Abstract

Development of Variable Attention Capture (VAC) Haptic Feedback Systems for Conveying Information at an Appropriate Level of Salience

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As the proliferation of visual and auditory communication media push human information processing to its limits, many researchers turn to the haptic modality – the sense of touch – as a means of conveying information. Presently, most haptic feedback systems are focal feedback mechanisms designed to deliver alerting cues. However, not all tasks are urgent and require a person's immediate and focal attention, so these attention-capture methods may distract a user from more critical tasks. Recently, researchers have begun to investigate ambient feedback systems that convey peripheral information without distracting a user from a more important task. So far no efforts have been made to combine these two separate categories to create a unified system for haptic attention capture. We thus propose the development of variable attention capture (VAC) feedback methods as a new design paradigm for fluidly modulating a user's attention capture along a spectrum depending on task priority. This proposed VAC feedback paradigm will allow for the development of versatile next-generation haptic devices capable of generating both focal and ambient stimuli depending on the task at hand.

This dissertation represents a first step in creating VAC haptic feedback systems that can convey information to a user at an appropriate level of attentional salience. We demonstrate that a VAC haptic device is able to produce relevant stimuli without unnecessarily competing for a user's limited attentional resources. As with all VAC devices, this allows the haptic device to provide important information to a user in a timely, accurate, and unobtrusive manner.

We begin the exploration of VAC haptic feedback through the specific application of seated posture guidance. This task is a good candidate for VAC haptics as it is typically lower priority and requires minimal cognitive bandwidth. A real-time posture sensing and feedback chair, Posture Seat, was prototyped for this purpose. We created VAC versions of the chair with either vibration or pressure actuators, and a non-VAC version with vibration actuators, to produce the necessary stimuli for haptic feedback. In our initial experiments with the non-VAC Posture Seat, we measured

users' ability to comply with postural guidance and their level of mental load while responding to the feedback. We tested various haptic actuator parameters for their influence on affect and attention capture, and integrated these parameters into the design of the vibrotactile and pressure-based VAC Posture Seat versions. Finally, we used the VAC Posture Seat for an in-the-wild study to investigate user compliance, level of mental load, attention capture, and task interference from haptic feedback. We thus were able to assess the impact of our VAC haptic system by comparing the VAC and non-VAC experiments.

Our results represent important findings in the development of VAC haptic systems. We demonstrated that VAC haptic actuators reduced the amount of disruption experienced by subjects compared to those tested on the non-VAC system. We found that actuation rate was the most significant parameter for achieving VAC – i.e., higher actuation rates produced more focal haptic stimuli, while lower actuation rates produced more ambient haptic stimuli. Thus, an increase in the bandwidth of actuator rate resulted in a wider range of attention capture. Actuation intensity was also an important parameter for VAC: increasing the resolution of intensities from sub-threshold to suprathreshold of detectability leads to better VAC. Finally, we found that pressure feedback was more conducive to VAC than vibrotactile feedback, potentially due to the prioritization of the activation of different cutaneous mechanoreceptors. Interestingly many parameters had no significant contribution to VAC due to widely variable user preferences, and thus could be user-defined without loss of VAC capability.

We have successfully designed, characterized, and tested a posture sensing and feedback system employing VAC haptic feedback, including in-the-wild studies for real-time posture correction. We demonstrate that VAC haptic feedback is both feasible and beneficial for modulating information priority and improving task performance in our Posture Seat system, and determined the main parameters for achieving VAC in our system. By quantifying the degree of attention capture in our system and characterizing the necessary parameters for doing so, we lay the foundation for a general approach in developing VAC-capable haptic systems. Our findings form the basis for further developments in VAC haptics that will produce a richness in haptic communication through utilizing the full range of haptic vocabulary, tone, and context.

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Chapter 1

Introduction

The Information Age has created both significant opportunities and daunting challenges for user interface designers. Consumers are surrounded by products and circumstances that demand their attention while they simultaneously perform tasks of varying priority and complexity. From computer pop-up windows to blinking highway signs, from ringing phones to audible guidance of GPS navigation systems, each device attempts to create salient, appropriate communication that reaches the end user in a timely manner. The brain constantly processes sensory stimuli from the environment and directs an appropriate level of attention to the most important task. Unfortunately, the proliferation of these visual and auditory communication media have pushed humans' information processing capabilities to their limits. The past few decades have seen an increase in research exploring the information communication capabilities of the skin as researchers turned to haptics to relieve overloaded visual and auditory perceptual channels.

1.1 Haptic Feedback

The word "haptics" derives from the Greek word *haptikos* meaning "able to touch" [116]. In the most general sense, haptics research deals with touch and kinesthetic senses, which encompass pressure, vibration, temperature, pain, and body forces and orientations[1] [154]. Since ancient times, humans have relied on their sense of touch to explore their immediate surroundings. Squeezing fruit to feel freshness and ripeness, struggling with the slipperiness of fish, stepping on a sharp rock,

[1] Although in some literature, the term "haptics" has been synonymous with "hand," we want to make the clarification that our use of the term "haptics" encompasses both hand and whole body sensing.

sensing the ground shake during an earthquake, basking in the warmth of the sun, etc. are all ways in which humans use their haptic sense to gain insight about their physical world.

Although the field of haptics has existed for at least 150 years [116], only within the last 50 years have researchers begun to extensively characterize and utilize the data transmission capabilities of the skin [2, 13, 28, 36, 55, 60, 65, 69, 72, 120, 122, 163] (see Appendix A). These early studies helped lay the foundation for the design of modern-day haptic feedback devices for applications such as:

- sensory substitution and augmentation (e.g. [14, 23, 39, 42, 66, 111, 130, 151, 158])
- collision alarms (e.g. [29, 32, 33, 34, 50, 58, 64, 74, 88, 91, 129, 133, 175])
- spatial navigation (e.g. [58, 64, 78, 90, 95, 99, 126, 145, 156, 155, 158])
- musculoskeletal guidance and motor learning (e.g. [3, 16, 52, 62, 68, 77, 79, 86, 109, 114, 159])
- immersive and augmented reality (e.g. [4, 56, 54, 79])
- and conveying complex or abstract messages (e.g. [21, 85, 84, 96]).

Much of existing haptics research has focused on safety-critical applications where the primary purpose of feedback is to capture a user's undivided attention to elicit a correct response as fast as

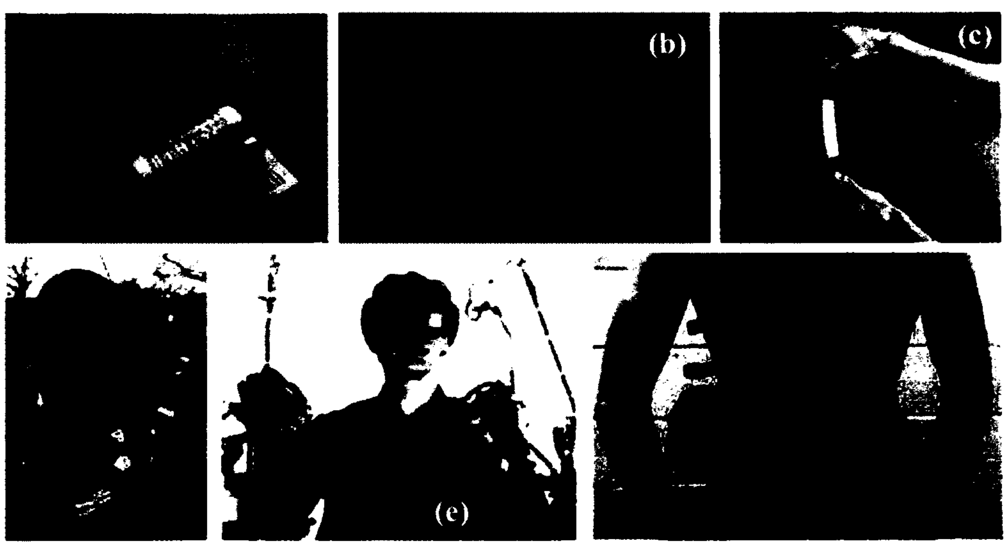

Figure 1.1: Examples of haptic feedback systems: (a) Optacon haptic reader for the blind [39], (b) commercially available PHANTOM Omni force feedback device, (c) haptic collision warning and navigation system, (d) MusicJacket haptic feedback violin coach [62], (e) immersive haptic virtual reality system, (f) tactile vest for conveying complex or abstract messages [64]. *Image sources:* [18, 59, 138, 139, 149, 153]

possible (i.e. focal feedback). Examples include in-vehicle vibrotactile feedback systems that can warn the driver of impending automobile collisions [29, 32, 33, 49, 50, 74, 88, 91, 133, 175], wearable systems that can enhance pilot situational awareness during low visibility flying conditions [58, 64, 90, 99, 175], and a tactile vest that communicates collisions with virtual objects [79].

Haptic feedback has also been used to supplement vision, audition, and proprioception to guide muscle movement. For example, the Haptic Radar headband [16] uses vibrotactile actuators ("tactors") to help the wearer detect objects near his head, TactaPack utilizes tactors to provide both spatial and temporal information to physical therapy patients [81], HAPI Bands use wearable tactors to guide yoga poses [125], and in-shoe vibrotactile displays are used as a navigation aid to guide blind people [158]. Haptic feedback has also been used to train athletes such as tennis players and swimmers [3, 77], and musicians such as pianists and violinists [52, 62]. In all of these cases, a user's attention is directed towards responding to haptic feedback to complete his primary task.

While multimodal reinforcement using haptics is generally a benefit, the success of haptic warnings and alarms creates an associated downside. When haptic methods are used for non-critical tasks, they may distract the user from a more important task (for example, we have all been distracted by an ill-timed vibrating phone). In fact, researchers have found that humans are only capable of handling one or two primary tasks yet can attend to multiple tasks in the periphery [164].

Some designers now recognize the need to create "calm" technology [164] and "ambient information systems" [112] for conveying less urgent information with minimal level of distraction to the user. MacLean's paper on ambient haptic feedback systems [83] has been influential in defining a new path for haptics research that allows the user more choice in how he allocates attention. This ambient, peripheral feedback allows the user to attend to his primary task or utilize the presented information at his convenience without unnecessary interruption. For example, the low-intensity shaking of a mechanical steering wheel linkage communicates a bumpy road without forcing the driver to act upon this piece of information. (Other examples are discussed in Section 2.2.)

So far no efforts have been made to combine focal and ambient methods of feedback into one unified system for haptic attention capture. Thus we propose *variable attention capture (VAC)* haptics as a new design paradigm that unifies the two categories of feedback to convey information to a user at an appropriate level of attentional salience. This allows for the development of versatile next-generation haptic devices capable of generating both focal and ambient stimuli depending on the task at hand.

1.2 Variable Attention Capture Haptics

Variable attention capture (VAC) feedback system are essential for fluidly moving between the center and periphery of a person's attention along a spectrum, depending on the secondary task priority. We call this spectrum the *attention capture spectrum* (Figure 1.2). To delineate different levels of attention capture, we use the 5 notification levels described by [89] – "ignorable," "change blind," "make aware," "interrupt," and "demand action." For example, a focal stimulus demands full user attention and an immediate action in response, thus falling under the category of "demand action." On the opposite end of the spectrum, an ambient stimulus is so gentle that it is ignored until a more convenient time when the user chooses to attend to it. This spectrum serves as a guide for characterizing the human response to VAC systems.

Figure 1.2: The *attention capture spectrum.* We use the same terms as Matthews [89] to describe each notification level (1-5) – ignore, change blind, make aware, interrupt, and demand action. VAC systems should be able to fluidly and dynamically shift along this full spectrum.

Defining an attention capture spectrum allows the urgency of a stimulus to be encoded into its mode of presentation. Time displays rest unobtrusively at the corner of computer screens until a loud alarm sounds to alert the user to a time-sensitive task. Extensive research on the saliency of visual and auditory signals have led to these everyday VAC visual and auditory technologies, as well as more advanced ones like aircraft cockpit head-up displays. However, little emphasis has been placed on the development of VAC haptic feedback systems, which is a critical step for the application of haptic technology in a manner that is both useful and relevant to the user.

While focal haptic feedback only occupies one portion of the attention capture spectrum – "demand action" and "interrupt" – ambient haptic feedback mechanisms become increasingly important as one moves along the attention capture spectrum. Hence ambient feedback is a major component of VAC haptics.

While most haptic feedback devices developed so far provide focal feedback (see examples from the previous section), very limited research has been conducted on ambient haptic feedback thus far. MacLean points out six characteristics of ambient haptic communication [83]: 1) provide context and awareness for an on-going situation, 2) unintrusively communicate relevant change, 3) require low mental effort to process, 4) support automatic behavior, 5) let us follow up as needed, and 6) act on our unconscious processes. We will incorporate MacLean's principles of ambient feedback to guide our development of VAC haptic feedback systems for appropriate attention management.

Our proposed VAC haptic feedback methods seek to combine both ambient and focal feedback mechanisms to create a unified system for haptic attention capture. When properly deployed, a VAC haptic device would be able to produce relevant stimuli without unnecessarily competing for a user's limited attentional resources, while simultaneously being able to convey important information in a timely, accurate, and intrusive manner. Therefore, we are interested in developing actuators and their control schemes that would allow us to modulate attention capture more intentionally over the full attention capture spectrum. By appropriately modulating the level of attention capture, VAC feedback systems allow the user to manage multiple tasks and interruptions while maintaining focus on their primary work task.

The specific aims of this work are:

1. To construct novel haptic feedback devices capable of variable attention capture.
2. To characterize variable attention capture in the context of the operation of these devices.
3. To demonstrate the utility of these devices in providing information in a timely, accurate, and unobtrusive manner.

1.3 Application: Seated Posture Guidance Using Variable Attention Capture Haptics

We begin our exploration of variable attention capture (VAC) haptics through the specific application of seated posture guidance via our Posture Seat system.

Computers are now an integral part of our daily lives. In a 2007 occupational employment and wages survey published by the National Bureau of Labor Statistics, it was found that over 23 million people were employed in the office and administrative support occupational group – the largest occupational group in the US [100]. Most, if not all, of these people spend about 6 to 8 hours each day working at their computers. Unfortunately not everyone maintains good sitting postures when working in front of their computers for so long. In fact, people will tend to slouch or assume some other "unhealthy" sitting position after a while. Over time, these bad postures develop into back pain, pressure sores, and other health issues. According to an "Ergonomic Hazards of the Seated Posture" analysis, poor posture is the single largest factor in office injuries, and office workers will likely suffer sometimes irreversible injuries if they do not consciously maintain correct sitting postures [127].

The primary interventions for this issue consist of providing basic guidelines for proper workstation configuration and maintaining "proper" or "good" posture (see Appendix B). In addition to positioning keyboards, monitors and writing surfaces at appropriate heights, ergonomic chairs have generally been used to passively correct and/or encourage proper posture [27]. Despite these guidelines and ergonomic adjustments, workers often have trouble maintaining these habits on their own. Motivated by this issue, we designed a posture sensing and feedback chair to guide the user into an appropriate posture.[2]

Informal interviews with ergonomics specialists and occupational therapists conveyed three important ideas. First, helping patients maintain a prescribed posture when they are at a desk would be beneficial. Many patients either forget or cannot accurately replicate the postures that are taught in therapists' offices. Second, monitoring what patients actually do outside the therapy environment would be helpful for therapists. At present, few therapists know whether their recommendations are followed. Third, an appropriate posture is highly variable both due to human variation as well as individual medical issues. It is therefore unlikely that there is a single correct posture. In fact, therapists may want patients to change among several postures using a regime that is customized for the individual.

We aim to correct the chronic problem of poor posture with as little disruption to the worker's primary task as possible. Multiple Resource Theory (MRT) suggests that humans should be able to process and perform certain types of tasks in parallel as long as the tasks do not utilize the same cognitive resource or overload a single cognitive resource [165]. For example, when a visual perceptual channel becomes overloaded, additional information may be better perceived if delivered through the auditory channel. Based on this theory, we assume that office workers (who rely heavily on visual processing) would find visual feedback devices distracting and thus unacceptable. In this research, we demonstrate that haptic feedback may be used to guide a person to a reference body

[2] Although there is debate over what is considered "good" posture, it is clear that some postures are more unhealthy than others. The prevalence of back pain, pressure sores, and other health issues indicate that people have trouble managing their postures. Some injuries can be traced back to people sitting in bad postures, and helping people avoid those postures would be a path towards reducing these injuries. Therefore, in our research, we do not propose what a healthy posture is (we will defer to posture experts), but rather we propose the design and development of a posture sensing and feedback chair that can guide a user towards or away from a given posture.

orientation, and that VAC haptic feedback will cause minimal disruption to the worker's primary task.

MRT may be used as a springboard to investigate how humans perceive and process non-critical stimuli and to design systems with subtle (ambient) feedback. We rely on user's preattention – the idea that humans can quickly acquire peripheral sensory data without directly attending to it [152, 171] – to simultaneously acquire multiple low-priority inputs, which can be synthesized and acted upon at a later time.

The haptic modality remains largely unaddressed by MRT [166]. This dissertation summarizes our exploration into VAC haptic feedback, and its effect on sensory-motor learning and cognitive function. To that end, we designed and implemented a haptic feedback system that guides individuals to a reference posture using continuously variable, real-time haptic feedback.

1.4 Dissertation Overview

The rest of the dissertation is organized as follows:

Chapter 2 presents a summary of related work on seated posture identification and feedback guidance systems, as well as existing ambient haptic feedback systems.

Chapters 3-9 report on specific user studies. In Chapter 3, we present the design of a real-time posture sensing and feedback chair system and assess its performance in a three-part user study. The study involves posture classification accuracy, posture repeatability of the test subject, and compliance to vibrotactile posture feedback guidance. Chapter 4 builds upon the work in Chapter 3 by conducting a user study to characterize the amount of primary task interference resulting from responding to vibrotactile seated posture guidance. Chapter 5 extends the work from the previous two chapters by comparing the effectiveness and level of disruption between a vibrotactile and visual posture feedback system.

Based on the results of Chapters 3-5, it became obvious that vibrotactile feedback caused undue disruption to a user and impaired his ability to perform a primary task. To mitigate unnecessary disruption, in Chapters 6-8 we shift our focus towards developing variable attention capture (VAC) haptic feedback systems that can deliver information to the user at an appropriate notification level, depending on secondary task priority.

In Chapter 6, we begin our investigation of VAC haptics by exploring different actuators and actuation parameters that influence a user's emotional *affect* (emotional response) and thus have an impact on attention capture. Utilizing the results of that study, Chapter 7 presents the design of a novel VAC haptic feedback pressure-actuated system, which we call a *pactor*, and the result of a user study that measures test subjects' pressure detection threshold and self-reported level of attention capture using these pactors. In Chapter 8, we characterize the level of attention capture that is achievable by tactors (vibration) and pactors (pressure) through a user study.

In Chapter 9, we integrate the VAC haptic actuators into our posture sensing and feedback chair and repeat the dual-task interference study to assess the amount of performance improvement with VAC haptics. We thus come full circle to our original problem of providing posture feedback guidance with minimal disruption to the user's primary task.

Chapter 10 concludes the thesis by providing a summary of my work and highlighting my contributions to the field of haptics and to the area of seated posture guidance. The chapter ends with an outlook for VAC haptics.

Lastly, Chapter 11 lists future research directions, including improvements to the Posture Seat system, as well as potential areas of development for variable attention capture haptic feedback.

The appendices provide additional background information on the human's sense of touch (Appendix A), generally agreed-upon guidelines for seated posture and seating systems (Appendix B), preliminary designs for the Posture Seat (Appendix C), and selection of pactor designs (Appendix D).

Although my doctoral work was carried out in the Department of Mechanical Engineering, this dissertation is in fact a multidisciplinary endeavor linking several disparate fields. In addition to employing principles from mechanical engineering, electrical engineering, and computer science in the development of our devices and control schemes, we also utilized concepts from psychology, cognitive science, and psychophysics to inform the designs of our human subject studies. Building on ideas from all of these fields, we were able to better understand and characterize the application of variable attention capture haptics.

Throughout this dissertation I will frequently use the pronouns "we" and "our." It is because my doctoral work represents a collaboration between myself and my former advisor, John Morrell, without whom this work would not have been possible.

Chapter 2

Related Work

In the last few decades, a number of research groups have developed posture sensing and classification systems. Others have investigated the effectiveness of haptic feedback in a variety of applications, but few have applied it to seated posture guidance or have explored ambient haptic feedback. To our knowledge, we were the first research group to combine real-time feedback with sensing in order to alter posture. In this chapter, we will review work related to seated posture identification as well as research on ambient haptic feedback systems.

2.1 Posture sensing and feedback

Researchers have devised several methods to measure sitting posture, including pressure-based, vision-based, and inertial-based systems.

In 1979, two researchers constructed a capacitative pressure measurement plate to study the pressure forces in sitting at various backrest angles [124]. They tested backrest angles of 90°-140° (in 10° increments) and found that only the 90° and 110° backrest angles displayed well defined pressure areas under the *ischial tuberosities* (sit bones) (Figure 2.1). These backrest angles are consistent with present-day guidelines for good sitting posture [22, 38].

Later, another research group [94] constructed a capacitative pressure mat (different from the previously mentioned group [124]) to measure the distance between the points of maximum pressure. They determined that the mean distance between the points of maximum pressure, which corresponded to the distance between the lower aspects of the *ischial tuberosities*, was on average 2.51cm greater for females than for males. They also found that the distance between points of

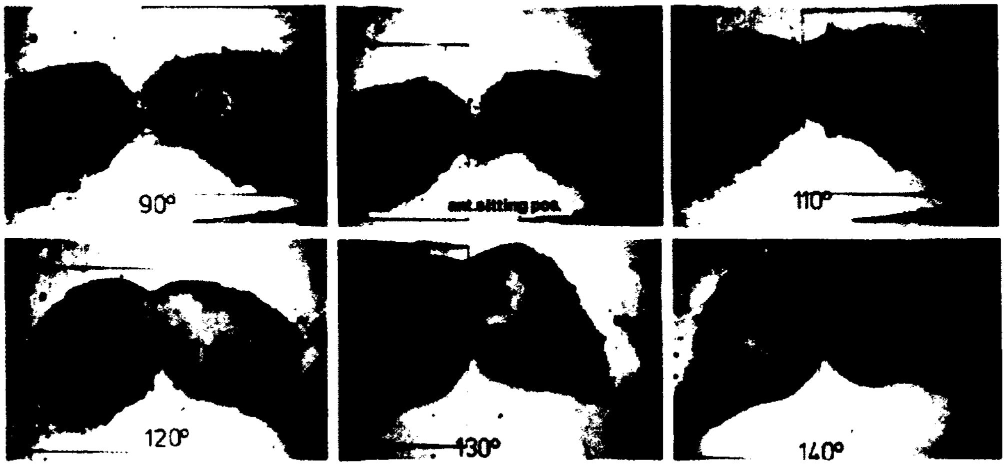

Figure 2.1: A capacitative pressure measurement system developed by Rosemeyer, et. al. [124] to measure pressure distribution on a seat by a seated subject at various chair backrest angles. Only the 90° and 110° backrest angles resulted in well defined pressure areas under the *ischial tuberosities* (sit bones). *Image source: Rosemeyer, et. al.* [124].

maximum pressure decreased with forward pelvic rotation, and increased with backward pelvic rotation. (See Appendix B for more information on posture.)

Other pressure-based posture sensing systems include the use of an XSensor pressure pad to evaluate ergonomics of five different chair designs for mobile agricultural machinery [51], a combination of the Tekscan pressure mats and the Vicon optical motion analysis system to study pelvic movement during manual wheelchair propulsion [144], a pressure mat to identify an automobile driver's activity based on his seated posture [121], and a large array of individual two-pinned pressure triggers to identify seated posture [172].

Vision-based technology is another commonly used method of measuring posture. For example, [45] presents a real-time body part tracking system call "Ghost" that uses a person's silhouette to determine his or her posture. In [92], a multi-camera motion capture system performing voxel data analysis determined the posture of a seated person for "smart" deployment of air bags. The Optotrak motion capture system was used in [98] and [136] to sense body orientation. LED markers were used by [31] to measure posture in the 85-110° range of motion.

Unfortunately there are numerous drawbacks to using vision systems in confined spaces to sense postures. These drawbacks include field of view, ambient lighting, obstructions, and background objects. Some researchers have turned to a third method of identifying postures: sensors attached directly to the human body. In [35], a whole-body pose tracking system used inertial and magnetic sensors to track posture. Wong and Wong [170] mounted accelerometers and reflective markers

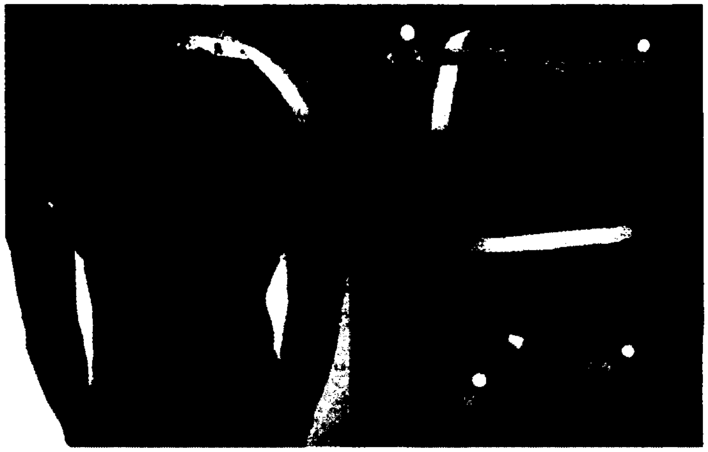

Figure 2.2: A method of sensing posture by attaching reflective markers and three-axis accelerometers directly on the subject's body to measure changes in curvature of the spinal column. *Image source: Wong and Wong* [170].

along the spinal column to measure the curvature of a person's back (Figure 2.2). Another example involves the use of a three degree-of-freedom (3-DOF) robotic arm cupped over a child's head to measure postural sway [119].

Work most relevant to our current research is [146]. In 2000, Tan et. al. developed a static posture sensing system that correlated a particular pressure distribution to a specific sitting posture. They used commercially available pressure mats consisting of a dense array of 1024 pressure sensors (Tekscan CONFORMat, $1500 for each mat not including software [147, 168]). With one mat placed on the seat cushion and one on the backrest (Figure 2.3), they were able to identify slouching, leaning in various positions, crossing legs, and sitting upright. For 30 subjects, the overall accuracy was 96% for familiar subjects (i.e. subjects whose pressure distribution the chair had "sensed" before) and 79% for first-time subjects. Their study indicates that it is plausible to correctly identify a person's sitting posture with the use of pressure sensors alone.

In 2007, Mutlu et. al. [97] developed an algorithm that down-sampled the sensor data from [146] and determined the near-optimal placement of square force-sensitive resistors (FSRs) on a Herman Miller Aeron chair. Their posture classification system achieved an accuracy of 78% using only 19 square FSRs. The best results (87% classification accuracy) were obtained using 31 FSRs. As in [146], the focus of this work was classification of a variety of different postures rather than creating an analog signal for feedback.

In 2011, following our research in [176], Schrempf et. al. [131] developed a seated posture biomechanics model and posture cost function for posture identification. Their model helped further

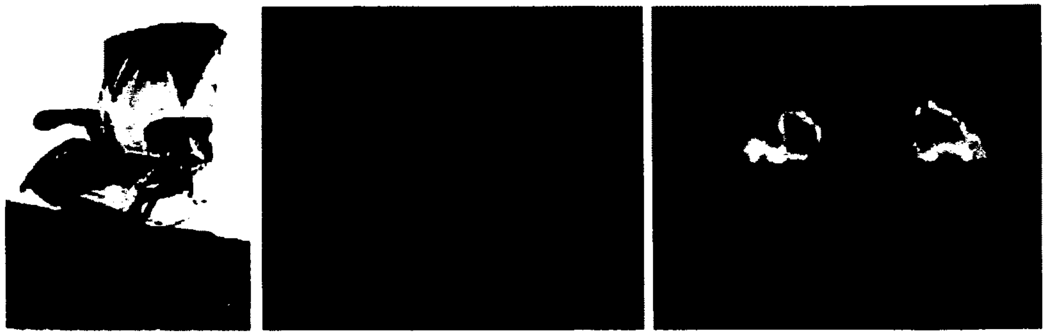

Figure 2.3: The use of commercially available, high resolution Tekscan CONFORMat pressure mats placed on the seat pan and seat back to identify sitting postures. (Left) Placement of Tekscan pressure mats on chair. (Middle) Pressure distribution on the seat back. (Right) Pressure distribution on the seat cushion. *Image source: Tan, et. al.* [146].

reduce the number of force transducers to four. They proposed using posture feedback for guiding effective sitting exercises but had not yet been deployed.

Several research systems and commercial products attempted to guide posture without actively sensing posture. For example, the Prototype Multi-Posture (PMP) chair [75] and Evolution Chair [30] require the user to actively balance on their unstable seating platform. MIT's 5-DOF Robotics Computer Monitor (RoCo) moved its "neck" to visually and subconsciously influence the user into a new posture as dictated by the monitor [1].

A number of patents exist for correcting a user's posture [37, 57, 70, 115, 132], however we encountered only one commercially available device that incorporated both posture sensing and real-time feedback: the iPosture [53]. It is a small, low-cost, wearable device that uses an accelerometer to sense the slouching posture through chest angle, and delivers vibrations to remind the user to sit or stand upright. Unfortunately a recent study by Johnson et. al. [61] found that the vibrotactile feedback from iPosture did not help users improve their posture. Other complaints aside, users expressed frustration with the single-point vibration that merely served as a reminder to correct the wearer's posture but gave no indication as to how to correct their posture.

Our proposed posture sensing system is similar to Tan and Mutlu in that it uses pressure sensors (specifically FSRs) affixed to the surface of an office chair. However we are able to significantly reduce the number of FSRs used by obtaining the pressure map for each person's postures (calibration) and matching his real-time posture pressure map to his calibration. Creating a low-cost, low-complexity system was an objective. Given the variability in humans and human postures, adjusting the system to the individual user seemed both necessary as well as desirable from a cost-reduction standpoint.

Our sensing system is also similar to iPosture in that both rely on calibration to the user, however our approach to haptic feedback relies on latent sensory motor instincts or reflexes and conveys spatial and temporal information using analog signals that vary intensity based on the magnitude of the error. Furthermore, our system deals with a quasi-static pose of the body rather than a dynamic one. As such, the sensory-motor skills in our application are more biased toward the modulation of force than the control of joint movement.

A final and important distinction in this research is our focus on pressure rather than kinematic orientation, although the two are highly coupled. The kinematic orientation of the body is usually observable through visual means, but the distribution of weight is not. Our FSR-based system is sensitive to small changes in the distribution of weight that are not typically observable without fiducial markers and an externally calibrated, high quality vision sensing system.

2.2 Ambient haptic feedback systems

The terms *ambient displays, peripheral systems,* and *notification systems* are all "labels for systems that present information within a space through subtle changes in light, sound, or movement, which can be processed in the background of awareness" [169]. Ambient visual and auditory displays are relatively easy to conceive – slowly changing background scenery on a computer screen, a wilting or blossoming flower to indicate household energy consumption, automatically pausing music or changing background sound in response to an incoming phone call or person, crescendoing music as a prelude to a scary movie scene, etc. [12, 83, 123, 134, 137]. However ambient haptic systems are far less prevalent and researchers are just beginning to explore the ambient haptic sense. This section presents existing research on ambient haptic systems.

The Aladdin doorknob described in [47, 83, 85] can act as a "haptic butler" that informs the visitor of activity inside the room. It provides force, motion and thermal feedback to the visitor who touches the doorknob and helps him decide whether or not to enter.

The Haptic Car Seat is another ambient feedback system that uses vibrotactile actuators to deliver gentle vibrations to the driver to inform him of cars in his blindspot or cars that are tailgating him [95]. The vibrations do not require the driver to take action. Instead, he can choose to drive normally or utilize the information to influence his decision to change lanes.

The Haptic Notification System (HaNS) timing awareness wristwatch deployed at the 2012

Haptics Symposium (among other places) is another system that utilizes low-intensity vibrotactile feedback to deliver gentle yet salient vibrations to the wearer. It is intended to help the speaker keep time during oral presentations. HaNS privately reminds the person of time but does not stop him from going overtime [143].

Similarly, haptic interactions wristwatch developed in [107] allows the user to query information from his mobile phone without removing the phone from his pocket. The wristwatch delivers different vibrotactile signals to convey numerical information tactually to the user for an eyes-free interaction.

Also in 2011, a haptic wristband for bookmarking an audio track on a mobile phone was developed [19, 102, 103, 104]. The device senses skin conductance to discern when the user is interrupted by another task so that it can automatically bookmark the audiobook or podcast and pause on the user's behalf. The user interacts with the haptic wristband to resume playback, rewind the track, etc. without needing to take out his phone.

A recent perceptual study by Pielot et. al. [110] on the boundaries of vibrotactile peripheral perception proved that certain vibration patterns *can* be ambient: when mobile phones in test subjects' pockets vibrated at intensities just above their detection threshold, only 16.7% of the stimuli were acknowledged within one minute and participants were not annoyed by the vibratory feedback. Similarly, when [5] explored haptic feedback actuation parameters that would emulate human touch through the ServoSqueeze and ServoTap wristband (Figure 2.4), they found that symmetric pressure actuation profiles felt more pleasant and more ambient to the test subjects than asymmetric profiles.

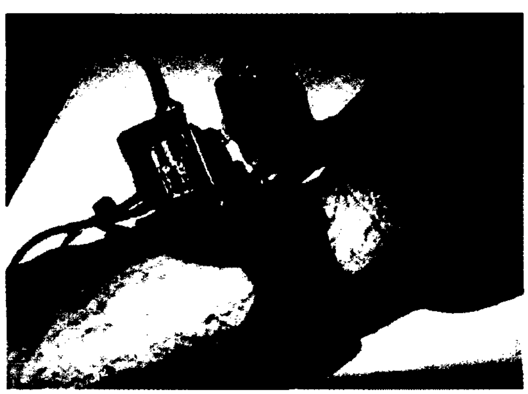

Figure 2.4: ServoTap (purple "finger") and ServoSqueeze (black wristband) mechanism for simulating human touch. *Image source: Baumann, et. al.* [5].

Subsequent to our published results [176, 177], other researchers have developed posture feedback systems and conducted studies similar to our own. Haller et. al. [44] designed a posture sensing and feedback chair [131] and conducted an experiment to determine which type of feedback (visual, physical, vibrotactile, Figure 2.5) would be most effective for seated posture guidance while simultaneously being least disruptive. They found that the physical object on the desk representing the user's seated posture was best, while vibrotactile feedback was most intrusive. Their work differs from ours in that we aimed to develop variable attention capture (VAC) vibration and pressure actuators for seated posture guidance that could intentionally modulate a user's level of attention across the attention capture spectrum.

The next few chapters present our research on the development of a novel real-time posture sensing and feedback chair as well as VAC haptic actuators for conveying information at an appropriate level of attentional salience.

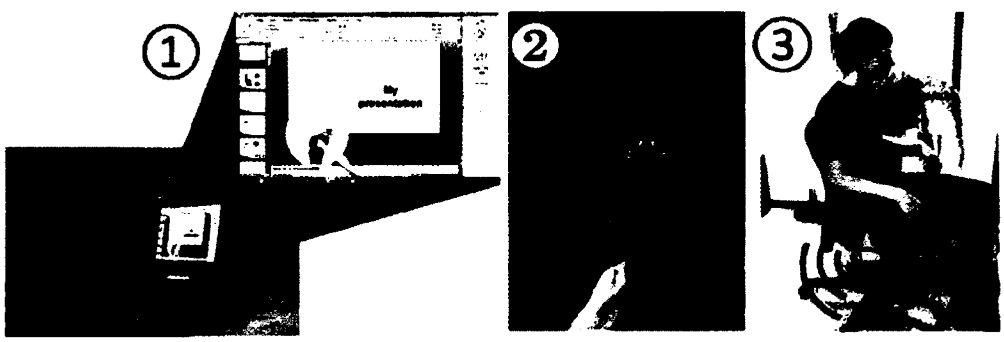

Figure 2.5: Another researcher's investigation of minimally disruptive posture feedback methods subsequent to our published findings [176]. The three feedback methods used by Haller, et. al. [44] were: (1) visual, (2) physical, (3) vibrotactile. *Image source: Haller, et. al.* [44].

Chapter 3

A Vibrotactile Feedback Approach to Seated Posture Guidance

3.1 Overview

This chapter begins our investigation of vibrotactile haptic feedback for improving the performance of a sensory-motor task, namely seated posture guidance. We present the Posture Seat system that can actively sense and guide a person to a desired posture. We then describe the user study that characterizes the performance of the Posture Seat system. We end with the results and implications of this study.

As described in Section 1.3 and Appendix B, our approach to posture feedback relies on posture guidelines proposed by the Occupational Safety and Health Administration (OSHA) [101]. We assume that spending more time in a posture that is consistent with guidelines presently proposed by OSHA would represent a significant improvement over not following such posture guidelines. These guidelines are usually presented pictorially and may be assessed visually. Additionally, based on the informal interviews with ergonomics experts (Section 1.3), we learned that a successful system must allow users to adjust their position periodically as maintaining any one stationary pose is fatiguing and potentially unhealthy. As mentioned in Section 1.3, we will rely on physical therapists and posture experts to specify acceptable deviations and durations for a variety of poses.

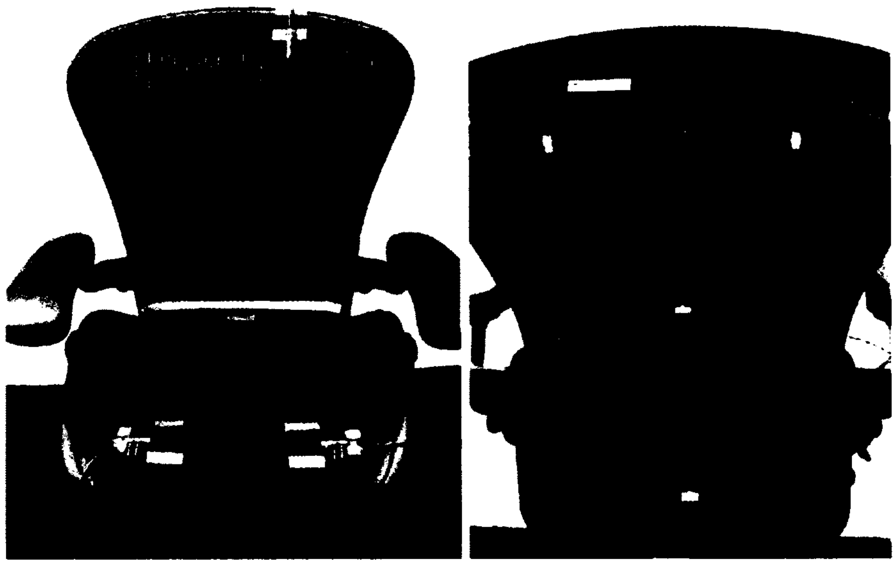

Figure 3.1: The "Posture Seat" posture sensing and feedback system. (Left) Locations of the 7 force-sensitive resistors (FSRs) for posture sensing. (Right) Locations of the 6 vibratory tactors for posture feedback. Only 4 tactors on the back of the seat are shown. The other two are on the bottom of the seat, near the front, under each thigh.

