Gescheider 1976; Bolanowski et al. 1988), this result supports the conclusion that FA II is the mechanoreceptor above 100 Hz. While FA II plays a role in sensing of tangential vibration above 100 Hz, the overlapping parts indicate that another mechanoreceptor besides FA II contributes to producing the curve slopes.

Figure 3-1 shows the relationship between the normal- and tangential-threshold curves as well. Open diamonds and solid circles in the figure denote normal and tangential thresholds, respectively. The normal- and tangential-threshold curves were similar when the stimulus frequencies were between 100 and 350 Hz. These curves were U-shaped and we believe that FA II was the participating mechanoreceptor. When the stimulus frequencies were below 100 Hz, the slopes of normal and tangential curves developed differently from each other. The exponents of the power functions fitted to the two curves were –0.74 and -1.22 for the normal and tangential curves, respectively. The tangential slope –1.22 seems to be similar to the slowly adapting type II unit (SA II) slope, while the normal slope –0.74 seems to be similar to the fast adapting type I unit (FA I) slope. These results suggest that SA II is the mechanoreceptor that contributes to producing the shape of the tangential-threshold curves below 100 Hz.

## 3.3 Characteristics of Velvet Hand Illusion

If we utilize VHI for tactile displays, we can manage material-feeling and surface texture in virtual reality. In this chapter, VHI is selected from several tactile illusions to accomplish a new tactile display. About VHI, we know the following:

- A virtual plane is perceptible from wire.
- A smooth and comfortable sensation is perceived as if the opposite hand was not the operator's hand.
- It is not always required that both hands be from the same person; the other hand must be moved synchronously with the other hand.
- VHI is caused regardless of movement such as active touch and passive touch.
- On the basis of observation using fMRI (functional Magnetic Resonance Imaging), it is assumed that a virtual plane between the hands is formed from two edges by a filling-in filter in the brain (Mochiyama et al. 2005).

In order to develop a new actuator array for a tactile display, we intend to examine the relationship between illusion intensity and the configuration of the mesh wire, in addition to the items listed above.

## 3.4 Psychophysical Experiments

### 3.4.1 Experimental Apparatus

To examine VHI, we have produced several kinds of wire mesh equipment with different mesh intervals. One of them is shown in Figure 3-2. The frame is made of acrylic board; two piano wires 0.8 mm in diameter are strung through the frame. Since VHI intensity seems to depend on tension of the wire, the piano wire was strung with sufficient tension using a bolt and a nut.

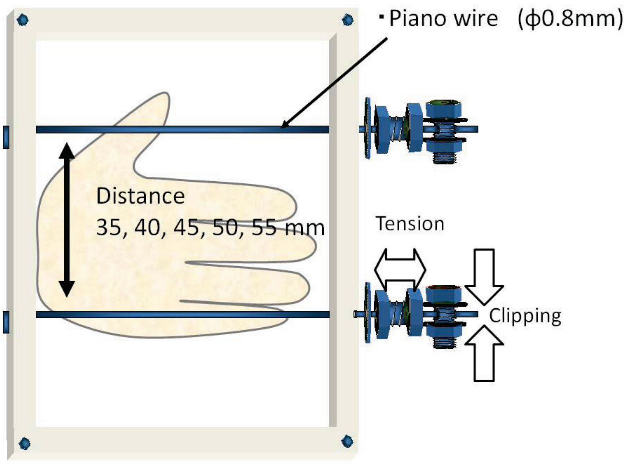


Figure 3-2. Frame equipped with two wires for VHI experiment.

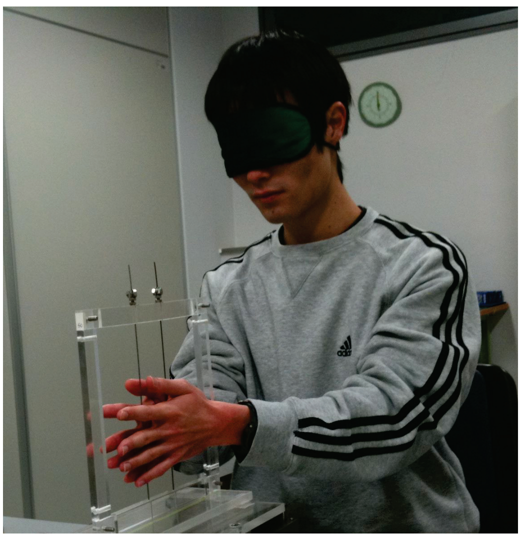

Figure 3-3. Scene of experiment.

In the active touch test, the equipment is fixed on a table and human subjects bring their hands together on opposite sides of the two wires and move their hands. In the passive touch test, the equipment is fixed on a motorized x-table and is moved with reciprocating motion, while the subjects do not move their hands, as shown in Figure 3-3.

### 3.4.2 Experimental Procedure

In this experiment, we aimed to obtain an optimum distance between two wires (wire spacing) for VHI using Thurstone's Paired Comparison (Gescheider 1997). As stimuli, we presented human subjects with five wire spacings: 35, 40, 45, 50 and 55 mm. A separate piece of equipment (set-up) was produced for each spacing. Pairs were produced from the five set-ups. In each trial, subjects touched two different set-ups using the thenar part of the hand, and chose the set-up that generated stronger velvet feeling. To control motion speed, human subjects moved their hands in time with a metronome (1 sound/sec). Since a stroke of hand motion was around 60 mm, the hand-motion speed was almost 120 mm/sec.

The above trial was performed for every pair to determine which set-up generates the strongest velvet feeling. Human subjects were eight persons in their twenties; all experiments were performed at a room temperature of 24 °C; all human subjects wore an eye-mask. Every subject reported that VHI was caused by two hands touching, not by one hand alone.

## 3.5 Experimental Results and Discussion

### 3.5.1 Active Touch Test

First, we examine the result of the active touch test. If the effect of wire spacing on intensity is examined according to the average of all subjects' answers, a flat curve that has slight inclination is obtained as shown in Figure 3-4. Since this result provides no optimum condition for VHI, we investigated the individual responses of each subject and found that they could be divided into two groups, I and II. Figure 3-5 a and b show experimental results for Groups I and II, respectively.

