ARMY RESEARCH LABORATORY

Suitable Body Locations and Vibrotactile Cueing Types for Dismounted Soldiers

by Timothy L. White

ARL-TR-5186 **May 2010**

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14. ABSTRACT
Although research has shown the potential of tactile displays as a means for providing information, there are several factors that must be taken into consideration in order to maximize the benefits of tactile cueing. The proper body location and tactile cue type must be carefully identified for specific types of users. This is due to the varying mission requirements and environments in which users must operate. For example, dismounted Soldiers perform maneuvers such as walking, running, crawling, and climbing. They must also remain attentive so that they can engage enemy threats as well as negotiate terrain obstacles. It is imperative that tactile stimulation be provided to the appropriate body locations and that the proper tactile cue types (i.e., signals or patterns) are provided to dismounted Soldiers. This summary report discusses the skin, the perceptual resolution and sensitivity of humans, and the suitable body locations and tactile cueing types for dismounted Soldiers.

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tactile, vibrotactile, dismounted, signals, patterns, cues, messages

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1. Introduction

Dismounted Soldiers are a vital component of the U.S. Army, and as a result of continuous technological advances, they are being inundated with complex battlefield information. Much of this information is being presented through the visual and auditory sensory channels. Receiving such an abundance of information can result in cognitive overload and performance degradation. Therefore, researchers are exploring different techniques of displaying this vital information and mitigating the grave consequences of cognitive overload and performance degradation. Wickens' multiple resource theory suggests that offloading information from overtaxed sensory modalities to other modalities can reduce workload (Wickens, 2002). Furthermore, Van Erp's prenav theory suggests that the performance of a human operator using an intuitive display is not affected by external stressors because the display does not rely on effortful cognitive resources (Van Erp, 2007). Therefore, if properly implemented, tactile displays may be a viable, intuitive solution in reducing sensory and cognitive overload from the visual and audio channels, thereby improving situation awareness and survivability on the battlefield. A tactile display can be defined as a device that presents information to the user by stimulating the skin (Gemperle et al., 2001). Offloading information to the tactile channel in an effective manner depends on the nature of the cognitive and sensory demands within the mission environment (Redden, 2006). In regard to dismounted Soldiers, careful consideration must be given to the body locations best suited to receive tactile information as well as the types of information (i.e., signals or patterns) that can be provided.

In recent years, there has been an increased interest in the use of tactile displays as an alternative means of effectively communicating information to military personnel. Some applications of interest include spatial orientation, navigation, vehicle control, directional warning and attention allocation, synthetic environments, and nonverbal communication (Van Erp and Self, 2008). For example, in the aviation arena, researchers explored using tactile displays as countermeasures for spatial disorientation. The Tactile Situation Awareness System (TSAS), developed by the U.S. Navy, and the Spatial Orientation Retention Device, developed by the U.S. Air Force, have both shown potential in aiding pilots in maintaining spatial orientation (Bles, 2008; McGrath et al., 2004; Rupert et al., 2002). Similar spatial orientation research findings were reported by Craig et al. (2004), Van Erp et al. (2002), and Van Erp et al. (2006).

Vehicle control is another mounted application in which tactile displays have been found to be useful. In one study, helicopter pilots were able to successfully monitor a simulated instrument panel to detect failed instruments and gauges (Diamond et al., 2002). Research has also examined the use of tactile display systems in moving ground vehicles (Krausman and White, 2008). Additional vehicle control research has been investigated by Ferris and Sarter (2008), Ferris et al. (2006), and Tilak et al. (2008). A wealth of research has been conducted in the area