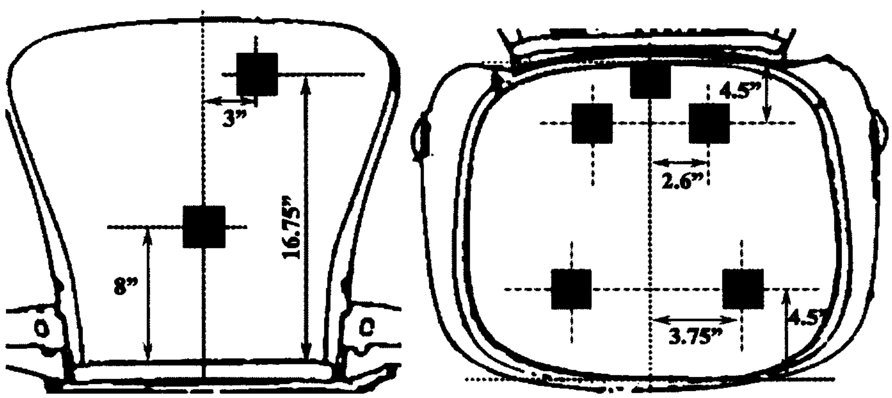

Figure 3.2: Placement of FSRs on seat bottom and seat back. The edge of the FSR placed at the rear of the seat is flush with the back edge of the chair.

3.2 System Description

3.2.1 Equipment

Our posture sensing and feedback system is a size B, fully adjustable Herman Miller Aeron chair with lumbar support, instrumented with 7 force-senstive resistors (FSRs) for posture sensing and 6 vibrating tactors for haptic feedback (Figure 3.1). The exact placement of the FSRs on the Aeron chair is shown in Figure 3.2. Each FSR (1.5" square Interlink 406 FSR, \$8.50) is connected to a

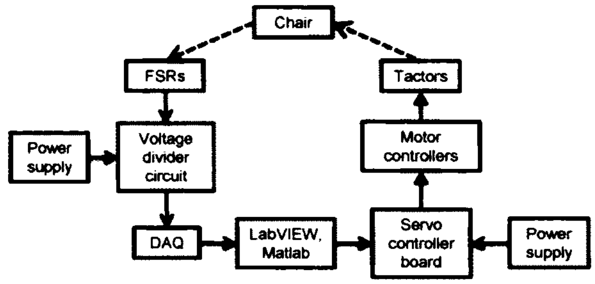

Figure 3.3: Block diagram showing the hardware connections for the Posture Seat system.

voltage divider circuit ($R_1 = 1.1k\Omega$) and powered by a regulated DC voltage. The output voltages are collected through a National Instruments data acquisition unit (NI DAQ USB-6212) connected to a PC running LabVIEW 8.5. (The process by which we arrived at the current design of the Posture Seat is explained in Appendix C.)

The tactors are composed of miniature pager motors (.44"L × .18"$Dia.$, 10Ω resistance, $1.30) enclosed in a custom ABS housing mounted on the back of a 1.5" × 1.5" × 0.125" Plexiglas plate. The tactors are each controlled by a 3kHz PWM voltage between 0-6V using a motor controller (Pixie-7P), which are run from a servo controller board (Lynxmotion SSC-32). LabVIEW is used to communicate with the servo controller board via a serial connection. The entire system is run on a Dell Optiplex GX620 (2.80GHz Pentium 4 processor, 2 GB RAM) with Windows XP Pro SP3. A block diagram of the system setup is shown in Figure 3.3. While the existing system makes use of general purpose PC's and software for research purposes, the system could be implemented with a small microcontroller since the bandwidth and computation requirements are modest.

The video capture devices used for verifying postures include a Logitech Quickcam Pro 5000 webcam and a Sony Digital Handycam DCR-TRV120 camcorder for capturing still images, and a Hitachi Hybridcam DZ-HS903A camcorder for recording live video.

3.2.2 Posture List and Sensor Placement

We evaluated our system performance against the same list of 10 postures in [97, 146]. Figure 3.4 provides examples of the postures and Table 3.1 gives definitions for each.

Initial sensor placement was based on dimensions from [25, 150]. While many FSR locations were evaluated, preliminary tests showed that the most important and distinguishable areas of the body for identifying the 10 postures are the *ischial tuberosities* (sit bones), thigh region close to the knee, lumbar region of the spine, and shoulder blades. Hence one FSR is placed under each *ischial*

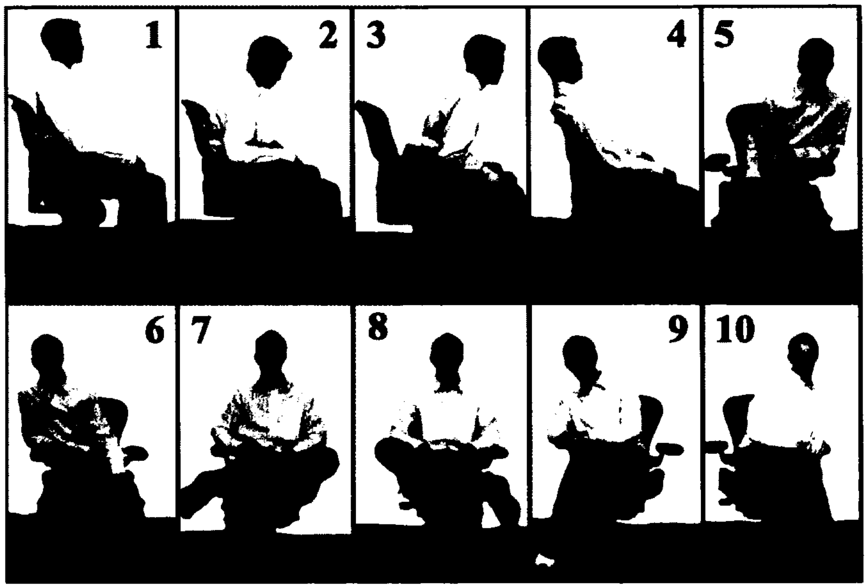

Figure 3.4: An example of each posture to be identified by our system: 1. upright, 2. slouching, 3. leaning forward, 4. leaning back, 5. leaning left, 6. leaning right, 7. left leg crossed over right, 8. right leg crossed over left, 9. left leg crossed over right and leaning right, 10. right leg crossed over left and leaning left.

Table 3.1: List of postures to be identified and their descriptions

	Posture	**Description**
1	upright	lordotic lumbar curve, back and thigh are at approximately 90°
2	slouching	kyphotic lumbar curve, hunched over
3	leaning forward	back straight and approximately 40°-60° from vertical
4	leaning back	back resting on seat back, relaxed
5	leaning left	leaning left about 20° with left arm resting on armrest
6	leaning right	leaning right about 20° with right arm resting on armrest
7	left leg crossed over right	left ankle resting on right knee, sitting centered in seat
8	right leg crossed over left	right ankle resting on left knee, sitting centered in seat
9	left leg crossed over right and leaning right	full cross with left knee over right knee, leaning right
10	right leg crossed over left and leaning left	full cross with right knee over left knee, leaning left

tuberosity, one under each thigh, one behind the lumbar curve, and one behind the left shoulder blade. Finally, the seventh FSR is placed in the center rear of the seat to ensure that the subject sits all the way back in the seat. A dimensioned diagram of the FSR locations is shown in Figure 3.2.

3.2.3 Posture Identification Algorithm

It is important to first characterize the posture classification accuracy of the 7-FSR posture sensing system. We begin by defining variables for the posture identification algorithm. Let $f_1, f_2, ...f_7$ be the FSR voltage reading from each of the 7 FSRs. Then for any unknown posture i, let $V_i = \begin{bmatrix} f_{1,i} & \dots & f_{7,i} \end{bmatrix}$ be the voltage array for posture i. Define V_j^* as the voltage array for a known reference posture j, where

$$\begin{aligned} V_j^* &= \begin{bmatrix} \frac{1}{n}\sum_{k=1}^{n}(f_{1,k,j}) & \dots & \frac{1}{n}\sum_{k=1}^{n}(f_{7,k,j}) \end{bmatrix} \\ &= \begin{bmatrix} f_{1,j}^* & \dots & f_{7,j}^* \end{bmatrix} = \frac{1}{n}\sum_{k=1}^{n} V_{k,j} \end{aligned} \tag{3.1}$$

is simply the average voltages for each set of known postures. The number of samples to average over is n. Note that j ranges from 1 (upright) to 10 (right leg crossed over left and leaning left). j can also be 0, in which case the posture is labeled as "other."

The posture identification algorithm computes the mean squared error between the voltages for body orientation i and the voltages for reference posture j.

$$MSE_{i,j} = \frac{1}{7}\left((f_{1,i} - f_{1,j}^*)^2 + ... + (f_{7,i} - f_{7,j}^*)^2\right) \tag{3.2}$$

The posture P_i assigned by the algorithm is the one with the lowest MSE computed against each j. The lowest MSE must also be below a threshold h in order for the posture to be valid, otherwise the posture is considered "other" ($P_i = 0$).

$$P_i = \begin{cases} G(min(MSE_{i,j}), j) & min(MSE_{i,j}) < h \\ 0 & min(MSE_{i,j}) \geq h \end{cases} \tag{3.3}$$

When the predicted posture is the same as the actual posture, it is recorded as a match. Finally, the total number of matches is used to compute classification accuracy.

3.2.4 Posture Feedback Algorithm

For the initial evaluation of our feedback system, we chose to focus on detecting and guiding subjects to one reference posture: sitting upright. The posture feedback algorithm involves calculating the MSE in real-time and activating haptic feedback when the cumulative MSE $E(t)$ rises above a

Table 3.2: Location of vibration, cause, and required motor action to properly respond to vibrotactile feedback and successfully eliminate vibrations. Multiple tactors may vibrate simultaneously to indicate multiple improper body orientations.

Vibrating Tactor Location(s)	**Possible Improper Body Orientation**	**Action Required to Eliminate Vibration**
lumbar	slouching	sit up
rear of seat	leaning forward or not sitting all the way back in the chair	sit back towards upright, or sit all the way back into the chair
left thigh only	left leg lifted or crossed over right	put left leg down
right thigh only	right leg lifted or crossed over left	put right leg down
left thigh and left shoulder	leaning right or left leg crossed and leaning right	sit centered in seat
right thigh and right shoulder	leaning left or right leg crossed and leaning left	sit centered in seat
left and right shoulders	leaning back	lean forward towards upright
all locations	not sitting in seat	sit down in seat

certain threshold for a period of time (discussed later). The feedback is provided through the vibration of the tactors at variable intensities proportional to the amount of absolute error at each FSR.

The location of the vibration corresponds to a particular motor action that needs to be taken. For example, if the tactor in the lumbar region vibrates, typically the subject is slouching, so the correct action would be to sit up straight. Table 3.2 lists the location of the vibration and the corresponding motor action that should be taken. Note that multiple tactors may vibrate simultaneously, indicating multiple actions need to be taken. This feedback mapping was designed to be intuitive so that subjects would not have to be distracted from their primary task while trying to sit in an appropriate posture.

Finally, a feedback activation time delay is incorporated into the system to allow brief movements away from the desired posture without triggering vibrations. However, if the subject continues to deviate from the desired body orientation, then the vibration will start. The time delay is encoded as a proportional-integral (PI) gain on MSE, where $K_p = 1$ and $K_I = 1/(\text{sampling frequency})$. In discrete time, the cumulative MSE can be determined by

$$E(t) = \begin{cases} 0 & \text{for } MSE(t) < H \\ K_p \cdot MSE(t) + K_I \cdot E(t-1) & \text{for } MSE(t) \geq H \end{cases} . \tag{3.4}$$

Additionally, at $t = 0$, $E(0) = 0$. As mentioned earlier, when $E(t)$ exceeds a certain threshold H, vibrotactile feedback will be activated.

3.3 User Study

We conducted a three-part user study evaluating the Posture Seat system (Figure 3.1). The first part of the study involves calibrating the Posture Seat to each test subject and determining posture classification accuracy. The second part looks at how repeatably each subject sits in each posture. Finally, the last part assesses the effectiveness of haptic feedback on sensory-motor skill performance (specifically, posture).

Prior to the start of the experiment, subjects are instructed to empty their pockets, as objects in the rear and side pockets may significantly alter the pressure mapping. Per the healthy seating guidelines in Appendix B, they are also instructed to adjust the seat height and armrest height until their feet are flat on the floor and their thighs are parallel to the ground, elbows 90° on the armrest. Subjects then sit in the chair in front of a computer desk while the cameras record live video or still images of the seated postures. The images are used as a visual reference to double-check that subjects are indeed sitting in a particular posture.

3.3.1 Part I - Posture Classification Accuracy

In the first part of the experiment, the subject is instructed to sit in each of the 10 postures while a snapshot of FSR voltages is recorded. The 10 postures are tested in sequence for the first trial, while the postures are randomized in the remaining three trials (Table 3.3). There is significant guidance by the experimenter in the first trial in order to standardize the body orientations (Figure 3.4 and Table 3.1). Less instruction is required in the subsequent three trials as the subject quickly learns the standard orientations. At the end of all four trials, the number of matches between the predicted posture and the subject's actual posture is computed using Equations 1-3.

Table 3.3: Test sequence for measuring posture classification accuracy (Part I)

Trial No.	No. of Postures	Order of Test
Trial 1	10 postures	In sequence (1. upright, 2. slouching, 3. leaning forward, etc.)
Trials 2 - 4	10 postures	Random order

3.3.2 Part II - Posture Repeatability

While it is important to know the posture sensing system's accuracy, it is equally important to understand the posture variability with a single subject over a period of time as well as when leaving and returning to the chair in the same posture. In this part of the experiment, each subject's posture repeatability is evaluated by sitting in a posture for 1 minute, then getting up, walking around, and sitting back down in the same posture, for a total of 3 trials (Figure 3.5). FSR voltage data is collected at 10Hz during the 1-minute trials. Repeatability was evaluated for "sitting upright" and three additional postures that were most similar to "sitting upright," since this is the focus of subsequent testing. Finally, an analysis of variance (ANOVA) is performed on the data sets to assess repeatability, and the MSE threshold for the upright posture is computed.

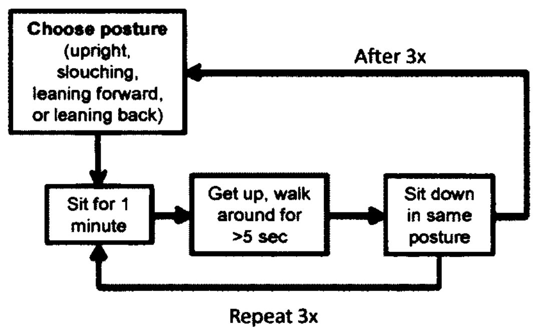

Figure 3.5: Test sequence for measuring subjects' posture repeatability (Part II)

3.3.3 Part III - Posture Feedback

In this part of the experiment, subjects are told to sit in a comfortable working position in the chair while doing their own work (e.g. checking email, surfing the web, etc.). When they feel the tactors vibrate, they can move their body in such a way so that the vibration stops. They are also presented with a digital knob to adjust the vibration intensity if the default setting is too weak or too strong. The vibration locations and actions to be taken is listed in Table 3.2. For this study,

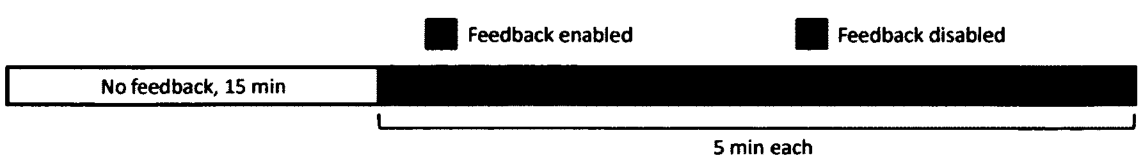

Figure 3.6: Test sequence for measuring posture feedback compliance (Part III)

only the upright posture is evaluated. However, the subject is not given prior information regarding the target posture and is merely instructed to respond to the haptic cues. Subjects repeat this part of the study on two separate days for a total of 2 trials.

The total test time is 45 minutes for each day. During the first 15 minutes there is no feedback and the subject's unguided working posture is observed ("no feedback" mode). The FSR voltage data is recorded at 1 Hz. At the end of the 15 minutes, haptic feedback is turned on ("feedback enabled" mode). If the subject is not sitting in the reference body orientation, at least one of the tactors will vibrate. The haptic feedback system is enabled for 5 minutes and then disabled for 5 minutes. The "feedback disabled" mode allows subjects to relax or change postures without triggering any feedback. This cycle is repeated 3 times for a total of 30 minutes. Figure 3.6 depicts the test sequence. FSR voltages are recorded at 10Hz to allow sufficiently fast haptic feedback. The MSE is recorded for the entire test and the amount of time spent in the upright posture is computed for each phase of the test, using a threshold that is determined in Part II.

3.4 Results and Discussion

This section presents the results from all three parts of the experiment. Discussions will emphasize the posture feedback portion (Part III) of the experiment.

3.4.1 Part I - Classification Accuracy

Excluding various preliminary tests, a total of 6 subjects (2 females, 4 males) were tested on the 7-FSR posture seat system for identification accuracy. The mean age of the subjects was 24±1.0 years, with an average height of 173±13.4cm and an average weight of 67.1±15.1kg. It was found that, using the method of MSE's, the posture sensing system achieved 86.4% accuracy for distinguishing among all 10 postures, and 93.8% accuracy for distinguishing among 4 postures.

For comparison, Tan et. al. [146] was able to achieve 96% classification accuracy for distinguishing among a set of 10 postures for "familiar" subjects (people whose postures have been detected on their COMFORMat posture seat system before) and 79% accuracy for first-time subjects. Each CONFORMat consisted of a grid of 1024 pressure sensors. Mutlu et. al. [97] achieved 87% posture classification accuracy using 31 FSRs and 78% accuracy with 19 FSRs. In the case of [146] and [97], identification of a posture was the primary objective, rather than measuring the error relative to a particular posture. It is encouraging that our "relative error" method of posture identification allows us to reduce our sensing requirements to 7 sensors meanwhile achieving a high classification accuracy.

Most of the incorrect matches were due to confusion between left leg crossed versus left leg crossed and leaning right, and right leg crossed versus right leg crossed and leaning left. (A number of test subjects were unable to fully cross their legs, resulting in "legs crossed" looking a lot like "legs crossed and leaning.") Hence, by examining only postures 1-4 (see Figure 3.4), we achieved a 7.4% improvement.

The remaining 6.2% error can be mostly attributed to distinguishing between upright and leaning forward. Some subjects were unable to lean forward by 40-50 degrees (from vertical). Therefore the system would often predict "upright" as opposed to the correct "leaning forward" posture. However even with these errors the posture sensing system is sufficiently robust at 93.8% accuracy.

3.4.2 Part II - Posture Repeatability

A total of 10 subjects (2 females, 8 males) participated in the posture repeatability study, six of whom were also participants in the posture classification accuracy part of the study. The mean age of the 10 subjects was 23.9±1.5 years, mean height 175±11.2cm, and mean weight 71.1±13.6kg.

Figure 3.7 (left) shows the variability (e.g. seated postural sway) within each 1-minute trial for all subjects combined. Not surprisingly, the variability was minimal, indicating that subjects were able to maintain a consistent body position during each 1-minute trial. This is further evidenced in Figure 3.8 where the subject did not substantially move around (e.g. wriggle or shift) during each trial and hence saw very little variability in his MSE values. However from Figure 3.7, we see that the leaning back posture exhibited considerably more variability than the other three postures, suggesting that subjects had a harder time sitting still in the leaning back posture, even though most of their body was supported by the chair compared to sitting in the other postures.

When comparing between trials for the same posture, there was sometimes a noticeable shift in the mean MSE (see Figure 3.8, bottom, for an example). Figure 3.7 summarizes the MSE shift from one trial to the next for each posture for all subjects combined. This shift was expected but also was not significant enough to result in a posture identification error except in a few cases. In these cases, the system confused "upright" with "leaning forward" (Figure 3.9). Therefore, it is reassuring that subjects were fairly consistent in their postures between trials.

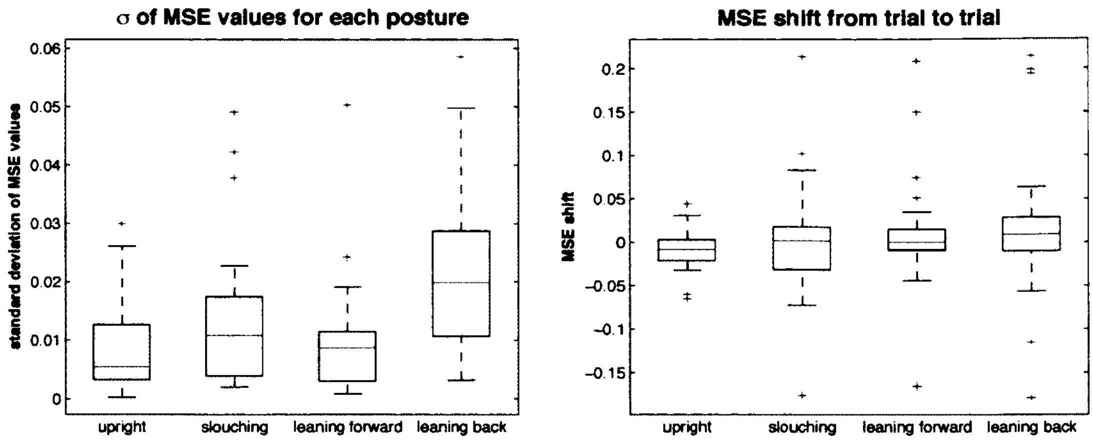

Figure 3.7: (Left) Standard deviation of MSE values for each posture for all subjects combined. Red crosses represent outliers. There was very little variability in MSE values within each 1-minute trial suggesting that subjects sat very still. Subjects exhibited a large amount of postural movement during each 1-minute trial only for the leaning back posture. (Right) Shift in average MSE from trial to trial for each posture, all subjects combined. Red crosses represent outliers. The MSE shift is centered around zero, indicating that subjects were fairly repeatable in how they sat even after getting up and walking around.

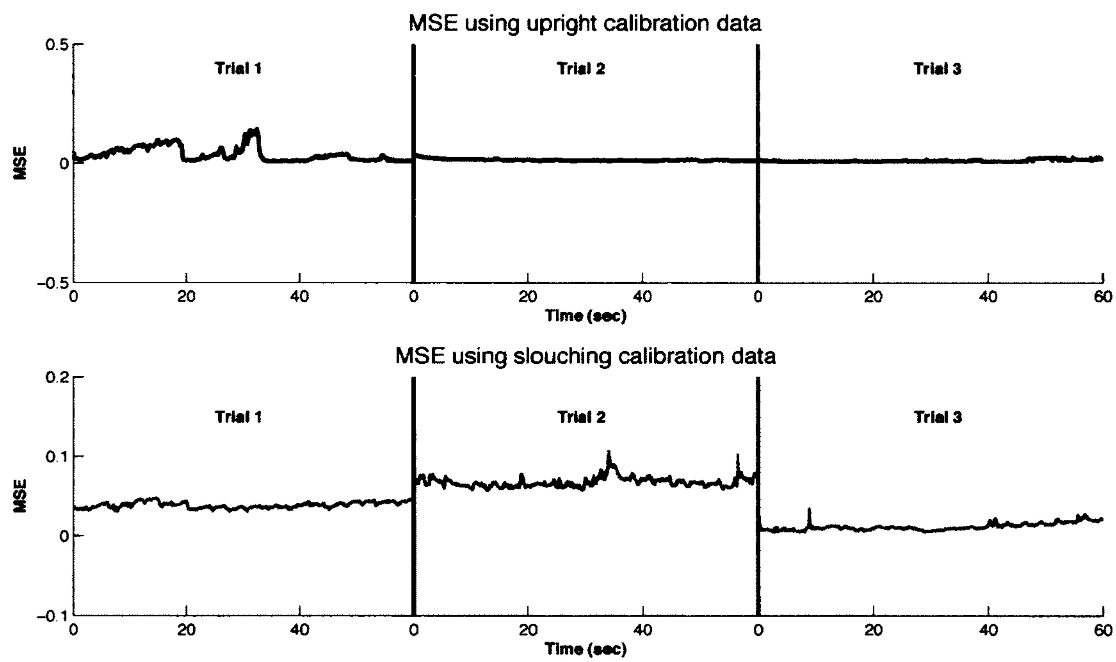

Figure 3.8: A representative plot from one test subject showing very minimal variation in the mean-squared error (MSE) within each 1-minute trial. (Top) MSE calculated against the upright calibration posture, and (bottom) MSE calculated against the slouching calibration data. (Bottom) Sometimes there was a noticeable but insignificant shift in MSE between trials.

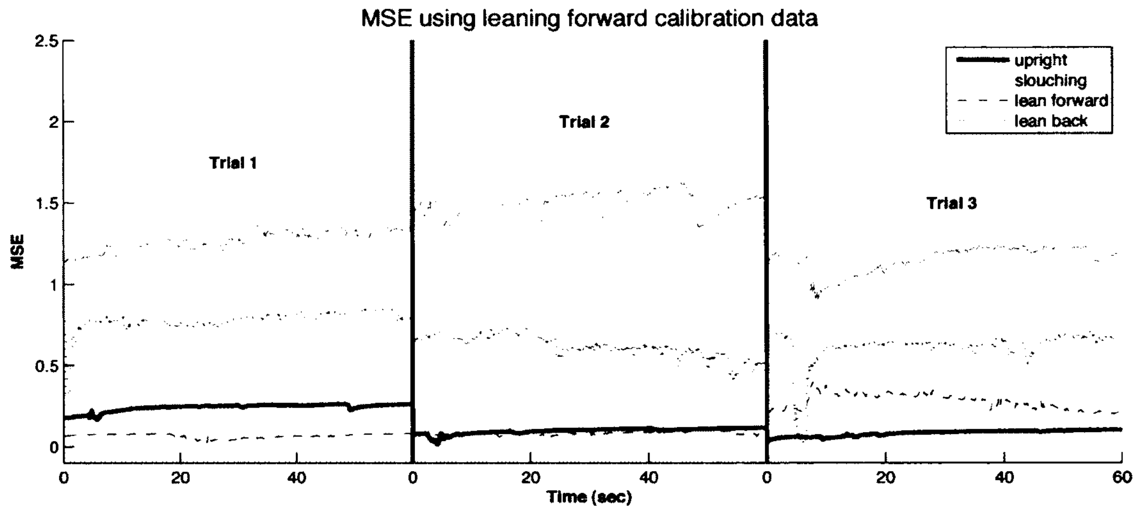

Figure 3.9: Plot of mean-squared error (MSE) calculated against the leaning forward posture over three 1-minute trials from one representative test subject. This example highlights occasional confounding effects between MSE values, which can lead to posture mis-identification. Notice that the upright MSE values are lower than the leaning forward MSE values for trials 2 and 3. This results in a posture classification error as the predicted posture corresponding to the lowest MSE is not the actual posture.

Table 3.4: MSE values for all postures calculated using the upright posture calibration. The values for each posture are distinct enough that classification errors are minimal.

Actual test subject posture	Average MSE and standard deviation across all test subjects
Upright	0.017±0.014
Slouching	0.780±0.162
Leaning forward	0.397±0.094
Leaning back	1.656±0.431

In the context of posture guidance, the repeatability of the system is more important than the ability to identify discrete postures. The average MSE for a given posture was slightly different each time the person sat down in the chair. However the variability was small compared to the MSEs for the alternate postures. Table 3.4 shows the variation in MSE values for the upright posture for all subjects. The small standard deviation and significant change in MSE for slouching, leaning forward, and leaning back are confirmation that our posture sensing and feedback system is both repeatable and accurate for our application.

The MSE threshold was empirically determined to be 0.07 for the upright posture for all subjects. This number was chosen taking into account the average MSE for upright posture, the upper bound envelope for upright posture, and any confounding effects with other postures. This threshold for haptic feedback activation was high enough to accept all upright postures, yet low enough so that non-upright postures could be detected and rejected.

As mentioned earlier, the focus of this study is to guide participants to a reference posture, not to specifically identify a posture. The data described above serves to demonstrate the sensitivity of the system to various postures with the magnitude of the MSE indicating how close the subject is to the reference posture. The next section describes how the MSE is used to generate feedback for the user.

3.4.3 Part III - Posture Feedback

All 10 subjects from the posture repeatability study participated in Part III of the experiment. During the "no feedback" phase (see Figure 3.6), all of the test subjects were observed and identified in a slouching or leaning back working posture. Over the course of two days of testing, three subjects sat in the upright posture on average 1.2% of the time on Day 1, and only one of the subjects sat in the upright posture on Day 2 (10.6% of the time). The remaining subjects did not sit in the upright posture at any time during the "no feedback" phase of the test.

During the "feedback enabled" phases, subjects responded well to the vibrotactile feedback. Within a minute of the initial onset of the haptic feedback, subjects were able to learn the vibration feedback mapping and adjust their body into the proper posture that would eliminate the vibration. As a result, subjects spent most of their time sitting in the upright posture. Subsequent vibrotactile feedback required only a few seconds of activation before subjects resumed the reference posture. This shows that the current vibration feedback mapping was indeed intuitive. Some subjects were "buzzed" more often than others, indicating that they relied on feedback to sit in the reference posture. Surprisingly, none of the test subjects adjusted the vibration intensity knob; all of them kept the knob at its default setting, leading us to believe that the feedback intensity was acceptable to the subjects.

When the feedback was disabled without the subjects knowledge ("feedback disabled" phases), all of the subjects initially continued to sit in upright or near-upright postures. However, as time progressed, most of the subjects became engrossed in their work (either on the computer or in their textbook assignments) and assumed slouching or leaning forward postures, or sometimes leaning left or leaning right postures. At the onset of the next "feedback enabled" phase, subjects would

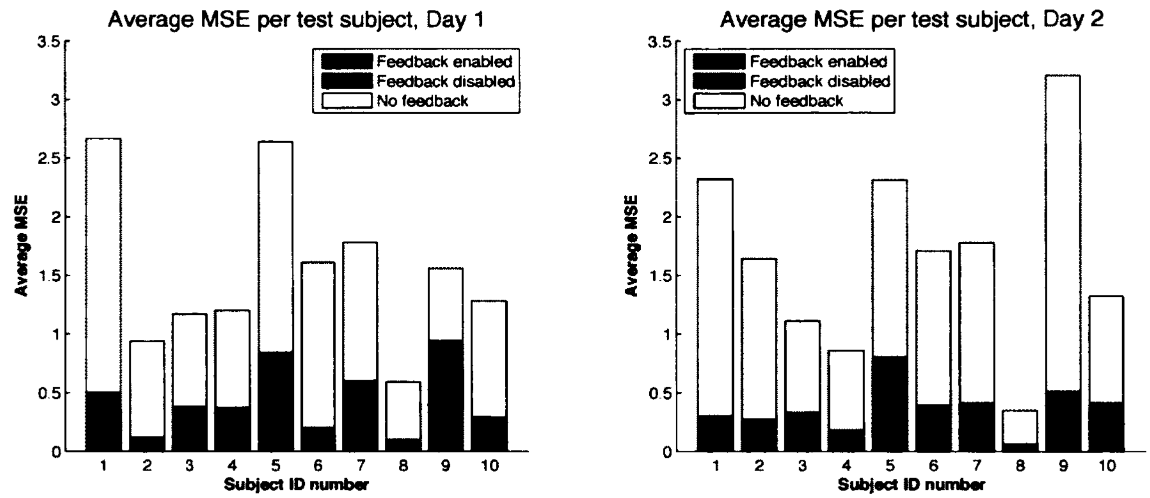

Figure 3.10: Plot of average MSE's for each feedback mode (no feedback, feedback enabled, feedback disabled) for all 10 subjects for both days. Low average MSE's are more favorable than high average MSE's as they indicate postures closer to the desired upright posture. In the "feedback enabled" mode, all subjects were able to successfully comply with postural guidance.

often jolt up and then move into the desired posture according to the vibrotactile feedback.

The MSE calculated against upright posture was lowest for all test subjects for the "feedback enabled" phases, low for the "feedback disabled" phases, and very high for the "no feedback" phase (Figure 3.10). In the absence of any incentives to sit in a particular posture, subjects clearly gravitated towards non-upright postures. However, with intermittent vibrotactile feedback, subjects moved their body to respond to the feedback and sat in the desired reference posture more often. When the feedback is disabled, subjects thought they would be buzzed if they sat in an inappropriate posture, so they continued to sit in the reference posture until they forgot or became tired. Therefore it is not necessary to enable feedback all the time when intermittent feedback seems to suffice.

By the end of the test on Day 1, all of the subjects suspected that the only allowable posture was the upright posture. However, when returning for the second day of feedback testing, which was at least 24 hours after their initial test, sometimes as long as one week after their initial test, none of the subjects assumed they were going to be guided into the same upright posture again. In fact, all of them suspected they were going to be guided into a different posture (data informally collected via a verbal interview). Therefore, when the tactors initially started vibrating, they actively focused on interpreting the vibration feedback mapping to sit in the appropriate posture. However, they quickly realized they were being guided into the same posture as Day 1.

Surprisingly, this knowledge did not encourage subjects to always sit upright, nor discourage them from paying attention to the vibrotactile feedback. When doing their work, subjects often forgot about the desired reference posture (or were tired of sitting in the same posture) and started slouching, leaning left or right, crossing their legs, etc. When the lumbar tactor and the tactors under their legs started vibrating, for example, they would suddenly remember to sit up straight and put their feet flat on the ground again. For future studies, we will attempt to guide the subject into multiple postures, as sitting in one single posture may not be comfortable for long periods of time. In this way, they can be guided into specific body orientations as opposed to instinctively assuming the "upright" posture.

Also on Day 2 of the feedback testing, during the feedback disabled phases, three of the subjects thought the feedback system was broken because they noticed they had been slouching, yet had not received any vibrotactile feedback. These three subjects verified their suspicion by purposely moving around in their chair (crossing legs, standing up, etc.) to try to enable the feedback. When their suspicion was confirmed, they sat in the slouching or leaning back posture and continued with their work before the next "feedback enabled" phase.

Only one of the test subjects voiced frustration with the upright posture. On Day 2, the subject managed to sit in a comfortable position (leaning forward and slouching with hunched shoulders) such that the vibrotactile feedback was not triggered. This result indicates that it is possible to sit in an "MSE-acceptable" posture yet not be in the reference posture, and demonstrates the limitations of our posture sensing system. It is therefore necessary to design a better sensing and classification system that can prevent this unwanted behavior. Simultaneously, this "cheating" behavior highlights the importance of obtaining a reasonably comfortable primary calibration; the subject might not have assumed the awkward posture if the primary calibration was more comfortable. Therefore addressing this user's attempts to circumvent the feedback might be accomplished by smarter sensing, or by ensuring the target posture is not too difficult or uncomfortable.

Finally, in post-testing interviews, subjects reported favorable attitudes towards the haptic feedback. Only a few subjects reported being significantly distracted by vibrotactile feedback. Since subjects were able to maintain the desired posture even when the system was disabled, it should be possible to optimize the periods of feedback and minimize distraction.

In summary, over the course of two days of feedback testing, subjects spent significantly more time sitting in the desired reference posture (upright) when there was haptic feedback than when there was not. Even when the feedback was temporarily disabled without the subject's knowledge, subjects would continue to sit in the reference posture, or close to the reference posture. Furthermore, subjects unanimously responded correctly to the haptic feedback. These results suggest that vibrotactile feedback can be effective in guiding and altering human motor behavior, especially as it relates to seated posture.

3.5 Conclusion

In this study, we have successfully implemented a simple, low-cost posture sensing and feedback system using only 7 FSRs and 6 tactors. The posture sensing system is fairly robust, achieving 86.4% accuracy for distinguishing among 10 postures and 93.8% for 4 postures. Additionally, we determined that test subjects sat repeatably in the four reference postures (upright, slouching, leaning forward, and leaning back), which aided in the identification process. The subjects' repeatability allowed for the easy computation of the MSE threshold for the upright posture. This threshold remained the same for all 10 test subjects, and was adequate for signaling the activation of vibrotactile feedback.

We have also successfully shown the effectiveness of haptic feedback for coaching motor behavior in the form of seated posture. When there was no feedback, a subject's natural working posture was slouching or leaning back in the chair. When the vibrotactile feedback was turned on, all of the subjects were able to sense the feedback and correctly respond to the guidance. During these feedback enabled phases, subjects received sporadic "buzzes" to guide them into the desired posture. When feedback was temporarily disabled without the subject's knowledge, they continued to sit in the desired posture, or close to the desired posture. This leads us to conclude that only intermittent feedback is required to cause a subject to sit for a period of time in a desired posture.

Our current study makes two contributions based on multiple resource theory and prior seat sensing research. First, we have designed and evaluated a low-cost, low-complexity system, and have developed a method for computing the magnitude of error from a reference pose. This method requires a short calibration procedure, and the system uses a continuously valued error signal indicating the degree of match rather than a binary match. Second, we have designed and implemented a haptic feedback system that guides individuals to a reference posture using continuously variable, real-time feedback. The feedback is zero or very small when the errors are small and becomes more intense when deviations are larger.

In conclusion, we have demonstrated that vibrotactile feedback can be an effective means of communicating musculoskeletal commands to the human sensory-motor system. Furthermore, the results of this study can be extended to apply to the domain of physical training and rehabilitation.

Chapter 4

Task Interference from Responding to Vibrotactile Posture Feedback Guidance

4.1 Overview

This chapter investigates the level of task interference from responding to vibrotactile posture feedback while performing standard office tasks. In the previous chapter, we have shown that all subjects sat in the upright posture more often when feedback was enabled than when feedback was disabled, demonstrating that vibrotactile feedback was effective for improving both performance and longer term training in sensory-motor tasks.

This chapter builds on our work in Chapter 3 to refine the design of a vibrotactile posture feedback chair. We now aim to characterize the amount of task interference that our feedback chair imposes on the user. The dual-task methodology is often used to assess task interference [15]. Since we are trying to simulate an office setting, we aim to evaluate the performance degradation of a typing task while the user is simultaneously responding to posture guidance.

4.2 System Description

4.2.1 Equipment

The posture sensing and feedback system used for this study is the same as the one used in the previous study with one modification: the FSR in the rear of the seat was replaced by an infrared distance sensor (Sharp GP2D120 4-30cm range) attached to the top of the seat back (Figure 4.1). This allowed for more accurate sensing of the leaning forward, upright, and leaning back postures.

A Sony Digital Handycam DCR-TRV120 camcorder was used for recording live video in order to verify the subjects' postures.

4.2.2 Posture List and Sensor Placement

We evaluated a subset of the postures studied in [97], [146], and Chapter 3: upright, slouching, leaning forward, and leaning back. Figure 4.2 depicts the postures we aimed to identify and Table 4.1

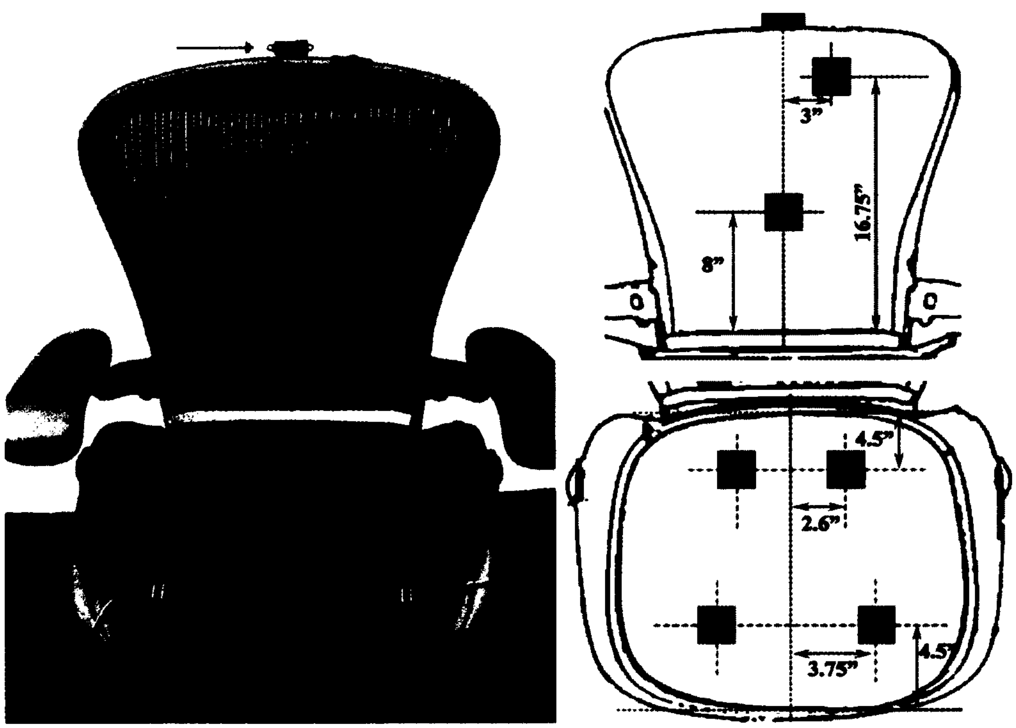

Figure 4.1: (Left) Slightly modified posture sensing and feedback chair with 6 force sensitive resistors (FSRs) and one infrared (IR) distance sensor (arrow). The FSR in the rear of the seat (Figure 3.1) has been replaced by the IR distance sensor for better back posture sensing accuracy. The locations of the tactors for posture feedback remain the same (see Figure 3.1). (Right) Placement of the FSRs (black squares) and IR distance sensor (black rectangle) on the seat back and seat bottom. Locations are based on key anatomical features as described in [25].