Since Group I shows a U-shaped curve, the subject feels strong VHI in both 35-mm and 55-mm wire spacing as shown in Figure 3-5 a. Although 35-mm wire spacing produces strong VHI in Group I, it is felt to be weak in Group II as shown in Figure 3-5 b. On the other hand, both Groups I and II feel strong VHI in wide wire spacing of 55 mm. This indicates that there are two kinds of feeling in wide wire spacing and narrow wire spacing, and that subjects are divided into two groups according to whether they can distinguish the two feelings or not. This result implies that VHI is generated by at least two sensations. If we can control these two sensations, there is a possibility to produce several variations on VHI such as a smooth and comfortable feeling and a plane feeling.

### 3.5.2 Comparison Between Active and Passive Touch

To compare the active touch condition with passive touch, the equipment is put on a motorized x-table and moved with reciprocating motion to make subjects feel VHI passively. Since the x-table moved with reciprocating motion (1 cyclic motion per second) and the stroke of its motion was 60 mm, the speed was around 120 mm/sec, the same as the motion speed of active touch. Compared to the case of active touch described in Section 3.5.1, VHI strength obtained from the passive touch test depends considerably on wire spacing as shown in Figure 3-6.

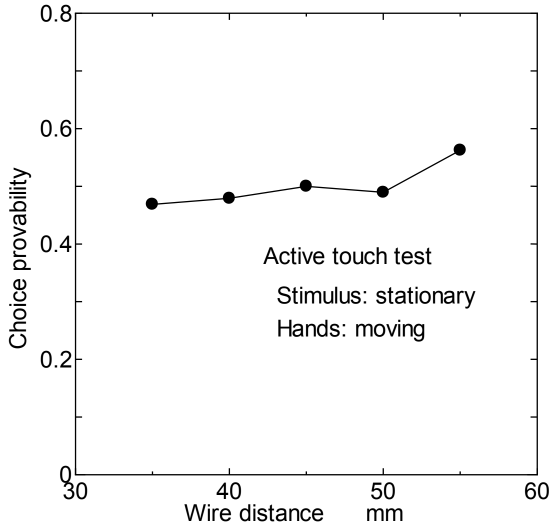


Figure 3-4. Average of VHI strength in active touch test.

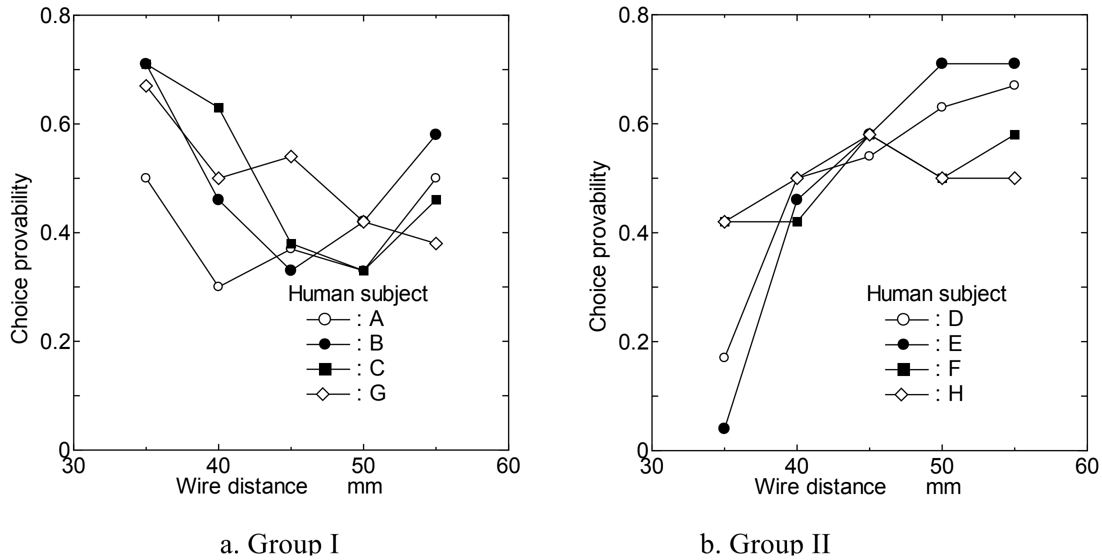


Figure 3-5. VHI strength for Groups I and II in active touch test.

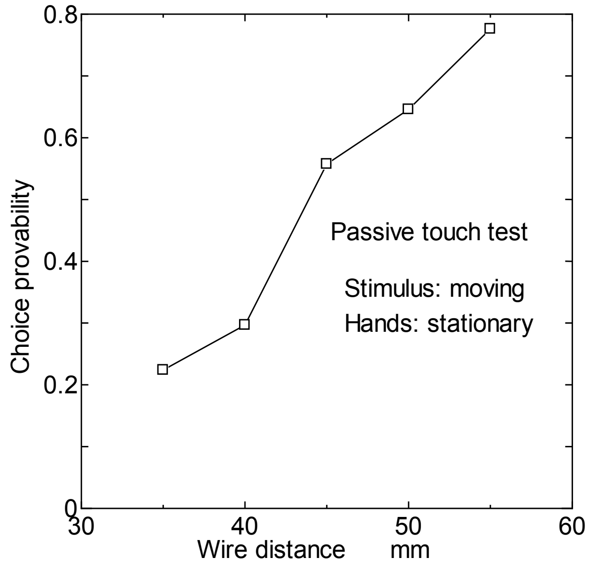


Figure 3-6. Average of VHI strength in passive touch test.

According to Thurstone's Paired Comparison, we obtained the interval scale for both of active and passive touch tests to compare the passive touch result with the active touch result as shown in Figures 3-7 and 3-8. Since the active touch test and the passive touch test were individually performed, the scale value obtained from each test is not compared with the other.

The slope of the regression line, however, indicates the sensitivity of VHI strength to wire spacing. The slope values of active and passive tests are 0.0122 and 0.114, respectively. Therefore, sensitivity of VHI strength on wire spacing difference caused by passive touch is nine times greater than that caused by active touch. In passive touch, VHI appears more easily.

