# The Importance of the Sense of Touch in Virtual and Real Environments

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**What would be worse, losing your sight or your sense of touch? Although touch (more generally, somesthesis) is commonly underrated, major somesthetic loss can't be adequately compensated for by sight. It results in catastrophic impairments of hand dexterity, haptic capabilities, walking, perception of limb position, and so on. Providing users with inadequate somesthetic feedback in virtual environments might impair their performance, just as major somesthetic loss does.**

Enabling bidirectional, programmable[1] touch interaction with virtual environments (VEs) is not trivial. Currently, this involves solving challenging problems in mechanical design, actuators, real-time systems, rendering algorithms, user–object interaction modeling, human capabilities, and other areas.[1] The engineering requirements of a touch-enabled application are, in general, demanding. Common requirements include sensing the state of a haptic interface[1] (typically 3 to 6 degrees of freedom), computing haptic collision detection, updating the state of the virtual object(s), and computing and displaying the necessary forces and/or torques to a user.

These tasks are typically performed at rates of 1 kHz or higher. At lower rates, the quality of the haptic simulation can decrease significantly. It's also necessary to ensure that touch capabilities are integrated with other display technologies in a reliable and meaningful manner for the application at hand. For example, in a surgical application offering visual and touch information, it's undesirable to have large, noticeable visual and force-feedback mismatches either in time or space. In addition to the stringent engineering requirements, researchers haven't exhaustively studied the capabilities of the human sense of touch as those of human vision and hearing.

Why ever use touch in human–computer interaction (HCI) and VEs? After all, visual feedback is adequate in a variety of situations, such as the graphical user interfaces used in personal computers. Such interfaces, in general, don't have the strict real-time requirements that touch-enabled systems commonly need. Nor do they require costly haptic hardware (common force-feedback interfaces cost several thousand dollars) to perform reasonably well. In addition, there is a common belief that visually displayed information often dominates touch information when they're simultaneously presented.[2] At first glance, these observations would seem to undermine the case for sophisticated touch-enabled interaction with VEs.

However, I believe that the importance of developing and using sophisticated, touch-enabled interfaces is considerable. In this article, I discuss basic reasons why touch-enabled interaction with real environments is essential. This includes skilled performance in situations requiring precise motor control by users (for example, using a tool during surgery), but also performance in everyday tasks, some of which we might not readily associate with touch. Later, I'll discuss some important implications of this for VEs and HCI.

This article does not pretend to be an exhaustive review of all relevant issues, which span extensive literature in fields such as engineering and neuroscience. It also doesn't aim to provide guidelines for interface design. Instead, it concentrates on discussing critical capabilities of touch by highlighting the catastrophic consequences of losing them.

For the sake of simplicity, I will use the terms *touch* and *somesthesis*[3] interchangeably.

## Effects of major loss of touch

What would be worse, losing your sight or losing your sense of touch? Most people will immediately assert that vision is more important and valuable than touch. It's possible to have at least a remote, approximate idea of the short-term effects of significant loss of vision or hearing by closing our eyes or by wearing ear plugs. What about a significant loss of the sense of touch? What would that be like?[3,4] This isn't a question we normally think about, and its answer might not come readily to us. This is due in part to the subtle, effortless performance of

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the normal sense of touch. In comparison, key functions of vision and hearing are much more readily apparent to us.

So what does touch do? To answer this question, I would like to discuss first what happens when most of the sense of touch is lost. There are two well-documented cases of patients, Ms. G.L. and Mr. Ian Waterman, who suffered such a loss on a permanent basis.[4-6] This loss was from damage in most of the nerves that carry sensory information to the central nervous system. Mr. Waterman lost most of his sensation from the collarline down, while Ms. G.L. lost hers from the level of her mouth downward, including her tongue.

Both patients retained temperature and pain sensation. Mr. Waterman temporarily lost sensation in his mouth, but Ms. G.L. did so permanently. This loss led to chewing difficulties and to impaired speech. Ms. G.L. had to relearn articulating her speech by using the sound of her voice as the source of sensory feedback.

Remarkably, these major sensory losses didn't extend to the patients' motor systems. Neither patient suffered damage to the nerves that communicate their central nervous systems to their muscles. As a result, the patients can exert voluntary muscle control. Contrast this to the total paralysis and loss of sensory information that affects quadriplegic patients after major damage to the spinal cord.

The impact of sensory loss on Mr. Waterman's life is the subject of a book by Jonathan Cole.[4] This book gives a glimpse not only about Mr. Waterman's illness, but also about his tremendous courage and determination in dealing with his devastating loss. Much of what follows in this article about Mr. Waterman's illness will be based on this book, unless otherwise noted. Note that Ms. G.L. suffers from similar, debilitating handicaps.