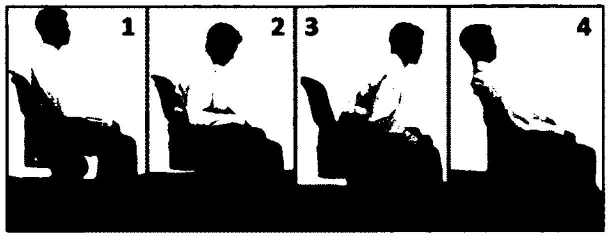

Figure 4.2: An example of each posture to be identified in this study: 1. upright, 2. slouching, 3. leaning forward, 4. leaning back.

Table 4.1: Description of each of the four postures to be identified

Posture	Description
upright	lordotic lumbar curve, back and thigh are at approximately 90°
slouching	kyphotic lumbar curve, hunched over
leaning forward	back straight and approximately 15°-30° from vertical
leaning back	back resting on seat back, relaxed

provides definitions of each posture. The choice of sensor placement is described in the previous chapter.

4.2.3 Posture Sensing and Feedback Algorithm

The mathematics of the posture identification algorithm is explained in the previous chapter. Even though the seventh FSR has been replaced by a distance sensor, the same algorithm can be used to compute the mean-squared error (MSE) from the voltage readings.

The posture feedback system guides the subject into three different postures: upright, leaning forward, and leaning back. (Subjects are not guided into the slouching posture as it is an unhealthy posture.) As explained in Section 3.3.3, the posture feedback algorithm calculates the MSE in real-time and activates haptic feedback when the MSE rises above a certain threshold. A threshold of 0.08V was selected empirically from previous experiments. Feedback is provided through the vibration of the tactors at variable intensities proportional to the amount of error at each sensor. At the onset of the feedback, the vibration intensity is also proportional to the elapsed time. This creates the effect of a gradually increasing vibration intensity to "gently" notify the subject (similar to an increasing volume alarm clock to gently wake up a person). The maximum feedback intensity may be adjusted by each test subject based on personal preference prior to the start of the experiments.

Table 4.2: Location of vibration, cause, and required motor action to properly respond to feedback guidance and eliminate vibrations. Unlike in Table 3.2, tactors vibrate sequentially depending on location of the most likely postural error. Additionally, leaning forward and leaning back directionality is encoded through continuous and pulsing vibrations on the shoulders.

Vibrating tactor location(s)	**Continuous or pulsating**	**Action required to eliminate vibration**
Lumbar	Continuous	Subject is likely slouching, need to sit up and reduce lumbar contact with back of chair
Left and right shoulders	Continuous	Subject is leaning back too much, need to move away from back of chair (i.e. sit upright or lean forward)
Left and right shoulders	Pulsating	Subject is leaning forward too much, need to lean back towards the back of the chair (i.e. sit upright or lean back)
Left thigh only	Continuous	Left leg is lifted or moved away from center of seat, need to put leg down or move towards center of seat
Right thigh only	Continuous	Right leg is lifted or moved away from the center of seat, need to put leg down or move towards center of seat

The location of the vibration corresponds closely to the region of the body where a sensory-motor action is needed. For example, if the tactor in the lumbar region vibrates, typically the subject is slouching, so the correct action would be to straighten the spine, decreasing the pressure on the lumbar sensor. Table 4.2 lists the location of the vibration and the corresponding required motor action. The feedback mapping was designed with the intent of being intuitive so that subjects would be able to quickly learn the mapping.

4.2.4 Typing Program

We developed our own typing program in order to gain access to detailed typing data. This simple program records the timestamp of each correct keystroke (Figure 4.3). The typing program is modeled after Typing Tutor 7. During each test, a short passage (mean 155 words, 882 characters) is presented on the screen. Test subjects are instructed to type the passage verbatim. Only correct keystrokes are recorded, i.e. incorrect keystrokes and backspaces do not display on the screen. After every 60 seconds, regardless of how far the subject has typed within the passage, the screen refreshes with a new passage. The passages refresh a total of 5 times for a 5-minute typing test. This refresh rate is chosen to prevent scrolling during the 5-minute test. The passages are designed to be long enough that someone typing less than 150 words per minute (wpm) will not be able to complete the entire passage in one minute. Each test duration is chosen to be 5 minutes as a compromise between typing fatigue and the number of feedback opportunities.

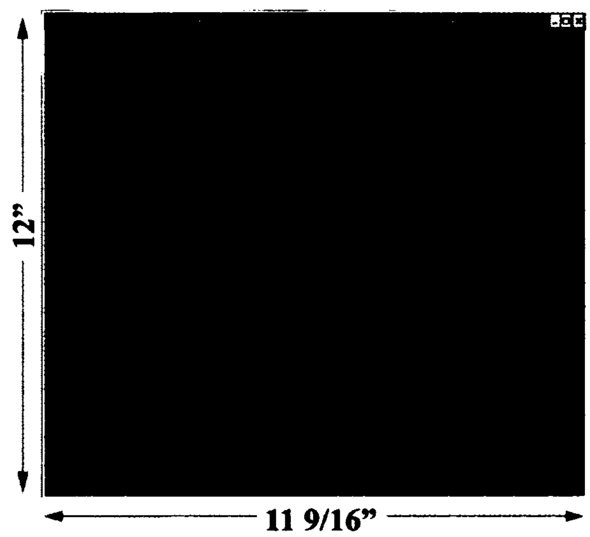

Figure 4.3: Typing environment used for the study. Test subjects had to type each passage verbatim and the timestamp of the correct keystroke was recorded. The computer monitor was placed 18” in front of the subject measured from the upright seated posture.

4.3 User Study

This section describes the user study to assess the amount of task interference experienced by test subjects as they perform a typing test while simultaneously respond to posture guidance. Prior to enrolling for the experiment, subjects perform an online typing test [113] and report their typing speed and the number of errors made for 3 trials. If the speed on all 3 trials is greater than 30 wpm, and the number of mistakes made is fewer than 10, then the subject qualifies for the experiment.

The experiment procedure is divided into three phases: calibration and pretest, dual-task test, and post-test (Table 4.3). The entire experiment takes approximately 45 minutes to 1 hour to complete, with 30 minutes of timed testing. Each phase of the test is explained below.

Calibration and training. The posture sensing system is calibrated to each subject. Subjects sit in the upright, slouching, leaning forward, and leaning back postures while calibration data is recorded. Subjects then perform a practice typing test in the typing environment. Finally, subjects familiarize themselves with the vibrotactile feedback mapping shown in Table 4.2. For example, when the tactors in the left and right shoulder pulsate, subjects are required to lean back until the vibrations stop. Since vibrotactile feedback is proportional to the amount of error, vibrations decrease in intensity as subjects move closer to the desired posture. In the experiment, subjects are guided into upright, leaning forward, and leaning back postures. (The slouching posture is an

Table 4.3: Test sequence for this study

Phase	Time Limit	Trials
Calibration and training	15-25 min	1
Pretest (typing only, then feedback only)	5 min each	1
Dual-task (typing with feedback)	5 min each	3
Post-test (typing only)	5 min	1

unhealthy posture and subjects are not guided to it.)

Pretest. Each subject's baseline typing speed is measured while the feedback is disabled. A second test measures the subject's baseline reaction time while the typing test is disabled. We define reaction time as the time it takes the subject to respond to the feedback and turn off the vibrations.

Dual-task test (DT). Subjects perform 3 trials of this test. In each trial, subjects type for 5 minutes while responding to vibrotactile posture feedback. The feedback guides the subject to a randomly assigned posture (upright, leaning forward, or leaning back) approximately every 30 seconds. If within each 30-second interval the subject deviates from the desired posture, the vibrations start again. Posture data is collected and feedback is updated four times per second. Subjects are told to maintain their normal typing speed. Their typing speed and reaction times are recorded.

Post-test. In this final phase, vibrotactile posture feedback is turned off and subjects' typing speed is measured again for a final 5-minute typing test.

Prior to the start of the experiment, subjects are instructed to empty their pockets, as objects in the rear and side pockets may substantially alter the pressure mapping. They are also instructed to adjust the seat height and armrest height until their feet are flat on the floor and their thighs are parallel to the ground per the proper seating guidelines presented in Appendix B.

4.4 Results

A total of 20 subjects (14 male, 6 female) participated in this study. The mean age and standard deviation of the subjects was 25$\pm$3.2 years, with an average weight of 71.6$\pm$17.7kg and height of 172$\pm$9.3cm. Sixteen of the 20 were observed to be touch-typists, while 4 were hunt-and-peck typists. Regardless of typing style, all test subjects were able to type faster than 35 wpm.

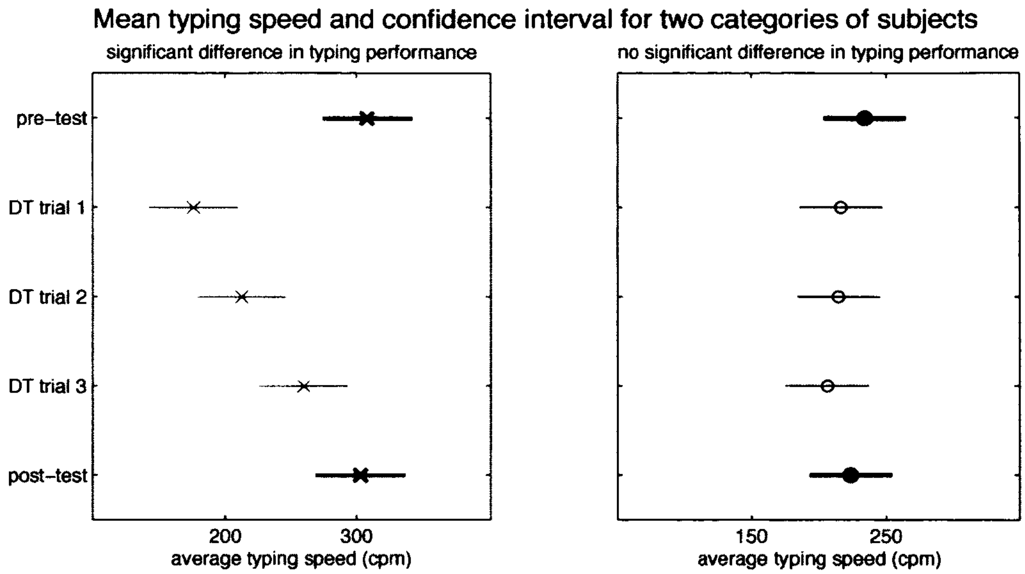

Figure 4.4: A representative plot of typing performance from two subjects illustrating two categories of results: (left) 55% of subjects experienced statistically significant decrease in typing speed between the single-task (pre- and post-test) trials and the dual-task (DT) trials 1-3, although 90% of subjects experienced some amount of typing performance degradation. The plot on the left also highlights improvement across DT trials (70% of subjects) whereas the plot on the right shows no such consistent improvement (remaining 30% of subjects). Bolded lines indicate pre- and post-test trials. For all subjects, there were no statistically significant differences between their pre- and post-test typing speed.

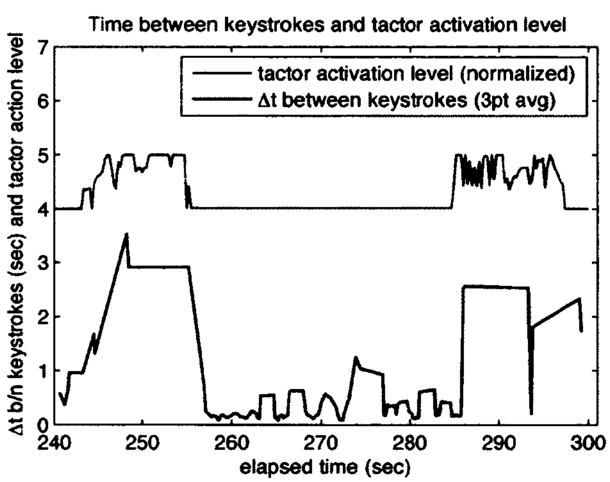

Figure 4.5: An illustrative plot from one test subject showing time between keystrokes and tactor activation level for the last minute in a five-minute test. Tactor activation level is offset for better clarity in the plot. For this subject, as well as many others, as soon as the tactor activated, the subject paused or stopped typing to respond to postural guidance, and resumed typing shortly after the vibrations stopped.

Typing speed. We define average typing speed as characters per minute (cpm), and instantaneous typing speed as characters per second (cps). The timestamp of each correctly typed character was recorded and the typing speeds were computed after the experiment

We define statistical significance as $p < 0.05$. We found that none of the subjects showed a significant difference in mean typing speed between the pretest and post-test phases. The median change in typing speed from pretest to post-test was +0.8cpm (+0.21%). Due to the wide variability in typing performance from subject to subject, the median was chosen to be the more reliable indicator.

A one-way ANOVA was performed on average typing speed for each subject, comparing pretest, DT trials 1-3, and post-test typing speeds. We found that 55% of the subjects exhibited a significantly lower mean typing speed during DT trials 1-3 versus the pre- and post-tests (an example of subjects in this category is shown in Figure 4.4, left). In total, 90% of the subjects showed some amount of decrease in mean typing speed between the pre- and post-tests and the DT trials. The median decrease in speed from the combined pre- and post-tests to the combined DT trials was 33.1cpm, while the median percentage speed decrease was 14.6%.

A snapshot of time between keystrokes and feedback level from one test subject is shown in Figure 4.5. Notice that when the feedback was on, the time between keystrokes often increased. This can be attributed to the subject focusing on adjusting his posture to stop the vibrations at the cost of typing slowly or stopping the typing altogether. Sometimes when the subject has successfully turned off the vibrations, his time between keystrokes may have remained high. This was due to the fact that he had lost his place in the passage and needed time to refocus on the typing task after the disruption. (Some subjects, such as the one whose data is shown in Figure 4.5, had trouble maintaining the desired posture through-out the 30-second interval. Vibrotactile feedback was triggered to guide the subject into the desired posture once again.)

We also found that 70% of the subjects exhibited a performance improvement from DT trials 1 through 3 (Figure 4.4, left). However the improvement was statistically significant for only one of the subjects. The median speed increase for all subjects from DT trial 1 to trial 3 was 25.7cpm (12.3%).

Finally, over half of the subjects in total exhibited a statistically significant difference in mean typing speed when analyzed by posture (DT trials 1-3 combined). Relative to the leaning forward posture, 20% of the subjects exhibited a significant speed increase for the upright body orientation (range: +14.0% to +59.5%). Meanwhile 45% of the subjects displayed a significant speed decrease in the leaning back posture (range: -11.5% to -34.6%). This implies that some postures could be sat in or guided into more easily while typing than others. In fact, almost all of the test subjects expressed difficulties in maintaining the leaning forward and leaning back postures while typing.

Reaction time. In Section 4.3, we have defined reaction time as the time it takes subjects to respond to the feedback and turn off the vibrations. When comparing the vibration pretest with the DT trials, we found that 30% of the subjects required significantly longer times to successfully respond to the vibrations by shifting their postures. The median reaction time for the vibration pretest was 3.250 seconds while the median reaction times for DT trials 1, 2, and 3 were 4.031, 4.500, 4.000 seconds, respectively. This result agrees with the prediction of faster response times in single-task performance than dual-task performance. It is promising that in the dual-task scenario, the reaction time increased by less than 2 seconds.

We expected the time required to move from one posture to another to be correlated with the required displacement of the body. Adjusting between the leaning forward and leaning back postures requires the largest change in body position, while adjusting between the upright and leaning forward postures requires the smallest change. When all of the subjects data were grouped together and analyzed by posture transition, we found that the leaning back posture resulted in the longest transition time, meanwhile moving into the upright and lean-ing forward postures required approximately the same amount of time. Table 4.4 lists the median transition times for each posture for all DT trials for all subjects combined.

Even though subjects' typing performance improved over the course of the three DT trials, we also found no correlation ($R^2 < 0.11$) between reaction time and the total amount of time using the system (vibration pretest and DT trials).

Table 4.4: Median time to respond to feedback, all subjects combined. Some postures were easier to move into than others while simultaneously typing.

Posture Transition	**Median Time**
Leaning forward to upright	3.250 sec
Leaning back to upright	3.750 sec
Upright to leaning forward	3.250 sec
Leaning back to leaning forward	3.735 sec
Upright to leaning back	5.250 sec
Leaning forward to leaning back	5.571 sec

4.5 Discussion and Limitations

The decrease in typing performance experienced by 90% of the test subjects indicates that the current vibrotactile posture feedback system is disruptive and takes the subject's concentration away from the typing task (i.e. induces a higher mental load). This also suggests that, while subjects claim to have learned the feedback mapping during the training phase, the mapping is still rule- or knowledge-based and has not become skill-based [117, 118]. In other words, the feedback mapping is still unfamiliar and requires a certain amount of mental processing to respond correctly. However it is encouraging that 70% of the subjects showed an improvement in typing performance over the course of the 3 DT trials. This implies that, over time, the feedback mapping may become skill-based and automatic, thus imposing lower mental workload on the user.

The disruptive nature of vibrotactile feedback points to an opportunity for context-sensitive feedback (see Chapter 11); future work may enable a system to infer a user's mental load and only interrupt the user when he is not highly focused on the primary task. The perceived disruption and annoyance of vibrotactile feedback also motivates us to evaluate other feedback mechanisms for posture guidance (see Chapters 6 and 7). Visual displays and acoustic feed-back aside, other possible methods include non-audible force feedback mechanisms that gently push (or pull) the users back for posture guidance. (This mechanism may be similar to that of a massage chair.) Because such a system delivers soft nudges (or tugs), it may cause less disruption to the user com-pared with vibrotactile feedback.

There was no significant correlation between reaction time and the elapsed time of the test. This result may be attributed to the reaction time particular to each test subject, and therefore does not necessarily increase or decrease over the course of the experiment. Additionally, in this short experiment, subjects may not have had time to adequately internalize the feedback mapping and therefore were at the higher bound-aries of their reaction time. A longer study over a period of several days or weeks may be needed to see a more substantial improvement in both the subjects reaction time as well as typing performance.

4.6 Conclusion

The goal of this study was to understand the level of task disruption that our vibrotactile posture feedback chair imposed on the office worker. We have shown that for more than half of the test subjects, responding to a change in posture command from our feedback chair imposed a statistically significant task interference. However, over the course of three dual-task trials of typing with vibrotactile feedback, most of the subjects showed improvement in their typing performance. Our previous research showed that subjects were able to maintain a desired position for at least five minutes even when the feedback system was disabled (Chapter 3). Together, these two studies suggest that the current implementation of of vibrotactile feedback causes substantial primary task disruption, and also initiating changes in posture too frequently is likely to be disruptive. However, subjects can improve their compliance to a given posture over time as well as the speed with which they can react to changes in the reference posture.

Chapter 5

Comparison of Visual and Vibrotactile Feedback Methods for Seated Posture Guidance

5.1 Overview

This chapter presents an extension of our work in Chapters 3 and 4: here, we compare the effectiveness of vibrotactile and visual feedback methods for guiding seated postures. For visually dominant office work such as typing on the computer, we presume that delivering posture feedback visually may overload the visual sense while haptic feedback may be a viable alternative. We perform two experiments to evaluate this assumption. The rest of the chapter describes a posture feedback system that uses either vibrotactile or visual feedback to guide the posture of a seated typist, and compares the effects of each type of feedback on both posture compliance and typing performance.

5.2 System Description

5.2.1 Posture Specification

In this research, our intent was to effectively distinguish between and guide subjects to four reference postures: upright, slouching, leaning forward, and leaning back. These were the same set of postures as in the previous study (Chapter 4, Figure 4.2). A description of each posture is listed in Table 4.1 in the previous chapter.

5.2.2 Prototype Development

The Posture Seat used for this study is exactly the same as the one used in the previous study (Chapter 4). The FSRs are adhered to the surface of the mesh seat and seat back. Sensor placement on the Posture Seat is based on ergonomic data from [25, 150]. Tactors for vibrotactile feedback were the same ones as were used in the previous study, and their placement is shown in Figure 4.1. Tactor vibration intensity is controlled by the applied voltage. Increasing the voltage increases the motor speed, which increases both frequency and amplitude of vibration.

Developing a visual feedback system comparable to the vibrotactile system is inherently challenging. There are differences in the visual and haptic senses. Visual display metaphors are well established while haptic display metaphors are relatively immature. Haptic icons are still notional [84] while vision affords much higher information densities. Since posture is an inherently spatio-proprioceptive task and it is generally accepted that the visual and haptic senses are better than the auditory sense for encoding spatial information, we deemed it most appropriate to compare vibrotactile and visual feedback in this seated posture task. Furthermore, both visual and haptic feedback have the benefit of being "private" in the office environment as they would be imperceptible to nearby workers.

Our desire is to compare two plausible approaches to posture feedback in an office task. As such, our visual system needs to fit on a standard LCD computer screen and have similar salience and attentional characteristics as the haptic feedback display. A visual display that is large or requires a mouse click to dismiss would be "unignorable," while one that is too small would be prone to inattentional blindness. As a compromise, we use a window area of approximately 3.5" x 12". The intent is to create a visual display that is analogous to the vibrotactile display to avoid biasing the results towards one feedback method or another. (More details about the visual feedback system are provided in Section 5.2.3.2.)

The primary control unit of the Posture Seat is a PC running LabVIEW and Matlab. LabVIEW interfaces with a NI-DAQ USB-6212 data acquisition box for obtaining posture data (pressure mapping and distance values). The appropriate posture feedback levels are calculated in Matlab. For vibrotactile feedback experiments, the commands are delivered via LabVIEW to the tactors.

The tactors are each controlled by a 3kHz PWM voltage between 0-3V using a motor controller (Castle Creations Pixie-7P), which are run from a servo controller board (Lynxmotion SSC-32). For visual feedback experiments, feedback is displayed on a 19" LCD computer monitor approximately 18" in front of the user.

5.2.3 Posture Sensing and Feedback Algorithm

The posture identification algorithm computes the mean-squared error (MSE) between calibration posture sensor values and real-time sensor values and generates a feedback command based on the magnitude of the MSE. The pressure and distance data are recorded as voltages. The sensing and feedback algorithms are the same as in Chapter 3. The posture MSE threshold, H, is chosen heuristically to maximize identification of independent postures. In this study, $H = 0.08$V.

The posture feedback algorithm involves calculating the MSE in real-time and activating feedback when the instantaneous MSE ($M_{i,j}(t)$, henceforth abbreviated $M(t)$) rises above the threshold H. The feedback is provided either through the tactor vibration at variable intensities proportional to the amount of posture error, or brightening or dimming the round indicators on the visual display.

For the feedback experiments, a feedback activation time delay is incorporated into the system to allow brief movements away from the desired posture without triggering feedback. The time delay is encoded as a proportional-integral (PI) gain on $M(t)$, where $K_p = 1$ and $K_I = 1/$(sampling frequency). If the cumulative MSE $E_{i,j}(t)$ (henceforth abbreviated $E(t)$) rises above a threshold g for a period of time, vibrotactile or visual feedback will be enabled ($a(t)$). In discrete time, the cumulative MSE can be determined by

$$E(t) = \begin{cases} 0 & \text{for } M(t) < h \\ K_p M(t) + K_I E(t-1) & \text{for } M(t) \geq h \end{cases} \tag{5.1}$$

and whether or not feedback is active is determined by

$$a(t) = \begin{cases} 0 & E(t) < g \\ 1 & E(t) \geq g \end{cases} . \tag{5.2}$$

The command to the tactors and visual icons is the product of $E(t)$ and $a(t)$. Note that at $t = 0$, $E(0) = 0$. Therefore $a(0) = 0$ as well. The threshold g is empirically set to 1.00, which corresponds to several seconds of allowable posture deviation before feedback turns on.

5.2.3.1 Vibrotactile feedback

The vibrotactile feedback is designed to deliver location-specific stimuli that facilitates localized adjustments in body orientation. Each of the six tactors is placed such that the perceived vibratory sensation is near the region of the body that should be moved: tactors under the thigh signify thigh movement, tactors behind the shoulder indicate upper back movement, a tactor in the lumbar region signifies lower back movement, and a tactor in the seat rear indicates full body movement. The vibration intensity is proportional to the amount of posture error. As the vibration "volume" becomes softer, the user is approaching the desired reference posture. The goal state is achieved when there is no vibration.

Table 5.1 lists the location of the vibration and the corresponding muscle motor action that needs to be taken. For example, if the tactor in the lumbar region vibrates, typically the person is slouching, so the correct action is to sit up straight. Similar to Chapter 4, vibrotactile feedback is delivered sequentially based on the location of the largest postural error in order to minimize feedback confusion.

Tactor vibration intensity may be increased or decreased but there is no inherent directionality encoding in the vibration. Thus, we must decide how to differentiate too much pressure from too little pressure. Anecdotally, we observed that some areas of our body had an instinctive repulsive response to vibration, leading us to believe that moving away from vibration might be a relatively natural response. We used this approach for all of the tactors on the back, increasing the vibration intensity as the pressure increases above the reference value. Conversely, when the pressure was too low, the tactors pulsed instead of vibrating continuously.

Table 5.1: Vibrotactile feedback mapping: location of vibration, cause, and required motor action

Vibrating Tactor Location(s)	**Possible Improper Body Orientation**	**Action Required to Eliminate Vibration**
lumbar	slouching	sit up
rear of seat	leaning forward or not sitting all the way back in the chair	sit back towards upright, or sit all the way back into the chair
left thigh only	left leg lifted or crossed over right	put left leg down
right thigh only	right leg lifted or crossed over left	put right leg down
left and right shoulders, continuous	leaning back	lean forward towards upright
left and right shoulders, pulsating	leaning forward	lean back towards upright

For the leg tactors, an unexpected behavior was observed. Participants in the preliminary testing seemed to initially press down with the leg when they felt a continuous vibration. Rather than work against instinctive responses, we reversed the mapping for the legs, with continuous vibration signaling too little pressure and pulsing signaling too much pressure. Although the mixture of continuous and pulsating feedback is inconsistent for the seat bottom and seat back, it appeared to be more natural for subjects.

5.2.3.2 Visual feedback

The visual feedback system is comprised of an icon to signify the current desired posture and six spatially located color changing round indicators to communicate the location and magnitude of the posture errors. As mentioned earlier, the size and dual nature of the display was selected so as to maintain salience while allowing the subject to continue typing.

At the top of the visual feedback window (Figure 5.1), a stick figure icon depicts the desired posture when the feedback is active, and disappears when the subject successfully sits in that posture. (The 3 different icons are shown in Figure 5.2.) Below the icon, six round indicators are overlaid on the graphic corresponding to a person's back and thighs, thus preserving the spatial location of the tactors. The colored indicators become more grey when the error is small, and become more red or blue when error is large. The brightness of the colored indicators is directly proportional to the amount of posture error. Indicators on the back turn bright red when there is too much pressure on the sensors (when guiding to upright and leaning forward postures), and they turn bright blue when there is not enough pressure (when guiding to the leaning back posture). Indicators on the thighs turn red when there is not enough pressure on the sensors. This mapping mimics the vibrotactile system; based on the inconsistent mapping that subjects demonstrated with the vibrotactile feedback, we chose to maintain the same directional bias with the visual system.

The visual feedback graphic occupies approximately 23% of the screen, small enough so that it does not affect the available screen area for the primary typing task, yet large enough for the viewer to notice changes. We deliberately avoid pop-up windows that require mousing actions since the vibrotactile system does not require users to move their hands from the keyboard. For the same reason, screen scrolling is disabled for the typing tasks.

The required muscle motor actions for each feedback location are shown in Table 5.2. Notice that this mapping is similar to the vibrotactile feedback mapping in Table 5.1.

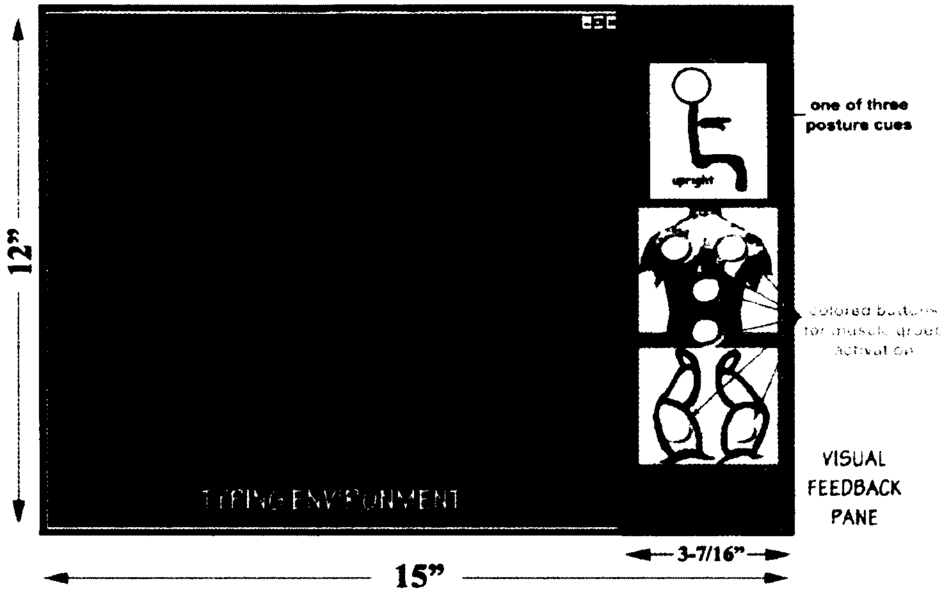

Figure 5.1: Monitor occupied by typing environment and visual feedback pane. Monitor was placed 18" in front of the subject as measured from the upright seated posture.

Figure 5.2: One of these three icons may appear at the top of the visual feedback pane to guide user into that reference posture.

Table 5.2: Visual feedback mapping: location of indicators, cause, and required motor action. This was designed to be a "visual equivalent" of the vibrotactile feedback mapping.

Indicator Location(s)	**Color**	**Possible Improper Body Orientation**	**Action Required to Dim Indicator**
lumbar	red	slouching	sit up
shoulders, lumbar, and lower back	red	leaning back	lean forward away from the back of the chair
shoulders	blue	leaning forward	lean back towards the back of the chair
left thigh only	red	left leg lifted or crossed over right	put left leg down
right thigh only	red	right leg lifted or crossed over left	put right leg down

5.3 User Studies

This section describes the procedures for two experiments that were performed using vibrotactile and visual feedback for seated posture guidance. The first experiment evaluated the effectiveness of each feedback method to achieve postural compliance (Section 5.3.2). The second experiment assessed the performance effects of responding to posture feedback while simultaneously performing a standard office task (typing) (Section 5.3.3).

5.3.1 Setup and Preparation

Prior to the start of all experiments, subjects were instructed to empty their pockets as objects in the rear and side pockets can shift, resulting in erroneous pressure readings. They were also asked to adjust the seat height and armrest height until their feet rested flat on the floor, their thighs became parallel to the ground, and their forearms were approximately horizontal. Cameras recorded live video or still images of the subjects' seated postures. The images were used as a visual reference to verify that subjects indeed sat in the posture recorded by the chair sensors.

5.3.2 Posture Compliance

In this experiment, we examined whether subjects sat in an upright posture while working on a computer, both with and without posture feedback. Subjects were instructed to sit in a comfortable working position in the chair while doing their own work (e.g. checking email, surfing the web, etc.). The system was used to take calibration readings for 4 different postures: upright, slouching, leaning forward, and leaning back. After calibration, participants were given practice time to learn the feedback mapping per Table 5.1 or Table 5.2. Training ended when the user verbally confirmed his familiarity and comfort with responding to the feedback. Subjects typically felt comfortable with the system after 3-5 minutes of practice.

The vibrotactile feedback group performed trials on two separate days for 45 minutes each, for a total of 2 trials. Results from the vibrotactile group showed no learning over the two-day period, so we ran only one trial with the visual feedback group. During each 45-minute trial, the system operated in one of 2 modes: *Unguided* mode and *Guided* mode.

When operating in the *Guided* mode, we aimed to provide feedback in a manner that would be tolerable during extended use. Providing too much feedback is likely to be disruptive while providing too little is likely to be ineffective.

We considered two approaches. The first approach was to set the threshold for the feedback higher so that the system would be active less often. The second approach was to set the threshold lower and disable the feedback periodically. This encourages subjects to assume the reference posture with greater fidelity while allowing them to relax occasionally. We chose the second approach since it is more consistent with physical therapy regimes and postural training methods. However, selection of the training cycle and threshold were heuristic for our work and need refinement by physical therapists in a future study.

The variables of interest for the posture compliance experiment are average MSE values for each mode, and reaction time to respond to upright posture feedback.

Unguided mode - 15 minutes. There was no postural guidance during the first 15 minutes of the study in order to observe subjects' natural working posture.

Guided mode - 30 minutes. The guided mode alternated between two periods: *Active* and *Inactive.* In the *Active* period, either vibrotactile or visual feedback was enabled. When the subject was not in the reference posture, at least one of the tactors would vibrate, or at least one of the round indicators would illuminate red or blue. The subject could feel the vibration of the tactors on their body, or see the visual icons on the computer screen.

In the *Inactive* period, feedback was deactivated for 5 minutes without the subject's knowledge. The inactive period allowed the subject to relax slightly without triggering any feedback. It was also an opportunity to observe how well the subject maintained an upright posture without feedback.

The active/inactive posture guidance cycle was repeated 3 times for a total of 30 minutes.

5.3.3 Task Interference in Dual-Task Scenario

The objective of this experiment was to characterize the effect of the posture feedback system on a typical office worker. Since office workers typically perform computer tasks, we chose typing speed as the first performance measure. The motor skill required for typing should impose relatively low cognitive load for experienced typists [63, 118]. Control of posture was the second task. Because subjects used the novel system for a short time, we expected their response to utilize primarily rule-based processing [118] for both vibrotactile and visual feedback.

Table 5.3: Test sequence for the task interference portion of the study

Phase	**Time Limit**	**Trials**
Baseline reaction time	5 min	1
Typing pre-test	5 min	1
DT (typing with feedback)	5 min	3
Typing post-test	5 min	1

We screened participants for an adequate level of typing proficiency through an online typing test [113]. In order to qualify for this task interference experiment, subjects needed to demonstrate that their average typing speed was greater than 30 wpm. Additionally, the number of mistakes per trial of the 75-word typing test needed to be fewer than 10.

Participants performed a typing test to familiarize themselves with the typing environment. Figure 5.1 in Section 5.2.3.2 shows the typing environment along with the visual feedback posture guidance (this is the same typing program that was used in Chapter 4). They were also provided a short training period to learn the vibrotactile or visual feedback mapping described in Table 5.1 or Table 5.2, respectively. Feedback was proportional to the mean-squared error from the reference posture; vibrations or brightness of the indicators decreased in intensity as subjects moved closer to the reference posture. In contrast to the posture compliance experiment, this experiment guided subjects into three postures: upright, leaning forward, and leaning back.

The experimental procedure was divided into three phases: pretest, dual-task test, and post-test (Table 5.3). The variables of interest are typing speed, time between keystrokes (interkey interval), and posture transition reaction time.

Pretest. Baseline reaction time to respond to feedback and typing performance were measured separately. We define reaction time as the time it takes the subject to reach the reference posture and turn off the feedback.

Dual-task test (DT) For each trial, the subject typed a passage for 5 minutes while simultaneously responding to vibrotactile or visual posture feedback. The feedback guided the subject to one of three randomly assigned postures (upright, leaning forward, or leaning back) approximately every 30 seconds. The subject was told to maintain his normal typing speed while complying with the posture feedback.

Post-test. In the final phase, posture feedback was turned off and the subject's typing speed was measured again for a final 5-minute typing test. This was to measure potential typing fatigue during the course of the experiment.

5.4 Results

This section presents the results of the two experiments involving vibrotactile and visual feedback posture guidance. We define statistical significance as $p < 0.05$.

5.4.1 Compliance to the upright posture

Table 5.4 shows the data from subjects who sat in postures that triggered feedback and required guidance to the upright posture. All 10 participants in the vibrotactile group and 15 out of 21 participants (71%) in the visual feedback group met this criteria. Six of the subjects in the visual feedback group sat in the upright posture throughout the trial and did not trigger any feedback.

Figure 5.3 shows the results of this experiment. Of the 25 participants reported in Table 5.4, all sat in a slouching or leaning back working posture prior to receiving postural feedback. In the *Guided* mode, subjects from both vibrotactile and visual feedback studies were able to adjust their posture appropriately to turn off feedback. During the "Guided mode - active" periods, most

Table 5.4: Test subject demographics for the posture compliance portion of the study

	Vibrotactile	Visual
N	10	15
male/female	8 / 2	8 / 7
age	23.9±1.45 years	24.8±3.63 years
weight	71.1±13.6 kg	68.9±12.0 kg
height	175±11.2 cm	172±11.2 cm

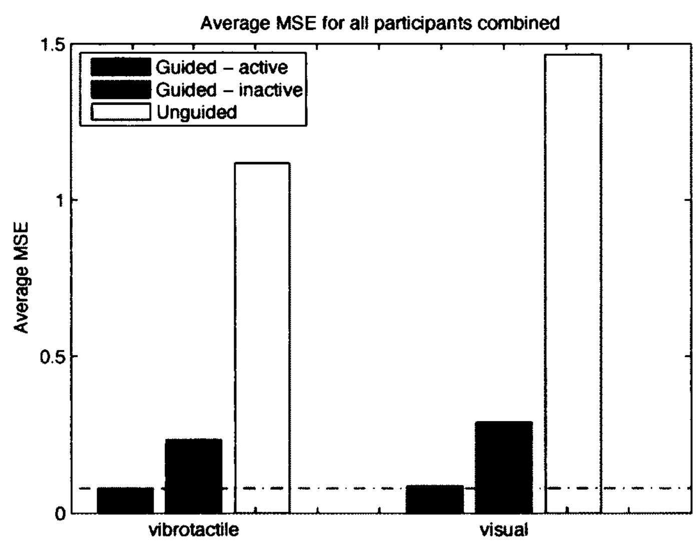

Figure 5.3: Comparison of average MSE between the vibrotactile and visual feedback groups for the three different experiment modes. MSE values below the threshold (blue dashed line, 0.08) indicates posture compliance. There were no statistically significant differences between the vibrotactile and visual feedback groups for each of the test phases, suggesting that vibrotactile feedback was comparable in effectiveness to visual feedback.

subjects sat in the reference posture. Some subjects experienced feedback more often than others, as would be expected.

When feedback was disabled without the users' knowledge ("Guided mode - inactive" periods), all of the subjects initially continued to sit in upright or near-upright postures. However, as time progressed, most subjects deviated from the upright posture.