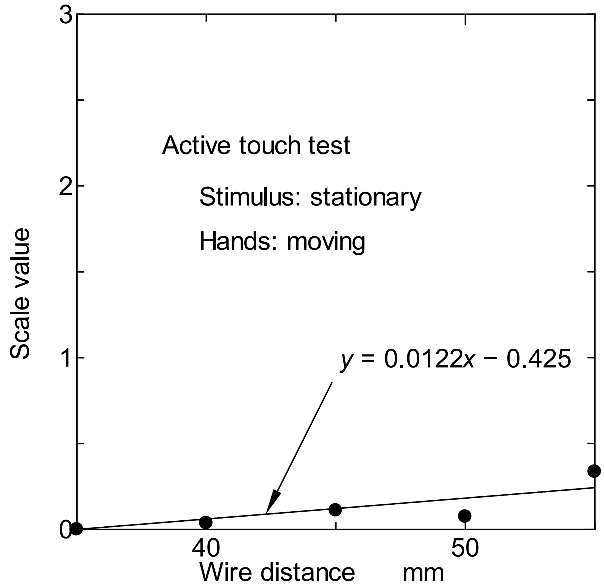


Figure 3-7. Variation in interval scale under active touch.

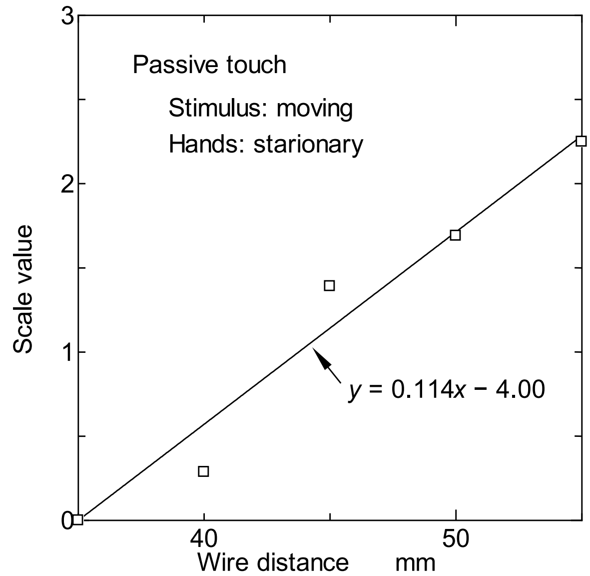


Figure 3-8. Variation in interval scale under passive touch.

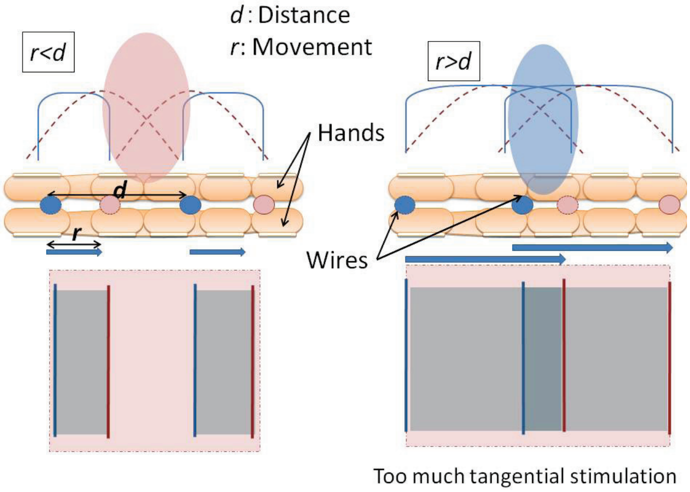


Figure 3-9. Model of VHI mechanism.

### 3.5.3 Mechanism of VHI

We assume that the plane feeling is caused by a constant pressure sensation. This assumption seems reasonable because we feel pressure, for example, if we press a hand against a wall. The smooth and comfortable feeling is assumed to be caused by the combined edge movement of wire and the pressure sensation.

As described in the former chapter, VHI is caused by two hands moving, not by one hand alone. It is not always necessary that the second hand be that of the subject; however, the other hand must be moved synchronously with the subject's hand. This fact means at least contact pressure is required for VHI.

In addition to pressure, moving-edge information is required because a stationary hand does not experience VHI. Although the area bounded by the two wires moves relative to the hands, relative motion between the two hands does not occur. Since tangential force does not occur on either hand, subjects misperceive their tactile sensation as though they were touching smooth virtual film with a zero coefficient of friction.

First, we introduce a model of the VHI mechanism from the result of active touch. In Figure 3-9, the left side shows the ordinal case, in which hand movement is within the distance between two wires. Tangential stimulation is applied to hands within the gray square areas. The central area accepts both normal force and tangential force. In this area, subjects experience VHI.

However, the right side of Figure 3-9 shows the case in which the distance is smaller than hand movement. It corresponds to the narrow distance case. In this case, the tangential stimulating area is overlapping as shown on the right side of Figure 3-9. The subjects belonging to Group I in active touch seem to judge this overlapping area as VHI. The large difference in VHI proportion found between Groups I and II for 35-mm wire spacing seems to be caused by active touch decided by each subject. If the hand movement is controlled, the difference is diminished.

On the other hand, we cannot find any human subject belonging to Group I in the passive touch test. This result shows that VHI sensation is controllable with wire spacing and that VHI sensation is reproduced more easily in tactile displays. The strength of VHI seems to be proportional to the size of the virtual film with a zero coefficient of friction.

### 3.5.4 Specifications of The Proposed Tactile Display

Finally, we discuss the abilities of an actuator for a VHI-based tactile display. First, both tangential and normal stimuli are required as discussed in the previous section. Although an array composed of three-dimensional actuators is not always needed, we require a combination of a two-dimensional actuator generating shearing force, and an actuator array generating pressure distribution.

According to Miyaoka's previous work in Section 3.2, for tangential stimulus, FA II is believed to be the mechanoreceptor above 100 Hz; FA II accepts both tangential and normal stimuli above 100 Hz. If VHI occurs above 100-Hz stimulation, we can generate VHI using an actuator array generating pressure distribution only. However, VHI occurs even with very slow hand motion. At normal speed, hand motion is within a range from 20 mm/sec to 120 mm/sec. Since wire diameter is 0.8 mm, frequency of edge generated by wire motion seems to be within 13 Hz to 75 Hz. For the actuator array, we still expect to generate both tangential and normal stimuli.

As explained in Section 3.3, VHI seems to be caused by tangential stimulation as a trigger under uniform pressure stimulation. Therefore, although an array composed of three-dimensional actuators has maximum dimension in force space, it is not always needed. We require a combination of a two-dimensional actuator generating shearing force, and an actuator array generating pressure distribution. It is noted that tactile displays are effective for generating VHI because VHI is very stable in passive touch.