of navigation. In maritime environments, the U.S. Navy has successfully demonstrated the use of TSAS in providing navigational cues in undersea diving operations (Dobbins and Samways, 2002; Van Erp and Self, 2008). In regard to land environments, dismounted Soldiers were able to successfully navigate using the Personal Tactical Navigator developed by the Netherlands Organisation for Applied Scientific Research Human Factors (Elliott et al., 2006; Elliott et al., 2010). Other navigation investigations have been reported by Davis (2006), Davis (2007), Dorneich et al. (2006), Elliott et al. (2007), Savick et al. (2008), Smets et al. (2008), and Van Erp et al. (2005). Utilizing tactile displays to provide directional warning and attention allocation information has shown great promise in a number of studies. For example, Carlander and Eriksson (2006) found that tactile displays were useful in mitigating the localization errors and high reaction times that resulted from the front-back confusion of three-dimensional (3-D) audio cues about enemy threats. Other directional warning and attention allocation findings have been reported by Asseman et al. (2008), Brill et al. (2004), Calhoun et al. (2002), Calhoun et al. (2003), Calhoun et al. (2004), Calhoun et al. (2005), Glumm et al. (2006), Glumm et al. (2007), Krausman et al. (2005), Krausman et al. (2007), Lindeman et al. (2003), Lindeman et al. (2005), McKinley et al. (2005), Mohebbi et al. (2009), Oskarsson et al. (2008), Redden et al. (2006), Sklar and Sarter (1999), Tan et al. (2003), Terrence et al. (2005), Van Erp (2005), Van Erp (2008), and White et al. (2009). Regarding synthetic environments, Van Erp (2000) suggests that tactile displays can be used to present navigation information to aid users in orientating themselves in virtual environments.

Communication is another emerging application of tactile displays. Brill et al. (2006) highlighted some advantages of utilizing tactile displays as a means for communicating U.S. Army hand-arm signals. For example, communication can be executed without maintaining visual contact (Brill et al., 2006). The feasibility of communicating with tactile displays is evident in the findings of Brewster and King (2005), Brown et al. (2006), Fuchs et al. (2008), Hoggan and Brewster (2007), Jones et al. (2006), Jones et al. (2009), Krausman and White (2006a), Krausman and White (2006b), Merlo et al. (2006), Merlo et al. (2008), Pettitt et al. (2006), and Rothenberg et al. (1977). Tactile displays have also been found useful in the area of robotics. In one investigation they were helpful in aiding Soldiers in monitoring robotic swarm status (Haas et al., 2009a). Other robotic findings have been reported by Chen and Terrence (2007), Chen and Terrence (2008), Haas and Stachowiak (2007), and Haas et al. (2009b). In summary, research has shown the potential of tactile displays in aiding military personnel in air, sea, and land environments in a variety of applications.

The purpose of this review is to identify the types of information that can be presented using the tactile modality, body areas suitable of receiving tactile information, and the types of information best suited for particular body locations of dismounted Soldiers.

2. The Skin

Humans habitually tend to think of the eyes and ears as the primary communication channels, with limited understanding of other sensory modalities as potential communication channels (Geldard, 1957). As a result, for many years, the skin was not considered as a potential channel for communication. Though the perceptual resolution of the skin was first examined by Ernst Heinrich Weber (1834/1978) in the early 1800s, Geldard (1957) explored the sense of touch as a means of communication. Comparisons of eyes and ears revealed that the eyes are more suitable for spatial discriminations and the ears are more suitable for temporal information (Geldard, 1960). However, the skin has the ability to make both spatial and temporal discriminations (Geldard, 1960). Geldard foresaw the sense of touch as a potential means for communication, and he designed the first tactile language, called "Vibratese," a tactile language composed of 45 basic elements by which the entire English alphabet and several numerals could be communicated. Each of the 45 elements was developed by varying intensity (three levels), duration (three levels), and body location (five loci) (Geldard, 1957). Geldard (1957) found that after 12 h of training, a participant was able to receive around 35 words/min, indicating that tactile stimulation can be a feasible means of communicating information.

The sense of touch comprises sensations caused by the stimulation of the skin (Levine and Shefner, 1991; Stevens and Green, 1996). However, painful or tissue-damaging stimuli are not regarded as a part of the sense of touch. The skin is the largest organ of the human body and, for the average adult, has a surface area of about 1.8 m^2 (Sherrick and Cholewiak, 1986). The skin is part of the integumentary system, which consists of skin, hair, and nails. It is made up of two layers: the epidermis and the dermis. The epidermis is the outer layer that is made of scale-like cells, and the dermis is the inner layer that contains blood vessels, lymph vessels, hair follicles, and sweat glands. There are three types of skin: glabrous, hairy, and mucocutaneous (Greenspan and Bolanowski, 1996). Glabrous skin refers to the hairless skin that is found on the palms and soles, and mucocutaneous skin (e.g., lips) refers to the skin that borders entrances to the body's interior (Greenspan and Bolanowski, 1996). Of the three types of skin, hairy skin covers most of the human body.