At the onset of the next active posture correction cycle, participants in the vibrotactile feedback study appeared startled when feedback activated and then moved into the desired posture according to the vibrotactile feedback guidance.

All participants in the visual feedback study experienced inattentional blindness at some point during the test and therefore did not adjust their posture until they noticed the feedback from the visual icon. We defined inattentional blindness as not responding to feedback within 10 seconds of activation. In one instance, one subject took about 170 seconds before reacting to visual feedback. In post-test interviews, subjects reported that they did not deliberately ignore the feedback and changed their posture as soon as they noticed the feedback.

The mean-squared error from the upright calibration posture (Equation 3.2) was lowest for all subjects during the *Guided* mode and and very high for the *Unguided* mode (Figure 5.3). There was no statistically significant difference between vibrotactile and visual feedback methods for the modes (Guided - active: p=0.295, Guided - inactive: p=0.966, Unguided: p=0.193.)

In summary, both vibrotactile and visual feedback methods were equally effective in guiding posture, although visual feedback appears to be more susceptible to inattentional blindness. In the absence of any incentives to sit in a particular posture, subjects gravitated towards non-upright postures. However, even with intermittent feedback, subjects spent significantly more time sitting in the desired reference posture (upright). All participants were able to achieve each of the reference postures, thereby turning off the feedback signals.

5.4.2 Task interference in dual-task scenario

A total of 20 people participated in the vibrotactile feedback group while 21 people participated in the visual feedback group. All subjects were able to type faster than 35 words per minute (wpm) based on the results of the online typing test [113]. A summary of the test subject demographics is shown in Table 5.5.

A within-subject ANOVA followed by multiple comparisons test were performed on average typing speed for each subject, comparing pretest, DT (dual-task) trials 1-3, and post-test typing speeds. We found that 55% of the subjects in the vibrotactile study exhibited a significantly lower mean typing speed during DT trials 1-3 versus the pre- and post-tests. In comparison, only 43% of the visual feedback study subjects exhibited a statistically significant typing speed decrease. The median typing speed decrease between baseline and DT trials was 14.6% for vibrotactile feedback and 12.6% for visual feedback. There was no statistically significant difference in performance degradation between the two feedback methods.

For both vibrotactile and visual feedback studies, typing speed improved from DT trial 1 to trial 3 (Figure 5.4), indicating that there was a learning effect for postural guidance. For visual

Table 5.5: Test subject demographics for the task interference part of the study

	Vibrotactile	Visual
N	20	21
male/female	14 / 6	10 / 11
age	25.5±3.2 years	25.7±4.8 years
weight	71.6±17.7 kg	68.7±13.1 kg
height	172±9.3 cm	170±11.3 cm

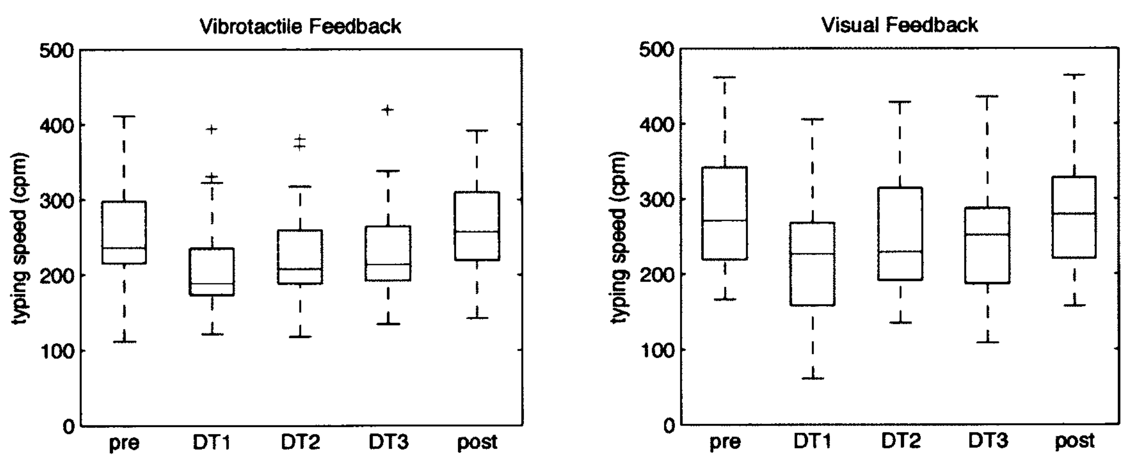

Figure 5.4: Comparison between vibrotactile and visual feedback groups of average typing speed, in characters per minute, for all subjects for each of the phases of testing. Red crosses indicate outliers. DT stands for Dual-task Test. In the vibrotactile feedback group, 55% of the subjects experienced statistically significant typing performance degradation from the single-task trials to the dual-task trials, while 43% of the people in the visual feedback group experienced such. Additionally, 70% of the people in the vibrotactile group experienced typing speed improvement from DT trials 1 through 3, and a comparable 67% of subjects in the visual group experienced typing speed improvement. For both groups, there were no statistically significant differences in typing performance between the single-task pre- and post-test trials.

Table 5.6: Important results from the dual-task interference experiment comparing vibrotactile and visual feedback methods

	Vibrotactile	**Visual**
% people with statistically significant typing speed decrease between single-task and dual-task trials	55%	43%
Median typing speed decrease (all subjects combined)	-14.6%	-12.6%
% people who improved between dual-task trials 1 through 3	70%	67%
Median typing speed improvement from dual-task trial 1 through 3 (all subjects combined)	+12.3%	+11.7%
% people with statistically significant changes in typing speed from single-task pre-test to single-task post-test	0%	0%
Median change in typing speed from pre-test to post-test	+0.21%	+0.21%
Median baseline (single-task) posture transition reaction time	3.0 sec	1.9 sec
Median dual-task posture transition reaction time	4.1 sec	2.5 sec

feedback, 14 out of 21 people showed a typing speed improvement between DT trials 1 through 3, with a median speed increase of 11.7%. For the vibrotactile feedback group, 14 out of 20 people showed a similar improvement, with a median speed increase of 12.3%.

Finally, when comparing the mean typing speed between pre-test and post-test phases, we found that none of the subjects showed a significant difference. The median change in typing speed from pretest to post-test was +0.21% for vibrotactile feedback and for visual feedback. Therefore, typing fatigue was not an important factor during the trials.

We found that the time between keystrokes (*dt*) increased substantially as subjects simultaneously tried to type while shifting their body in response to postural guidance. Some people focused solely on adjusting their posture at the cost of stopping their typing altogether. When subjects successfully adjusted their posture to turn off feedback, they often lost track of their place in the passage and needed time to refocus after the interruption.

Lastly we analyzed reaction time for transitions between each posture. The posture transitions were: upright to leaning forward, upright to leaning back, leaning forward to leaning back, and vice versa for the other three transitions. In the baseline phase (single-task posture transition without typing), subjects consistently responded to visual feedback approximately 1.1 seconds faster than vibrotactile feedback for all posture transitions (3.0 seconds for vibrotactile feedback and 1.9 seconds for visual feedback). In the DT phases, participants responded to visual feedback approximately 1.6 seconds faster than vibrotactile feedback for all posture transitions (4.1 seconds for vibrotactile feedback and 2.5 seconds for visual feedback). Results are summarized in Table 5.6.

5.5 Discussion

We aimed to compare the level of posture compliance and mental workload when responding to vibrotactile and visual feedback. Our results indicated that vibrotactile feedback and visual feedback had similar levels of effectiveness for guiding seated postures.

There was no statistically significant difference between vibrotactile and visual feedback for posture compliance; participants for both studies were able to attend to the feedback and sit in the appropriate posture within a few seconds. Additionally, test subjects maintained their reference posture even when feedback was disabled without their knowledge, suggesting that intermittent feedback may suffice to achieve posture compliance although choosing an appropriate duty cycle requires further investigation.

The task interference experiments revealed that both vibrotactile and visual posture feedback methods were disruptive in the dual-task typing scenario, with vibrotactile feedback causing a slightly greater disruption. The degradation could be due to several factors, including delayed action selection as a result of rule-based learning [118] and overloading of the response modality, explained as follows.

While subjects understood the feedback mapping during the training phase, the feedback mapping had not been sufficiently internalized and required the user to think about the appropriate motor response. However it was encouraging that approximately two-thirds of the subjects improved their performance over the course of the 3 DT trials. This implied that the feedback mapping could become skill-based and automatic over time, thus imposing lower mental load on the user. A study using longer trials is needed to understand long-term training effects using both types of feedback.

It is also possible that the typing performance degradation was due to response modality overload. While the feedback methods were different, both typing and posture adjustment required sensory-motor control and it is possible that these two tasks were competing for similar mental resources. An alternative method for determining the mental workload contribution from response modality might involve measuring subjects' speech rate while verbalizing a given passage. In this manner, the output modalities for the two tasks would be separate. However, we are focused on postural correction for office workers and as such, typing seems to be the most appropriate task.

Finally, analysis of the posture transition reaction times revealed that subjects responded slightly faster and more accurately to visual cues than vibrotactile cues even though the current embodiment of visual feedback design was susceptible to inattentional blindness. The faster response could be the result of providing icons for which there was no haptic analog. However, the difference in posture transition reaction time between visual and vibrotactile feedback was less than 2 seconds, suggesting that the two systems were comparable in performance when considered in the context of office work where posture changes might be recommended approximately every 20-30 minutes [22, 38].

5.6 Conclusion

Our posture guidance system using vibrotactile or visual feedback was effective for coaching posture. Although the task interference experiments showed that vibrotactile feedback was slightly more disruptive than visual feedback in a dual-task scenario, subjects' typing performance progressively improved over the course of the typing trials. This suggests that with enough training it is possible to learn and internalize the vibrotactile feedback mapping so that the action selection process may be more automatic.

The similar performance between vibrotactile and visual feedback should be encouraging to designers of feedback displays. Specifically, it implies that designers have the flexibility of using either feedback modality to guide whole-body sensory-motor tasks. In situations where the visual modality may be overloaded, the haptic feedback modality may be employed, and vice versa. Importantly, in cases where external visual displays might not be available or desirable, vibrotactile feedback could serve as a viable alternative. By decoupling the feedback method from the task, vibrotactile posture guidance could be used for many jobs in which a computer is not present, such as soldering, sewing, inspection and other seated activities.

In the informal post-experiment interviews with the test subjects, some of them reported that vibration felt insistent and annoying. This disruptive nature of vibrotactile feedback prompts us to investigate alternative forms of haptic feedback that can overcome these effects in two ways: first, by designing actuators that can potentially activate more mechanoreceptors in the skin other than those sensitive to vibration; and second, by reducing disruption to the user by reducing the negative affect associated with our actuators and actuation parameters – we hypothesize that stimuli linked to negative affect would be more attention-grabbing. Our findings from Chapters 3-5 set the stage for the development of haptic feedback systems that can deliver information at varying levels of attention capture.

Chapter 6

Haptic Actuator Design Parameters That Influence Affect and Attention

6.1 Overview

In the last three chapters, we found that vibrotactile haptic feedback methods were successful at guiding seated posture, albeit at the expense of primary task performance. Thus haptic devices that capture a user's attention can be annoying or disruptive when the user needs to focus on another task of higher priority. In this chapter, we undertake a comprehensive study to explore the affective (emotional) response to several haptic actuator designs and actuation parameters for better management of user attention. First, we design novel pressure actuators that reduce actuation frequency into a region that can be perceived as a pure displacement instead of vibration. Second, we characterize subjects' emotional responses to a wide range of haptic stimuli, including our vibration and pressure-based actuators, in order to systematically determine how we are altering both affect and attention. This study would thus provide detailed insight into the design of VAC haptic actuators by exploring the parameters that have the greatest influence on affect and attention capture.

6.2 Related Work on Affect

Affective design (designing for feelings or emotional responses) has been explored across many different disciplines, ranging from marketing to nursing to robotics [1, 8, 26, 48, 108, 140, 174]. In a simulated search-and-rescue mission, Bethel and Murphy found that robots with affective expression were perceived as more friendly and attentive to simulated disaster victims [8]. Yohanan, et. al. explored affective computing through the development of *Hapticat* to render a broad range of user affect with minimal creature features [173]. Haans, et. al. investigated remote social touch mediated by a vibrotactile vest and found that stimulus location on the body significantly impacted affective response [43]. Finally, most relevant to our present study is the work by Baumann, et. al. that found that symmetric pressure actuation profiles were more relaxing than asymmetric profiles [5].

Our current study builds upon existing knowledge on affect to investigate whether haptic actuator device designs can elicit positive affect and thus be capable of modulating user response along the attention capture spectrum as explained in Section 1.2.

6.3 Haptic Actuator Design

Mechanoreceptors in the skin are responsive to certain types of stimuli (Appendix A). For example, Pacinian corpuscles, Meissner corpuscles, and hair follicle receptors are sensitive to vibration while Ruffini corpuscles and Merkle discs are sensitive to pressure. Careful design of haptic actuators can selectively stimulate one or more mechanoreceptors to induce a desired sensation or behavioral response. In Chapter 4, we found that vibration on the back evoked an attention-getting, "annoyed" response that distracted the person from performing his office task. This led us to believe that devices or signals that elicit negative affect may only fall into the "demand action" end of the attention capture spectrum (Figure 1.2). We would like to examine whether a pure pressure stimulus, activating different mechanoreceptors than a vibratory stimulus, might be more apt for modulating attention across the whole spectrum.

In this study we explore the design of pressure actuators, called "pactors," and compare them to vibrotactile "tactors" for affective response, attention capture, and novelty of stimulus. Pactors are comprised of high-torque servo motors attached to cam arms that produce linear displacements at the "contactor head" – the part that comes in contact with the human. The contactor head, which can assume any number of geometries, presses against a person's skin at different speeds and actuation profiles. Although pactors can be actuated repeatedly to produce a tapping sensation, we will only consider simple pressure profiles in this study.

We use the same vibrotactile actuators ("tactors") as the ones developed in [95]. Tactors are comprised of eccentric mass motors mounted on an acrylic plate or rubber pad.

6.4 Affect, Attention, and Novelty Indices

The primary aim of the affect study is to explore key design parameters that influence affect. A secondary goal is to determine design parameters that influence attention capture and the perception of novelty. We will start with a broad set of tactor and pactor parameters in the preliminary study and reduce the size of this parameter list so that the affect study (Section 6.7) may be more tractable.

We will model an "affect index" as a function of the parameters that influence affect:

$$I = f(p_1, p_2, ... p_n). \tag{6.1}$$

In the simplest case, index I may be a linear combination of the individual parameters. In reality I may also contain terms that capture the interaction effects of the various parameters. The parameters p_i may represent both discrete and continuous variables, such as material type, intensity, radius of curvature, etc. The above equation can also be used to compute the attention and novelty indices.

Given the inherent variability in human cognitive function and the discontinuous nature of discrete parameter choices, it is unlikely that an absolute scale can be used for the affect, attention, and novelty indices. Instead, we propose to measure the relative change in the indices as each parameter is modified. In essence, we are interested in changes in parameters that will yield the greatest ΔI.

6.5 Parameter List

We will begin by examining the effect of vibratory and pressure feedback on affect while varying body location, stimulus intensity, actuation profile, material and geometry (see Figure 6.1 for reference). In a preliminary test with 5 subjects, we found that subjects could only distinguish 2 levels of

Table 6.1: Haptic actuator test parameters

Body Site	Act. Type	Intensity	Profile	Material	Geometry
arm	vibration	low	step	plastic	flat
back	pressure	high	ramp	rubber	large R
					medium R
					small R

actuation intensity (low and high) and two types of actuation profile (step and ramp). Additionally, subjects could not discern the difference between acrylic and ABS plastic for all geometries, and between ABS and rubber for the hemisphere with the smallest radius of curvature (henceforth called "small R"). Furthermore, the triangular geometry with sharp edges was unacceptably uncomfortable so we omitted it from use. Finally, we found that subjects could only somewhat differentiate between a flat surface and a small R for vibration on the back.

Based on the results of the preliminary test, we narrowed down the levels for each parameter for the affect study to only the ones that were easily discernible, which are presented in Table 6.1. The specific material-geometry combinations that were discernible during preliminary testing are shown in Figure 6.1. The dimensions of each contactor head – the piece of the actuator that comes in contact with the human body – are shown in Figure 6.2. Each of these 14 tactors and pactors varied in actuation intensity (low and high) and actuation profile (step and ramp), for a total of 56 combinations to test in the affect study.

The representation of the intensities and profiles implemented for each haptic actuator is shown in Figure 6.3. Vibration intensity is a function of voltage which increases both frequency and amplitude simultaneously. We commanded the tactors at 40% and 80% of full intensity for the low and high intensities, respectively. The arm pactors created a displacement of 0.25" and 0.40" for low and high intensities, and the lumbar pactors displaced the back by 0.40" and 0.75".

The choice of body site was motivated by an evaluation of wearable and "environmental" devices – haptic actuators that could be "built in to" the user's existing environment as opposed to being an additional device. We decided to use only the arm for the presentation of stimuli from a wearable haptic device and only the back for the presentation of stimuli from a seat.

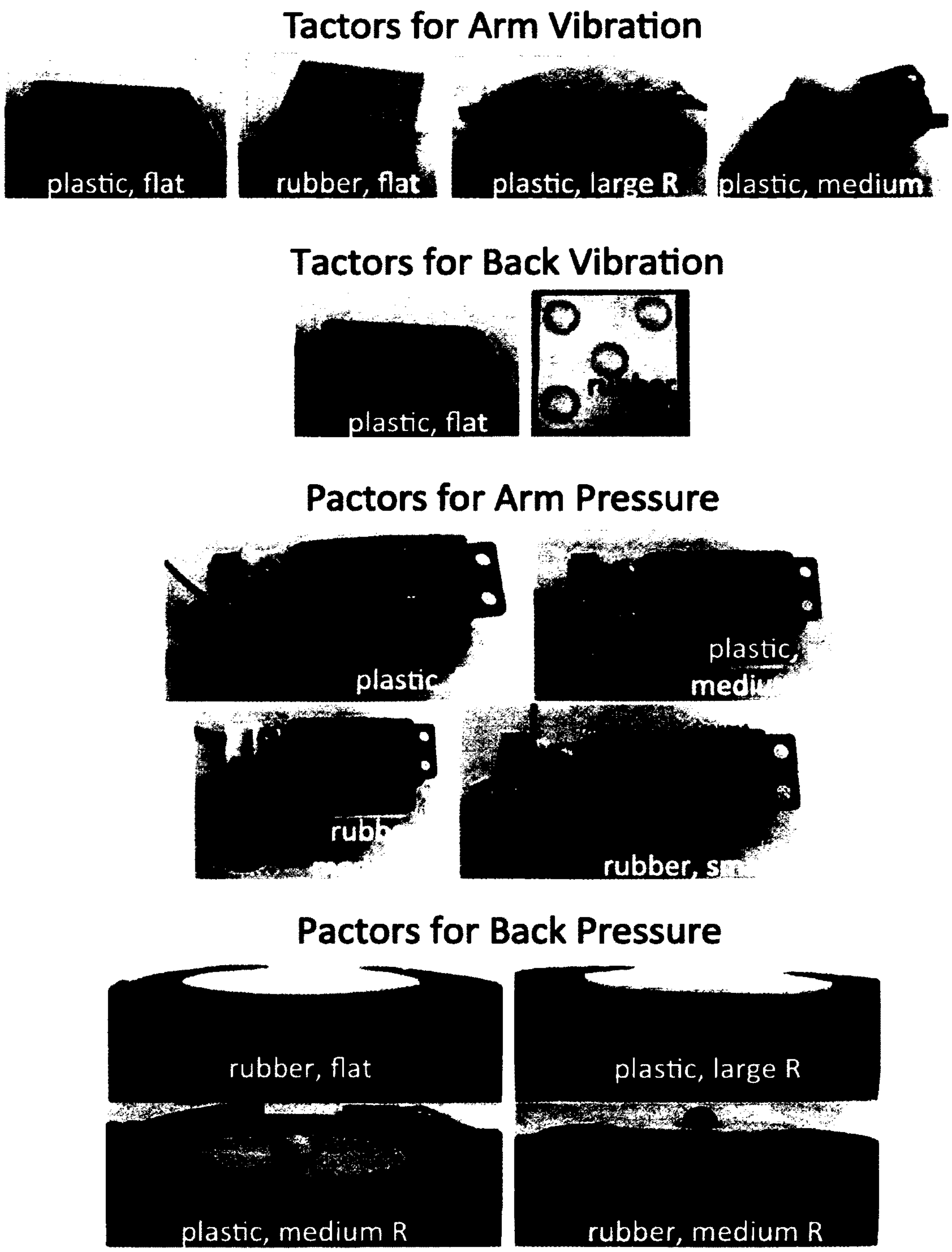

Figure 6.1: Vibration and pressure actuators (tactors and pactors, respectively) used to deliver stimuli to the arm and back. Actuator designs vary in actuation type (vibration, pressure), material (hard plastic - acrylic or ABS, soft rubber), and geometry (flat surface, large radius of curvature, medium radius of curvature, and small radius of curvature).

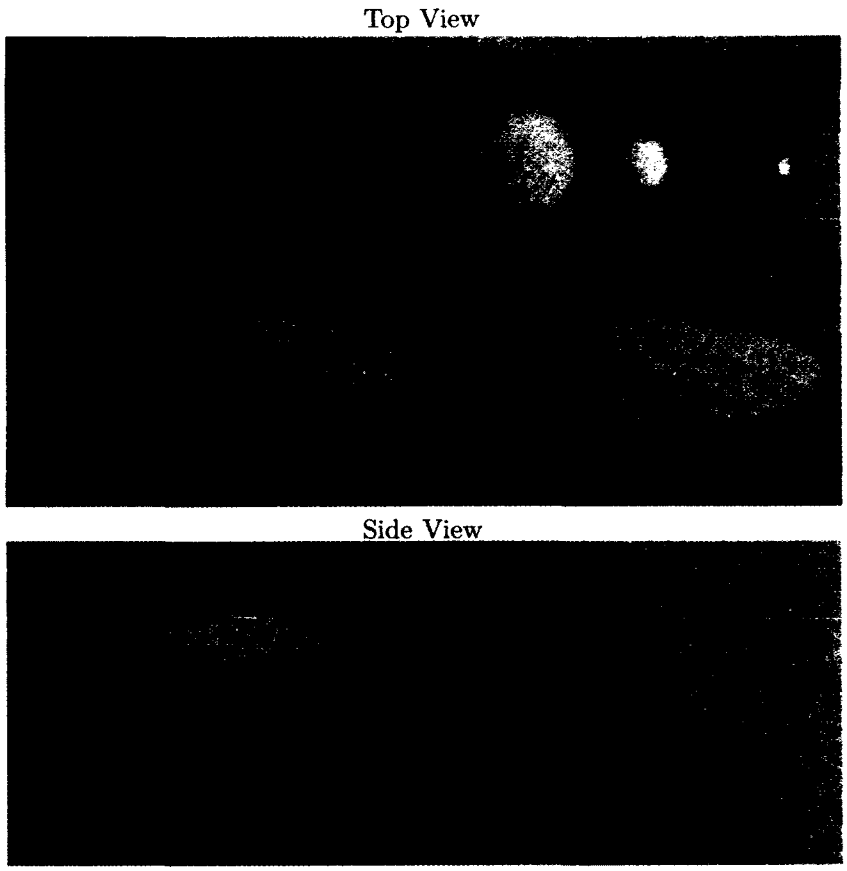

Figure 6.2: Dimensions of the haptic actuator contactor heads. (a) pactor - acrylic, flat; (b) tactor - acrylic, flat; (c) tactor - rubber, flat; (d) tactor - plastic, large R; (e) tactor and pactor - plastic, medium R; (f) pactor - rubber, medium R; (g) tactor - rubber, small R; (h) pactor - plastic, large R; (i) pactor - rubber, large R.

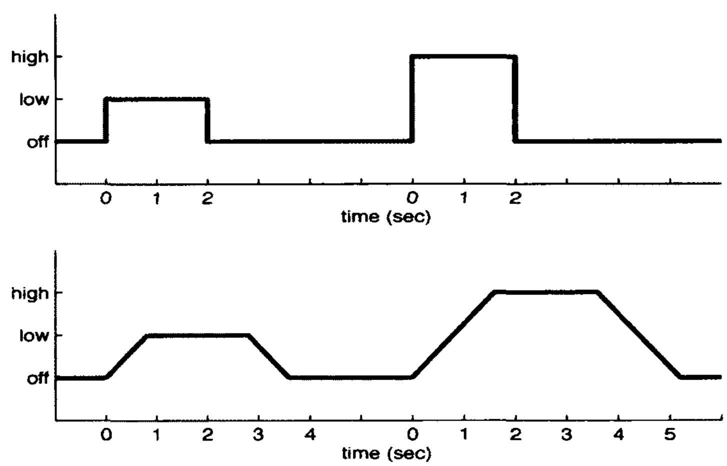

Figure 6.3: Actuation intensity and profile for the haptic feedback devices. The duration of ramp profiles is longer than that of the step profiles. Two-second hold times apply to both profiles.

6.6 Equipment and Hardware

Tactors were comprised of miniature pager motors enclosed in a custom ABS housing mounted on the back of a 1.5" x 1.5" x 0.125" acrylic plate or soft rubber pad. The tactors were each controlled by a 3kHz pulse-width modulated (PWM) voltage between 0-3V using a motor controller, which were run from a PC-based servo controller board.

Pactors utilized Futaba S3003 and Hitec HS805BB servo motors and custom cam arms. The cam mechanism converted rotational motion to a linear displacement of the contactor head. The amount of displacement was controlled via position feedback inside the servo.

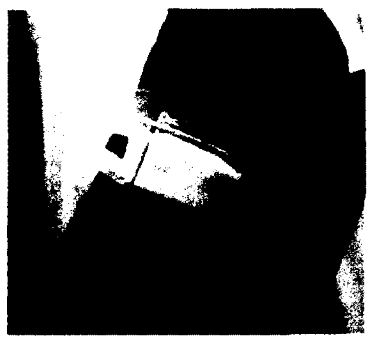

Figure 6.4: Placement of arm actuators. Actuators come in direct contact with the medial lateral aspect of the upper arm and are secured in place by a velcro arm strap.

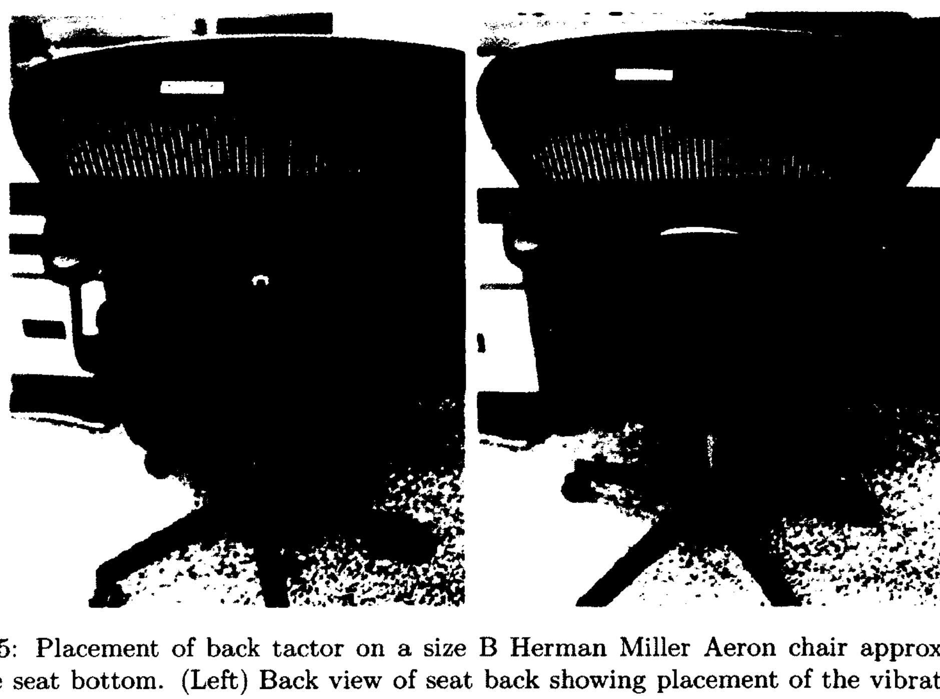

Figure 6.5: Placement of back tactor on a size B Herman Miller Aeron chair approximately 8" above the seat bottom. (Left) Back view of seat back showing placement of the vibratory tactor. (Right) Aeron lumbar support pillow with back pactor embedded.

A set of 14 different tactors and pactors were used to stimulate the arm and back, which are shown in Figure 6.1. Arm tactors and pactors were placed on the medial lateral aspect of the upper arm and were secured in place by a velcro arm strap (Figure 6.4). The pressure actuators were constrained to linear travel in order to deliver pure pressure to the skin. The back tactor was affixed to the back of a size B Herman Miller Aeron chair approximately 8" above the seat, as shown in Figure 6.5. The back pactor was embedded in the Aeron lumbar support pillow and was placed approximately 8" above the seat back (Figure 6.5).

Tactors and pactors were run from the same Lynxmotion servo controller board. LabVIEW 2010 was used to communicate with the servo controller board via a serial connection. The entire system was run on a Dell Optiplex GX620 (2.80GHz Pentium 4 processor, 2 GB RAM) with Windows 7.

6.7 User Study

As stated in Section 6.5, the primary goal of this study was to measure subjects' affective response to various haptic feedback actuators and actuation parameters, while a secondary goal was to determine the impact of these parameters on attention capture and perceived novelty. A total of 56 combinations of the 6 parameters listed in Table 6.1 were tested. Each stimulus was presented to the test subject for 2-5 seconds, long enough for the subject to perceive the stimulus and formulate a visceral reaction. However, based on feedback from preliminary testing that users were fatigued after one hour of testing, each test subject was only presented a maximum of 44 combinations (randomly selected out of the 56) so that the experiment could be completed within one hour. Test subjects were randomly assigned into one of two groups: Group A received all of the arm stimuli first followed by the back stimuli, while the Group B received all of the back stimuli first followed by the arm stimuli. This was done in order to counterbalance the presentation of stimuli to the arm and back. A randomly generated test sequence was developed for each subject in order to eliminate ordering bias.

Test subjects were instructed to wear short-sleeve shirts since arm actuators needed to be in direct contact with their skin.

Prior to the start of the test, subjects removed everything from their pockets as cell phone vibrations and even phantom vibrations (e.g. perceived vibrations in the absence of real vibrations) might alter the results of the affect study. Subjects donned noise canceling headphones playing white noise so that sound from the actuators would not influence their perception of the actuators.

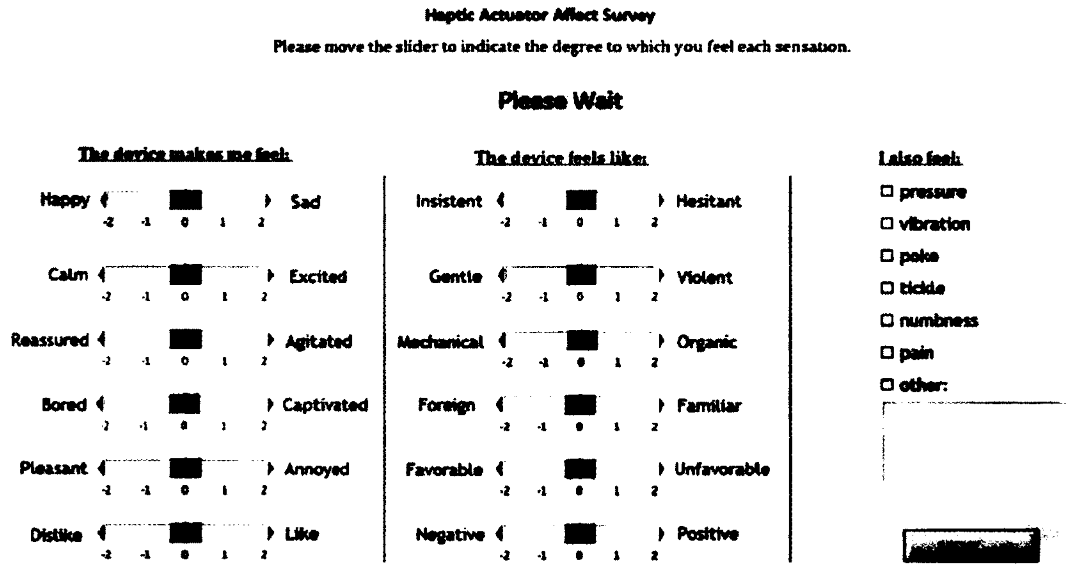

Figure 6.6: Affect survey of the haptic stimulus. This survey is completed after each stimulus presentation, for a total of 44 trials.

Subjects then filled out a short pre-experiment positive and negative affect schedule (PANAS) mood questionnaire to assess their baseline mood [160, 161]. We adopted a standard 4-point scale PANAS questionnaire typically used in psychology experiments to assess mood [148]. Questions include "I feel calm," "I feel secure," "I feel tense," etc. Test subjects were instructed to spend only about 2 minutes answering this survey.

Next, subjects were presented examples of pressure and vibration stimuli on the arm and back in order to familiarize them with the sensations. The definitions of the adjectives in the affect survey shown in Figure 6.6 were explained to the test subjects. This familiarization phase lasted less than 5 minutes.

The bulk of the experiment was the affect test. A randomized test sequence was generated for each subject. For each trial, a haptic actuator was selected (based on the test sequence) and a stimulus was presented to the subject's body. When the stimulus was active, the text "Please Wait" appeared on the screen. When the text cleared, the subject moved the sliders shown in Figure 6.6 to indicate how he felt about the stimulus. When he submitted the survey, a new stimulus was presented. The subject repeated this process up to 44 times. At the end of the trials, or at the end of one hour, whichever came first, the subject answered a post-experiment PANAS questionnaire, which was the same as the one administered in the pre-test.

We developed an affect survey that was modeled after the self-assessment manikin (SAM) tool [7, 11] in order to tailor to our needs and used some of the same antonym-pair descriptors as the ones used in [5]. The SAM tool is a pictorial survey that helps researchers plot a test subject's affect on the 2D or 3D affect grid comprising of "valence," "arousal," and "dominance" dimensions [141, 142]. Since our affect survey was a departure from the SAM tool, we opted to analyze affect as one lumped affect index (Equation 6.1).

The survey questions were designed such that, out of the 12 antonym pairs, 6 measured affect, 4 measured attention capture, and 2 measured novelty of the stimulus (Table 6.2). Test subjects could select additional words such as poke, tickle, numbness, etc. that further described their sensation. They could also enter other sensations in the free response text box.

At the conclusion of the experiment, test subjects were asked in an informal interview about their preferences for a specific type of feedback and for their overall impressions of the actuators and actuation profiles.

Table 6.2: Grouping of adjectives to measure affect, attention capture, and novelty

Affect	Attention	Novelty
Happy/Sad	Calm/Excited	Mechanical/Organic
Reassured/Agitated	Bored/Captivated	Foreign/Familiar
Pleasant/Annoyed	Insistent/Hesitant	
Dislike/Like	Gentle/Violent	
Favorable/Unfavorable		
Negative/Positive		

6.8 Results

This section presents the trends and statistical analyses between the actuator parameters and affect, attention, and novelty. The affect, attention, and novelty indices range from -2 to +2. The PANAS mood index ranges from -1 to +1. We define statistical significance to be $p < 0.05$. All statistical analyses were carried out in STATA 11.

A total of 30 subjects (14 males, 16 females) participated in the experiment. The average age was 24±3 years. The average weight, height, upper arm length, and medial upper arm circumference were 65.9±12.1kg, 167±32cm, 27±3.1cm, and 30±3.2cm, respectively. All test subjects reported at least some amount of experience with haptic actuators, with a few people reporting extensive experience.

Table 6.3: Parameters and interactions between parameters that result in significant changes in affect. Actuation profile became a significant variable in the two-way interaction analyses.

Stimulus change	Δ Affect	p-value
arm →back	-0.130	0.001
vibration→pressure	+0.187	0.000
intensity low→high	-0.158	0.000
step→ramp	+0.305	0.000
plastic→rubber	+0.108	0.020
flat→smallR	+0.160	0.004
arm→back & vibration→pressure	-0.278	0.000
arm→back & low→high	-0.269	0.001
arm→back & step→ramp	+0.240	0.002
vibration→pressure & step→ramp	+0.262	0.001
arm→back & vibration→pressure & step→ramp	+0.351	0.022

6.8.1 Parameters that significantly influence affect

Linear regression models were run on each of the parameters as well as their interactions to determine their effects on affect. The statistically significant changes in the affect index from baseline are summarized in Table 6.3. The baseline case was taken to be arm vibration at low intensity with a step input using flat plastic, which had a baseline affect index I of -0.140.

When all of the parameters were treated as independent, then body site, actuation intensity, actuation profile, material, and geometry exhibited a statistically significant impact on affect. Moving the body site from arm to back changed the affect index by -0.130. Increasing the intensity from low to high changed the affect index by -0.158. Changing the profile from step to ramp input increased the affect index by 0.305, etc. (Table 6.3).

When we took into account two-way interaction effects in the linear regression analysis, we found four instances yielding statistically significant results, and these are reported in Table 6.3. While actuation type was not significant in the single variable analysis, it became significant in the two-way interaction effects. As such, we included it in the table.

When we performed a linear regression with up to three-way interactions, only the interaction among body site, actuation type, and profile was significant. The four-way interaction analysis yielded no statistically significant results.

Table 6.4: Parameters and interactions between parameters that result in significant changes in attention

Stimulus change	Δ Attention	p-value
arm→back	+0.214	0.000
vibration→pressure	-0.240	0.000
intensity low→high	+0.325	0.000
step→ramp	-0.389	0.000
flat→smallR	-0.215	0.000
arm→back & vibration→pressure	+0.315	0.000
arm→back & low→high	+0.291	0.000
vibration→pressure & low→high	+0.239	0.001
vibration→pressure & step→ramp	-0.409	0.000

6.8.2 Parameters that significantly influence attention

The same set of linear regression analyses were run for attention as for affect. When all of the parameters were treated as independent, body site, actuation type, intensity, profile, and geometry had a statistically significant influence over attention. These are the same parameters that significantly impacted affect with the exception of actuator material.

Taking into account two-way interaction effects, we found that the interaction between body site and actuation type, between body site and intensity, between actuation type and intensity, and between actuation type and profile were also statistically significant. Unlike the results for affect, the interaction between body site and actuation profile was not statistically significant in affecting attention ($p = 0.060$).

The three-way and four-way interaction linear regression results did not achieve statistical significance. The variables and interactions that caused significant attention changes are listed in Table 6.4. An increase in the attention index signifies greater attention capture.

6.8.3 Parameters that significantly influence novelty

The same set of linear regression analyses as affect and attention were performed for novelty. When all of the parameters were treated as independent, body site, actuation type, intensity, profile, and geometry showed statistically significant influences on novelty. These were the same parameters that significantly affected attention.

Running a linear regression with interactions, we found that only the two-way interactions between body site and actuation type, between body site and intensity, and between actuation

Table 6.5: Parameters and interactions between parameters that result in significant changes in novelty

Stimulus change	Δ Novelty	p-value
arm→back	+0.264	0.000
vibration→pressure	-0.126	0.018
intensity low→high	+0.164	0.000
step→ramp	-0.262	0.000
flat→smallR	-0.211	0.001
arm→back & vibration→pressure	+0.257	0.005
arm→back & low→high	+0.215	0.018
vibration→pressure & low→high	-0.283	0.002

type and actuation profile significantly impacted the novelty index. The variables and interactions that caused significant novelty changes are listed in Table 6.5. An increase in the novelty index implies that the stimulus felt more unfamiliar and mechanical to the test subject.