## 3.6 Conclusion

To determine specifications of an actuator for a tactile display enhanced by VHI, we investigated the relationship between wire distance and intensity of illusionary sensation using psychophysical experiments with Thurstone's Paired Comparison under both active and passive touch conditions.

According to the results, strength of VHI depends on the distance between two adjacent wires. VHI caused by passive touch is considerably stronger than that caused by active touch. This result suggests that VHI is controlled by mechanical external stimulation using tactile displays.

In this chapter, the mechanism of VHI is considered to be as follows: although the area bounded by two wires moves relative to the hands, tangential force does not occur on the hand surface except for the wire-passing portion, causing operators to experience the illusion of touching a smooth virtual film with a zero coefficient of friction. Since VHI becomes weaker for a small distance between two adjacent wires, excessive tangential stimulation prevents the occurrence of VHI.

Therefore, VHI control requires two actuations: one is for tangential actuation generating a moving-edge feeling on the subject's hand surface; the other is for normal actuation generating pressure on the subject's hand surface.

# Chapter 4

# Simulation of Velvet Hand Illusion Using FEM

We reveal the reason behind (VHI) by FEM analysis. We also investigate the possibility of using the results of the analysis to design a haptic display which utilize VHI. We collected the simulated responses of a number of SAI afferents, which are responsible for detecting the edges, to relate them to the mechanism of the illusion.

## 4.1 Introduction

Understanding the reasons behind sensory illusions can provide valuable information about human perception mechanisms. This information can be used in the development of both bio-inspired sensors (e.g., tactile sensors) and human-machine interface devices (e.g., haptic displays) (see Chapter 1).

Because of its excellent dexterity and its ability to detect such different tactile cues as edges, textures and hardness, the human tactile system has tempted researchers to implement some of its characteristics in the design of tactile sensors (Zhang, Mukaibo and Maeno 2007; Herrera 2007). Also interest in virtual environments, specifically in haptic display technologies is increasing because being able to touch, feel and manipulate objects in addition to seeing and hearing them is essential for realizing the full promise of virtual environments (Bresciani, Drewing and Ernst 2008). However, to date, since haptic devices can't generate a copy of "the actual stimulation" to give perception of the real world, the investigation of other approaches remains more appealing.

Considering the characteristics of human tactile perception, haptic displays do not necessarily have to generate a sensory flow that strictly corresponds to the actual stimulation that leads to this percept in the "real" world, but "only" a sensory flow that elicits this percept (Bresciani, Drewing and Ernst 2008). In other words, if a haptic illusion is utilized in the design of a haptic display, it does not need to generate "stimulation A" that actually causes the "complex perception", but only a simpler "stimulation B" that is only necessary to trick or *illude* the person into sensing the same complex perception that "stimulation A" elicits.

Until recently, however, haptic illusions failed to get the attention compared to other sensory illusions: namely visual illusions. Such visual illusions as the well-known barber pole illusion, the Ouchi illusion and the Müller-Lyer illusion have been extensively studied. Recently a set of psychophysical experiments studied the "haptic versions" of these illusions (see Chapter 2)

For instance, in the visual Müller-Lyer illusion, a person perceives that the two lines are different in length while they are actually identical (Section 2.3.1). The tactile Müller-Lyer is caused by relief-like figure. When judging the length of two equal convex lines by touching them, a person typically claims that the line with inward-pointing arrows is longer (Section 2.5.1). Besides the Müller-Lyer illusion in tactile sensation, there are several tactile illusions such as VHI (Mochiyama et al. 2005) and the fishbone and comb illusions (Hayward 2008).

Our interest in the velvet hand illusion is mainly derived from the perception it elicits, touching a given material (velvet), so studying its mechanism and the reason behind it might enable us to utilize it in the design of a haptic display. VHI is caused by such a wire mesh Figure 2-12. A person rubs his/her hands together on both sides of wires strung through a frame, producing the sensation of rubbing a very smooth and soft velvet-like texture.

In this study we predict the responses of a number of SAI afferents (Merkel disks) in a fingertip subjected to VHI using FEM analysis. The