Mr. Waterman was a skilled, 19-year-old butcher when illness struck him. He could never again practice his craft. It isn't known what caused his illness. It's believed that, during recovery from a viral infection, an autoimmune reaction by his body destroyed most of his sensory nerves. This resulted in the loss of most of his sense of touch within a few days. Immediately after the loss, Mr. Waterman couldn't walk or stand upright. He could move his limbs, but couldn't control them in a precise way. When he wasn't looking at his limbs, he couldn't tell their position or whether they were moving. When not looking at them, his fingers and, particularly, his arms would move uncontrollably. Sometimes his arms would unwittingly hit him. When lying in bed, he could not feel his body or the bed itself. The resulting floating sensation was terrifying.

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After the onset of his illness, it took him two months to relearn how to sit up, but relearning to stand up took about one and a half years longer.[5] Several months later, he learned to walk again, albeit with a slow step, which is the case to this day. This functional recovery wasn't based on neurological recovery—that is, Mr. Waterman's sensory nerves and touch capabilities didn't improve. For example, he never recovered the ability to perceive the position or movement of his limbs without using his sight.

Most, if not all, of Mr. Waterman's relearned capabilities were based on conscious, painstaking control of his limbs and body, guided through his sight. It's possible, however, that his extensive pre-illness experience with body control (for example, when walking or using tools) helped him relearn some capabilities.

These days, to perform an action, Mr. Waterman must visually track the state of his body and environment, and exert an extensive, conscious effort to apply appropriate muscle force during the right duration to accomplish the task at hand. Decades after losing his sense of touch, Mr. Waterman must apply this visually guided, conscious effort to perform most purposeful actions. This goes on every moment of every day. Mr. Waterman compares this effort to running a daily marathon.

Early on with his illness, when visual information was unexpectedly interrupted (as when lights go off) and he was standing up, Mr. Waterman immediately fell to the floor. This was because of his inability to supervise his body without sight. Years later, Mr. Waterman could avoid falling in such situations only by exerting an incredible, conscious effort to tense many of his muscles. Maintaining this effort during a few minutes resulted in a complete mental and physical exhaustion that required several days of rest for recovery.

Also, during physical therapy for his illness, Mr. Waterman tried learning to swim, but decided to give up. He couldn't see or feel his body, and hurt his feet by hitting the bottom of the pool with excessive force. The loss of position sense in his limbs had other consequences. Sometimes, when waking up in the morning, Mr. Waterman would feel momentarily terrified when finding a hand on his face, not realizing for a while that the hand was his own.

Mr. Waterman also learned to use sight to control his arms and hands. For example, he learned to control the spontaneous arm movements that he experienced early on. However, even with full visual feedback, Mr. Waterman is unable to use his hands normally. He tends to use slow, ponderous movements involving only three fingers. He also tends to use excessive force to hold objects, particularly when not visually attending to them. For the same reason, even with full vision, Mr. Waterman prefers to deal with rigid objects instead of deformable ones such as plastic cups. Mr. Waterman avoids taking a cup from someone else, and has to wait until a hot drink cools down before sipping it in case it spills.

Mr. Waterman was determined to lead a life as full as possible. With immense drive and determination, he relearned the ability to write, obtained qualifications for office work after attending a special school for a year, and got himself a job. Throughout his career, he was promoted and led an independent life, but had to adjust his work and leisure activities to deal with the extreme demands his illness imposed. For example, tasks involving simultaneous cognitive load and fine motor-control activity (such as handwriting) nearly exceeded the limits of his ability. In such cases, as when taking the minutes of a meeting, he was forced to constantly switch his attention from consciously controlling his handwriting to listening to people.

Mr. Waterman's illness clearly changed his life in major ways. However, Mr. Waterman finds it difficult to explain his illness and its consequences to other people, including some of his physicians.

Temporary loss of hand dexterity similar to Mr. Waterman's has been demonstrated in normal persons when their fingers are anesthetized.[7-11] In such conditions, persons apply excessive force and frequently drop objects they manipulate. They also experience difficulties adapting to the loads involved and precisely positioning their fingers.