6.8.4 Preferences for specific parameter combinations

The matrix of actuator parameters, their corresponding affect, attention capture, and novelty is shown in Figures 6.7 and 6.8. For simplicity, the material and geometry parameters were omitted from this matrix since subjects did not show sensitivity to material or geometry.

Looking at Figure 6.7, it is apparent that the majority of test subjects disliked the high intensity pressure applied to the back with the step input (row 15, dark red). Over half of the subjects also disliked the high intensity step input vibrations on the back. However, close to half of the subjects preferred the ramp profiles for both pressure and vibration on the back, and the ramp profile for pressure on the arm (dark green rows). About a third of the subjects found vibrations on the arm to be pleasant while another third felt the exact opposite about arm vibrations. Generally subjects did not feel sadness from the haptic stimuli.

Interestingly, over half of all subjects felt the haptic stimuli were insistent and mechanical (dark orange and dark grey columns, respectively, in Figure 6.8), suggesting that different designs would need to be pursued to make haptic actuators feel more organic and familiar. Finally, pressure and vibration on the arm seemed to be more familiar and gentle than feedback on the back.

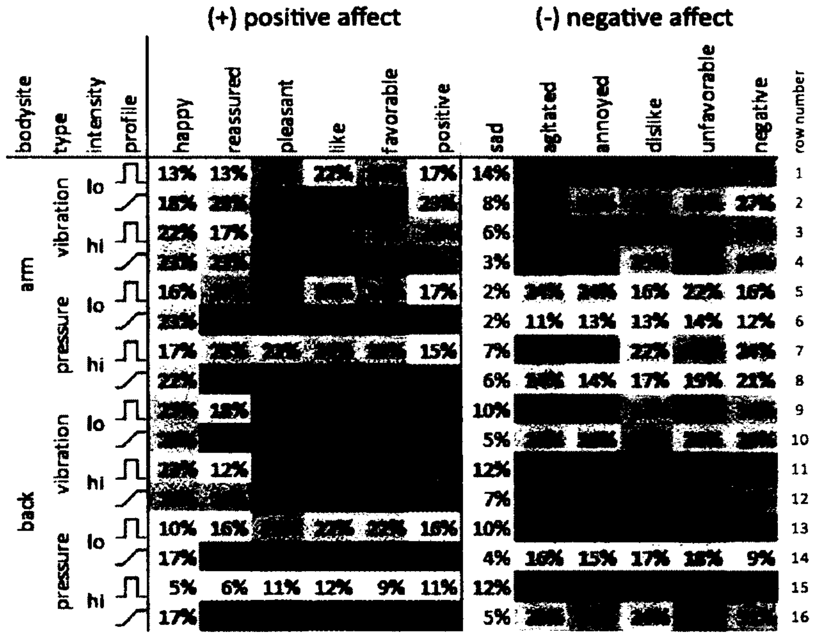

Figure 6.7: Matrix of haptic actuator parameters and their corresponding affect ratings. Numbers show percent of subjects who selected a certain adjective for each combination of test parameters. Green represents positive affect while red represents negative affect. Most subjects had a strong negative reaction to high intensity, step profile pressure on their back (row 15). More subjects liked the ramping pressure and vibration profiles than the step profiles.

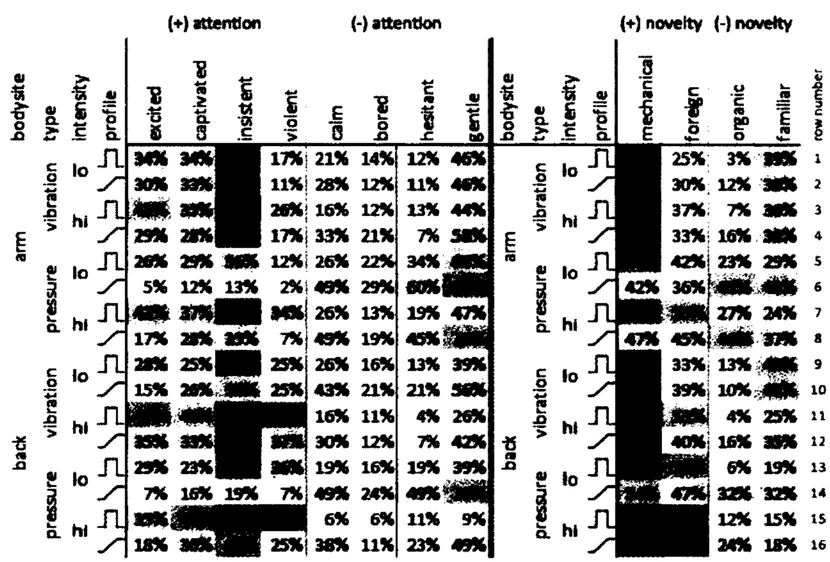

Figure 6.8: Matrix of haptic actuator parameters and their corresponding attention and novelty ratings. Numbers show percent of subjects who selected a certain adjective for each combination of test parameters. Most people thought vibration stimuli were "insistent" while only the high intensity step profile pressure on the back was noted as such. All of the vibratory stimuli were deemed "mechanical" by most of the test subjects while pressure stimuli were considered more "organic" and "familiar."

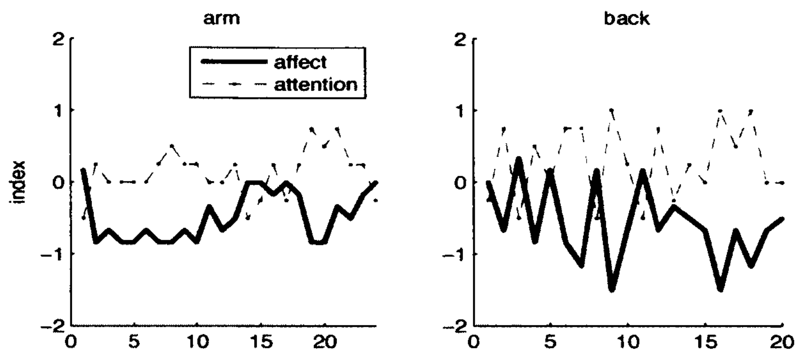

Figure 6.9: A representative plot from one subject's affect and attention data to illustrate the direct negative correlation between affect and attention. Trial numbers for the arm and back are displayed on the x-axes, and the affect and attention indices are plotted on the same y-axis.

6.8.5 Correlations between affect, attention, and novelty

We noticed that for almost all test subjects there was an overall negative correlation between affect and attention (average $R = -0.50 \pm 0.33$, min $= -0.89$, max $= +0.38$). In other words, a stimulus that was perceived as unfavorable captured the user's attention better. An example plot showing a strong negative correlation between affect and attention is displayed in Figure 6.9.

Similarly, we found a negative correlation between novelty and affect (average $R = -0.51 \pm 0.20$, min $= -0.82$, max $= -0.02$) and a positive correlation between novelty and attention (average $R = 0.39 \pm 0.23$, min $= -0.22$, max $= +0.76$). Stimuli that were perceived as novel (foreign, mechanical) were usually scored lower in affect than stimuli that were familiar and organic. Stimuli that were perceived as novel were positively correlated with attention; new stimuli tend to capture a user's attention better than familiar stimuli.

6.8.6 Correlations between pre- and post-experiment mood

We utilized the PANAS mood questionnaire to investigate trends in subjects' current mood and their affective response to the haptic actuators. We found that all test subjects exhibited a neutral to positive baseline mood at the beginning of the study (average mood index 0.234±0.051, min=0.103, max=0.325 on a scale of -1 to +1). However by the end of the study there was a statistically significant negative shift in their mood ($p = 0.01$) as subjects felt less "calm" and "pleasant" by the end of the experiment, as evidenced by their individual PANAS adjective ratings. The average post-experiment mood index was 0.181±0.098, with a range of -0.020 to +0.309.

Anecdotal evidence from post-experiment interviews suggest that this mood shift could be a result of a number of reasons, such as "boredom with test" and general "dislike of listening to white noise for an hour," and may not necessarily be caused by the haptic actuators. This negative mood shift is consistent with Salminen's finding that test conditions (naturalistic vs. lab setting) impacted affect, with greater negative affect derived from the lab setting [128].

6.8.7 Correlations between biographical, physiological data and affect, attention, novelty

We collected information about each test subject's age, gender, height, weight, arm length, and arm circumference. When analyzed as independent variables, we found no correlation between each of the variables and affect, attention, and novelty. We also found that only the interaction between age and gender in two-way interaction analyses resulted in a statistically significant effect on affect (p=0.004); females tended to give higher affect ratings of the devices than males.

6.8.8 Anecdotes

In the post-experiment interview, subjects shared with us their overall impressions of and preferences for the haptic actuators. Sixteen out of 30 subjects preferred vibrations on the back and were annoyed by pressure on the back. Meanwhile 7 subjects preferred just the opposite. Additionally 8 subjects liked pressure on the arm but not vibration on the arm, and 5 preferred the opposite.

We found a similar bimodal distribution for stimulus intensity and actuation profile. Five people consistently preferred low intensity profiles while 5 consistently liked high intensity profiles. Three subjects consistently preferred the step profile while another 3 consistently preferred the ramp profile. The remaining subjects did not exhibit a consistent preference for intensity and profile.

Six of the test subjects mentioned that the long duration of the vibration stimuli were unfavorable and preferred shorter duration bursts. The onset of the vibration stimuli excited or captivated them, but the three-second or longer stimulus length was too long and "annoyed" or "agitated" them.

Twenty-six out of 30 subjects could not consciously discern the different materials and geometries contacting their skin. Only one person felt the edge of the flat plastic actuator against their arm. Another subject noted a "cold" sensation from the flat plastic actuator contacting their arm. The two others preferred the soft rubbery material to the hard plastic material.

Finally, additional words that were used to describe the haptic actuators included "poke," "finger touch," "tap," and "natural" for the pactors acting on the arm and the back, and "itchy," "insect-like," "massage-like," and "cell phone-like" for vibrations on the arm and back. One subject also thought the vibrations on the back felt "friendly."

6.9 Discussion and Conclusion

In this study we varied six different parameters - location of stimulation, feedback actuation type, actuation intensity, profile, material, and geometry, and measured subjects' responses to combinations of these parameters. We see from Table 6.3 that actuation profile exhibited the greatest change in the affect index among the independent parameters while actuator material had the smallest statistically significant change. Table 6.4 shows that actuation profile is also the most influential parameter for attention capture. We are encouraged by these results because a parameter such as material or actuation type is essentially fixed after the device is designed whereas the profile and intensity are inherently adjustable in real time.

The statistically significant effect of actuation type on attention, where changing from vibration to pressure decreased the attention capture index by 0.240 points, confirmed our assumption in the posture seat task interference study (Chapter 4) that vibration is attention-demanding and that pressure is less intrusive. When designing haptic devices for ambient feedback, it may be preferable to utilize pressure rather than vibration. However, the interaction effect between actuation type and actuation profile actually decreased the attention index by 0.409 points, suggesting that haptic device designers should primarily manipulate the actuation profile parameter to achieve the desired attentional salience.

Interestingly there was a negative correlation between affect and attention for almost all subjects, meaning that devices with negative affect were better able to capture a user's attention. This result suggested that devices that feel more pleasant might be attended to at the user's convenience.

We also found a positive correlation between attention and novelty, and a weak negative correlation between affect and novelty. These trends implied that negative or unfamiliar sensations tended to capture attention better than positive or familiar sensations. It is recommended that haptic device designers manipulate actuation parameters to induce familiar sensations such as finger poke, palm touch, or massage in order to achieve positive affect, effectively shifting towards the "ignorable" side of the attention capture spectrum (Figure 1.2).

Finally, while test results showed parameters with consistent significant effects on affect, we found inconsistencies with the subjects' verbal interview responses. Some people preferred high intensity vibrations on their back while others disliked them. Similarly some people preferred low intensity pressure on the arm while others preferred high intensity pressure. While the numerical data shows that no "volume" control is needed, anecdotal evidence shows that people have highly variable preferences and that haptic device designers should incorporate an intensity control to allow users to adjust to their desired intensity level.

In conclusion, the key findings from this study are the following:

- There is a negative correlation between affect and attention; devices that have negative affect generate positive attention capture.
- Actuation profile most significantly impacted affect and attention. Other parameters with statistically significant effects on affect and attention include: body site, actuation type, actuation intensity, and actuator geometry (changing from flat to smallR). Haptic device designers should choose the body site and physical implementation of the actuator based on their application constraints, and dynamically control actuation profile and intensity to modulate affect and attention capture.
- Some of the two-way interaction effects among the parameters tested, such as the interaction between body site and actuation intensity, were also significant. Designers should therefore take into consideration the potential interaction effects between the parameters that they choose.
- Preferences for haptic feedback intensity varied by test subject. One easy way to address this variability is to incorporate an adjustable intensity control to allow users to customize the feedback to their liking.

Chapter 7

Design and Evaluation of Pactors for Managing Attention Capture

7.1 Overview

This chapter continues our exploration of haptic actuator designs and actuation parameters for better management of user attention. Guided by the results of the previous study, this chapter describes our first attempts at designing variable attention capture (VAC) pressure actuators, called *pactors*, that are able to modulate the frequency of stimulation into the range that is perceived as pressure rather than vibration.

7.2 Design of Pactors

Our design of VAC pactors is founded on our knowledge of mechanoreceptors in the human skin; Pacinian corpuscles, Meissner corpuscles, and hair follicle receptors are sensitive to high frequency skin displacements (e.g. vibrations) while Ruffini corpuscles and Merkel discs are sensitive to low-frequency skin displacements (e.g. pressure). These mechanoreceptors typically act in concert and careful design of haptic actuators can stimulate these mechanoreceptors to induce a desired sensation or behavioral response. We know from Chapters 4 and 6 that high frequency vibratory signals create negative affect and get attention quickly. Additionally, sudden on-off applications of pressure such as an impact can also trigger high frequency skin displacements and result in an insistent and unfavorable response, causing rapid attention capture [5].

Given this information, we set out to design pactors that can:

- generate a range of low frequency skin displacements
- actuate smoothly at various rates
- actuate normal to the body, as shear motions typically induce high frequency vibrations
- withstand normal and shear force overload conditions

Furthermore, we sought to create a design that would be compact, easy to control, and relatively inexpensive (< \$100).

We will initially implement these pactors in an office chair. Chairs provide an excellent testbed because they have a well defined structure on which to attach devices and controllers. Additionally, seated applications are commonplace and provide myriad opportunities for incorporating haptic feedback mechanisms.

7.2.1 Actuator Selection

The first design task was to select actuators powerful enough to deliver forces that would be perceived as "strong" and "attention grabbing." We conducted a preliminary evaluation to measure the force and displacement on various parts of a person's body that would be felt as "strong" through an office chair without being painful. We found that all volunteers perceived forces and displacements higher than 45N and 2cm as "very strong" and all volunteers withstood at least 55N on their lumbar region without feeling pain. (No stimuli on the shoulder and thigh regions of the body felt painful.) Therefore we concluded that our actuator should be able to output forces of approximately 45N to ensure that the user will perceive the force on their body while avoiding any sensations of pain. Simultaneously, our actuators must be able to advance and retract with a frequency between 0.1Hz-2Hz to mimic a gentle nudge to a slow tap.

We evaluated a full range of available DC motors and hobby servos for these design criteria (see Appendix D) and selected the Hitec HS-805BB sail servo for its high torque and reasonably fast speed (2.42Nm stall torque and no-load speed of 7.48rad/sec at 6V).

7.2.2 Pactor Design

We prototyped a number of mechanisms that converted the rotational motion of the RC servo to a translational motion at the tip of the pactor (see Appendix D) and converged on the crankshaft pactor design, shown in Figure 7.1. This design was selected for its robustness, excellent overload tolerance and back-drivability, low friction (and thus smooth actuation), and ability to achieve single-point displacement normal to the person's body. Additionally this design incorporates only a small number of moving parts, making the manufacturing and assembly process easy. The design is able to achieve a maximum force output of 190N, a range of travel from 0-2cm with 0.001cm resolution, and a maximum actuation rate of 7.1cm/sec.

We designed custom contactor plates to interface with the chair at each body site (Figure 7.1). The area of these plates was a balance between making them too small, which might feel painful when actuated, and making them too large, which might require more actuation force in order to not feel weak. The contours were designed based on the approximate body curvature at each location.

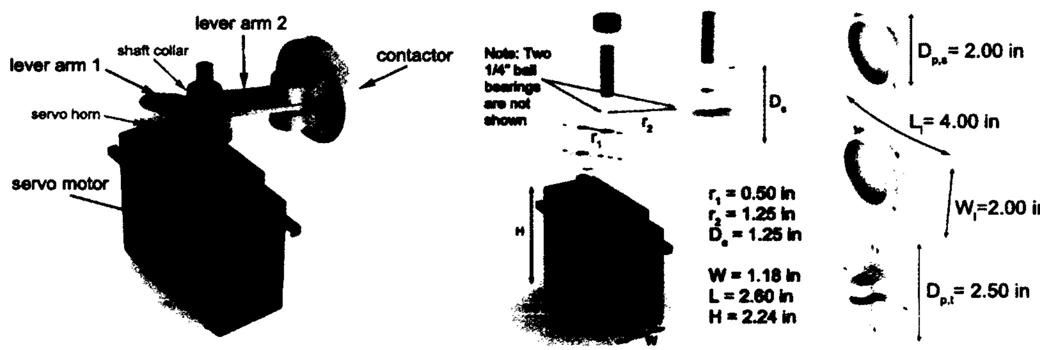

Figure 7.1: (Left) The final pactor (pressure actuator) design capable of 0-2.0cm of displacement and up to 190N of output force. (Center) Exploded view of pactor including critical dimensions. (Right) Contactor plates for the shoulder (top), lumbar (middle), and thigh (bottom) pactors.

7.3 User Study

We conducted a study to measure skin displacement detection thresholds and level of attention capture and urgency using the pactors while the subject sat in our instrumented office chair. The test system comprised of a fully adjustable size B Herman Miller Aeron chair outfitted with force sensors and pactors actuating on five parts of the body (Figure 7.2). Five 1.5" square force-sensitive resistors (FSRs) were affixed to the contactor plates to measure forces exerted by the pactors. Three

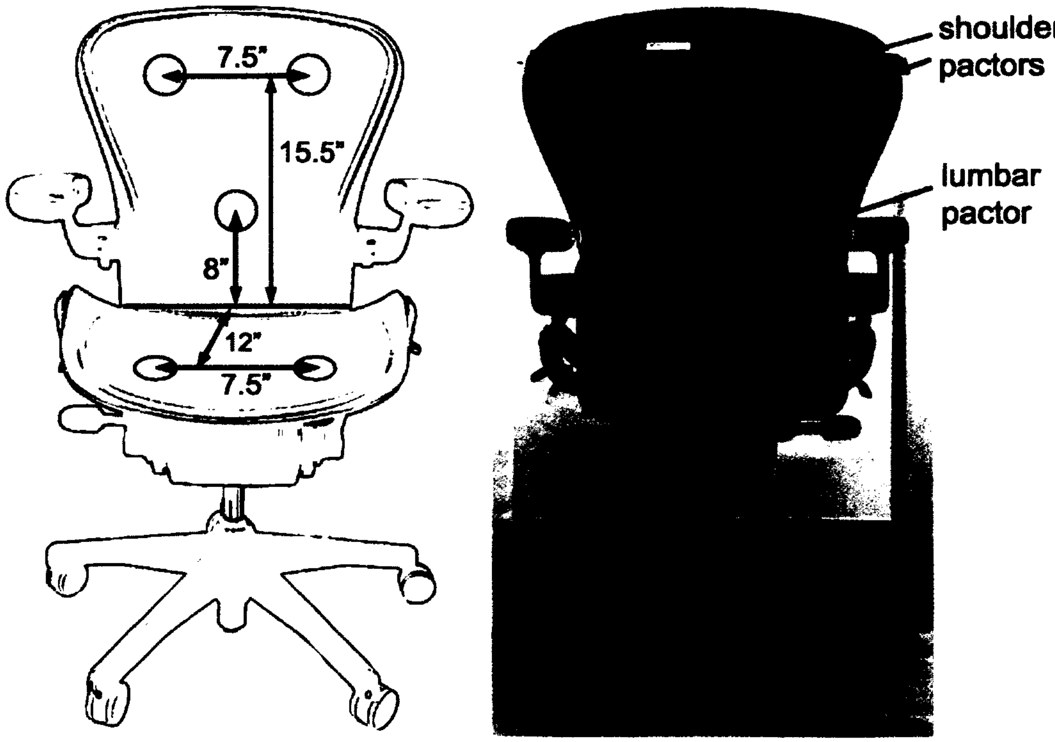

Figure 7.2: Aeron chair instrumented with pactors. (Left) The locations of tactile stimuli exerted from the chair to a seated person. The shoulder and thigh stimulus regions are equally spaced relative to the centerline of the chair. (Right) Pactors are attached to the back of the chair via a custom-designed support frame.

pactors were attached to the back of the chair and actuated on the left and right shoulders and the lower back (Figure 7.2 and 7.3). Two additional pactors were sewn under the chair and actuated on the posterior region of the thigh (Figure 7.4). The pactors were driven via PWM signals from a motor controller board (Lynxmotion SSC-40).

The experiment was divided into four phases: set-up, training, stimulus detection trials, post-experiment interview.

Set-up In this phase, subjects were instructed to sit in the chair with their feet flat on the ground and their back contacting the back of the chair. The pactor support plate on the back of the chair was adjusted until shoulder and lumbar contactor plates touched the mating plates but only lightly enough that the FSRs registered a zero load. No additional adjustments were needed for the thigh pactors. All participants wore noise canceling headphones playing white noise to mask potential noise from the RC servos.

Training Subjects were presented with at least six examples of each kind of stimulus on all five

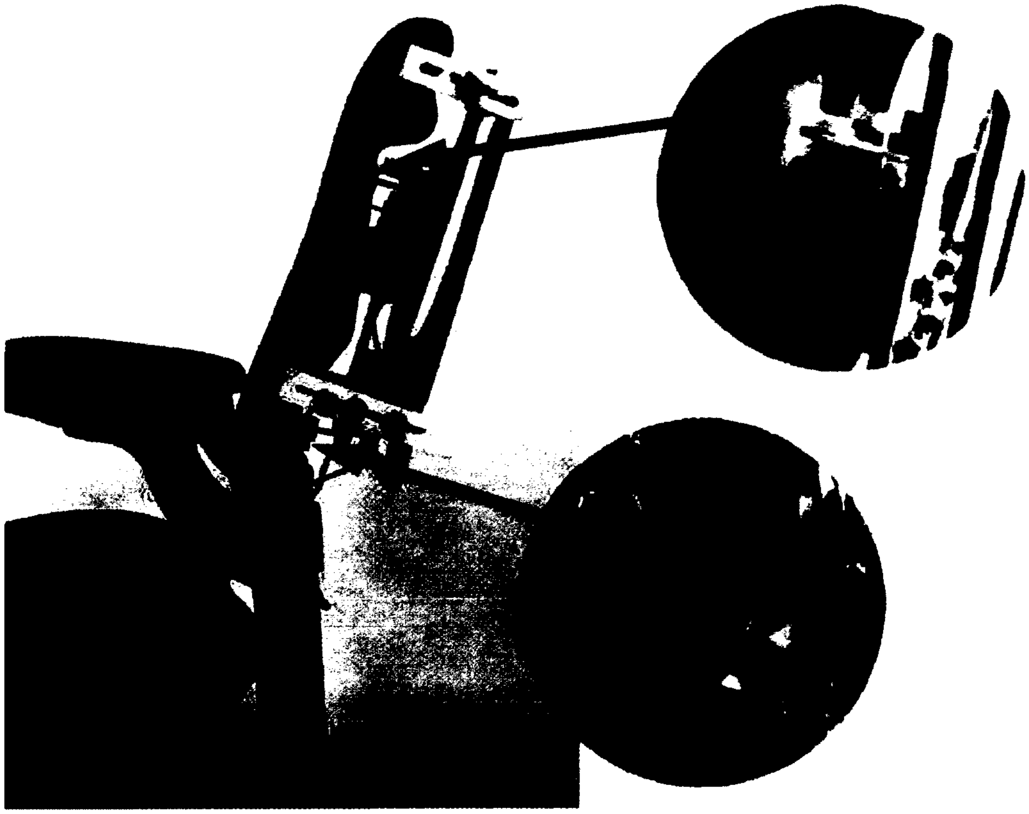

Figure 7.3: Side view of the chair showing the mounting for the shoulder and lumbar pactors. (Top inset) A view of the shoulder pactor and mating contactor plates. (Bottom inset) A view of the lumbar pactor showing the contoured mating contactor plate.

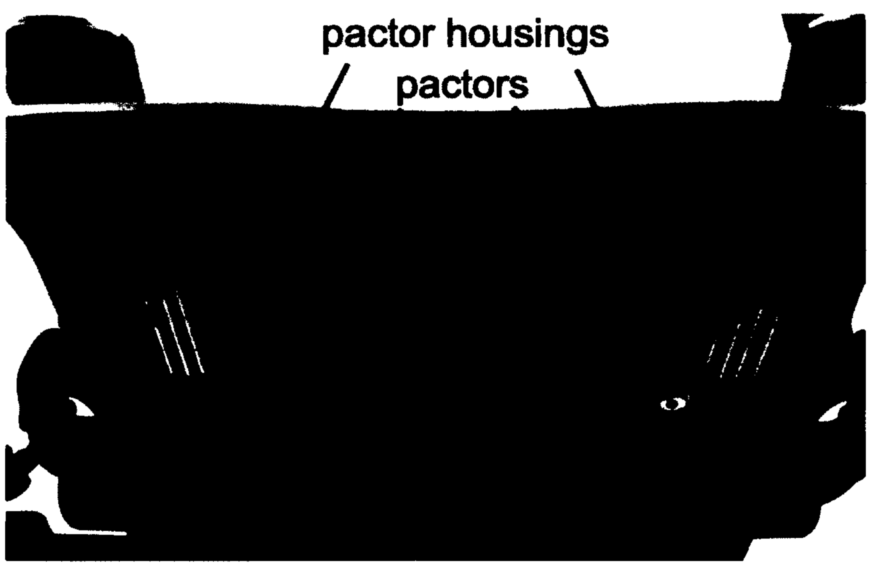

Figure 7.4: A bottom-up view of the thigh pactors and their housings sewn into the bottom of the chair.

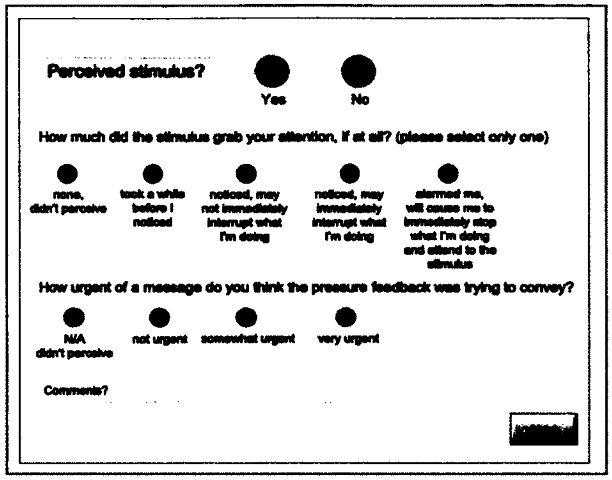

Figure 7.5: Survey response screen presented to the subject after each trial to measure perception, attention capture, and urgency. A new stimulus is delivered after the subject clicks the Next button.

parts of their body (left and right shoulders, left and right thighs, and lumbar region of the back). The stimuli rates and intensities ranged from slow to fast and from null (0cm) to maximum (2cm). Subjects were also shown the response screen (Figure 7.5) and were given instructions on how to respond after each stimulus ends. The meaning of each choice was explained so all subjects would interpret the choices in the same way.

Stimulus detection trials This portion of the experiment was divided into trial blocks, one for each combination of body site and actuation rate. We utilized a standard psychophysical 2-down/1-up staircase test method with two-alternative forced choice (2AFC) to determine the displacement perceptual thresholds. (See Figure 7.6 for details.) Since the test was adaptive, the displacement magnitude, which we call *stimulus intensity*, within each trial block depended on the subject's response to the previous stimulus. Preliminary testing indicated that 6 reversals were needed to accurately converge on the threshold. The sequence of the trial blocks was randomly generated in order to eliminate ordering bias.

For each trial, subjects were presented with a stimulus at one of the actuation rates on one region of their body; sometimes the stimulus would be a null stimulus. The actuation rates were 0.137cm/sec, 1.08cm/sec, and 7.34cm/sec, which we termed "slow," "medium," and "fast," respectively, for ease of reference (Figure 7.7). Note that the "fast" actuation rate was 6.8 times faster than the "medium" rate, which in turn was 7.9 faster than the "slow" rate. This roughly 7x rate of change was chosen based on the knowledge that human perception of stimulus change is logarithmic rather than linear [40].

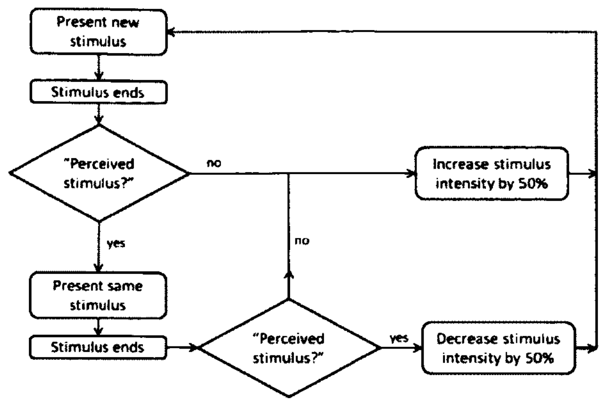

Figure 7.6: Flowchart of the 2-down / 1-up two-alternative forced choice test method of psychophysical threshold testing for each body site and actuation rate.

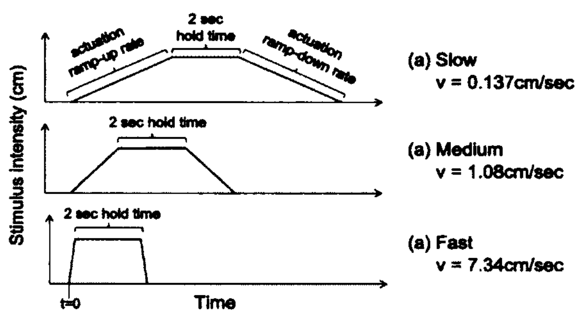

Figure 7.7: A representation of the slow, medium, and fast stimulus actuation rates. Each stimulus has a two-second hold time. The displacement ("stimulus intensity") is varied depending on each trial.

During each trial, the stimulus ramped up to its desired magnitude, followed by a two-second hold time, before it ramped down at the same rate. When the stimulus ended (pactor returned to neutral position), subjects were prompted to provide subjective feedback on their perception of the stimulus and their level of attention capture and urgency due to the stimulus (Figure 7.5). They were informed that some stimuli were null so not perceiving the displacement could be normal. A new stimulus would be presented after the subject clicked the Next button. The trial proceeded until 6 reversals had been reached. A threshold value was calculated based on the average of the last 4 reversals.

The independent variables in this study were body site, pactor actuation rate (displacement rate), and pactor stimulus intensity (displacement magnitude). The dependent variables were displacement detection threshold, level of attention capture, and level of urgency.

Post-experiment interview After all the trials were completed, test subjects were asked the following questions in an informal interview: whether or not they liked the sensations on various parts of their body, out of all the stimuli which ones were most gentle and potentially least disruptive, and which ones were most urgent and attention grabbing.

7.4 Results and Discussion

A total of 25 subjects (12 male, 13 female) were recruited from the Yale community and ranged from 19-31 years of age, with the average age of 24±3.4 years. Participants' heights were between 152cm-191cm, with a mean of 173cm±8.4cm. Participants weighed between 48kg-89kg with an average weight of 70kg±11.4kg. There were no statistically significant differences due to gender for detection threshold ($p = 0.107$), attention capture ($p = 0.590$), and urgency ($p = 0.206$), so both male and female data were analyzed as one group.

7.4.1 Detection threshold

We performed an ANOVA with body site and actuation rate as the independent variables and found that both were significant factors determining detection threshold ($p < 0.001$), but their interaction effect was not significant ($p = 0.741$). Post-hoc pairwise comparisons with Bonferroni corrections ($\alpha = 0.005$) revealed no statistically significant difference in detection thresholds between the left and right shoulders ($p = 0.181$), and between the left and right thighs ($p = 0.692$). This is consistent with existing literature that the left and right sides of the body are balanced [69, 163]. Therefore we present data from the left and right shoulders as one "shoulder" group and left and right thighs as one "thigh" group.

The post-hoc analysis on actuation rate incorporating Bonferroni corrections ($\alpha = 0.0167$) showed a statistically significant difference in detection threshold between the slow and medium actuation speeds ($p < 0.001$), and between the slow and fast actuation speeds ($p < 0.001$). However there was no significant difference in detection threshold between the medium and fast actuation rates ($p = 0.939$). This means that even though participants were able to distinguish a difference in the two speeds (i.e. that one was fast than the other), the perceptual threshold at these two rates were almost the same. Therefore from a design standpoint, either the medium or fast speed – or any speed in between – can be employed and the user's ability to detect the stimulus will remain relatively constant.

The median threshold displacement for each actuation rate and for each body site is presented

Table 7.1: Median detection threshold values for each body site and actuation rate.

	Shoulders	Lumbar	Thighs
Slow	0.299cm	0.333cm	0.325cm
Medium	0.059cm	0.106cm	0.031cm
Fast	0.067cm	0.100cm	0.045cm

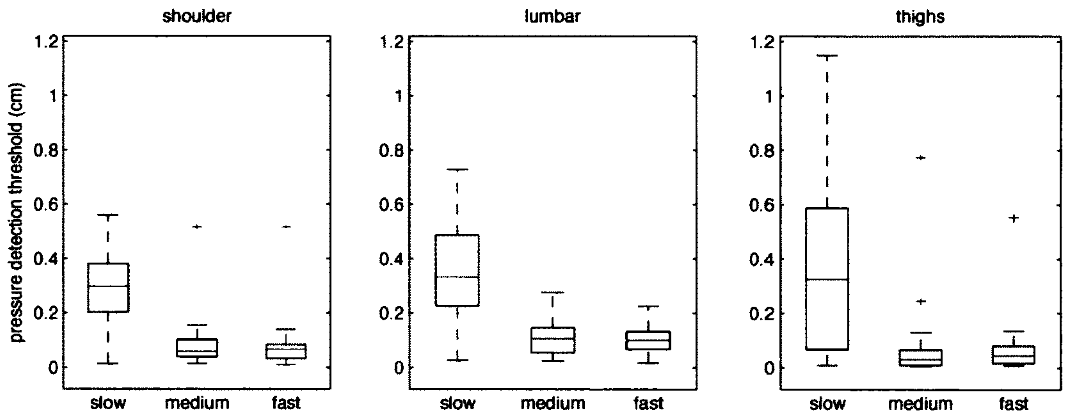

Figure 7.8: Displacement detection thresholds grouped by body site and actuation rate. The red crosses represent outliers. Actual median values are given in Table 7.1. The left and right sides of the body are balanced (i.e. there were no statistically significant differences between the two sides), hence data is lumped together as one shoulder group and one thigh group. The detection threshold for the slow actuation rate was significantly different than the medium and fast rates for all three body sites, while detection thresholds from the medium and fast actuation rates showed no statistically significant difference.

in Table 7.1. The boxplots in Figure 7.8 show the detection thresholds as a function of actuation rate for each body site. It can be seen that the detection threshold was actuation rate dependent – the detection threshold for the slow actuation rate was much higher than that for the medium and fast actuation rates across all body sites.

The fact that the medium and fast actuation rates did not yield significant differences in detection thresholds, even though these two rates were approximately seven times apart, point to the possibility that the detection threshold saturated above a certain actuation rate. It is possible that this behavior follows a sigmoid function typically observed in psychophysical studies, in which case we should expect to see saturation at slower rates as well.

At the slowest rate, subjects required a greater displacement before they could detect the stimulus. This indicates that a change in displacement can go unnoticed for a longer period of time if the change is slow enough. Additionally, when the stimulus is noticed, it is detected at a higher displacement than that for the faster actuation rates.

There was a wider spread in detection thresholds for the thigh compared to the shoulders and lumbar region. This is likely due to the fact that the density of mechanoreceptors is lower in the posterior region of the thigh than the lumbar and shoulder regions.

Finally, the spread in detection thresholds was very wide for the slow actuation rate, compared to the very tight distribution for the medium and fast rates. The wide spread indicated that there was greater uncertainty for each person and greater variability from person to person in detecting slowly changing skin displacements.

7.4.2 Attention capture

Table 7.2 and Figure 7.9 show the average stimulus intensity corresponding to each level of attention capture, grouped by actuation speed. There is a positive correlation between attention capture and skin displacement ($R^2 = 0.67$); overall, as the amount of displacement increases, so does the level of attention capture. However, from the figure we see that as the actuation speed increases, a smaller displacement is needed to elicit the same level of attention capture.

We performed a regression analysis with attention capture as the dependent variable and body site, actuation speed, and stimulus intensity as the independent variables and found a significant interaction effect between stimulus intensity and actuation speed ($p < 0.001$). (Body site was not significant ($p = 0.136$).) The interaction effect is evident from Figure 7.9; simply reducing the actuation speed without regard for stimulus magnitude may still elicit an attention-getting response. Conversely a fast stimulus at a low intensity may not capture a person's attention.

It is also evident from the figure that the attention capture response curve is not linear but possibly sigmoidal. We surmise that there is a plateauing effect at the low and high ends of the attention capture spectrum, and a steep slope between the two plateaus. This could potentially reflect psychophysical sensory perception findings that our senses saturate at the high intensity end of the spectrum while fail to detect at the low intensity end.

It is interesting to note that we did not observe saturation at the low end of the attention capture spectrum for the slow actuation rate. It is possible that the curve is still sigmoidal, but in the range that we have tested the results show more of a linear relationship. This is very encouraging because it means that the slow actuation rate can achieve greater dynamic range for attention capture than the medium and fast actuation rates.

Given the interaction effects between pactor displacement and actuation speed, and the po-

Table 7.2: Average displacement that corresponds to each level of attention capture (Figure 1.2).

	Level of Attention Capture				
	1	**2**	**3**	**4**	**5**
Slow	0.202cm±0.247cm	0.559cm±0.490cm	0.950cm±0.721cm	1.760cm±0.472cm	1.967cm±0.234cm
Medium	0.053cm±0.093cm	0.159cm±0.215cm	0.603cm±0.607cm	1.684cm±0.514cm	1.944cm±0.255cm
Fast	0.051cm±0.085cm	0.137cm±0.161cm	0.436cm±0.449cm	1.508cm±0.547cm	1.855cm±0.384cm

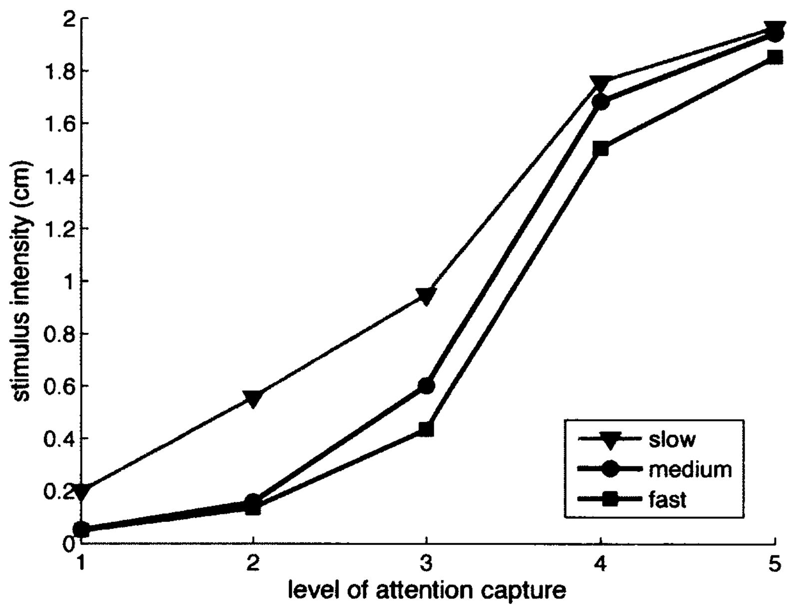

Figure 7.9: Average displacement corresponding to each level of attention capture for all body sites combined. Actual mean values are listed in Table 7.2. The current design of pactors is capable of spanning the entire attention capture spectrum. Also, there is a significant interaction effect between actuation rate and stimulus intensity ($p < 0.001$).

tentially sigmoidal response curve, we conclude that when designing for VAC, it is necessary to consider both the stimulus intensity and actuation speed. In particular, one must choose a low stimulus intensity as well as a slow actuation rate when designing for an ambient level of feedback.