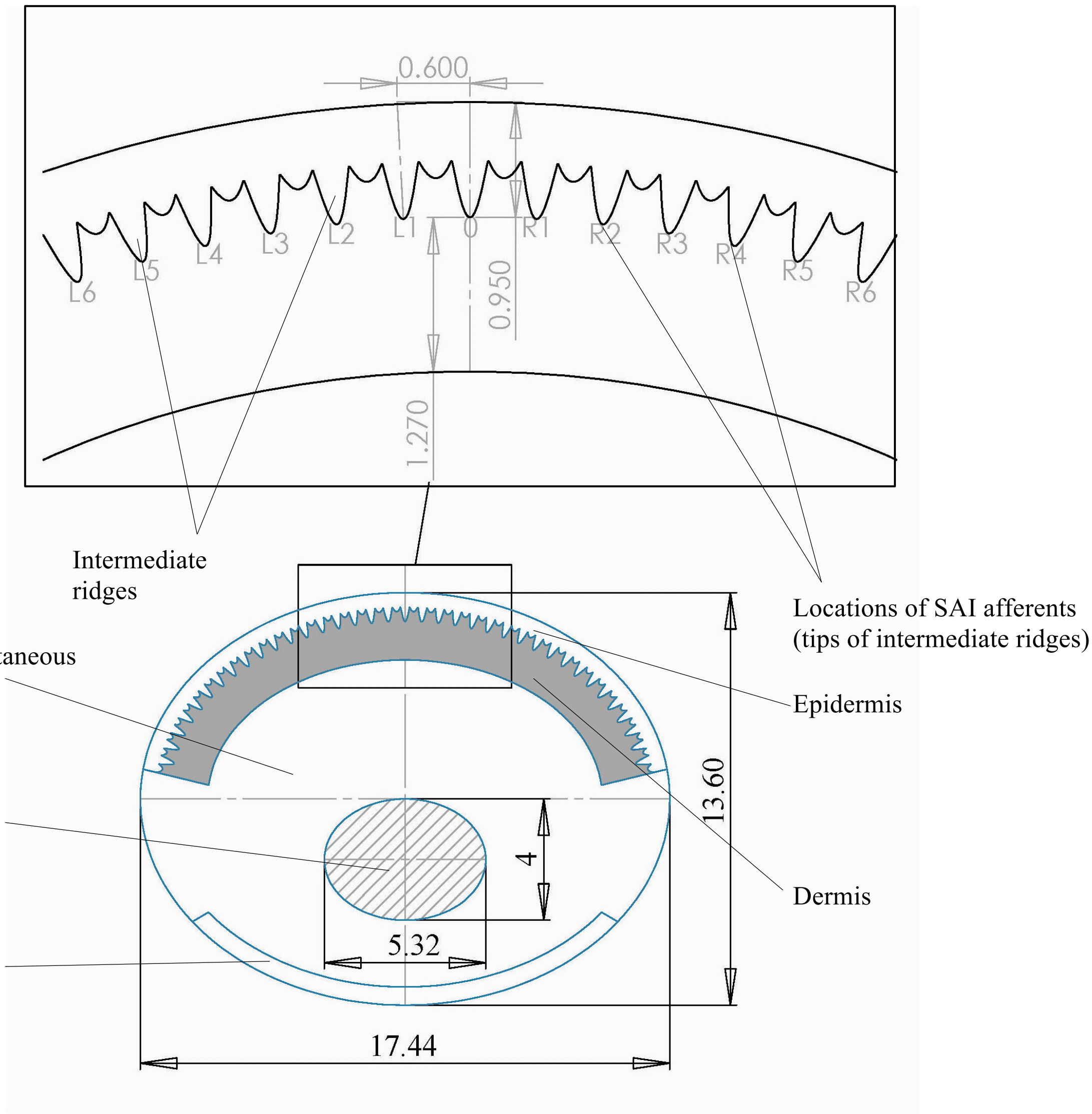


Figure 4-1. Geometry of fingertip model (dimensions are in mm).

modeled response can then be used in the design of a haptic display to generate a stimulation that delivers the same response (i.e., the same perception) to the person touching it.

## 4.2 Modeling Procedure

### 4.2.1 Background

When we contact an object with our skin, it deforms according to the shape of that object and due to the layered structure of our skin, the stress-strain state generated inside the skin is believed to be optimized to deliver mechanical stimulation to the mechanoreceptors, which are strategically located at the boundaries of those layers (Maeno, Kobayashi and Yamazaki 1998).

The mechanoreceptors transform the mechanical stimulation into a series of neural pulses "action potential" that carries the stimulation to the brain. One type of these mechanoreceptors is called "Slowly Adapting type I" (SAI), which is known to encode curvatures and edges (Lesniak and Gerling 2009).

Researchers proposed both continuum models (Srinivasan 1989; Sripati, Bensmaïa and Johnson 2006) and finite element models (Maeno, Kobayashi and Yamazaki 1998; Gerling and Thomas 2005; Gerling and Thomas 2008; Wu et al. 2006) to determine the stress-strain state inside the skin and tried to correlate a mechanical value (either stress or strain based) generated inside the fingertip at the location of the SAI afferents with the action potential generated by them that was measured in monkeys (Phillips and Johnson 1981) or in man (Johansson and Flanagan 2009). In some reports (Dandekar, Raju and Srinivasan 2003; Lesniak and Gerling 2009; Sripati, Bensmaïa and

Johnson 2006) good fitness between the rate of spikes fired by an SAI afferent and the Strain Energy Density (SED) at the location of these afferents was achieved; this result has become the typical value to account for SAI response.

Lesniak and Gerling (Lesniak and Gerling 2009) combined a FEM model of the fingertip and a neuron model to study the response of a single SAI receptor and compared it with the results of psychophysical data obtained by Phillips and Johnson (Phillips and Johnson 1981).

### 4.2.2 The FEM model

Although recently more complex models that account for the nonlinear elasticity and the time-dependent mechanical properties of the skin tissue were proposed (Wu et al. 2006) and used to study the fingertip under vibration or large displacement, linear models are sufficient for simulating the fingertip under contact in low speed (low frequency) and for small displacements around 1 mm (Lesniak and Gerling 2009).

In this study we use a two-dimensional plane strain linear layered FEM model that represents a cross section of an average human index fingertip. Our model resembles the one used in (Gerling and Thomas 2008) and (Lesniak and Gerling 2009) without simulating the collagen fibers.

The fingertip is considered elliptical with a long axis of 17.44 mm and a short axis of 13.6 mm (Lesniak and Gerling 2009). In addition to the bone and nail, it is assumed to consist of three soft tissue layers, starting from the outer one: epidermis, dermis and the subcutaneous tissue.

Figure 4-1 shows the thickness used for every layer in addition to the boundary between the epidermis and dermis layers. The boundary between the two layers has sinusoid shapes called the intermediate ridges.

The elements located at their tips are considered the location where SAI receptors are located and the SEDs of these elements are considered the responses of the afferents discussed above.

We numbered the center one Rec. 0 (for receptor number 0), Rec. Li (for receptor on left side letter i) and Rec. Ri (for receptor on right side letter i), where $i = 1\sim 8$ with numbering starting from the one next to the center receptor going in both directions.

The soft tissues layers are assumed to be linearly elastic with a young modulus of 0.136 MPa for the epidermis, 0.08 MPa for the dermis and 0.034 MPa for the subcutaneous tissue. Poisson's ratio is assumed as 0.48 for all layers (Maeno, Kobayashi and Yamazaki 1998). Both the bone and the nail are assumed to be rigid. The model contains approximately 17,300 elements and 46,800 nodes. The simulation was performed by ANSYS Academic Release 12.0.1.