We can also informally demonstrate that, immediately after local anesthesia to the hand, it's extremely difficult to grasp and manipulate small objects or perform skilled actions such as buttoning a shirt or lighting a match.[12] This happens even with full visual feedback during the tasks. It's interesting to note that, when part of a limb is mechanically compressed (as when sleeping on an arm), sensory and motor nerves are also compressed. The flow of neural information might be greatly disrupted, and numbness and impaired dexterity follow (see Table 1 for more examples). Experiencing such a condition gives a remote glimpse of Mr. Waterman's illness,

***Table 1. Understanding some effects of loss of touch/somesthesis through common, everyday situations.***

| Area of Major Somesthetic Loss | Approximate Equivalent and Some Consequences |
|---|---|
| Hand/arm | Sleeping on an arm. Difficulty controlling/moving the hand/arm and manipulating objects. Numbness. |
| Leg | A leg that "falls asleep." Difficulty walking and maintaining a stable posture. Tendency to fall. |
| Mouth/tongue | Local dental anesthesia. Difficulty speaking and chewing. Involuntary drooling. Numbness or "fat lip" sensation. |

Note: The approximate equivalents of somesthetic loss mentioned here are experienced even with full visual feedback. Also, an "asleep" arm or leg might involve disruption of sensory and motor nerve information due to applied pressure. Somesthetic losses in the patients discussed in the text involved only disruption of sensory nerve function.

## Relevant Terminology

As mentioned in the introduction, *touch* and *somesthesis* are used interchangeably throughout this article. Strictly speaking, these terms refer to different phenomena that share a number of common characteristics. *Somesthesis*[1] includes not only cutaneous (skin) sensations (what we usually think of as touch) but also the capability to sense the movement and position of our limbs (called *kinesthesis* or *proprioception*; *kinesthesia* or *kinaesthesia* is frequently used instead of kinesthesis). Kinesthesis relies on specialized sensory receptors located in muscles, tendons, and joints, but also on skin receptors in the hands.

Although the term *kinesthesis* (derived from a Greek word for *movement*) might seem to imply that sensing limb position relates to sensing limb movement, this is not so in general. Some joints have movement-sensing capabilities but not static-position-sensing ones.[2]

What is the relationship between the terms *haptic*, *touch*, and *somesthetic*? In experimental psychology and physiology, the word *haptic* refers to the ability to experience the environment through active exploration, typically with our hands, as when palpating an object to gauge its shape and material properties. This is commonly called *active* or *haptic touch*,[3] in which cutaneous and kinesthetic capabilities have important roles.

However, the words haptic and haptics are increasingly used to refer to all somesthetic capabilities. This is particularly so within the community that performs research on haptic interfaces,[4,5] haptic rendering algorithms,[6] and applications[4,6] involving somesthetic information. Typically, a haptic interface stimulates cutaneous and kinesthetic sensory channels through force-feedback that varies depending on a user's limb movements. Note that touch interaction with everyday, real objects also involves force-feedback: objects return forces that follow the physics of the interaction. Such forces typically depend also on a person's limb movements.

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which is, however, purely sensory. His motor nerve function appears not to be affected, unlike what happens during limb compression.

We have a glimpse now of what loss of touch does to normal human performance. A brief digression on relevant terminology is pertinent here (see the sidebar, "Relevant Terminology").

We can see that Mr. Waterman lost all kinesthetic capabilities and most cutaneous sensations (with the exception of pain and temperature) from his collarline down. He retained the sensation of muscle effort, cramping, tiredness, and tension.[4] Mr. Waterman isn't able to profit from active touch: he can't gauge the properties of objects (such as shape or texture) by haptically exploring them. To a large extent, Mr. Waterman can't use force-feedback information about the environment to control his body or perceive the world. Note, the perceptual role of force-feedback is in itself a relatively new area of research.[13]

Summarizing, the major loss of somesthetic capabilities results in the following issues:

- Loss of the capability to sense limb movement and position.

- Major impairment in skilled performance, even with full vision and hearing. This is worsened as visual information degrades.

- Abnormal movements and the inability to walk following the loss of somesthesis. Patients must exert immense effort to relearn how to walk (Ms. G.L. did not attempt to regain this ability[5]).

- Major loss of precision and speed of movement, particularly in the hands.

- Major difficulty performing tasks that combine significant cognitive loads and fine motor skills such as writing minutes during meetings.

- Major difficulty learning new motor tasks, relearning lost ones, or using previous experience to guide these processes.

- Loss of the unconscious ability to communicate through body language.[5] Relearning a limited repertoire of gestures is possible.

It's difficult to imagine experiencing the effects of even partial impairment of somesthesis. As we have seen, Mr. Waterman had difficulty explaining his illness to other people. Perhaps this was because even normal, skilled people tend to be unaware of how touch contributes to their abilities.[14]

Much remains unknown about somesthetic function. The overall effects of major somesthetic loss could probably surpass those of blindness or deafness.

### Loss of touch vs. inadequate touch information in VEs and HCI

What can we learn from patients such as Ms. G.L. and Mr. Waterman? Clearly, a key lesson is that somesthetic information is critically important for fast, accurate interaction with our environment. We perform normal somesthetic functions effortlessly, without our conscious awareness of much of what they do. Without adequate somesthetic feedback, achieving normal and top performance in tasks that require high levels of dexterity is extremely difficult, if not impossible. By *high levels of dexterity* I don't necessarily mean virtuoso piano playing or world-class heart surgery. By comparing Mr. Waterman's condition to normal performance in everyday tasks, we notice how the normal grasping and handling of common objects seems deceptively simple at first glance, but actually requires exquisite dexterity that relies on adequate somesthetic information.