The skin has many sensory receptors for receiving sensations like vibration, pressure, texture, temperature, and pain. The mechanoreceptors of the skin are sensitive to mechanical pressure or deformation of the skin (Sekuler and Blake, 1990). A cross section of human skin is shown in figure 1. There are four types of mechanoreceptive afferents in glabrous skin: the fast-adapting type 1 (FAI) afferents that end in Meissner corpuscles, the fast-adapting type 2 (FAII) afferents that end in Pacinian corpuscles, the slow-adapting type 1 (SAI) afferents that end in Merkel disks, and the slow-adapting type 2 (SAII) afferents that end in Ruffini endings (Greenspan and Bolanowski, 1996; Johnson, 2001). As shown in table 1, they are each defined by their rate of

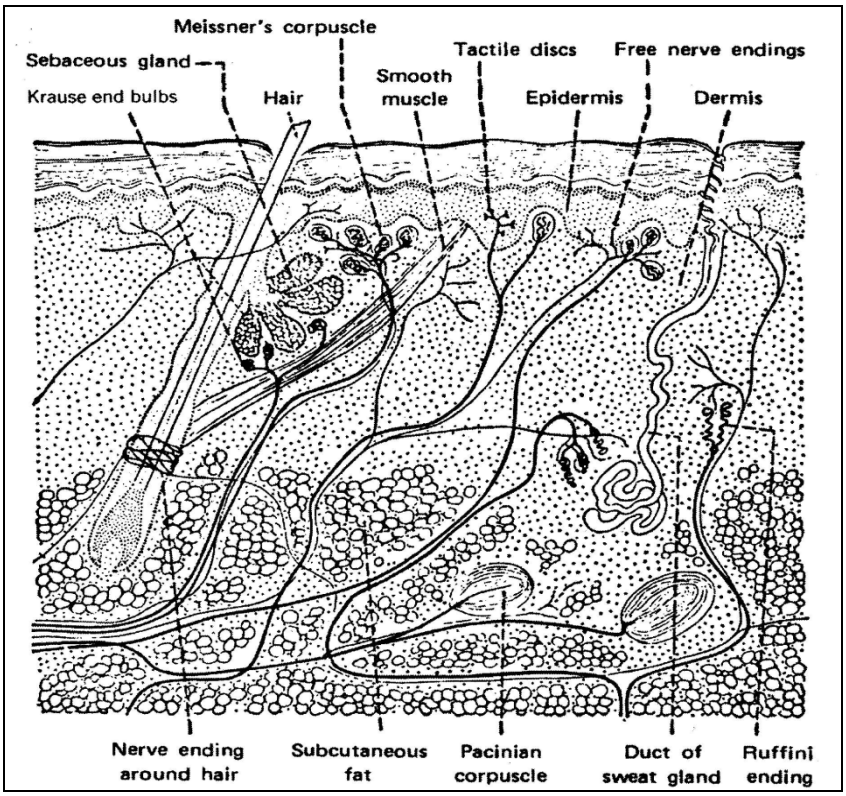

Figure 1. Cross section of the human skin. (Reprinted with permission from Schiffman [2000]. Copyright 2000 John Wiley & Sons, Inc.)

Table 1. Mechanoreceptor characteristics in glabrous skin.

Mechanoreceptor	**FAI (Meissner)**	**FAII (Pacinian)**	**SAI (Merkel)**	**SAII (Ruffini)**
Receptive Field Size	Small	Large	Small	Large
Adaptational Property	Rapid	Rapid	Slow	Slow

adaptation and receptive field size (Greenspan and Bolanowski, 1996). Adaptation refers to how mechanoreceptors respond to sustained skin indentation (Greenspan and Bolanowski, 1996). The rapidly adapting mechanoreceptors respond when the skin is actively being indented, while the slow-adapting mechanoreceptors respond when the skin is being stretched and during sustained indentation (Greenspan and Bolanowski, 1996). The receptive field refers to the area of skin that will generate a response in a sensory neuron when stimulated, and this area is dependent on the intensity of the stimulus (Greenspan and Bolanowski, 1996). The receptive fields of Pacinian corpuscles and the Ruffini endings are larger than the receptive fields of the Meissner corpuscles and the Merkel disks.