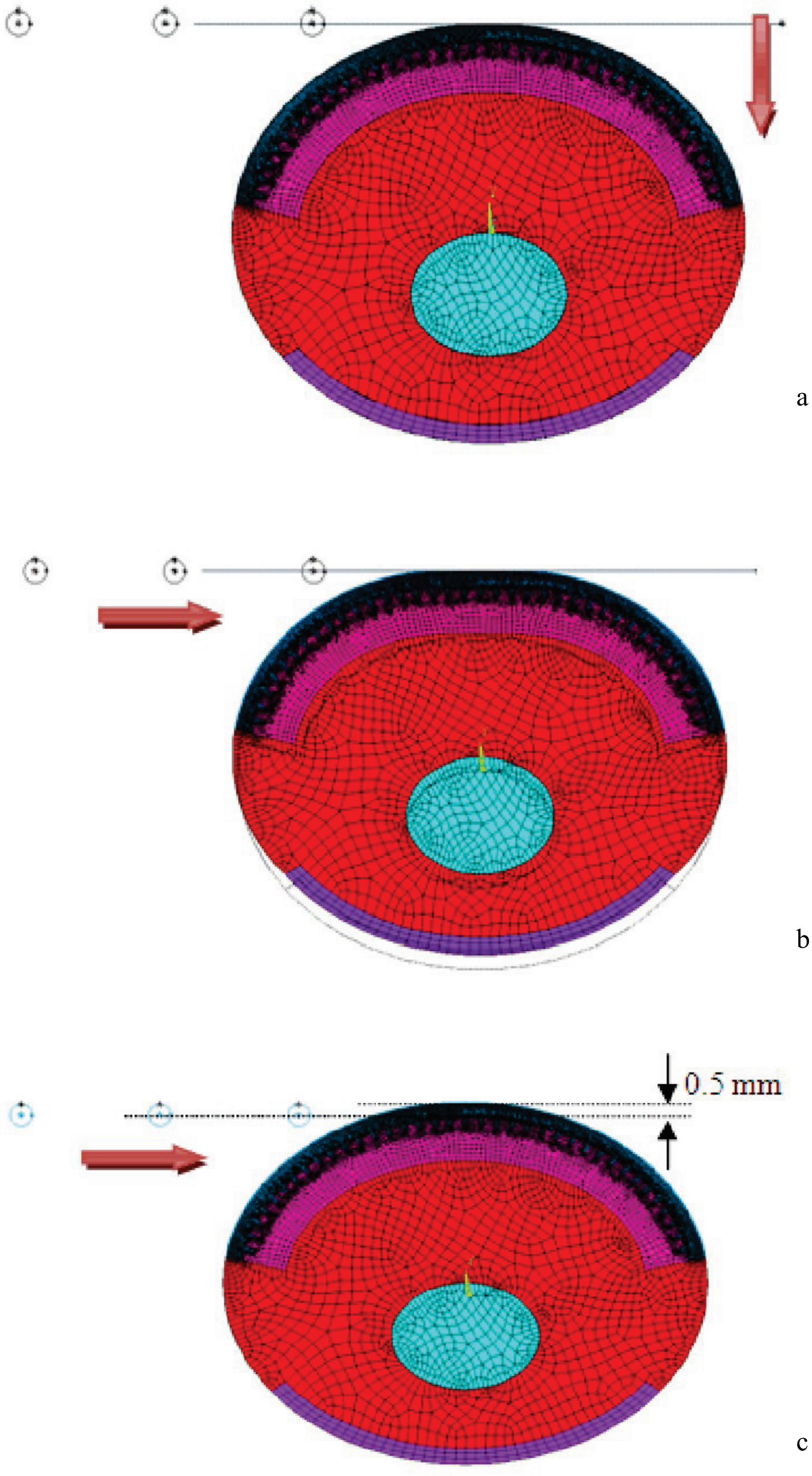


Figure 4-2. FEM model: (a) Start of VHI case, (b) VHI case after compression and (c) start of one finger case

### 4.2.3 Simulating VHI

The following are the minimum conditions for VHI to be felt: (1) the use of both hands, (2) the presence of at least two wires either parallel or perpendicular to the fingers and (3) rubbing the hands against the wires (Mochiyama et al. 2005) (also see Secion 3.3).

Although the reasons behind this illusion remain unclear, we believe that the repeated contact between one finger and the other and then with the wire triggers Fast Adapting Afferents (FAI) and that the shape and the dimensions of the wires (small and edge-like) also stimulate SAI. The combination of these two responses could function as a perception of VHI.

Here we tackle the SAI response alone by simulating a simple version of VHI on just two opposing fingers instead of the whole hand (VHI case) and compare with a finger touching the wires without the existence of a second finger (one-finger case).

#### VHI case simulation

This simulation starts by pressing the finger with a rigid plane with a displacement of 0.5 mm to account for the opposing finger effect (Figure 4-2 a and b) and then the wires ($D = 0.8$ mm and simulated as rigid bodies), which have their centers aligned with the fingertip surface have their centers aligned with the fingertip surface, move horizontally at 21 mm/sec and deform the already pressed finger. The friction between the wires and the fingertip surface is assumed to be 0.3. We use 3 wires with a pitch of 5 mm. The boundary condition constrains the two nodes near the middle of the nail in both the $X$ and $Y$ directions.