7.4.3 Urgency

The perception of urgency was well correlated with the level of attention capture ($R^2 = 0.79$). A regression analysis on urgency showed the same results as attention capture: body site was not significant ($p = 0.307$) and the interaction between actuation speed and displacement was significant ($p < 0.001$). As actuation speed increased, urgency also increased (from "not urgent" to "very urgent"), and as stimulus intensity increased, so did the level of urgency. Therefore haptic device designers must choose appropriate levels of both actuation speed and stimulus intensity to achieve the desired level of urgency.

7.4.4 Anecdotes

In the post-experiment interview, participants were asked to reflect on their overall impressions of the experiment. About half of the participants thought the sensations from the pactors were pleasant and sometimes "massage-like." Others neither liked nor disliked the sensations overall. However five participants disliked the displacements under the thighs and described them as "weird," "unfamiliar," "uncomfortable," and even "inappropriate." One participant remarked that pressure under the thighs felt "ticklish." These responses are consistent with the subjective dislike of stimuli on thighs found by Karuei, et. al. [69]. Given these responses, it is probably not advisable to deliver tactile feedback to the underside of thighs through a chair.

About a third of the people thought the high intensity and fast actuation rate was unpleasant or uncomfortable and felt like a punch. Surprisingly, the slow actuation rate was annoying for half of the participants as they waited what seemed to be "a long time" before they could perceive any stimulus and sometimes became "paranoid" when trying to anticipate the stimulus.

7.5 Conclusion

In this chapter we have presented the design of a variable attention capture (VAC) actuator called a pactor for delivering tactile stimuli. Our current low-cost pactor design was sufficient in delivering low frequency skin displacements that spanned the attention capture spectrum from "ignorable" to "demand action" (Figure 1.2).

In our evaluation of pactors, we found that actuation rate was a significant factor affection detection threshold, attention capture, and perceived urgency. The interaction effect between actuation rate and stimulus intensity was also significant for attention capture and urgency. Additionally, we observed a saturation effect for detection thresholds at the medium and fast actuation rates in our tests (1.08cm/sec and 7.34cm/sec, respectively). Finally there were no significant differences in detection threshold, attention capture, and perceived urgency among the body sites we tested. These results lead us to conclude the following:

- Haptic actuators can achieve VAC by reducing actuation rate. This effectively reduces skin displacement frequency to levels that are perceived as pure pressure, something that is not easily achievable with eccentric-mass-motor vibrotactile actuators.

- The combination of actuation rate and stimulus intensity is crucial for effectively modulating attentional salience.
- Haptic stimuli have relatively similar effects when delivered through the shoulders, lumbar, and thighs.

In summary, we have demonstrated that our pactors have good potential for varying the level of attention capture, which will allow for a greater range of applications of the haptic feedback.

Chapter 8

Evaluation of Tactors and Pactors for Variable Attention Capture (VAC) Haptics

8.1 Overview

In this chapter, we continue our investigation of VAC haptics by comparing the attention capture bandwidth of two specific tactors and pactors through a user study. Specifically, we examine how various actuation rates, coupled with different distractor tasks, can impact a user's stimulus detection time. In the context of tactors and pactors, we define actuation rate as the rate of change of a stimulus intensity, e.g. V/s driving voltage for tactors that corresponds to a perceived rate of change in vibration frequency and amplitude, and cm/s displacement for pactors that corresponds to a perceived rate of change in pressure.

Sensing and responding to haptic stimuli, especially when conveying information of lower priority, should not adversely impact a worker's concentration or performance on his primary task. In our within-subject experiment, we sought to measure how different vibrotactile and tactile stimuli can modulate subjects' attention capture (through measuring response time) while they performed a simultaneous office task.

8.2 Hardware Description

We instrumented two size B Herman Miller Aeron chairs with tactors and pactors in the lumbar region (Figure 8.1). Tactors were off-the-shelf eccentric mass vibrotactile actuators (10mm x 3.4mm shaftless vibration motors, Pololu #1636) affixed to the center of a 1.5"x1.5" foam pad (for noise and vibration damping) and attached to the lumbar region of the vibration chair with self-curing adhesive tape. Pactors were comprised of RC sail servomotors (Hitec 805BB) with an attached linkage arm and a contactor plate that interfaced with the back of the chair. All actuators were driven via PWM signals from a motor controller board (Lynxmotion SSC-40), and commands were sent at a rate of 50Hz. Accelerometers (Pololu MMA7341L 3-axis accelerometer ±3/11g) and force sensors (Interlink 1.5" square FSRs) affixed to the front of the chair were used for passive monitoring of vibrations and pressures and were not used for active feedback in this study. Sensors were connected to a 16-bit A/D data acquisition box (NI-DAQ USB-6212) and data was processed in LabVIEW 10.0 and Matlab R2011b.

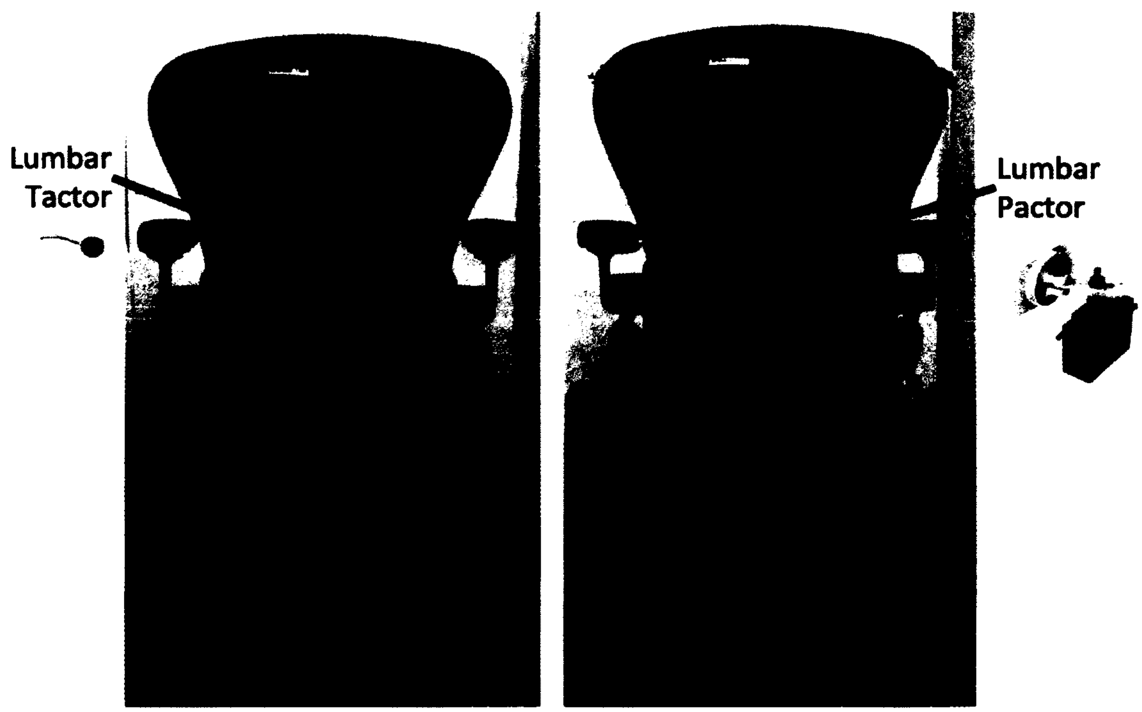

Figure 8.1: Back view of the vibration (left) and pressure (right) chairs used in this study. The lumbar tactors and pactors are circled.

8.3 User Study

The study is divided into two groups, a vibration group and a pressure group, and participants were randomly assigned to one of these groups. There are six phases of the experiment: set-up, single-task baseline, dual-task reading, typing practice, dual-task typing, and post-experiment interview (Figure 8.2).

In the "set-up and practice" phase, subjects were instructed to sit in either the vibration chair or the pressure chair (depending on their random group assignment) with their feet flat on the ground and their back contacting the back of the chair. For the pressure chair, the pactor support plate was adjusted until the pactor contactor plate came in contact with the subject's back while the FSRs registered a zero load. No adjustments were needed for the vibration chair. All participants wore noise canceling headphones playing white noise to drown out the sound of vibration motors and actuations of RC servos. Subjects were instructed to sit still during each trial as postural shifts may affect their perception of the stimuli.

Once settled into the chair, participants received vibration or pressure stimuli at various actuation rates, and familiarized themselves with the haptic stimuli and the response screen. They were instructed to click the large button on the computer screen when they perceived the stimulus (Figure 8.3). The actuation rates used in this study are listed in Table 8.1. The pactor actuation rates were the same as the ones employed in Chapter 6, plus one additional (slower) rate. The psuedo-equivalent tactor actuation rates were determined through preliminary testing.

Next, we measured each subject's baseline (single task) response time to detecting a stimulus at each actuation rate. The sequence of actuation rates were randomly generated prior to the start

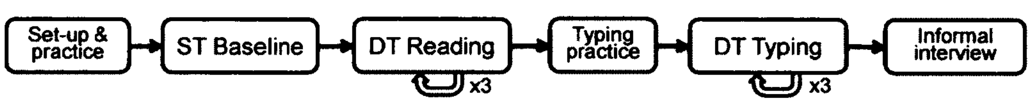

Figure 8.2: Test procedure for this study.

Table 8.1: Tactor and pactor actuation rates used in this study.

Vibration (tactor driving voltage)	**Pressure** (pactor displacement rate)
0.03V/s	0.076cm/s
0.15V/s	0.137cm/s
2.40V/s	1.08cm/s
20V/s	7.34cm/s

Figure 8.3: Test subjects were instructed to click this large button to acknowledge stimulus perception. This window spanned the entire 19" computer screen. The monitor was placed 18" in front of the seated test subject.

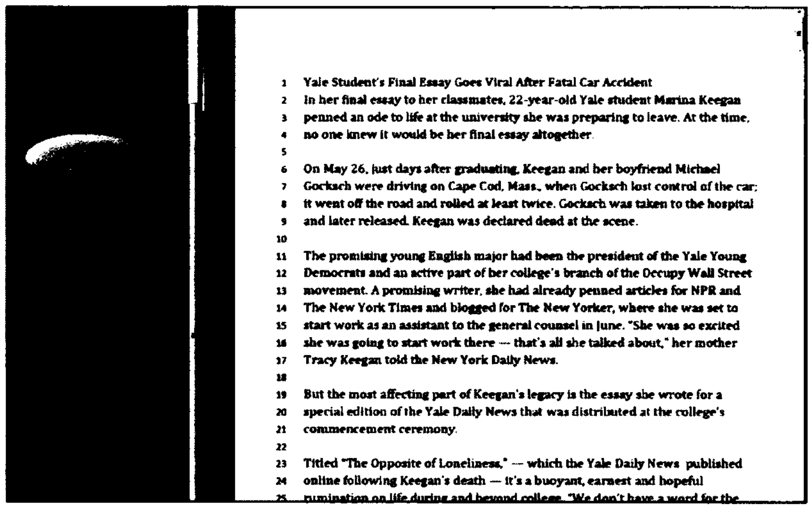

Figure 8.4: In the dual-task reading task, subjects were instructed to read a passage at their normal reading pace (scrolling as necessary), and to click the button as soon as they perceived the stimulus. The window spanned the width of the 19" monitor, which was placed 18" in front of the subject.

Figure 8.5: In the dual-task typing task, subjects were instructed to type the passage verbatim starting at the cursor. The typing screen refreshed with a new passage every 60 seconds to eliminate the need for scrolling with the mouse in the middle of typing with the keyboard. The window spanned the width of the 19" monitor, and was placed 18" in front of the test subject.

of the experiment. The four different actuation rates were repeated four times, and the first four stimuli were discarded from data analysis as they were considered "practice" runs. During each trial, as the stimulus constantly increased in intensity at a rate specified in Table 8.1, subjects were instructed to click a large button as soon as they perceived the stimulus (Figure 8.3). However they were also told that this was not a race against time so they should respond calmly. This "ST Baseline" phase ended after the subject detected the last stimulus.

For the next set of three trials, subjects were given a reading task while they tried to perceive and acknowledge haptic stimuli ("Dual-Task Reading Trials," or simply "DT Reading," Figure 8.4). A passage was randomly chosen from a pool of articles, and subjects were instructed to focus on reading the passage verbatim. The topic of the articles ranged from current events (e.g. story of a cancer patient) to technical writing (e.g. faculty tenure process), and were chosen to engage a wide audience. For each trial, as subjects read the passage, a stimulus would be presented after a random time interval between 15-30 seconds and subjects were asked to click a button on the screen to acknowledge that they perceived the stimulus. The sequence of stimulus actuation rates as well as the passages were randomly generated in order to eliminate ordering bias. The first stimulus of each trial was eliminated from data analysis as a training sample. Each trial ended when the final (seventh) stimulus was perceived. Subjects then answered a post-trial survey about how interesting and engaging the passage was, as well as the line number where they stopped reading at the end of the trial. This was repeated three times.

After the DT Reading trials, subjects practiced typing in our custom typing program (Chapter 4 for five minutes to gain familiarity with the program. After the typing practice, for the following set of three trials, we measured subjects' response time to detect a stimulus while performing a typing distractor task ("Dual-Task Typing Trials," or simply "DT Typing"), similar to the DT Reading trials. The sequence of stimuli and passages were again randomly generated in order to eliminate ordering bias. Subjects were told to focus on the typing task and type at their normal speed. The subjects' experiment window displayed the typing program and the "click-to-acknowledge" button (Figure 8.5). The trial ended when the last (seventh) stimulus was perceived, or when the five-minute typing test ended, whichever came first. The first trial was eliminated from data analysis. A post-trial survey was administered to assess how engaging the passage was.

At the end of the experiment, subjects were asked about their thoughts and feedback in an informal interview.

8.4 Results and Discussion

A total of 41 people participated in the study and their demographics are presented in Table 8.2. All of them typed faster than 40 words per minute (wpm) and made fewer than 5 errors as assessed via an online typing test software [113]. As mentioned in the Experiment sections, the first four stimuli in the ST baseline phase were discarded from analysis, and the first stimulus in each of the DT Reading and DT Typing trials were omitted from analysis.

Table 8.2: Test subject demographics

	Vibration Group	Pressure Group
N	20 (12 females)	21 (10 females)
Average age	22±3.2 years	22±3.3 years
Average height	173±9.4cm	173±9.9cm
Average weight	66±10.5kg	68±11.8kg
Average reading rate	210±59wpm	167±68wpm
Average typing speed	59±19wpm	58±13wpm

8.4.1 Response Time

Response time is defined as the time (in seconds) from stimulus onset to the time that the subject clicks a button to acknowledge the stimulus. Haptic actuators capable of achieving variable attention capture (VAC) will exhibit a range of response times that varies with actuation rate. A wider range in response times is considered more desirable as it provides more opportunity for a designer to adjust priority.

Figure 8.6 shows the average time to notice a vibration or pressure stimulus at various actuation rates for different tasks. It can be seen that as actuation rate increases, the time to respond decreases. This trend is exactly what we expected – rapidly increasing stimulus intensities tend to attract attention (Chapters 6 and 7). We also see a marked difference between the vibration and pressure groups for the two slowest rates – it appears that on average it takes considerably more time for people to detect pressure stimuli than vibration stimuli at very slow actuation rates.

The figure also highlights a somewhat consistent increase in response times from DT Reading to DT Typing, but not much difference in response times between ST Baseline and DT Reading. The systematic response time increase for DT Typing can be attributed to competing motor responses – typing on the keyboard and clicking with the mouse both required the same hand motion, while

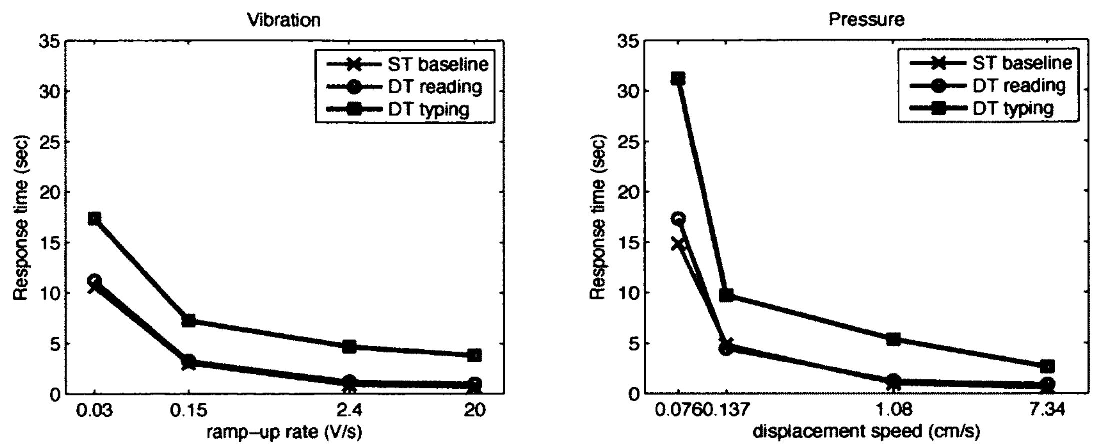

Figure 8.6: Average response time to vibration and pressure stimuli at various actuation rates for single- and dual-task scenarios. There was a statistically significant difference in response times between the dual-task typing task and the dual-task reading, as well as between the dual-task typing and baseline single task for both vibration and pressure groups. Additionally, there was a statistically significant difference in response times between the slowest and fastest actuation rate for the vibration group, and between the two slowest actuation rates and the fastest actuation rate for the pressure group. Statistical findings are summarized in Table 8.3.

Table 8.3: Statistical analysis of response time to stimuli with ST Baseline and an actuation rate of 6.0V/s or 7.34cm/s as the basis for analysis.

Vibration		**Pressure**	
factor	*p-value*	*factor*	*p-value*
DT Reading	0.803	DT Reading	0.744
DT Typing	< 0.001	DT Typing	< 0.001
rate1=0.03Vs	< 0.001	rate1=0.076cms	< 0.001
rate2=0.15Vs	0.341	rate2=0.137cms	0.004
rate3=2.4Vs	0.347	rate3=1.08cms	0.919

reading and clicking utilized separate response modalities (eyes and hands). Therefore the response times for DT Reading were more similar to those of ST Baseline.

An ANOVA was conducted with actuation rate and task as the independent variables and response time as the dependent variable. The results showed that there was a statistically significant difference among the actuation rates ($p < 0.001$) and tasks ($p < 0.001$), as well as a statistically significant interaction effect between actuation rate and task ($p < 0.001$). A multiple comparison test with Bonferonni corrections verified that, for the vibration group, DT Typing yielded significantly different results than ST Baseline and DT Reading, and the slowest vibration actuation rate (0.03V/s) yielded significantly different results than the fastest vibration actuation rate (20V/s). Similarly for the pressure group, DT Typing exhibited significantly different response times than the

ST Baseline and DT Reading groups. However, the two slowest pressure actuation rates (0.076cm/s and 0.137cm/s) were both significantly different from the fastest rate (7.34cm/s). The statistical results are summarized in Table 8.3.

For both vibration and pressure groups, we found the longest response times and greatest variability for the slowest actuation rate. In the ST Baseline case, subjects waited an average of 10.6 ± 0.17 or 14.9 ± 0.89 seconds from the onset of the stimulus to perceive and respond to the vibration or pressure stimulus, respectively, for the slowest actuation rate. In the DT Typing scenario, an average of 17.4 ± 0.73 or 31.3 ± 1.5 seconds elapsed before subjects reacted to the vibration or pressure stimuli, respectively, for the slowest actuation rate. In contrast, less than 0.7 ± 0.03 seconds elapsed in the ST Baseline case with the fastest actuation rate before subjects acknowledged the stimulus. These results again suggest that reducing the actuation rate will reduce the time until the signal is at a perceived level to respond to, which implies a reduction in attention capture.

We note that the response time to a vibration stimulus saturated earlier than pressure as actuation rate increased. We think that the vibration stimuli activated a certain set of mechanoreceptors that tend to elicit a more attention-grabbing behavioral response. Vibration actuation rates would need to be greatly reduced into an even lower frequency and lower amplitude domain before we could see response times similar to the slowly actuating pressure stimuli.

Comparing the two response time curves, it seems that pressure feedback exhibited greater overall attention capture dynamic range than vibration within the range of rates we tested. However the rapid increase in response time for a small decrease in actuation rate may suggest that attention capture is less controllable with pressure at slow actuation rates. This is further suggested by the fact that response times to pressure stimuli showed greater variability than response times to vibration stimuli at the slow actuation rates. While we acknowledge that haptic actuators could be improved and more rates could be tested to achieve a smoother curve, these curves suggest that both types of feedback are capable of modulating attention capture.

Finally, for reference, we correlated the vibration and pressure intensity level to the time of stimulus detection. Table 8.4 shows the mean vibration and pressure detection intensity (adjusted by each subject's reaction time) for the three tasks and the four actuation rates. For the pressure group, intensity is represented as a force, whereas for the vibration group, intensity is a combination of vibration frequency and amplitude. Note that for the fastest actuation rates, by design, the maximum stimulus intensity was always reached when subjects acknowledged the stimulus.

Table 8.4: Average stimulus intensity at detection for each actuation rate, adjusted by baseline response time.

Vibration				
	0.03V/s	0.15V/s	2.4V/s	20V/s
ST Baseline	58.6±2.2Hz	76.2±1.7Hz	110±7.0Hz	157Hz
	0.31±0.02g	0.48±0.02g	0.97±0.14g	3.11g
DT Reading	60.8±4.3Hz	84.2±3.0Hz	137±1.9Hz	157Hz
	0.33±0.04g	0.57±0.04g	1.97±0.14g	3.11g
DT Typing	104±2.8Hz	135±1.5Hz	157±0.1Hz	157Hz
	0.86±0.04g	1.81±0.09g	3.11g	3.11g
Pressure				
	0.076cm/s	0.137cm/s	1.08cm/s	7.34cm/s
ST Baseline	1.66±0.15lbs	2.13±0.16lbs	1.31±0.10lbs	9.27lbs
DT Reading	2.12±0.17lbs	1.88±0.16lbs	2.32±0.26lbs	9.27lbs
DT Typing	4.91±0.34lbs	4.62±0.40lbs	9.00±0.12lbs	9.27lbs

8.4.2 Anecdotes from informal interview

In the informal post-test interview, 17 out of 21 participants in the pressure study reported that they were able to delay immediately acknowledging the pressure stimuli during the typing task if the intensity was weak ("subtle"), and that they would finish typing the word or sentence before clicking the acknowledgement button. Additionally, 13 people said that only the rapid, high intensity pressure stimulus was annoying and disruptive to their reading and typing tasks. A quarter of the people noted that the gradual increase in pressure caused them to gradually and subconsciously change their posture without interrupting their office task, which was desirable. Only two people reported that they did not like pressure on their body.

In comparison, exactly half of the 20 participants in the vibration study said that they were able to finish typing a word or sentence before clicking to acknowledge the stimulus for the weak ("faint") vibrations. A total of 13 people reported that they would click the button immediately if the vibrations were "strong" (high intensity and fast actuation rate) because the vibrations felt insistent and disrupted them from their typing task. One person mentioned that he would make more typing mistakes at the rapid onset of a vibration stimulus, possibly because it was startling.

Interestingly, 3 subjects liked the vibration stimulus so much that they completed the entire typing task without clicking the button to acknowledge and turn off the stimulus for all three typing trials. In contrast only one subject did not turn off the pressure stimulus on one trial.

In the pressure group, a handful of participants remarked that the slowest actuation rate was somewhat "annoying" as they tried to anticipate the stimulus, and felt "paranoid" about whether they were actually perceiving the stimulus. For future studies, it might be advisable to actuate tactile stimuli faster than 0.076cm/s to avoid this "paranoia" effect.

8.5 Conclusion

This chapter examined the attention capture bandwidth of tactors and pactors as an investigation into variable attention capture (VAC) haptics. We have shown that by modulating the actuation rate, we can elicit different levels of attention capture with both tactors and pactors. Furthermore, we observed that pressure stimuli were less noticeable and therefore less distracting at slower actuation rates than vibration stimuli. However response times to pressure increased more sharply and exhibited greater variability, making it less easy to control.

We also found that the distractor task – more specifically, the response modality of the distractor task – had a significant effect on response times. If the person was typing, he will be more inclined to ignore the slowly actuating haptic stimulus (due to response modality conflict) than if he were reading.

In summary, we have found that both pactors and tactors exhibited response time curves that are indicative of variable attention capture, each advantageous in its own way. This finding will allow for a greater range of applications of haptic feedback, especially for conveying information of varying priority. We hope that the implications of our study will also help influence the design and control of future VAC haptic feedback systems for presenting information at an appropriate level of attentional salience.

Chapter 9

Evaluation of Two Types of VAC Haptic Feedback Systems for Seated Posture Guidance

9.1 Overview

In this chapter, we revisit the problem of seated posture guidance. Here, we investigate the effectiveness of two different variable attention capture (VAC) haptic feedback systems for seated posture guidance. Specifically, we are interested in learning how well users can comply with VAC haptic feedback as well as determining how minimally disruptive VAC haptics can be. Previously, we learned that actuation rate was most significant for achieving VAC, and that both pressure and vibration feedback could be controlled to exhibit VAC characteristics. In this final experiment, we integrate our VAC haptic actuators into office chairs and apply the lessons learned from past studies to seated posture guidance, thus coming full circle to our problem presented in Chapter 3.

We begin with a description of the two VAC posture sensing systems, followed by a discussion of the posture feedback algorithm. We then present the experimental design and the results of the experiment. Additionally, we compare the results of this study to our earlier experiment with non-VAC haptics (Chapter 3).

9.2 System Description

For this study, we aim to identify the same set of four postures as in Chapters 4 and 5: upright, slouching, leaning forward, and leaning back. (See Figure 4.2 and Table 4.1 for descriptions of each posture.)

9.2.1 Equipment

The two Posture Seat systems used in this study are similar to the one used in Chapter 4 and 5. The posture sensing system is a size B, fully adjustable Herman Miller Aeron chair instrumented with 6 force-senstive resistors (FSRs) and one infrared (IR) distance sensor. The placement of the sensors is the same as in Chapter 4 (see Figure 4.1).

There are two methods of delivering feedback: vibration and pressure. The vibration chair uses 6 vibrating tactors for haptic feedback, while the pressure chair uses 6 pactors for pressure feedback. Each FSR (1.5" square Interlink 406) is connected to a voltage divider circuit ($R_1 = 1k\Omega$). The sensing system (FSRs and IR distance sensor) are powered by a regulated 5V DC voltage. A National Instruments USB-6212 data acquisition unit (DAQ) is used to sense analog inputs.

Tactors for the vibration chair are composed of pancake eccentric mass motors (10mm x 3.4mm

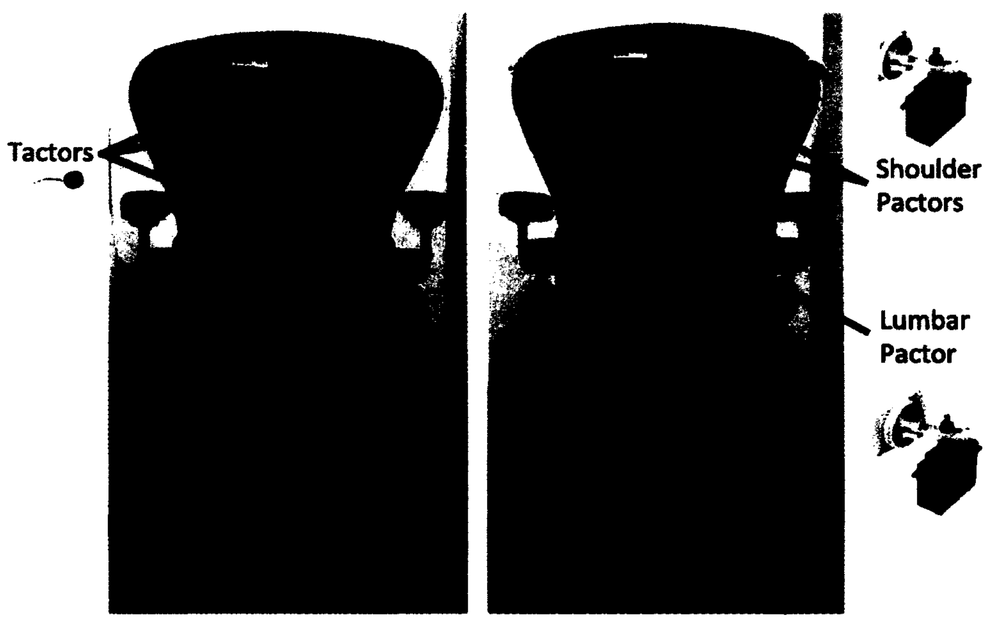

Figure 9.1: (left) Vibration chair with tactors, (right) pressure chair with pactors used for this study. Only the tactors and pactors on the back of the chairs are shown. The two others are mounted on the bottom of the seat under each thigh.

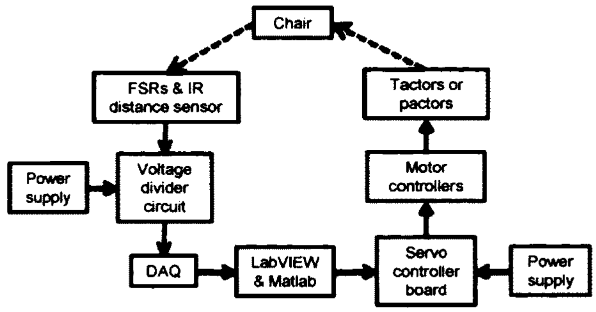

Figure 9.2: Block diagram showing the hardware connections for the posture sensing and feedback chairs.

shaftless vibration motors, Pololu #1636) surrounded by a 1.5"x1.5"x0.25" piece of soft polyurethane foam. The tactors are each controlled by a 3kHz PWM voltage between 0-6V using a motor controller (Pixie-7P), which are run from a servo controller board (Lynxmotion SSC-32). LabVIEW 2010 is used to communicate with the servo controller board via a serial connection.

Pactors for the pressure chair are comprised of an RC servo motor (HS805BB), custom-designed linkage arms, and contactor plates. (The design of the pactors is described in Chapter 7.) Pactors are attached to the back of the Aeron chair with custom made 0.250" plywood mounting plates.

Each feedback system utilizes five tactors or five pactors. The actuators are placed directly behind the left shoulder, lumbar, and thigh FSRs. The right shoulder actuator is located at the same height as the left shoulder actuator, and mirrored about the centerline of the chair. Actuator mounting locations on the back of the chair are shown in Figure 9.1. A block diagram of the entire system is shown in Figure 9.2.

We also used a Hitachi Hybridcam DZ-HS903A camcorder for recording still images and live videos for posture verification.

9.2.2 Posture Sensing

9.2.2.1 Calibration mode

The posture calibration algorithm is similar to the one described in Chapter 3. In essence, the user is directed to sit in each of the 4 postures as described in Figure 4.2 and Table 4.1. The 7 sensor values are recorded automatically, resulting in a unique set of values for each posture for each user. We refer to these as the "calibration values" for the "calibration postures."

9.2.2.2 Classification mode

After calibration is complete, the system switches to posture-classification mode in order to verify the classification accuracy for each user. The user sits in each of the postures from a randomized list of postures while our sensing system records the sensor values once the users stabilize in their posture. The mean-squared error (MSE) is computed between the sensor readings and the user's four sets of calibration values. If the MSE is below a threshold H, the posture identification algorithm assigns the posture corresponding to the lowest MSE. However, if MSE $> H$, the posture is considered "other." When the predicted posture is the same as the actual posture, it is recorded as a match. Finally, the total number of matches is used to compute classification accuracy. (This is the same classification procedure as described in Chapter 3.)

Based on a preliminary evaluation of the current posture chair system, the threshold H was set to 0.06V for this study as a balance between natural postural sway and potential confounding effects of other postures.

9.2.2.3 Real-time sensing mode

The real-time sensing mode is employed in conjunction with real-time posture feedback, which will be discussed in the next section. In this mode, there is a target posture that the user must reach. MSE is only computed between the user's current real-time sensor values and his target posture calibration values, as opposed to all 4 sets of calibration values. An MSE $< H$ indicates that the user is sitting in the desired posture.

9.2.3 Posture Feedback

The purpose of posture feedback is to use haptic stimuli to guide the user into a specific reference posture. The allowable postures are upright, leaning forward, and leaning back. Even though calibration values were recorded for the slouching posture, the user will not be guided into it as it is an unhealthy posture.

For the posture feedback algorithm, let $s_1, s_2, ...s_7$ be the voltage reading from each of the 7 sensors (6 FSRs and one IR distance sensor). Let V denote the array of instantaneous sensor values while a user is sitting in the chair, i.e. $V = \begin{bmatrix} s_1 & \dots & s_7 \end{bmatrix}$. Also let V_p^* denote the array of values for each calibration posture, where $p \in \{1\text{=upright}, 2\text{=slouching}, 3\text{=leaning forward}, 4\text{=leaning back}\}$. For a given target posture p, the feedback algorithm computes the mean-squared error between the current sensor values and the calibration values:

$$MSE_p = \frac{1}{7}\left((s_1 - s^*_{p,1})^2 + ... + (s_7 - s^*_{p,7})^2\right). \tag{9.1}$$

If $MSE_p > H$, where threshold $H = 0.06V$, then the user is sitting in an incorrect posture and feedback will be activated. (Otherwise feedback will remain off as the user is in the target posture.)

The location of the feedback stimulus and the corresponding action that the user must take to eliminate the vibration or pressure feedback are shown in Tables 9.1 and 9.2. The feedback location and intensity are based on the sensor location L with the greatest absolute error e_L:

$$e_L = max(|s_1 - s^*_{p,1}|, ...|s_7 - s^*_{p,7}|). \tag{9.2}$$

The location-specific feedback intensity I_L is linearly proportional to e_L within a predetermined error range e_{max}:

$$I_L = \frac{I_{max} - I_{min}}{e_{max}} e_L + I_{min}. \tag{9.3}$$

Since $I_{min} = 0$, and e_{max} was empirically determined to be 1, Equation 9.3 simplifies to

$$I_L = \begin{cases} I_{max} \cdot e_L & \text{if } e_L < e_{max} \\ I_{max} & \text{if } e_L \geq e_{max} \end{cases} \tag{9.4}$$

Finally, when the user is guided to a new target posture, a time-dependent intensity filter is applied to the feedback intensity such that

$$A_L = \begin{cases} r \cdot I_L \cdot Z & \text{for } Z < 1/r \\ I_L & \text{for } Z \geq 1/r \end{cases} \tag{9.5}$$

in discrete time, where Z is the discrete timestep and r is the actuation rate. The update rate was 50Hz and the actuation rate in discrete time was 0.01V/Z for vibration and 0.02cm/Z for pressure. A_L is the final stimulus intensity that is delivered to the user.

In summary, posture feedback is activated when the MSE between the user's real-time posture and the reference posture is greater than threshold H (H=0.06V), indicating that he is not sitting in the target posture. While MSE $> H$, the algorithm searches for the sensor "location" that corresponds to the greatest absolute error. Once the location is determined, body-site-specific

Table 9.1: Vibration feedback mapping: location of vibration and correct action to take to eliminate vibrations.

Location of Vibration	**Action to Take**
shoulders, continuous	lean forward away from back of chair
lumbar, continuous	sit up straight, arch back
legs, continuous	lean back towards back of chair
legs, pulsing	lean forward away from back of chair

Table 9.2: Pressure feedback mapping: location of pressure and correct action to take to eliminate pressure

Location of Pressure	**Action to Take**
shoulders, steady	lean forward away from back of chair
lumbar, steady	sit up straight, arch back
legs, steady	lean back towards back of chair
legs, tapping	lean forward away from back of chair

feedback may be triggered. Haptic feedback intensity was controlled to be directly proportional to amount of absolute error at the sensor location. This variable-intensity analog feedback will help the user discern how close he is to the reference posture. Additionally, a time-dependent intensity filter is applied to the first onset of postural feedback for guiding to a new posture. The filter is a simple linear function that increases in intensity over time. The rate of increase ranges from 0.03V/s to 1.2V/s for vibration feedback, and 0.076cm/s to 4.06cm/s for pressure feedback, proportional to the amount of absolute error at the sensor. These rates were chosen based on the results of the study in Chapter 8 that displayed variable attention capture within these actuation rates. The maximum driving voltage for vibration was 3V, which corresponded to a vibration intensity of 157Hz and approximately 3.11g. The maximum displacement for pressure feedback was 2.0cm, which corresponded to approximately 45N force. When the user adjusts his posture towards the target posture, stimulus intensity will decrease to signal he is moving in the right direction towards the reference posture. During this phase of active adjustment, a time-dependent intensity mask is not applied. Finally, when MSE $< H$, indicating the user is sitting in the target posture, feedback turns off.

9.3 User Study

We conducted a user study to evaluate the effectiveness of VAC haptic feedback in guiding the user to a reference posture. We also aimed to measure the level of task interference due to responding to VAC feedback while the user performed a simultaneous office task. Since we are trying to simulate an office setting, we will evaluate the performance degradation of a typing task while the user simultaneously responds to posture guidance. Finally, we will compare the results of this experiment to the results of our prior posture sensing and feedback experiments (Chapter 5) that used non-VAC haptic feedback.

Test subjects were randomly assigned into one of two posture study groups - vibration group or pressure group. The test procedure for both groups is listed in Table 9.3.

For the calibration phase, subjects were instructed to sit in the instrumented office chair in four different postures – upright, slouching, leaning forward, and leaning back – while the system recorded the calibration sensor values ("Calibration Mode"). Their postures were visually verified by the experimenter and photographs of their postures were automatically recorded for future reference.

Next, for the classification accuracy phase, subjects were told to sit in the posture that appeared on the screen while our system recorded their static posture sensor readings ("Classification Mode"). The sequence of postures (4 postures repeated 3 times) was randomized prior to the experiment and each subject sat in a total of 12 postures. If our system was able to correctly identify the person's posture at least 11 out of 12 times, then the experiment was allowed to continue. Otherwise a re-calibration was required. If after three calibration attempts our system was still unable to correctly identify the user's posture, the experiment would terminate.

If posture classification was successful, subjects would continue to the training phase of the ex-

Table 9.3: Test sequence for both vibration and pressure study groups

	Test phase	Duration
1	Calibration	5 min
2	Classification Accuracy	8 min
3	Feedback training	8 min
4	Baseline response time	5 min
5	Typing training	5 min
6	Baseline typing test	5 min
7	Dual-task typing and posture guidance	5 min x 4 trials
8	Post-experiment interview	5 min

periment. Depending on their experiment group, they would receive vibration or pressure feedback training for guiding into the upright, leaning forward, and leaning back postures. As mentioned before, they were not guided into the slouching posture as it is an unhealthy posture. Test subjects were given a reference sheet with the feedback mapping and the correct action to take (Tables 9.1 and 9.2), which were also explained to them verbally. Test subjects could take as long as needed to master their motor response to feedback, but most subjects took less than 3 minutes to correctly respond to the feedback.