Hairy skin has five types of mechanoreceptive afferents: the fast-adapting hair follicle, field, and Pacinian afferents and the slow-adapting Merkel disk (SAI) and Ruffini ending (SAII) afferents (Macefield, 2005; Vallbo et al., 1995). Additionally, research indicates that the hair follicle and field afferents possess subtypes (Brown and Iggo, 1967). Though both the hair follicle and field afferents have high-sensitivity spots, they differ in that the hair follicle afferents respond to hair movements, and the field afferents respond to actual skin contact. The Pacinian afferents differ from the field afferents because they can be activated by remote stimuli and the field afferents cannot (Macefield, 2005). An investigation of the receptive field characteristics of hairy skin on the forearm indicated that the hair follicle, field, and Pacininan afferents had larger receptive fields than the SAI and SAII afferents (Vallbo et al., 1995). The findings of this research may also be representative of the hairy skin that covers other parts of the body excluding the face and hands (Vallbo et al., 1995).

The skin is a very complex organ of the human body. However, the characteristics of the mechanoreceptive afferents and their distribution throughout the skin reveal why the perceptual resolution and sensitivity of the skin vary at different body locations. Because of mission requirements, operational environment, and body-worn equipment of dismounted Soldiers, body locations covered with glabrous skin are not feasible locations for tactor placement. Therefore, it is important to identify body locations covered with hairy skin for optimal placement.

3. Perceptual Resolution and Sensitivity

In order to optimally utilize tactile displays to communicate information, perceptual resolution and sensitivity must be taken into consideration. The perceptual resolution and sensitivity of the skin vary because the perceptibility and the density of the receptors vary across the skin surface (Cholewiak and Collins, 2003; Gemperle et al., 2003). This was evident in the findings of Weber's research on perceptual resolution. Weber utilized two methodologies for his research: the compass test and the error of localization test (Stevens and Green, 1996). The compass test or two-point discrimination test measured the smallest distance at which two points of stimulation can be discriminated (Stevens and Green, 1996). The error of localization test was used to measure the accuracy with which a person can localize tactile stimuli (Stevens and Green, 1996). Weber's (1834/1978) research showed that perceptual resolution was best on the fingertips and the tip of the tongue (Stevens and Green, 1996). Further research on the discrimination of pressure of the skin revealed that the just-perceptible increase in pressure of the skin is proportional to the pressure of the original stimulus (Stevens and Green, 1996). Over time, this finding was generalized to other sensory modalities. It became known as Weber's law, which states that the change in a stimulus intensity required for a just noticeable difference is a constant ratio of the original stimulus (Levine and Shefner, 1991; Matlin, 1983; Stevens and

Green, 1996). Another notable finding by Vierordt (1870) indicated that two-point discrimination thresholds are inversely proportioned to the mobility of the body part for which it is measured. This finding became known as Vierordt's (1870) law of mobility (Cholewiak et al., 2004; Stevens and Green, 1996).

Weinstein (1968) extended previous research conducted in the areas of perceptual resolution and sensitivity. He assessed the ability to detect, discriminate, and localize pressure stimuli applied to different areas of the male and female body (Sorkin, 1987; Weinstein, 1968). Two notable findings by Weinstein (1968) are (1) that body locations with accurate localization seem to correspond with good two-point discrimination and (2) that body locations with accurate localization and good two-point discrimination do not imply good tactile sensitivity to pressure (Stevens and Green, 1996; Van Erp, 2007). In regard to tactile sensitivity, women were generally more sensitive than men. The findings of his research agreed with the findings of Weber and Vierordt. The figures in the appendix illustrate his findings on pressure sensitivity, two-point discrimination, and point localization thresholds.