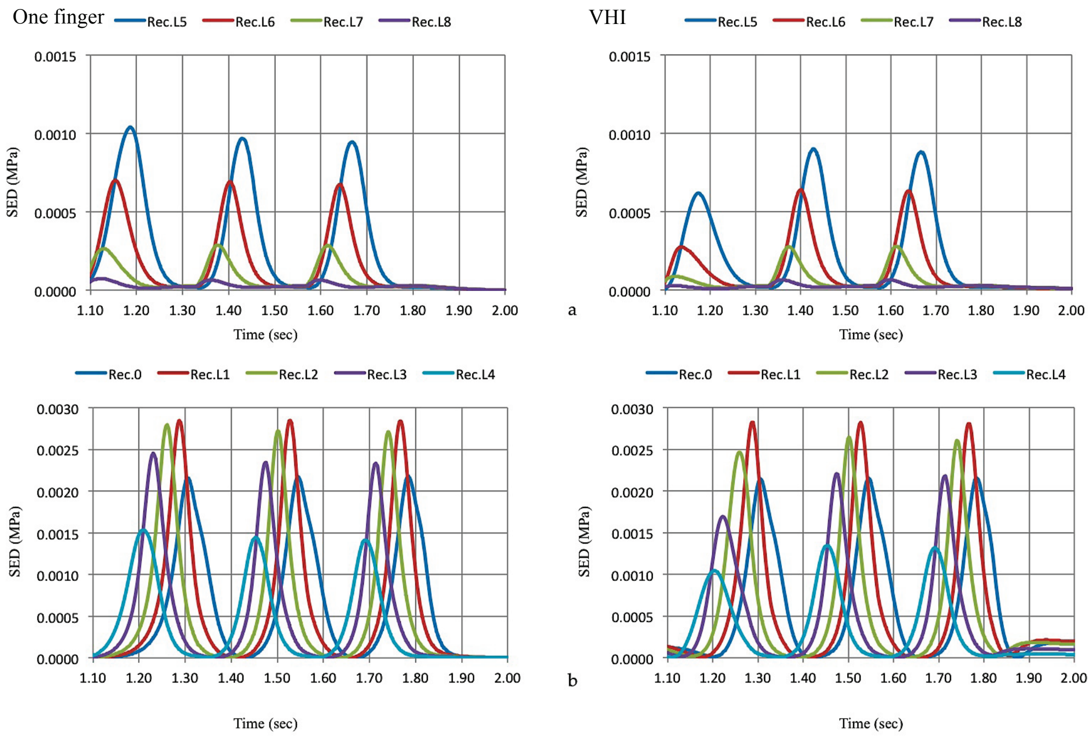


Figure 4-3. SED at location of SAI receptors on left side of fingertip in addition to center receptor (see Figure 4-1) VHI case (right) and one-finger case (left); (a) Recs. L5~L8, (b) Recs. L1~L4 and Rec. 0

### One-finger case simulation

For this case there is no compression because we assume no opposing finger. The three wires have their centers at a distance of 0.5 mm vertically from the top point of the surface of the fingertip (Figure 4-2 c) to insure that the difference between the two cases is only due to the compression by the rigid plane (the opposing finger effect) and not because of a different compression induced by the wires. The other parameters are the same as the VHI case.

## 4.3 Results

As explained above and shown in Figure 4-2 the wires contact the fingertip on the left side, deform it and leave the contact area from the right side, which means that the receptors on the fingertip's left side are stimulated

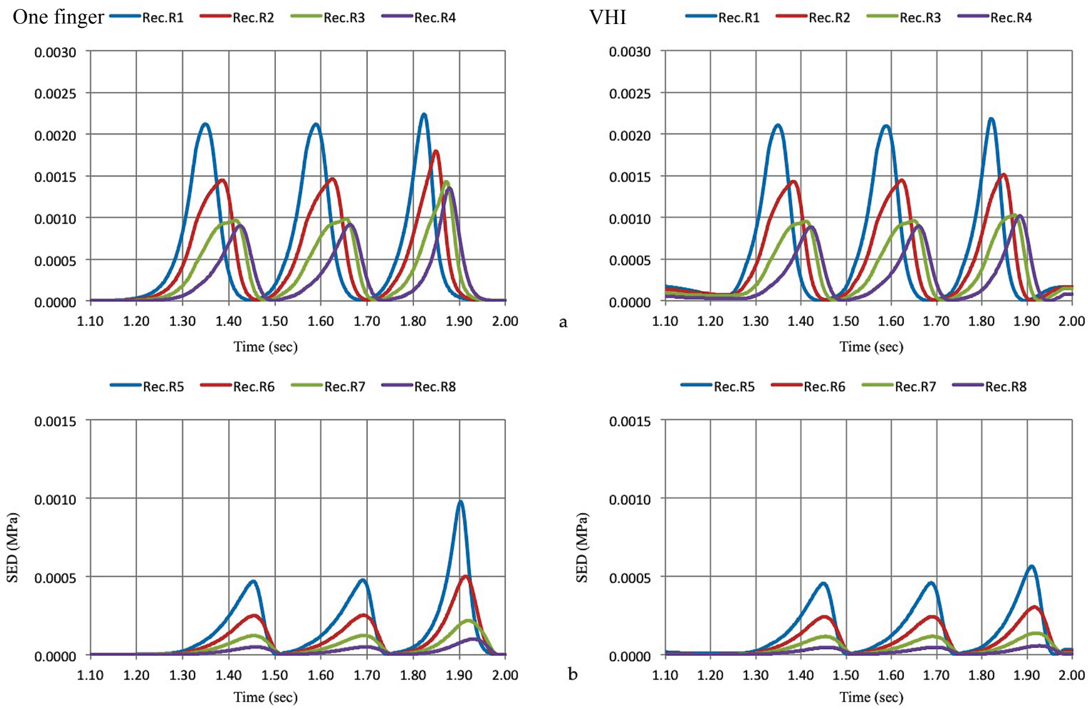


Figure 4-4. SED at the location of SAI receptors on right side of fingertip (Figure 4-1) for VHI case (right) and one-finger case (left); (a) Recs. R1~R4, (b) Recs. R5~R8

first. The SEDs collected from the elements at the locations of the SAI receptors are shown in Figures 4-3 and 4-4. On the right of both Figures the SEDs for the VHI case is shown and the SEDs for the one-finger case is shown on the left.

Figure 4-3 illustrates the SEDs of the receptors on the left side of the fingertip in addition to the center receptor (a-Recs.L5~L8, b-Recs. L1~L4 and Rec. 0) and Figure 4-4 illustrates the SEDs of the receptors on the right side (a-Recs. R1~R4, b-Recs. R5~ R8).

## 4.4 Discussion

The response of the SAI afferents is related to the perception of edges and their depths. If a low edge deforms the skin, the SAI afferent near that edge responds less compared with the response if the edge is higher, which deforms the skin more deeply. As mentioned above we use SED at the location of such afferents to account for this response.

From the results in Figure 4-3 and 4-4 we notice a considerable decrease of the response of the SAI afferents to the contact of the simulated wires for the VHI case compared with the one-finger case, despite the small amount of compression (0.5 mm).

In Figure 4-3 a, for Rec. L7 there is almost no response for the VHI case at the initial contact, but a notable response for the one-finger case. For Recs. L5 and L6 the response from the first wire for the VHI case is almost half of that for the one-finger case.

In Figure. 4-3 b, for Recs. L4 and L3 the response of the first wire is about 30% less for the VHI case than the one-finger case.

In Figure 4-4 a, the responses obtained from Recs. R3 and R4 to the last wire for the VHI case are about 25% less than those for the one-finger case. In Figure 4-4 b, when the last wire passes, the responses obtained from Recs. R5 and R6 for the VHI case are almost half of those for the one-finger case.

We believe that the decrease of the response of the SAI receptors illustrated above plays a role in the perception of VHI mainly due to the decrease of the feeling of the wires touched. The main difference of the response between the two cases is for both the first wire when it starts to touch the fingertip and the last wire when it leaves the fingertip.