After subjects indicated their familiarity with the feedback, we measured their baseline response time to postural feedback guidance. In this phase, subjects were guided to a randomly selected posture at predetermined random time intervals ranging between 20-30 seconds. They were told that feedback intensity was proportional to their postural error so moving closer to the target posture would result in "softer" stimuli and no stimuli at all when the target posture was reached. In total, they were guided to 15 postures, i.e. 5 times for each of the 3 acceptable postures.

Next, subjects received training on our typing environment. This is the same typing environment as was used in Chapter 4 (Figure 4.3). Subjects were instructed to type verbatim the passage shown on the screen. Meanwhile, the timestamp of their correct keystroke was automatically recorded. The screen refreshed with a new passage every 60 seconds to eliminate the need for scrolling with the mouse. Even though we allotted 5 minutes of training, all subjects expressed their comfort and familiarity with the program after about 2 minutes. Regardless, all subjects completed the five-minute training.

After the typing practice, we measured subjects' baseline typing speed without posture feedback.

Finally, we combined the typing and posture feedback in the "dual-task typing and posture guidance phase" (DT trials). Subjects were told to type the passage verbatim as before, while simultaneously responding to vibration or pressure posture guidance. Their primary objective was to perform the typing task and the secondary objective was to respond to posture guidance. They performed the dual-task trials a total of 4 times. The first trial was discarded from analysis as a "practice" trial.

At the end of the experiment, subjects were asked informal interview questions including how disruptive the vibration or pressure stimuli was, whether or not they stopped typing due to sensing haptic stimuli, etc. Subjects were also given the opportunity to express any other comments related to the study. The entire study lasted approximately 1 hour and 15 minutes.

All participants wore noise canceling headphones playing white noise for phases 3-7 (see Table 9.3).

9.4 Results and Discussion

A total of 51 people participated in the experiment. The test subject demographics for each experiment group are presented in Table 9.4.

Table 9.4: Test subject demographics

	Vibration Group	**Pressure Group**
N	26 (15 females)	25 (12 females)
Average age	22±3.5 years	22±3.7 years
Average height	168±8.9cm	168±8.1cm
Average weight	64±11.4kg	63±10.0kg
Median familiarity with haptic feedback devices	"some"	"some"
Average time spent sitting in office chair per day	7±2.9 hours	6±2.9 hours
Average time spent on computer each day	7±2.8 hours	6±2.8 hours
Average typing speed	62±18wpm	66±20wpm

9.4.1 Calibration and Classification Accuracy

All participants were calibrated to the upright, slouching, leaning forward, and leaning back postures. The posture sensing system was able to identify postures with 92%-100% accuracy for all 51 subjects. Therefore, all 51 subjects were able to continue with the experiment.

9.4.2 Dual-task trials – typing performance

The following table summarizes the typing performance results of the dual-task (DT) trials. As mentioned before, the first DT trial ("trial 0") was discarded as practice. For comparison, the bottom half of the table shows the results of the dual-task trials from an earlier study that did not use VAC haptics (Chapter 5).

In the top half of the table, we see that participants from both vibration and pressure groups experienced an average of about 11%-12% typing speed degradation from baseline to the dual-task trials. These results were slightly better than the 13.2% typing performance decrement seen in the

Table 9.5: Comparison of aggregate typing performance between the VAC tactor and VAC pactor groups (vibration and pressure groups, respectively). For reference, typing performance from the non-VAC study (Chapter 5) is also presented.

	Vibration *(n=26)*	**Pressure** *(n=25)*
Avg. baseline typing speed	326 cpm	345 cpm
Avg. DT typing speed	287 cpm (-12.0%)	307 cpm (-11.0%)
Sig. diff, baseline to DT	9 people (35%)	4 people (16%)
(earlier study, for reference)	**Vibration** *(n=20)*	
Avg. baseline typing speed	257 cpm	
Avg. DT typing speed	223 cpm (-13.2%)	
Sig. diff, baseline to DT	11 people (55%)	

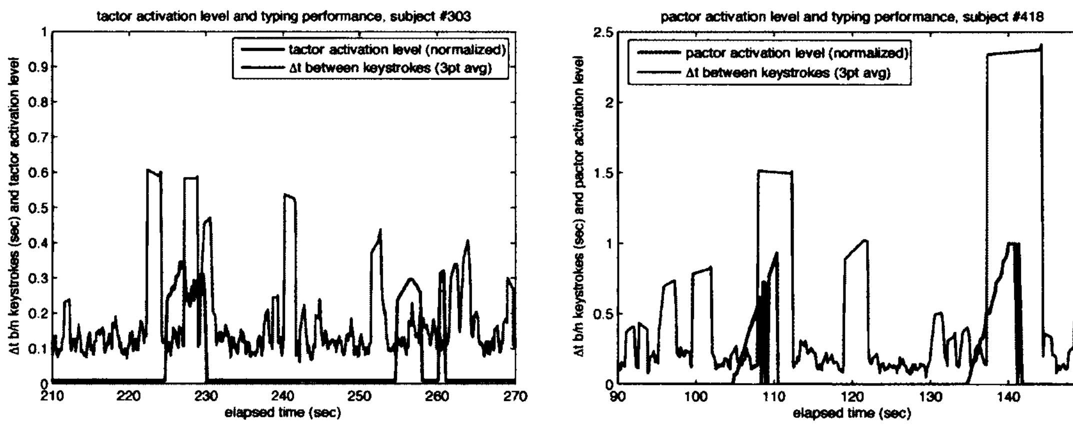

Figure 9.3: An illustrative plot from one test subject in the tactor group and one in the pactor group showing time between keystrokes and actuator activation level from a one-minute snapshot. As actuator activation level increased (red line), subjects' primary task performance were less affected by the VAC feedback; they were able to delay responding until a more opportune time. These VAC example plots stand in contrast from the non-VAC example in Figure 4.5 where subjects were significantly impacted by the vibrotactile posture feedback guidance.

earlier study, although the differences were not significant. However a closer examination of each subject's typing performance revealed that some subjects were able to delay responding to postural guidance until a more convenient time. Figure 9.3 shows two examples of such behavior (one from the vibrotactile group, the other from the pressure group). When the VAC haptic actuator slowly ramped up in feedback intensity (bolded red lines), subjects continued to type normally (blue lines) until some later point when they decided to pause typing and adjust their posture. A paired t-test comparing typing speed during active feedback and inactive feedback (moments of sitting in the reference posture) revealed that there was no statistically significant difference in mean typing speed (vibrotactile feedback: $p = 0.3177$, pressure feedback: $p = 0.4858$). This supports our claim that VAC vibration and VAC pressure feedback can be minimally disruptive to a worker's primary task.

We performed a between-subject unpaired t-test to examine the effect of feedback modality (vibration or pressure) on typing performance for the baseline and dual-task trials. We found no statistically significant difference between the vibration and pressure groups for typing performance (baseline: $p = 0.5008$, dual-task: $p = 0.4391$).

A within-subject t-test with trial type (baseline or dual-task) as the independent variable revealed that 35% of the people in the vibration group experienced statistically significant typing speed decrease from baseline to the dual-task trials ($p < 0.05$), while only 16% of the people in the pressure group experienced significant typing speed decreases. We contrast this with results from Chapter 4 (bottom half of Table 9.5) where 55% of the subjects exhibited significant typing speed decreases due to responding to vibrotactile feedback. These results lead us to believe that vibratory sensations may be, in general, more disruptive than pressure sensations. Much more careful design of vibrotactile feedback may be needed to achieve the same level of VAC as pressure feedback.

9.4.3 Dual-task trials – response time to posture guidance

The average response times to postural feedback is shown in Table 9.6. Again, for reference, we list the posture feedback response times from Chapter 4 without VAC haptics in the bottom half of the table. Our results indicated that subjects complied with VAC haptic feedback for seated posture guidance within a reasonable amount of time.

From the table, we see that the average time to respond to pressure feedback was always longer than that for vibration feedback. An unpaired t-test was conducted to assess the effect of the type of haptic feedback on time taken to achieve the desired posture. There was a statistically significant difference between the vibration and pressure groups for transitioning to the upright posture ($p = 0.002$), with responses to pressure taking almost twice as long as responding to

Table 9.6: Comparison of average response times to posture feedback guidance between the VAC tactor and VAC pactor groups (vibration and pressure chairs, respectively). For reference, posture transition response times from the non-VAC study (Chapter 5) is also presented.

	Vibration *(n=26)*	**Pressure** *(n=25)*
Transition to UP	2.265 sec	4.195 sec
Transition to LF	4.231 sec	4.412 sec
Transition to LB	4.819 sec	6.065 sec
(earlier study for reference)	**Vibration** *(n=20)*	
Transition to UP	3.500 sec	
Transition to LF	3.493 sec	
Transition to LB	4.510 sec	

vibration feedback. The response time difference between the vibration and pressure groups did not reach statistical significance for transitioning to the other two postures ($p > 0.05$). Additionally, transitioning to leaning forward and leaning back postures usually took longer than responding to upright posture feedback. This is expected as more motion is required to transition to these two "extreme" posture locations.

Comparing these results to the results obtained from Chapter 5, we see that the posture transition response times under VAC haptic feedback were comparable – about 1-2 seconds slower – to no VAC haptic feedback. This is very much acceptable as postural compliance is the less important task.

9.4.4 Anecdotes

In the post-experiment informal interview, subjects had the opportunity to voice their thoughts about the feedback. In the vibration group, 8 out of 26 people thought the vibrations were intuitive, 6 of which clarified that the back vibrations were intuitive but the leg vibrations required more mental processing. In contrast, 12 out of 25 people expressed that pressure feedback was intuitive, and that pressure feedback on the back was more intuitive than under the legs.

Six people thought vibrations in general were disruptive. Still 8 others thought that vibrations themselves were not really disruptive but rather the act of changing posture was disruptive, causing them to pause their typing even if the feedback was "quiet." In comparison, 10 out of 25 people in the pressure group said that the act of changing postures was disruptive while pressure itself was not. Twelve others thought that pressure feedback was not distracting. Only one person voiced that pressure feedback was annoying and disruptive.

These comments were consistent with the quantitative data that showed that more people in the vibration group (compared to the pressure group) experienced a statistically significant typing performance decrement while simultaneously responding to posture feedback. Furthermore, these comments support that the act of changing postures while trying to perform another task is in itself a taxing task and induce a non-zero performance decrement to the primary task.

A total of 9 people felt that vibration feedback would have been less disruptive if they had internalized the feedback mapping through more practice (more than just the 4 trials in the experiment), while 8 people in the pressure group said they had learned the feedback by the end of the last dual-task trial. A longer duration or multi-day experiment would be needed to further assess the cognitive cost and learning effects of using VAC haptic feedback for seated posture guidance.

Finally, two people reported experiencing phantom vibrations, and two others thought the subtle vibration stimuli were most disruptive since they tried to anticipate the stimuli, and would have preferred a clearer (more intense) signal.

9.5 Discussion

In this study, we found that all 51 subjects were able to successfully comply with vibration or pressure feedback posture guidance. While the response times for transitioning into the upright, leaning forward, or leaning back postures differed within each group, the response times were very similar when compared across the vibration and pressure groups. Additionally, the transition times under VAC haptic feedback were, on average, only 1-2 seconds slower than no VAC haptics. In exchange for this slower response time, subjects were less hindered in their primary tying task; fewer subjects in the VAC groups experienced significant performance degradation than the non-VAC group. These results are encouraging; first, they suggest VAC vibration and pressure stimuli can elicit similar behavioral responses. Second, our current implementation of VAC haptic feedback can guide users to a desired posture in a very reasonable amount of time.

In the dual-task trials, we saw similar overall typing performance degradations for subjects in both pressure and vibration groups. Additionally, in the informal interview, we learned that many subjects did not find vibration or pressure feedback disruptive, but rather the act of adjusting their posture was disruptive to their typing. We surmise that the consistent performance decrement may be due to the nature of the simultaneous tasks – regardless of how ambient the feedback may be, both typing and posture adjustment required sensory-motor control and perhaps these two tasks were competing for the same mental resource. Because we see a consistent performance degradation regardless of the haptic feedback rate or intensity, we are led to believe that there may be mental resource competition between the hands and the body response modalities. However we don't know if the performance decrement will be generalizable to other primary tasks that do not involve typing, or if any amount of whole-body movement will cause performance degradation of another task.

The decrease in typing speed in the dual-task phase could also be due to a learning effect. Although we did not see a significant typing speed increase between dual-task trials 1-3 in this study, subjects were clearly expending mental resources to translate the haptic stimuli into motor responses; the responses are not yet second nature. We know from Rassmussen [118] that there are skill-based, rule-based, and knowledge-based forms of learning. It's possible that the duration of the experiment was not sufficient for subjects to internalize the feedback mapping into skill-based learning and respond to the feedback automatically. Perhaps a longer study over a period of multiple days or weeks may be needed to assess this learning effect.

The similarity in posture transition response times between the vibration and pressure groups, with the exception of responding to upright posture feedback, suggest that they are comparable in effectiveness in guiding the user to a particular posture. However, we also found that VAC pressure feedback was slightly less disruptive than VAC vibration feedback. This could be due to differences in the current implementation of our pressure and vibration feedback systems – possibly pactors were easier to control and therefore could modulate attention capture between "ignorable" to "demand action" more easily. Perhaps in a future study we could redesign the tactors with even greater actuation bandwidth for VAC. However several subjects in the vibration group mentioned that, in general, vibration stimuli were annoying to them. From Chapter 6 we know that things that elicit negative affect tend to elicit greater attention capture, which in this case will be more disruptive to the primary task of typing.

Finally, many subjects expressed that feedback from the back of the chair was more intuitive than feedback from under the legs. This is because multiple directional encodings were assigned to the actuators under the legs (i.e. toward or away from back of chair), while only one encoding was mapped to the actuators in the back the chair (i.e. move away from back of chair). The dual-encoding under the legs led to a little bit of confusion, but many subjects were able to internalize the feedback mapping and execute the correct response with a little bit of practice. Therefore, in the future, if minimal learning curve is desirable, then it is advisable to map only one motor response to each actuator.

When compared to the results of a prior study without VAC haptics (Chapter 4), we see that far fewer subjects experienced statistically significant typing performance decrement in the presence of VAC haptics. We are encouraged by this result that proves VAC haptic feedback causes less disruption to a user's primary task, while simultaneously acknowledging that even greater improvements can be made to the current implementation of our two VAC haptic feedback chairs for more fluid modulation of attention capture.

9.6 Conclusion

In this study, we evaluated the effectiveness of variable attention capture (VAC) haptics for seated posture guidance, and its level of disruption to a primary (typing) task. For reference, we compared the results of this study to an earlier study we conducted on posture sensing and feedback that did not utilize VAC haptics.

We learned that VAC haptics was successful in guiding users to a desired seated posture within a reasonable amount of time. Responding to VAC haptic feedback was less disruptive to their typing task than responding to non-VAC haptic feedback. However subjects exhibited a consistent typing performance degradation from responding to feedback, which could be due to competing response modality resources and learning effects, and not necessarily due to VAC haptics. Finally, VAC vibration feedback was slightly less preferred than VAC pressure feedback for seated posture guidance due to the inherent "annoying" nature of vibratory stimuli.

Our current work explored the feasibility of VAC haptics for the specific application of seated posture guidance. These results demonstrate that VAC haptic feedback is both feasible and beneficial for modulating information priority and improving task performance. This work has the potential to extend into other areas needing different levels of feedback for tasks with differing priorities. We hope that our work not only helps improve office worker health with minimal disruption to their productivity, but also provide a basis for further research into variable attention capture (VAC) haptic feedback systems to appropriately manage user attention.

Chapter 10

Summary and Outlook

The primary objective of this dissertation was to introduce the concept of *variable attention capture* (VAC) haptic feedback as a new design paradigm in the field of haptics for conveying touch information at an appropriate level of attentional salience. The specific aims of this research were to construct devices capable of delivering VAC haptic stimuli; characterize variable attention capture through user studies in the context of the operation of these devices; and show that these devices are useful and beneficial for providing information in a timely, accurate, and unobtrusive manner.

To that end, we successfully designed, characterized, and implemented low-cost vibration- and pressure-based feedback systems for the application of seated posture guidance. This Posture Seat system, utilizing only seven sensors, was capable of identifying 4 common postures – upright, slouching, leaning forward, and leaning back – with greater than 91% accuracy, and 10 common postures with greater than 86% accuracy. We used a continuously valued error signal to compute the degree of match rather than a binary match, thus allowing us to provide feedback intensity proportional to the magnitude of posture error. This system produced minimal feedback intensity when errors were small and increased in intensity with larger deviations.

Our user studies showed that this initial non-VAC Posture Seat system was successful in guiding subjects to a desired posture: we observed immediate posture compliance in response to vibrotactile haptic stimuli, and test subjects were observed to sustain their target posture for a short period even after feedback ended (Chapter 3). However, we noted that the initial implementation of vibrotactile feedback caused considerable primary task interference (Chapter 4), while being similar in effectiveness to visual feedback methods (Chapter 5). To overcome the disruptiveness of vibrotactile feedback, we focused our research on determining parameters that most significantly impacted attention capture in order to develop effective VAC haptic feedback systems.

In our investigation of parameters conducive to variable attention capture (Chapter 6), we found that temporal factors – actuation rate and profile – had the greatest effect on attention capture, followed by stimulus magnitude. Additionally, we observed a negative correlation between attention capture and affect (stimuli with negative emotional associations increased attention capture) and a positive correlation between attention capture and novelty (novel stimuli increased attention capture). Other actuator and stimulus parameters such as material, geometry, location on body exhibited less pronounced effects on attention capture. We concluded that actuation rate and profile should be the primary factors modulated in the design of VAC haptic feedback systems. Additionally, since preferences varied by subject, a haptic feedback intensity "volume" control should be incorporated to accommodate each user's preference.

Based on the findings from Chapter 6, we developed novel pressure-based actuators (pactors) capable of varying actuation rate and intensity (Chapter 7). We also redesigned tactors to span a wider range of actuation rates and intensities. Perceptual studies revealed a favorable response time curve for both actuators, indicating that they were capable of modulating attention capture across a spectrum (Chapter 8).

When VAC tactors and pactors were integrated into the Posture Seat for posture guidance, our in-the-wild study showed that fewer test subjects experienced significant performance degradation in their primary office task when using the VAC system compared to using the non-VAC system (Chapter 9). We thus demonstrated that VAC haptic feedback is both feasible and beneficial for modulating attentional salience and improving task performance in the context of seated posture guidance.

Our research was the first to develop a posture sensing and haptic feedback mechanism for real-time seated posture guidance. We demonstrated the simplicity and efficacy of such a mechanism and anticipate that this could be adapted for medically valid studies. We believe that this low-cost, easy-to-use Posture Seat system would be useful as a tool for occupational therapists, posture experts, and even everyday consumers to monitor and correct unhealthy sitting postures to help mitigate injury.

Our work was also the first to explore VAC haptic feedback as a new design paradigm for integrating focal and ambient haptic feedback systems to fluidly modulate a user's level of attention capture. Our work laid the foundation for a general approach to developing and characterizing VAC haptic feedback systems. As our knowledge of the haptic attention capture spectrum increases, we could further increase our ability and sophistication of encoding information in haptic stimuli. We envision that a complete understanding of the human haptic sense may eventually result in systems capable of a haptic "language," synthesizing haptic vocabulary, tone, and context to produce effective communication. We hope that others may build upon my doctoral work to expand and fully utilize that language through the development of their own VAC haptic feedback systems that can deliver information at an appropriate level of salience, thereby melding seamlessly into the user's environment.

Chapter 11

Future Work

The user studies in this dissertation uncovered many interesting findings which serve as the basis for future research. This chapter lists potential short-term and long-term research directions that advance the field of haptics as a viable "language" for communication. We begin by discussing research goals that can improve the capabilities of the current posture sensing and feedback system. This is followed by a discussion on areas of future development for VAC haptics that help explore the full range of the haptic "language" for more effective information communication. Lastly, we end with our recommendations for potential applications of VAC haptics outside of seated posture guidance.

11.1 Future work for the Posture Seat system

Smarter posture sensing system

First, we would like to improve the posture sensing capabilities so that it can accurately identify 10 or more of the most common seated postures with greater than 86% classification accuracy. This may involve developing a learning algorithm or a weighted posture cost function instead of the current method of computing the mean-squared error (MSE) for each posture.

Additionally, we would like to develop sensors that could be embedded in any standard office chair. Currently the posture sensing system works only when force-sensitive resistors (FSRs) are affixed to the pellicle surface of the Herman Miller Aeron chair. With most other office chairs, especially well-cushioned office chairs, the analog outputs from the FSRs on or inside the chairs are significantly attenuated. Therefore the posture sensing system would be more versatile if the sensors could be adapted to fit a variety of office chairs. This could be achieved, for example, through the use of different sensors, the development of housings for the current FSRs to amplify the signal, or the integration of signal amplification circuitry.

Better actuators

Second, we would like to increase the bandwidth and fidelity of our VAC haptic actuators. Currently tactors for the Posture Seat are comprised of eccentric mass motors whose frequency and amplitude responses are a non-linear function of driving voltage with a lot of variability, rendering them hard to control. They also have an undesirable deadband in the low frequency and low amplitude region, the region most critical for ambient haptic feedback. Furthermore, there is variability from tactor to tactor, making it difficult to ensure the same level of stimulation is delivered for a given driving voltage. Therefore we seek to improve the bandwidth of VAC tactors by exploring a different vibratory actuation technology (perhaps voice coil actuators) that has a lower turn-on voltage and is capable of delivering low frequency and amplitude vibratory stimuli (close to 0.1Hz) to the human body. The performance of such an actuator must be more repeatable than the current tactors. By increasing the vibration resolution and controllably decreasing the vibratory intensity, we will be better able to achieve ambient attention capture [83].

We would also like to improve the form and function of our pactors. Currently, pactors are larger and heavier than desired, and we would like to downsize them to be more portable like tactors. Smaller pactors will also improve their versatility, for example, for embedding into a variety of office chairs or even for wearable haptics. Additionally, we would like to eliminate the undesirable vibratory artifact as pactors should deliver only pressure-based stimuli.

Finally, we would like to "soundproof" the tactors and pactors to eliminate the high frequency buzzing noise so users need not wear noise canceling headphones, or be preemptively influenced by noise from the actuators.

Stimulus-response compatible feedback mapping

Our choice of feedback mapping for seated posture guidance (moving towards or away from vibration or pressure depending on cueing location) was based on what was assumed to be the natural motor action. However through our studies we learned that encoding two different feedback schemes on one body site created confusion. Hence for future studies we will deliver only one kind of stimulus at each body location and investigate what is the most effective stimulus to deliver, along with the most optimal body locations for such a stimulus.

Longer duration studies for learning and retention

Although most study subjects indicated that the haptic feedback seated posture guidance was intuitive, the feedback still cost them non-zero performance decrement. Therefore we conclude that internalizing the haptic feedback mapping might have required more time than was available during our posture guidance studies. To truly transition from rule-based processing (high mental effort) to skill-based processing (automatic, low mental effort) [117] would require more practice with the feedback system and thus longer trials. Multiple weeks or months of using the system may be necessary to evaluate long-term motor skill learning.

Concurrently, we would like to evaluate sensory-motor skill retention by investigating optimal on/off feedback duty cycles in order to reduce the user's dependence on feedback for seated posture guidance. Furthermore, by integrating VAC haptic feedback, we hope to gain a better sense of worker productivity over an extended period of time.

Medical efficacy - preventative and rehabilitative

Finally, we would like to collaborate with physical therapists and posture specialists to evaluate the medical efficacy of our Posture Seat for back pain preventative care and rehabilitation. Our subject population comprised of readily available student volunteers who represent one type of user group and may not necessarily be the direct beneficiaries of the Posture Seat. Therefore a study utilizing a larger population with more careful attention to selecting the population of interest, including patients with chronic low back pain, is an appropriate next step.

11.2 Future work for VAC haptics

Quantifying the attention capture spectrum

First and foremost, we would like to quantify each notification level along the attention capture spectrum. Currently we draw loose connections between response time and levels of attention capture: shorter response times indicate more focal feedback and longer response times mean more ambient feedback. However there is no numerical definition associated with each of the notification levels, or with the general terms "focal" and "ambient" feedback. Therefore, by quantifying the notification levels along the attention capture spectrum, we will provide a more rigorous way of characterizing how VAC haptic feedback systems modulate attention along this spectrum.

Context sensing

A crucial part of context-sensitive haptic feedback is sensing the user's context. We wish to develop robust methods of sensing the context of a user's environment (such as utilizing a vision system to detect user activity) as well as the user's mental workload and interruptibility (such as EEG, heart rate, or skin conductance) so that a timely and appropriate level of feedback may be delivered to the user.

Design of new VAC actuators

In addition to improving the existing tactors and pactors, we aim to develop a new set of VAC haptic actuators that combines tactors and pactors into one system. This integrative unit can deliver slowly actuating pressure stimuli to convey less urgent information and fast-actuating vibrotactile stimuli for more urgent information. Additionally we would like to explore a combined thermal and low frequency actuation mechanism that could better emulate human touch. According to [26], people correlate heat and low-frequency motion with human contact. To our knowledge, so far no research has been conducted in designing and evaluating a thermally modulated low-frequency actuator for ambient haptic feedback.

Perceptual studies with VAC haptics

A largely unexplored area of haptic perception is how well people can perceive haptic stimuli on different parts of their body while the person is in motion. Most of the haptic perceptual studies involve detection of a stimulus when maintaining a static pose, while only a small portion of haptic studies involve stimulus detection while moving. However many of our everyday activities involve some sort of movement, and feedback that is easy to identify when stationary may become hard to identify when in dynamic motion. Therefore it would be beneficial to investigate which haptic feedback characteristics are most salient while a person is in motion, and to what degree we can modulate these stimulus parameters to achieve variable attention capture.

Trained associations VAC vibrotactile feedback

Vibrotactile feedback often feels "unnatural" and usually elicits an attention-getting response, even at low intensities. But can these sensations be learned to be processed in the background even at the onset? It would be interesting to investigate whether we can "train" a peripheral haptic sense to react to certain vibratory sensations and ignore others. Additionally, it would be interesting to create or reverse any ingrained negative cultural or experiential associations with certain haptic stimuli to elicit only positive affective response and thus negative (low) attention capture. This would be the beginnings of establishing a haptic feedback "vocabulary" that makes formal associations between words and haptic sensations.

11.3 Applications of VAC haptics

Finally, we would like to explore VAC haptics for a broad range of applications in addition to seated posture guidance. For example, VAC haptic feedback could be integrated into the car seat to convey variable-priority information to the driver about objects in his blindspot or a tailgating car. (Early stages of this work is presented in [95]). These notifications are not simply binary on-off alerts but are more subtle and fluid, allowing the driver to attend to the signals when needed.

Another area of application would be to integrate VAC haptic feedback into a variety of muscle guidance tasks and rehabilitation devices. For example, our partial weight bearing compliance aid for orthopedic surgery patients delivers ambient (low intensity) vibrotactile stimuli to the patient to confirm that he has reached his partial weight bearing target load, and delivers a salient (high amplitude and pulsing) vibratory signal to alert the patient that he has exceeded the safe weight bearing range [24]. Sensory-motor guidance devices (for rehabilitation as well as sports training) can provide continuous ambient feedback to confirm a normal or positive action, and deliver attention-getting feedback for a negative action.

A final area of application for VAC haptics could include background activity monitoring. For example, a VAC haptic wristwatch that ticks more intensely or rapidly can warn a presenter when his time is about to expire (similar to [143], or when the volume of trades in a stock market increases dramatically. Another example can be a wearable haptic display that monitors and conveys the heart rate of loved one, and changes to a more urgent signal when the heart rate becomes abnormal. These devices all aim to move fluidly between the focal and periphery of one's attention to convey timely and relevant information to the user.

In summary, variable attention capture haptics is a nascent research area within the field of haptics. The studies presented in this thesis provide only a glimpse of what can be achieved with VAC haptics; there are myriad opportunities for further developing VAC haptics, from perception to application. We hope that this dissertation has put forth a framework for further research in the area of VAC haptics to help fully characterize and utilize our rich haptic sense.

Appendix A

Cutaneous Senses

The skin is the largest organ in the human body and covers an area of approximately $1.8m^2$ [135]. Skin can be divided into two types: glabrous and hairy. Glabrous (non-hairy) skin is found only on plantar and palmar surfaces, whereas hairy skin is found on all other parts of the body. Mechanoreceptors in glabrous and hairy skin sense a wealth of touch stimuli from our environment, including pressure, vibration, temperature, and pain. They are located at different depths of the dermis and epidermis, and come in different form factors. Figure A.1 illustrates the different kinds of mechanoreceptors classified by morphology, and lists the ones that are common to both glabrous and hairy skin.

Each mechanoreceptor exhibits a specific rate of adaptation that allows it to sense a particular type of stimulus, such as pressure or vibration. The types of adaptation speeds and the corresponding mechanoreceptor characteristics are:

- Slowly Adapting Type I (SAI) - exhibit sustained response to static stimulus, small receptive field for "precision" sensing, sensitive to "form" and "roughness"
- Slowly Adapting Type II (SAII) - exhibit sustained response to static stimulus, large receptive field for "gross" sensing, sensitive to "skin stretch"
- Rapidly Adapting Type I (RAI) - exhibit transient response to stimulus onset and offset, small receptive field for "precision" sensing, sensitive to "flutter" and "slip"
- Rapidly Adapting Type II (RAII) - exhibit transient response to stimulus onset and offset, large receptive field for "gross" sensing, sensitive to high frequency vibrations. Only Pacinian

Corpuscles are RAII.

Figure A.2 shows the neural spike train of slowly adapting and rapidly adapting mechanoreceptors in response to a stimulus. It can be seen that when a stimulus is held steady, neurons from the slowly adapting mechanoreceptors continue to fire, alerting the human to a constant pressure stimulus. On the other hand, neurons from the rapidly adapting mechanoreceptors, which are sensitive to vibratory stimuli, activate only when there is a change in the stimulus.

Each type of mechanoreceptor also has a specific sensitivity bandwidth. For example, Meissner Corpuscles found in glabrous skin is sensitive to vibratory stimuli in the range of 0.4Hz to about 800Hz [10], whereas Pacinian Corpuscles are sensitive to vibrations between 150Hz - 300Hz [135]. Table A.1 summarizes the basic properties of cutaneous mechanoreceptors, which are derived from

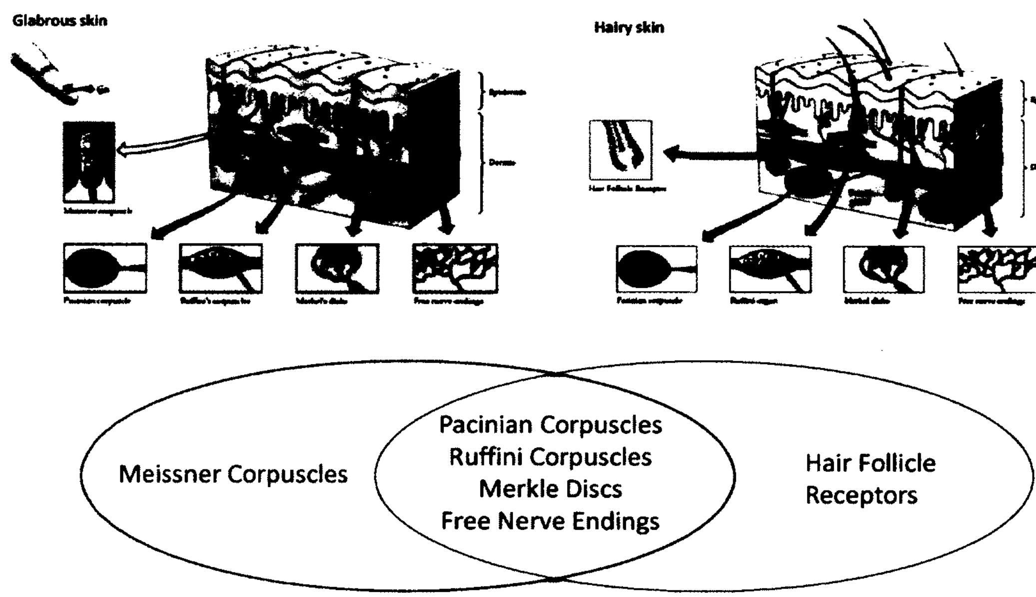

Figure A.1: Mechanoreceptors in glabrous (top left) and hairy skin (top right). The Venn diagram further illustrates which mechanoreceptors are present in each type of skin. *Image sources:* [9, 71]

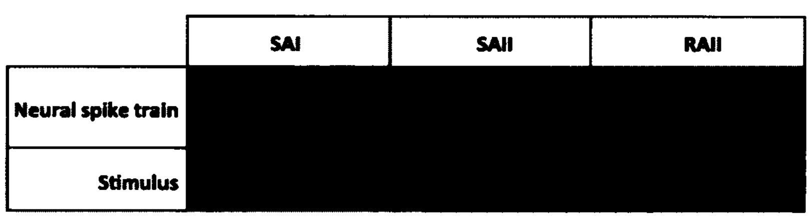

Figure A.2: Neural spike train of slowly adapting and rapidly adapting mechanoreceptors in response to a stimulus. Spikes indicate neuron activation from stimulus. *Adapted from Kandel, et. al.* [67]

Table A.1: Summary of basic properties of specific mechanoreceptors.

Receptor	Location and Size	Sensitivity	Adaptation Speed
Pacinian Corpuscles	deep dermis, large receptive field	vibration (150Hz-300Hz)	RAII
Ruffini Corpuscles	dermis, large receptive field	pressure	SAII
Merkel Discs	epidermis, small receptive field	pressure	SAI
Free Nerve Endings	various	pressure, vibration, temperature, pain	SA and RA
Meissner Corpuscles	dermis, small receptive field	vibration (2Hz-40Hz, up to 400Hz)	RAI
Hair Follicle Receptors	dermis	hair displacement, vibration (<1Hz to >1500Hz)	RAI

the work of many researchers [60, 93, 135, 167].

In a human's everyday interactions with his environment, typically multiple mechanoreceptors are stimulated in concert to enable to the human to perceive a wide range of sensations. As such, psychophysicists have attempted to characterize humans' perceptual thresholds for various sensations. Weber [116] popularized the method of two-point detection thresholds for characterizing unidimensional pressure stimuli for various parts of the body [162, 163] (See Figure A.3). He found that if the skin was touched in two separate points within a single receptive field, the subject would be unable to feel two separate points. However if the two points spanned more than a single receptive field then both points would be felt. Thus the size of a mechanoreceptor's receptive field and the density of mechanoreceptors in a given area of the skin determines the degree to which detailed stimuli can be resolved: the smaller and more densely clustered the receptive fields, the higher the perceptual resolution. From Figure A.3 we see that fingers have the lowest two-point detection thresholds, indicating highest sensing resolution. Therefore it comes as no surprise that most haptic feedback systems convey information through the fingers [39, 41, 46, 76, 85, 96, 105, 106]. Although fingers have the highest haptic sensitivity, other parts of the body are also beneficial for haptic feedback displays and many researchers have indeed developed haptic feedback systems that utilize other parts of the body [17, 64, 80, 145, 158].

Haptic interface designers have tried to characterize the minimum separation distance between two active vibratory stimuli before they become perceived as one single stimulus. Unfortunately Weber's two-point detection threshold method cannot be easily extended to apply to vibratory

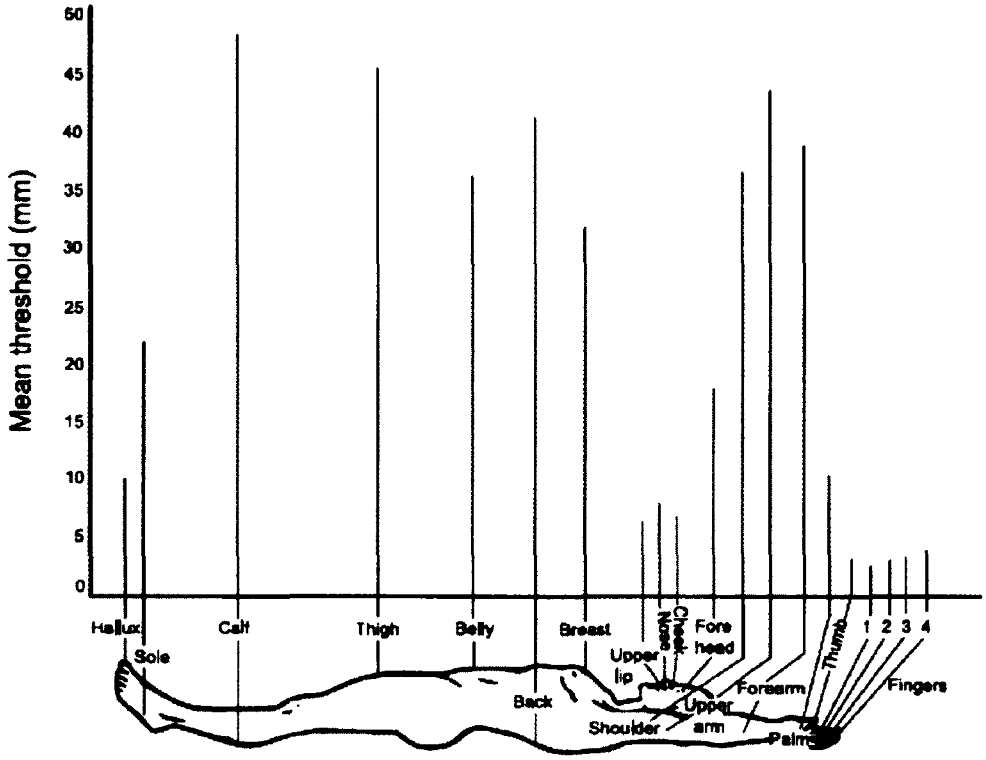

Figure A.3: Weber's two-point detection threshold for different body sites [163]. *Image source: Velazquez* [157].

stimuli due to the complex nature of vibratory signal transmission through the skin. There is sufficient damping within the skin and variability between persons that vibration waves may propagate through deep tissue for one subject (who may feel a generalized numbness or pain) but not for another subject (who may feel only an acute localized tingle). The perception of vibration intensity is also a function of proximity to bone structure; more acute in bony areas than fleshy areas [20]. Due to this complexity, most modern haptic perceptual studies have centered around characterizing vibration perception [20, 23, 42, 55, 65, 69, 73, 87, 93].

Appendix B

Posture

Good posture is important to the long-term health and well-being of the body. According to the Cleveland Clinic [22], posture is defined as the "position in which you hold your body upright against gravity while standing, sitting, or lying down." Good posture will help with the following [22]:

- keep bones and joints in the correct alignment so that muscles can be used properly
- decrease the abnormal wearing of joint surfaces that could result in arthritis
- decrease the stress on the ligaments holding the joints of the spine together
- prevent the spine from becoming fixed in abnormal positions
- prevent fatigue because muscles are being used efficiently, allowing the body to use less energy
- prevent strain or overuse problems
- prevent backache and muscular pain
- contribute to good appearance

Unfortunately defining "correct" posture is often a challenge as the guidelines differ from source to source; there is no one set of widely accepted, quantifiable guidelines. Most occupational therapists say a neutral posture that is 10 degrees hunched from the fully upright posture is best , while others believe the reclined position with full back support constitutes proper posture. In this dissertation, we adopt the definition of "good" sitting posture from the Cleveland Clinic and the Global Spine Network. According to these sources, proper sitting posture entails the following [22, 38]:

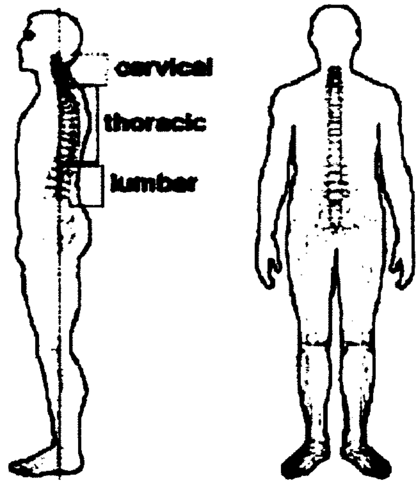

Figure B.1: (Left) Side view and (right) front view of normal spinal alignment. The spine exhibits three normal curves: cervical, thoracic, and lumbar. *Image source: Cleveland Clinic* [22].