In today's virtual environments and HCI, much emphasis is given to visual and, to a lesser degree, auditory displays. Very little somesthetic feedback is provided. As we have seen, Mr. Waterman's skilled performance is severely limited even when using full vision and hearing.

We can speculate that using an interface that provides poor somesthetic feedback is analogous to experiencing a version of Mr. Waterman's illness, with at least some of the consequences. Mr. Waterman's handicaps suggest that in some important cases (for example, when training in a surgical simulator or when actually performing robotic surgery[15]), it could be impossible for users to achieve the highest performance if the interface doesn't provide adequate somesthetic information about the users' interaction with the real or virtual environment. This situation would be more serious if visual or other sensory information is also impoverished or absent.

There are clear limitations to the analogy between Mr. Waterman's illness and the use of interfaces that provide poor somesthetic feedback. After all, when using such interfaces, users have full sensory information about their body. However, when using an interface to interact with a real or virtual environment, users must control their body and also figure out how their actions change the state of the environment they access through the interface. Users must also figure out how changes in the environment will affect their actions in the future.

This is analogous to controlling your body. We could think of this as the problem of controlling a user's extended body, which would include the interface and related software and hardware entities, such as a remote surgical robot or avatar. If the interface doesn't provide meaningful somesthetic information about the environment's state, users are deprived of potentially critical information to learn and perform many tasks with speed and accuracy through their extended body. This would seem to be particularly so if users employ the interface to deal with a large number of degrees of freedom, as when working with tools or multiple objects with complex behaviors, such as simulated or real organs during virtual or actual robotic surgery. In a similar scenario, surgical abilities acquired through training with cadavers or actual operations might not easily transfer to procedures performed through somesthetically poor robotic surgery systems.

From all of the information I've presented, it's possible to get the impression that effective, touch-enabled interaction with real or virtual environments requires a potentially large number of degrees of freedom in the somesthetic information provided to users. This is not necessarily so. For example, major gains in body posture control in real environments can be obtained from minimal touch information applied to a fingertip.[16] It's likely that such simple touch information would be equally effective for postural control in a fully immersive VE, for example. In this regard, the major research question is to identify which sources of somesthetic information are important for tasks of interest, and which degree of fidelity (including the number of degrees of freedom) is needed when providing this information to users through interfaces.

As we've seen, appreciating the capabilities of the sense of touch/somesthesis is surprisingly difficult. Perhaps as a result of this, and as previously mentioned, a common belief is that touch is frequently dominated by vision in multimodal conditions.[2] An alternative view[17,18] is that touch or visual information can be more or less useful to users, depending on the relative appropriateness of each modality for the task at hand. Cognitive factors (including attention) and the user's age can also have a role.[17] But, as I've discussed here, the evidence indicates that vision can't fully compensate for the major loss of somesthesis because of disease or injury. The extent to which vision can compensate for missing or poor somesthetic information during interface use is an open problem.

## Final remarks

Much work remains to be done on somesthesis, and on its application to HCI and VEs. It's possible that new and surprising somesthetic or closely related capabilities remain undiscovered. For example, recent research[19] involving Ms. G.L. and Mr. Waterman found that their illnesses affected how they judged other people's actions. When observing normal people lifting small boxes, Ms. G.L. and Mr. Waterman couldn't tell whether people expected a heavy or light box before starting to lift it. Normal people didn't show this deficit. Such findings could be relevant to touch-enabled, collaborative VEs in which a user needs to gauge other users' actions. Somesthetic capabilities have been less investigated than, for example, visual ones. However, I believe that there's plenty of available basic research that hasn't been applied to interface design, and its potential remains to be explored.

I must point out that a major loss of somesthesis is a rare condition. Would all people affected by it show the same handicaps that Mr. Waterman and Ms. G.L. experience? It seems likely, given the massive feedback loss and the results of research involving performance of normal people under local anesthesia.[7-11]

What is clear is that somesthesis is critical for normal human functioning at many different levels, from controlling the body to perceiving the environment, as well as learning about and interacting with it. This strongly argues for the importance of providing adequate somesthetic information when using interfaces to interact with real or virtual environments. This also highlights the relevance of current and future research on haptic technology and of its cross-fertilization with somesthesis research. These exciting fields promise to contribute much to our knowledge of human capabilities and to new applications that exploit and support the rich, subtle functions of the sense of touch. **MM**

## Addendum

Warning: Do not try to induce any of the conditions described in this article. Applying pressure to nerves can damage them. Do not experiment on yourself or on anybody else.

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