In this chapter we only modeled one finger where the actual illusion happens on all the fingers of both hands and the actual illusion happens when rubbing but we only modeled passing wires over the fingertip. The

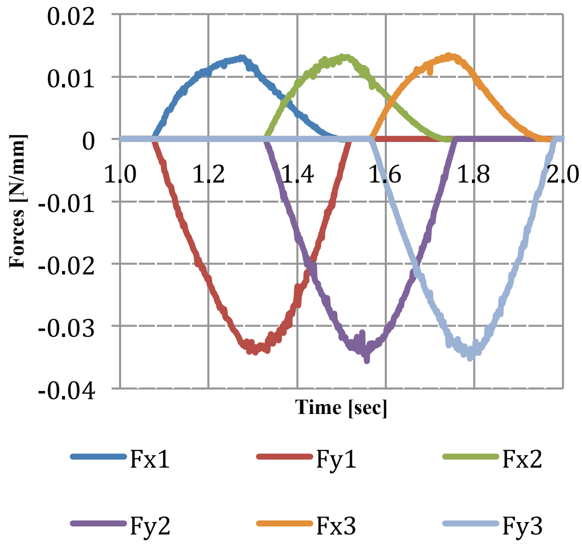


Figure 4-5. Forces applied by the wires on the finger for the VHI case

importance of the first and last wires becomes clear, because in the actual illusion there is always a wire that is starting to touch or going to leave one of the fingers.

The change from the touch to no touch state is also important because we believe that the response of the Fast Adapting (namely FAI) receptors that fire only when the touch state changes could be related to the perception of VHI.

## 4.5 VHI Based Haptic Display

The principle behind the design of a VHI haptic display is the replacement of the forces generated by one hand and the wires on the other hand, so when we touch the proposed display with one hand, the forces induced by the display elicits the perception of VHI and we feel like touching velvet i.e.:

$$\sum F_d = \sum F_h + \sum F_w$$

where; $\sum F_d$ are the forces generated by the display, $\sum F_h$ are the forces generated from the other hand, and $\sum F_w$ are the forces generated from the wires.

Both $\sum F_h$ and $\sum F_w$ in addition to the force distribution can be calculated using FEM analysis. For example using the analysis explained above, the forces applied by the wires on the finger $\sum F_w$ can be calculated for the VHI case and are shown in Figure 4-5. $F_{xi}, F_{yi}$, where *i=1-3*, are the horizontal and vertical components forces applied by wires 1-3 (see Figure 4-2) on the finger.

## 4.6 Conclusion

Even with a simple model we illustrated how the response of SAI afferents could play a role in the perception of VHI. The response of some SAI receptors is reduced by up to 50%, which means that the perception of the wires is reduced compared with the case of simply touching them. We also proposed a method to utilize such simulation to design a VHI based haptic display in the future.

# Chapter 5

# Conclusions

Many types of robots and machines require sensing capabilities that enable them to perform various tasks independently. Vision sensors help robots to recognize objects, shapes and colors while tactile sensors can provide information about roughness, hardness and curvature of touched objects, which makes manipulation and interaction with such objects possible. Several sensors designs have been proposed, but they do not have the excellent features that human sensing own (specially human skin). This makes studying the human tactile sensing an effective methodology in order to develop tactile sensors that have the advantages our tactile system does. It also plays an essential role in designing tactile displays for virtual reality.

In Chapter 1 of this thesis we show a number of examples of how imitating nature's designs, materials and technologies can produce effective solutions in many areas of research and manufacturing, then present a brief overview of human tactile system illustrating the importance of understanding its mechanisms (such as detecting edges and textures) in order to either imitate them to develop new sensors or design new tactile displays based on such mechanisms.

To achieve such understanding, the aforementioned mechanisms have been studied using experiments and modeling. In particular, studying the mechanisms of sensory illusions has been highly beneficial to the research on human perception. In Chapter 2 several optical and tactile illusions are reviewed. Such review establishes that while the mechanisms of many optical illusions have been determined, the reasons behind tactile illusions in general are still unspecified. One special tactile illusion called (VHI) is of a special interest to us because of the unique perception (touching a velvet-like material) it elicits. In addition to providing information about the human tactile perception, studying the mechanism of this particular illusion can be beneficial for the design of a new tactile display, which can provide the same perception. To accomplish this target we used both psychophysical experiments and finite element modeling.

In Chapter 3 we describe a series of experiments (using Thurstone's Paired Comparison), which was performed to determine the parameters affecting the intensity of VHI (mainly the distance between the wires), the difference between active and passive touch, the mechanism by which the illusion occurs, and the characteristics of a potential tactile display that could use this illusion in its design.

To further investigate the illusion, specify the type of mechanoreceptor related to it, and determine the tangential and normal forces that will be used in the proposed tactile display, a finite element modeling of a fingertip under a contact condition similar to that of the illusion was conducted.

Chapter 4 presents a description of the FE modeling procedure in which the response of SAI receptors was predicted for a simplified case of the illusion then compared with the case of a fingertip contacting wires.

The final conclusions of this thesis are as follows:

- Because the experimental conditions for active touch can't be controlled (subjects rub the wires at different speeds), it is better to utilize passive touch for further experiments.
- Within the range of wire distances used in the experiments (Chapter 3), the intensity of VHI increases with the increase of wire distance for the passive touch illusion.
- The predicted SAI response (Chapter 4) for a fingertip under VHI contact condition is considerably lower than that of a fingertip simply touching wires. This suggests that SAI play a role in the perception of VHI because the reduced response means *less feeling of the wires*, which corresponds to the illusory feeling.
- While we can not decide if the reason of illusory perception is peripheral or central because the coding mechanism of tactile information is so complex and not determined yet, the decrease of the response of SAI afferents suggests that the illusions could be of a peripheral origin.
- The vertical and horizontal components of the contact forces obtained from the FE modeling could be used for the proposed tactile display.

This work can act as a basis for future research in several directions, which include the following:

- Performing detailed psychophysical experiments on VHI to study the effects of different parameters such as speed of rubbing, and diameter of the wires could help to better understand its reason.

- To correlate with the results obtained experimentally, a more realistic model that tackles the whole hand could be built.
- Based on the results obtained in this work a tactile display could be designed to deliver normal and tangential forces which tricks the person touching it into believing that he/she is touching a velvet-like material.
- The FE modeling of the fingertip could aid in the ongoing development of three-axis tactile sensor described in a paper by Yussof et al. (2007).

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