- Sit up with back straight and shoulders back. Buttocks should touch back of chair.
- All 3 normal back curves (cervical, thoracic, lumbar) should be present while sitting (Figure B.1).
- Sit at the end of the chair and slouch completely. Draw yourself up and accentuate the curve of your back as far as possible. Hold for a few seconds. Release the position about 10 degrees. This has been commonly described as a "good" neutral posture.
- Body weight should be distributed evenly on both hips.
- Knees should be bent at right angles. Knees should be even with or slightly higher than hips. Use footstool if necessary. Do not cross legs.
- Keep feet flat on floor (or footstool).
- Avoid sitting in the same position for more than 30 minutes.

Another way to determine "correct" posture is to examine pelvic rotation. When a person changes his sitting posture, for example, from sitting upright to slouching, he accomplishes this by rotating his pelvis. In effect, he is using his *ischial tuberosities* (i.e. "sit bones") as rockers to reposition his body. This is consistent with the findings presented in [94].

Ischial tuberosities are rounded, bony prominences found at the base of the pelvis [6] as shown in Figure B.2. They take most of the person's weight when the person is properly seated. Additionally,

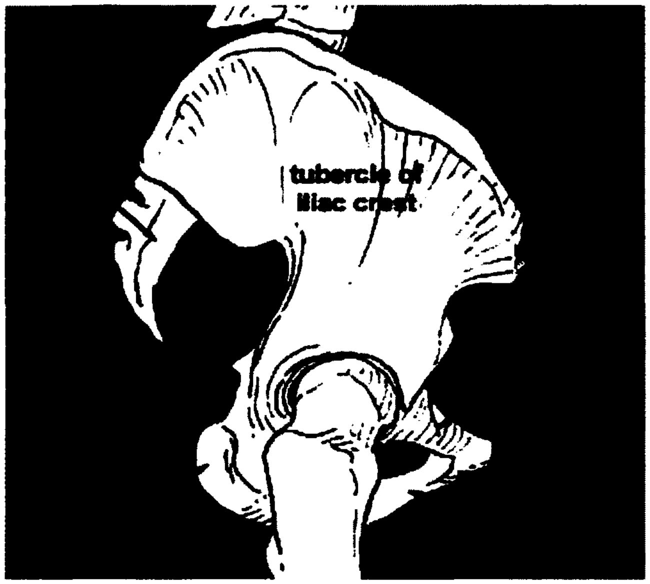

Figure B.2: Side view of pelvic bones. The *ischial tuberosities* (sit bones), circled in red, are located at the base of the pelvis. *Image source: Lollylegs* [82].

the pelvis is at a slight anterior tilt and the thighs are supported by the seat surface. This pelvic position promotes the normal curvature of the spine and allows the person's head to sit directly over the pelvis. Furthermore, the hips are at 90° flexion.

Additionally, selecting the proper chair will aid in maintaining correct sitting postures and thus help prevent posture-related injuries. According to [6] and [127], an ideal chair should have:

- adjustable chair height that allows knees to be bent at approximately 90° and feet to rest flat on the floor. The chair should allow the user to operate the keyboard with elbows at approximately 90°.
- adjustable armrests that should be located directly under shoulders (width adjustment) at the level of elbows (height adjustment).
- adjustable chair tilt with seat pan and backrest position fixed relative to each other in order to facilitate movement from one proper posture to another throughout the day.
- proper seat pan depth that is deep enough to allow approximately 1" gap behind the knees, and shallow enough to allow user's feet to rest flat on the floor.
- height-adjustable backrest that allows support of the entire back and head

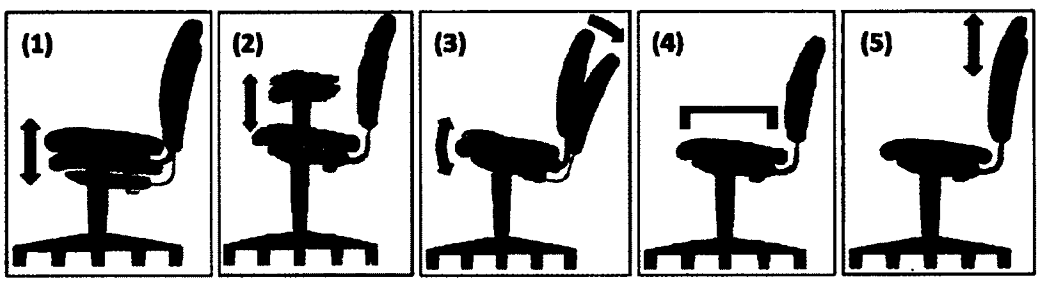

Figure B.3: Elements of an ideal chair for good posture. (1) adjustable height of chair, (2) adjustable armrests (height and width), (3) adjustable chair tilt with seat pan and backrest position fixed relative to each other, (4) proper seat pan depth, and (5) height-adjustable backrest. *Image source: Safe Work* [127].

Appendix C

Preliminary Designs for the Posture Sensing System

This chapter describes our preliminary work developing a posture sensing chair. This work ultimately motivated the design of our current Posture Seat system.

C.1 Selection of posture sensing system

The posture sensing chair will be used in an office setting. It is therefore necessary to take into account the physical space occupied by the posture sensing system, the environment in which the system is used, and the cost of the system. Of the three posture measurement methods discussed in Related Work, the most viable measurement method to pursue is pressure distribution. This is because pressure sensors can be packaged in relatively small spaces, such as within the seat cushion, without encroaching on already-limited cubicle and office space. Pressure sensors are not susceptible to the lighting limitations of the vision system and bodily contact requirements of the accelerometer method. And pressure sensors – different from pressure mats – are relatively inexpensive.

C.2 Design criteria

In previous work that used pressure distributions to determine posture, many researchers purchased off-the-shelf pressure mats from Tekscan or XSensor [51, 146]. Although these commercially available pressure mats have very high resolution, they may be too costly to integrate into a common office chair. For example, the Tekscan CONFORMat pressure mat alone, excluding software, is $1500 [168]. It is thus necessary to seek a cheaper alternative to such a pressure mat system in order for the posture-sensing chair to remain competitive with commercially available office chairs. One such alternative is to use a small array of force-sensitive resistors (FSRs) placed at key locations to obtain an appropriate pressure distribution. The FSRs cost on the order of $10 each. Indeed the small array of FSRs will be used in this first concept of a posture-sensing chair.

Any discussion of sensing leads to a discussion regarding accuracy. It is important to note that the approach for this research is not to accurately measure pressure, but to accurately recognize a variety of postures. An ideal solution would be to correctly identify postures for a range of individuals. A less perfect system might be trained to recognize postures for a single individual. Regardless, the goal of this sensing approach is to discern postures, and small inaccuracies – to the extent they are repeatable – are not a large concern.

After the selection of the FSRs and the construction of the chair, it is important to determine the set of postures to measure. As a first concept, only five distinct postures will be measured: sitting upright, slouching, leaning back, right leg crossed over left leg, left leg crossed over right leg. Pressure distribution "templates" will be developed for each of these postures for each user. These templates will aid in the matching of the real-time posture to one of the predetermined postures.

The posture-sensing chair should also be able to provide real-time feedback (haptic, auditory, visual) about the user's dynamic pressure distribution and posture. While the types of feedback are undetermined at this time, the goal is to create "natural" feedback – that is, feedback that corresponds to physical quantities in the system.

In summary, the first concept of a posture-sensing chair aims to achieve the following:

- dynamically sense posture and provide feedback
- use FSRs to develop pressure mappings of specific postures
- use hard, flat seating surface, and move to a contoured cushion in the future
- develop posture templates for each individual for 5 postures: sitting upright, slouching, leaning back, right leg crossed over left leg, left leg crossed over right leg
- match an individual's new posture to one of five existing posture templates

- provide visual, haptic, and/or auditory posture feedback to encourage proper posture during routine office tasks

C.3 First prototype posture sensing chair

We prototyped a posture-sensing chair that was constructed with a hard, flat seat surface, a cushioned seat back, and cushioned armrests. Two FSRs (1.5" square, Interlink) were taped to the surface of the seat. The distance between the FSRs was 3.0", which was optimized for the distance between the *ischial tuberosities* (sit bones) of one subject. Additionally, the FSRs were placed approximately 10.75" from the front edge of the seat, and approximately left-right centered on the seat (Figure C.1). The battery pack, data acquisition system, and electronics were mounted on the underside of the seat (Figure C.2). Holes were drilled in the seat to allow for connection between the FSRs and the circuit board. The data acquisition system was connected to a computer running LabVIEW SignalExpress 2.5.1 and LabVIEW 8.5.

The five postures to be measured are shown in Figure C.3. Identifying the postures involved:

1. sitting directly above the FSRs, trying best to ensure that, in the upright posture, the lower aspect of the left *ischial tuberosity* lies directly above the left FSR, and the lower aspect of the right *ischial tuberosity* lies directly above the right FSR. When the *ischial tuberosities* are aligned directly over the FSRs, the output voltage will be approximately the same for both sensors and also at a relative minimum.

2. clicking the "Record" button in LabVIEW SignalExpress, and then selecting the inputs to record. Data will be recorded at 1kHz.

3. maintaining the posture for at least 15 seconds, and then clicking "Stop" to stop and save the recording.

Overall, there seemed to be distinct characteristic voltage ranges for each of five postures measured. When the voltage outputs from the left FSR were plotted against those of the right FSR, there could be seen distinct "spatial locations" of each of the five postures (Figure C.4). Using the combined spatial plot of the five postures as a guideline, it was possible to determine a person's posture solely by looking at their spatial voltage plot.

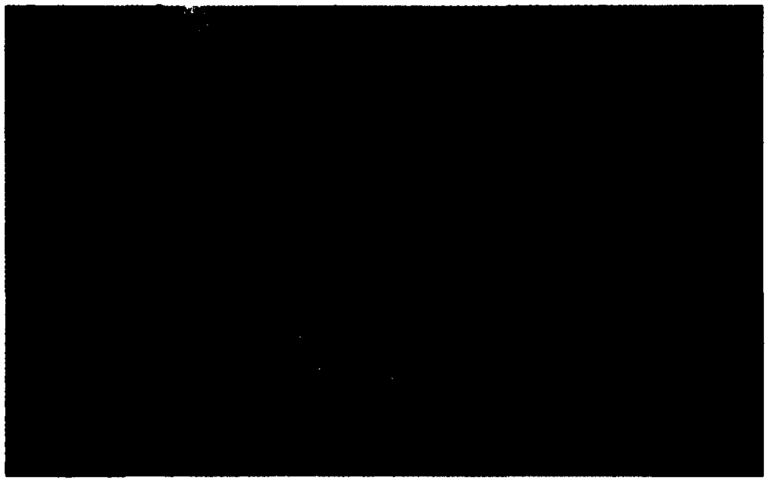

Figure C.1: Relative positions of the two force-sensitive resistors (FSRs) on the first prototype of the Posture Seat.

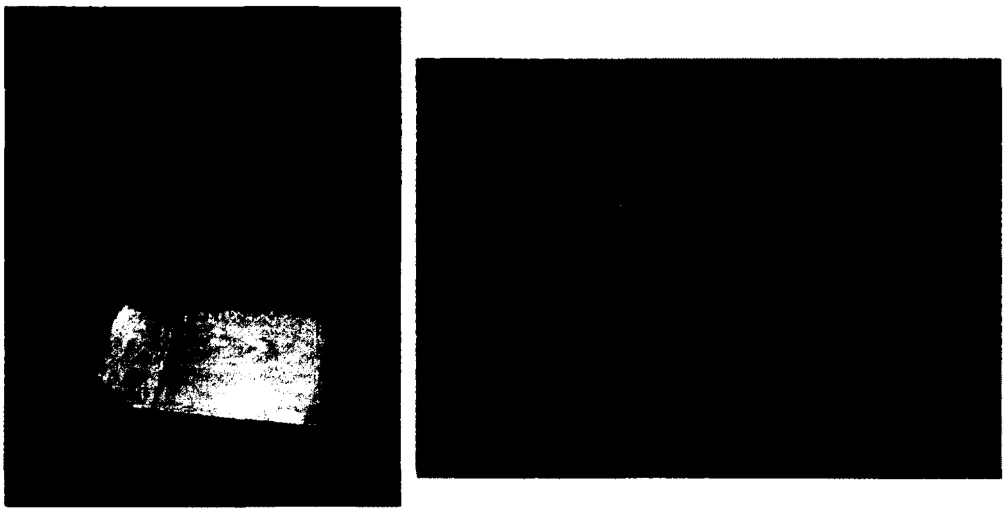

Figure C.2: The first prototype sensing chair setup. (Left) Two FSRs are taped to the surface of the seat. (Right) Underside of the chair showing the data acquisition unit (DAQ), circuit board, and battery pack.

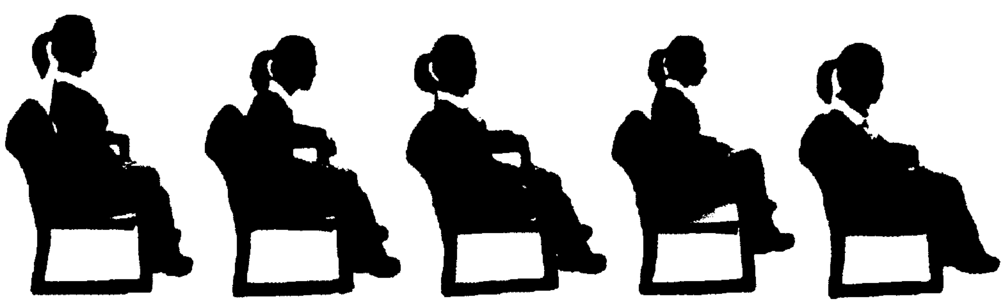

Figure C.3: Examples of each of the 5 postures to be sensed. From left to right: sitting upright, slouching, leaning back, right leg crossed over left leg, and left leg crossed over right leg.

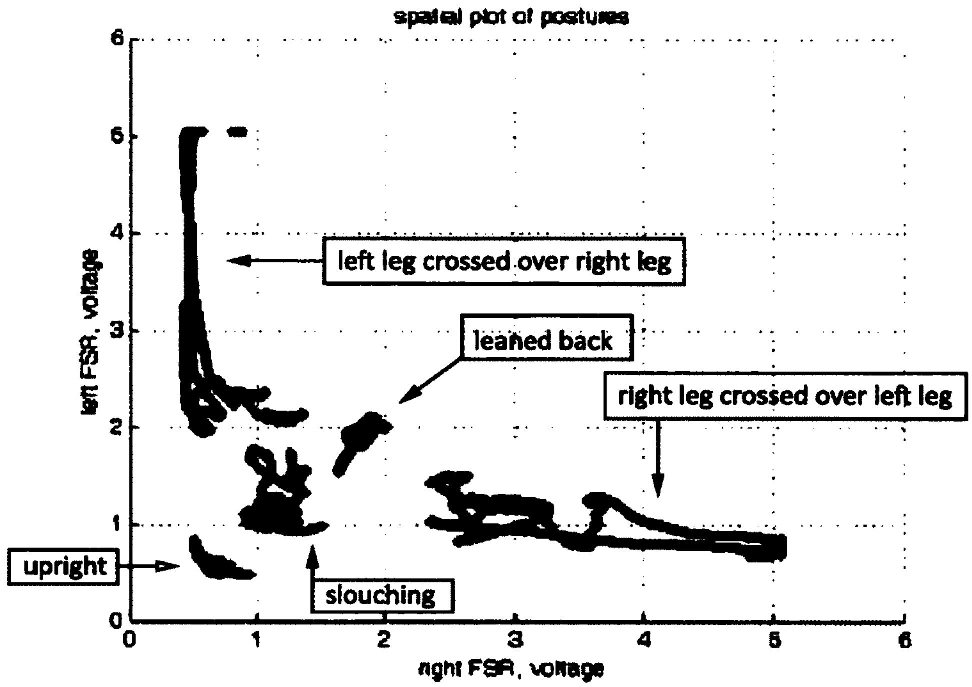

Figure C.4: Plot of all data from each of the five postures for one subject. Each posture was maintained for 15 seconds for 3 trials each. There are distinct spatial locations for the five postures.

C.4 Summary and implications from the first prototype

We discovered that even with only 2 FSRs it was possible to identify the 5 distinct postures for one test subject. However, there were some postures that were identified with greater confidence than other postures. For example, the right-leg-crossed-over-left-leg and left-leg-crossed-over-right-leg postures were always distinguishable from the other postures. The sitting upright posture was distinguishable from the leaning back posture. However, it was somewhat difficult to distinguish between sitting upright and slouching, and between slouching and leaning back, since the two postures pairs exhibited an insignificant voltage difference. Therefore, it may be necessary to incorporate additional FSRs, potentially on the seat back, for detecting curvatures of the spine.

The current design of the posture sensing chair is unable to accommodate different people as the system is rigid and is very sensitive to the alignment of the FSRs under the *ischial tuberosities*. Even with the same test subject it is not guaranteed that the subject's *ischial tuberosities* will lie directly above the FSRs after the subject gets up and sits back down. Therefore, in order for this posture-sensing system to be versatile, methods for increasing the system sensitivity to a wider range of people and postures need to be investigated. These methods might include using a compliant medium such as the chair pad to transfer the loads to the sensors when the *ischial tuberosities* are not directly over the FSRs, as well as simply increasing the number of FSRs, which we will discuss later.

C.5 Second and third prototypes of the Posture Seat

The second iteration of the Posture Seat sought to improve the accuracy of posture identification as well as seating comfort. This iteration utilized a standard fabric, cushioned computer chair to improve user comfort (Figure C.5). Four FSRs were initially adhered to the surface of the seat. Unfortunately the contour of the seat pan and the surface deformation of the cushion from the seated user produced erroneous pressure mappings. To improve the signal-to-noise ratio, we developed mechanical "signal enhancers" (Figure C.6) for the FSRs and embedded them between the seat cushion and hard plastic backing of the seat pan. This solution allowed surface forces to be transmitted to the embedded FSRs. In a preliminary study with four subjects, the upright and leaning with legs crossed postures were always identified correctly. Additionally, subjects expressed comfort with sitting in this chair.

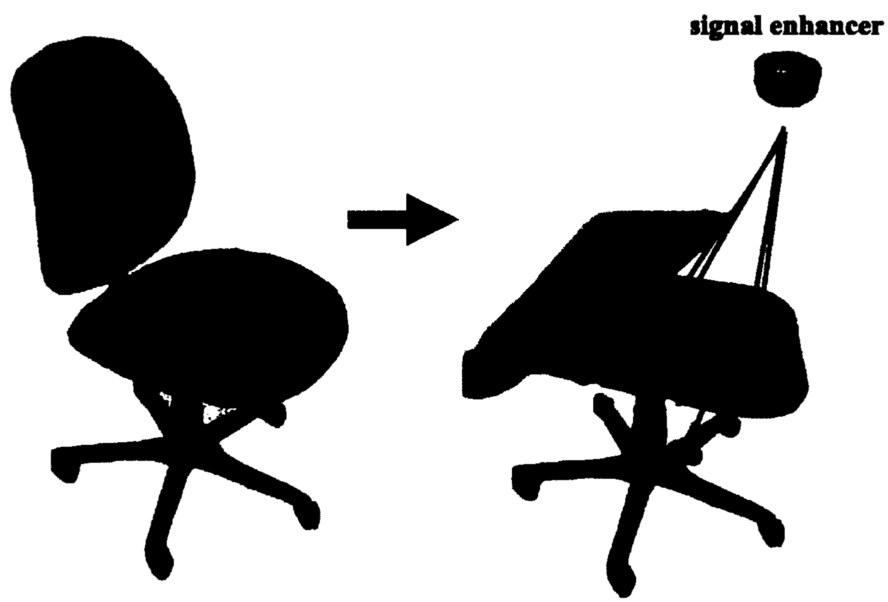

Figure C.5: The second iteration of the Posture Seat that improved the sensing accuracy and was more comfortable to sit in. Four signal enhancers were embedded between the hard plastic base and the foam cushion of the seat corresponding to the locations of the *ischial tuberosities* (sit bones) and the center of the thighs.

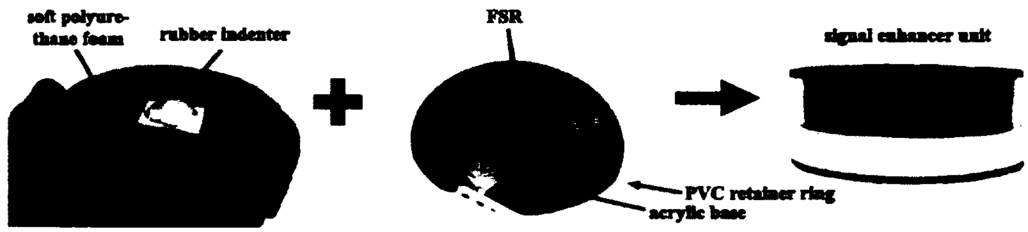

Figure C.6: Prototype "signal enhancers" for the cushioned office chair to improve the FSR signal-to-noise ratio. As the user sits on the chair, the hard rubber tip presses on the FSR to register a force reading.

In the third iteration, we tried to expand the list of identifiable postures to 10 – the same postures as classified by [97] and [146]. We embedded 4 FSRs in the seat pan and 3 bend sensors in the seat back of a leather (executive) office chair (Figure C.7). The bend sensors were adhered to the surface of custom-made flexible bow-like supports to measure deflection in the seat back. Although this posture seat configuration was able to sense the slouching and leaning back postures in addition to upright and leaning with legs crossed, subjects expressed discomfort with the rigid beams in the seat back. Additionally, subjects could not ensure their *ischial tuberosities* were always above the embedded FSRs and signal-to-noise ratio was low even with the "signal amplifiers."

In the fourth and final iteration of the Posture Chair, it was discovered that adhering FSRs to the surface of a Herman Miller Aeron chair produced the cleanest signal. The seat pan and seat back of this chair are made of a pellicle mesh material held in high tension, which allowed the FSRs to conform to the person's body along with the chair. Additionally, subjects were able to visually assess the location of the FSRs so that they may sit directly on top of them. Therefore in all of our reported studies, we used a size B, fully adjustable Herman Miller Aeron chair.

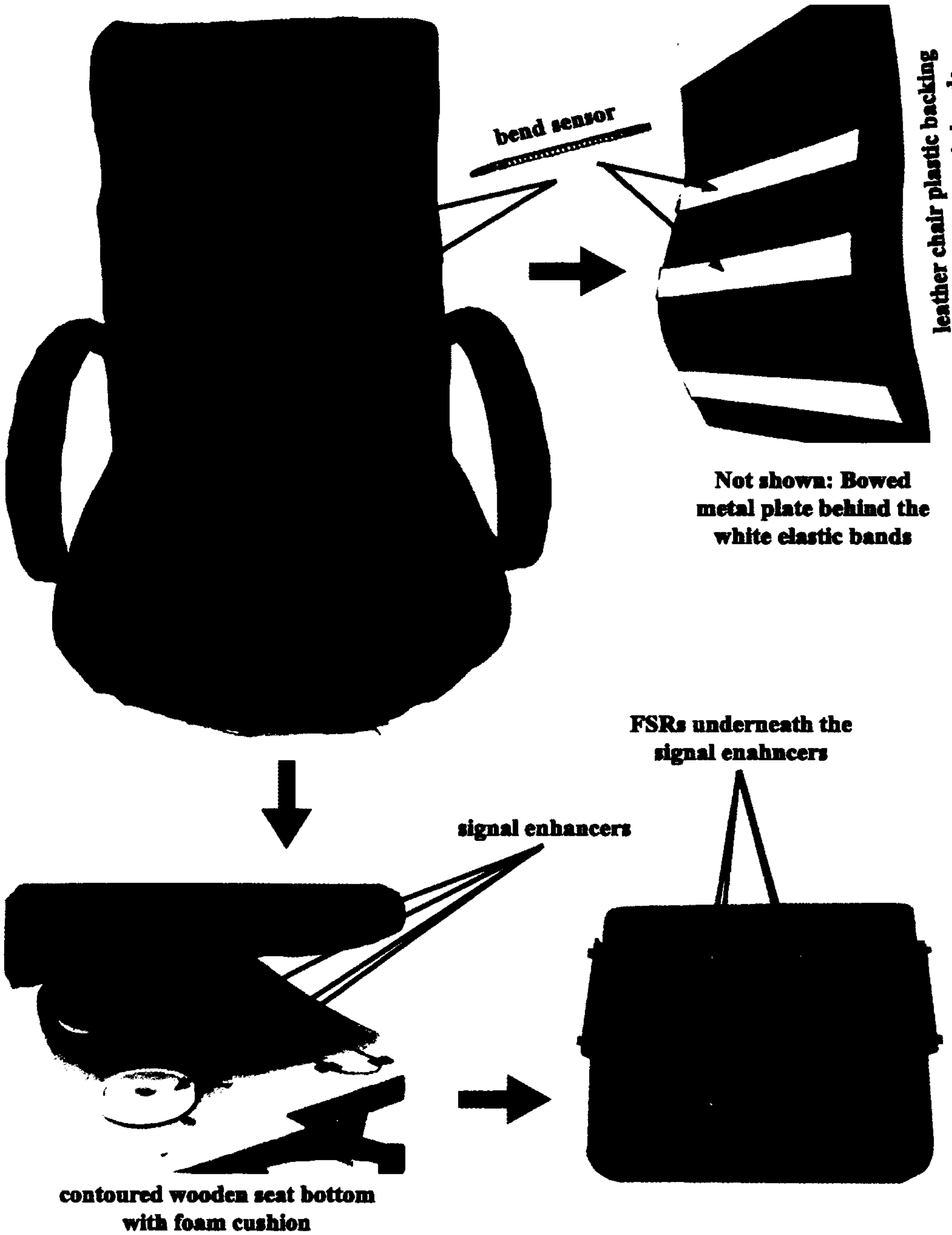

Figure C.7: The third iteration of the Posture Seat that could identify more postures than the first and second iterations due to the presence of bend sensors embedded behind the elastic bands in the seat back. In the seat bottom, signal enhancers were embedded between the hard wooden surface and foam cushion. FSRs were taped directly to the wooden surface and the signal enhancers pressed directly onto the FSRs.

Appendix D

Pactor Design Selection

D.1 Motor Selection

In the design of pactors (pressure actuators), we need to select motors with sufficient dynamic range, i.e. motors need to be powerful enough to deliver forces that will be perceived as "strong" and "attention grabbing" (the "demand action" end of the attention capture spectrum). Preliminary studies indicate that the motor should be able to output forces of approximately 45N (which translates to 2.25Nm of torque assuming a 0.05m lever arm) to ensure that the user will perceive the force on their body and react strongly to the stimulus. Simultaneously pactors must be able to actuate and retract with a frequency slower than 0.2Hz to at least 2Hz to mimic a gentle nudge to a slow tap.

The motors we considered were high-end precision DC motors such as Maxxon motors and Faulhaber motors, position- and velocity-controlled RC servo motors, and low-cost DC hobby motors. Precision DC motors such as Maxxon and Faulhaber motors have excellent torque and speed output and have excellent position and speed control, but they are relatively expensive (several hundred dollars for each motor) and require a high voltage and current source. Low-end DC hobby motors, such as the ones sold from Pololu.com, are cost-effective (usually around $40 including encoder) and can spin at high speeds but have low torque output (and thus need an additional gearbox) and sometimes require a 12V power source. RC servo motors, such as Futaba and Hitec motors, are very easy to program and can run off a 6V power source. Some RC sail servos output sufficiently high torque and speed, and are much more cost-effective than the high-precision DC motors. However they are noisy during actuation. Because the disadvantages associated with RC servo motors for our chair application were minimal and acceptable, RC servo motors were chosen to be driving the mechanism for pactors. Specifically, the Hitec HS-805BB sail servo with 2.42Nm of torque at 6V and a no-load speed of 0.14sec/60° was selected.

D.2 Pactor Concept Generation

We prototyped a number of pactor designs that converted the rotational motion of the servo to a translational motion at the tip of the pactor. The total displacement at the contactor tip needed to be approximately 2cm in order to be reliably perceptible. Our designs included an eccentric cam with rollers, slider with guiderail, crankshaft, pin slider, large displacement scissor linkage, rack-and-pinion, and plunger with leadscrew (Figure D.1). For these pactor designs we aimed to use the minimal number of components and low-cost materials, and be easily manufactured and assembled. All of these pactors were rapidly prototyped using 3D printers, laser cutters, as well as traditional metal machining tools.

We evaluated these pactor prototypes per the design requirements outlined in Section 7.2. In our initial testing, we found that some of the designs couldn't exert enough force at the tip, jamed easily, had poor tolerance to shear forces, and was too bulky in its current configuration. Other designs, such as the slider with guiderail, had long lever arms and therefore could not produce enough force

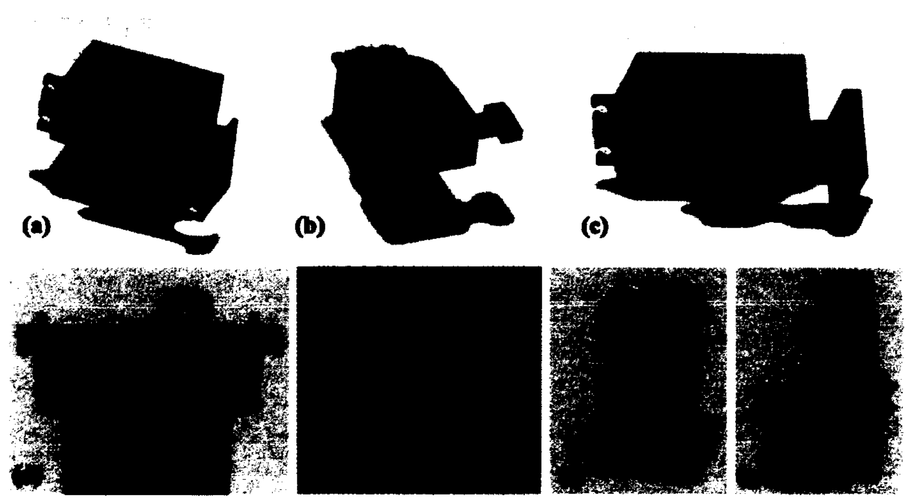

Figure D.1: Some initial pactor (pressure actuator) prototypes incorporating the high-torque HS805BB servo: (a) eccentric cam with rollers, (b) slider with guiderail, (c) crankshaft, (d) pin slider, (e) scissor linkage, (f) rack-and-pinion, and (g) plunger with leadscrew.

Pactor Concept	Cam & Slot with Rollers 	Guiderail and slot 	Crankshaft 	Pin Slider 	Scissor Linkage 	Rack & Pinion 	Plunger & Leadscrew 
Output Speed	+	+	+	+	+	+	−
Output Force	+	−	+	+	O	+	++
Current Draw	−	−	−	−	−	+	+
Range of Motion	−	+	+	+	+	+	+
Robustness (survives normal force overload conditions)	+	−	+	−	−	−	+
Survives Shear Forces	+	−	+	−	O	+	−
Design Complexity	+	O	O	−	−	−	−
Hardware Cost	+	O	O	O	−	−	−

Figure D.2: Pugh chart that aided in the pactor concept selection process.

at the contactor tip without additional gear stages, which would add to the complexity of the design. The cam and crankshaft designs were by far the simplest and met the output force and speed requirements. However the eccentric cam design produced a side-to-side sensation of motion even though the contactor plate moved normal to the contact surface. The scissor linkage design was a challenge to manufacture and assemble as each part needed to be precision machined in order to reduce slop in the final assembly, and there were too many parts to assemble. Finally, the leadscrew mechanism (utilizing a continuous rotation HS805BB servo) was too slow in achieving the desired displacement, required additional hardware for position control, and could not withstand normal force overload conditions.

The Pugh chart in Figure D.2 summarizes the advantages and disadvantages of each of the designs we considered. In the end the crankshaft design was selected for its robustness, excellent overload tolerance, fast actuation speed, high output forces, ability to achieve single-point displacement normal to the person's body, and reasonable manufacturing process and cost. (It also had the fewest disadvantages out of all the designs.)

D.3 Final Pactor Design

The final crankshaft design that was used in the user studies is shown in Figure 7.1. It has a maximum force output of 190N, a range of travel from 0-2cm with 0.001cm resolution, and a maximum actuation speed of 7.1cm/sec. Aside from the servo, servo horn, ball bearings, shafts and shaft collars, all other components were fabricated on the 3D printer with ABS plastic.

We developed custom contactor plates to interface with the chair and the human body for each body site. The shoulder contactor plate was a simple circular plate approximately 2" in diameter with small "wings" that enabled the plate to be sewn onto the mesh chair. The 2" contact area was chosen based on the sensation of a human hand push. The lumbar contactor plate, on the other hand, was contoured to conform to the curvature of a seated person's back in order to eliminate unwanted pressure sensations at rest. Finally, due to the space constraints under the chair, a special housing was designed for the thigh pactors. The housing was sewn onto the underside of

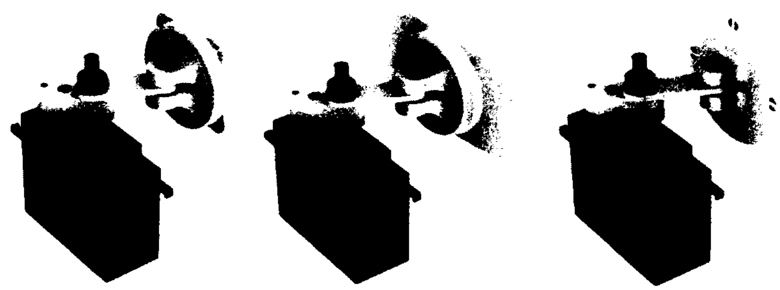

Figure D.3: (From left to right) Final pactor designs, including mating contactor plates, for the shoulders, lumbar, and thighs.

Figure D.4: Bottom-to-top view of thigh pactor enclosed in a wooden housing for mounting under the seat bottom. Pactor housing is sewn into the chair mesh via the four "feet." The contactor plate for the thigh pactor has a larger area than the shoulder plate in order to accommodate the variability in subject thigh sizes and positions in the seat. Also there is no need for a mating contactor plate as the pactor plate is sewn into the chair mesh.

the mesh chair. As such, the thigh pactor plate always remained in contact with the bottom of the chair, obviating the need for an additional mating plate. However the area of the contactor plate needed to be larger than the shoulder mating plates in order to achieve the same amount of pressure sensation under the thigh. The different contactor plates and mating plates are shown in Figure D.3, and the special thigh pactor housing is shown in Figure D.4.

In addition to the pactors themselves, we prototyped numerous mounting mechanisms to attach the lumbar and shoulder pactors to our Aeron office chair (Figure D.5). The mounting plate needed to be rigid enough to withstand the high torque of the HS805BB RC servo motors. Additionally it should be lightweight so that the center of mass and dynamic performance of the chair would not be altered. Based on these design constraints, we arrived at our current pactor chair backplate design which consisted of two 1/4"-inch plywood mounting plates (Figures 7.2 and 7.3). This is a variation of the one-piece plywood backplate with slots for adjustable pactor placement. We used this version for our pactor user studies related to posture guidance.

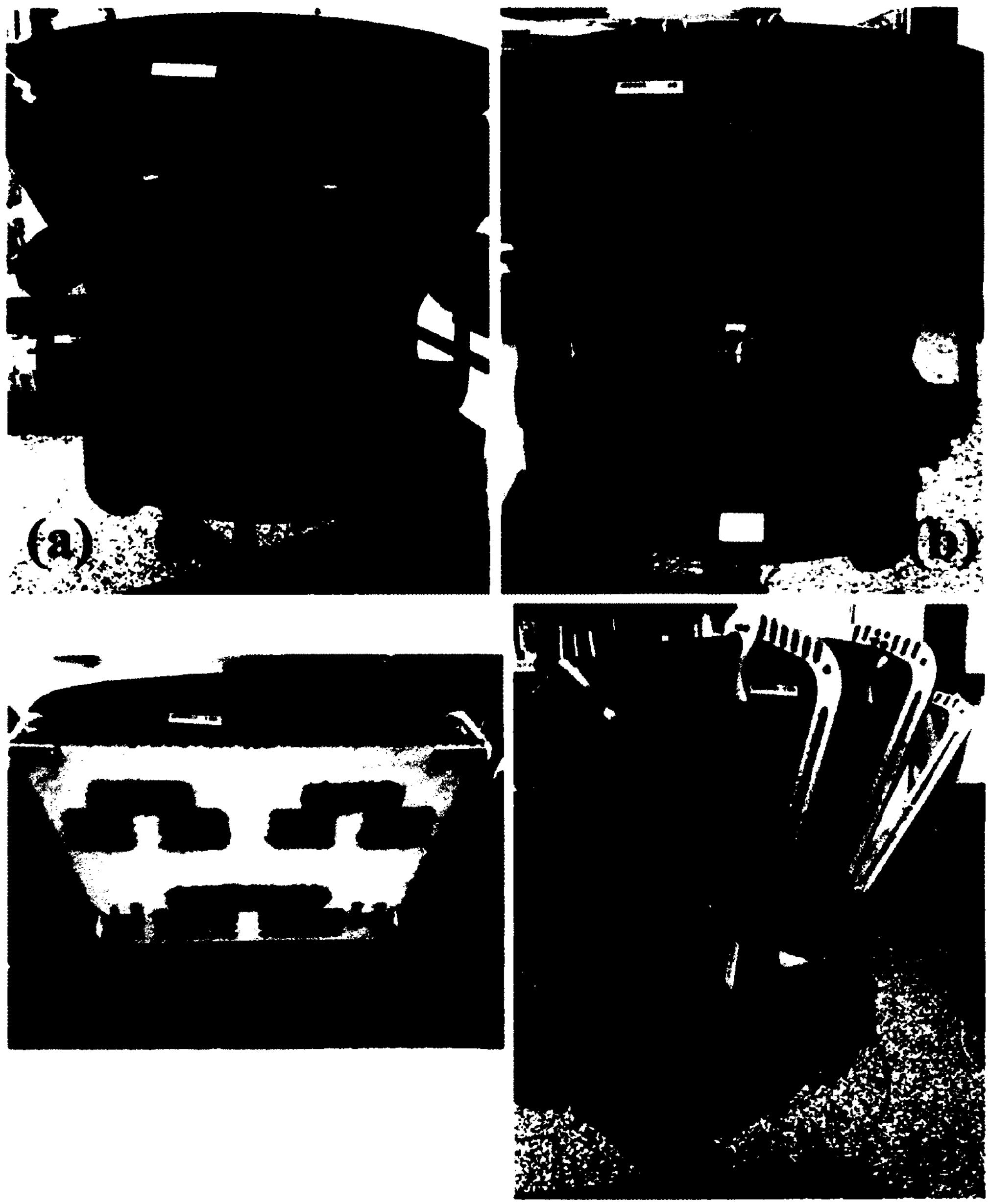

Figure D.5: Prototypes of the shoulder and lumbar pactor mounting mechanisms for the Aeron chair: (a) sewable mounts similar to the thigh pactor housing, (b) metal net and lumbar pillow plastic mounts, (c) one-piece plywood or sheet metal backplate with slots for adjustable pactor placement, and (d) a "claw" that allows full vertical adjustment of pactors.

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