Since the work of Weinstein (1968), Stevens and Choo (1996) investigated spatial acuity of the body from childhood to advanced age. Contrary to Weinstein's research, which utilized the two-point discrimination task, this research employed a gap detection task (Stevens and Choo, 1996). The gap detection task was employed because Johnson and Phillips (1981) found that, with sufficient practice, humans are able to discriminate two points with very small or zero separation from a single point using the two-point discrimination task (Johnson and Phillips, 1981). Discrimination of such small or even nonexistent separation cannot be a result of spatial resolution. Since length discrimination is superior to two-point discrimination, the gap detection task was used (Jones and Vierck, 1973). These tasks differ in that a tactile line broken by a gap is used instead of two points (Stevens and Choo, 1996). The results of this investigation were consistent with the previous findings of Weber and Weinstein. An additional finding of this research was that spatial acuity declines with age, particularly on the hands and feet (Stevens and Choo, 1996).

The previously discussed research on perceptual resolution and sensitivity was conducted by applying pressure to the skin. However, the majority of the tactile display systems that are currently being used employ vibrotactile stimuli (Cholewiak and Collins, 2003). The responses of mechanoreceptive afferents in the skin depend on the frequency, amplitude, and duration of the vibrotactile stimuli as well as the location of the stimuli (Jones and Sarter, 2008). Though vibrations with frequencies between 20 and 500 Hz can be perceived, Jones and Sarter (2008) identify optimal sensitivity with frequencies between 150 and 300 Hz. At a given frequency, the amplitude level required for detection varies across body sites (Von Békésy, 1959). Amplitude and frequency parameters must be chosen carefully, especially when encoding information because of their interactions; it is not recommended that they be manipulated simultaneously during vibrotactile communications (Jones and Sarter, 2008). If the amplitude provided at a given body location is increased at a constant frequency, the perceived amplitude as well as the

perceived frequency increases (Jones and Sarter, 2008). With regard to duration, results from one investigation showed that participants prefer that the duration of vibrotactile alerts be between 50 and 200 ms (Kaaresoja and Linjama, 2005). The flexibility to manipulate parameters like frequency and amplitude depend on the design of the tactors used to provide stimulation.

There are two main categories of tactors: inertial shakers and linear actuators (Mortimer et al., 2007). Inertial shakers employ the motion of an internal eccentric mass to produce vibration, and linear actuators employ a contactor that is driven against the skin (Mortimer et al., 2007). Although the operating characteristics of these two types of tactors differ, they both have been successfully utilized in stimulating the receptors of the skin. Due to the varying distribution of the receptors in the skin and the overlapping frequency ranges at which they respond, it is not possible to target one particular receptor type. Unlike linear actuators, the manipulation of frequency and amplitude is limited when inertial shakers are utilized (Mortimer et al., 2007). Designers should make sure that tactors operate at levels consistent with the previously mentioned optimal sensitivity levels of the human body. However, there may be other reasons beyond the sensitivity of the receptors to explore new tactor designs, such as reducing power consumption or physical discomfort.

4. Dismounted Soldier Body Locations and Tactile Cueing

As mentioned previously, research has shown the variability of the perceptual resolution and sensitivity of the skin. Vibrotactile cues have been successfully utilized in a number of applications. In regard to dismounted Soldiers, careful consideration must be given to the types of vibrotactile cues and body locations at which they can be best perceived. When utilizing tactile displays, dismounted Soldiers must be ready to move their weapons to engage an enemy and be attentive to the terrain and enemy threats (Van Erp and Self, 2008). There are a number of body locations that have low perceptual resolution thresholds and low-sensitivity thresholds. Myles and Kalb (2009) found the forehead, temples, and the lower part of the back of the head to be very sensitive. In figure 2, the bordered areas highlight several suggested areas for tactor placement. In general, most tactile research has focused on the upper limbs, hands, and torso.

Because mission requirements, operational environment, or body-worn equipment of dismounted Soldiers may interfere with placement or perception of vibrotactile signals, some body locations are less feasible for the placement of tactors. For example, the hands are not a feasible location because tasks that depend on the use and the mobility of the hands may interfere with the tactile stimuli. Placement of tactors on the legs or front of the torso may be infeasible because Soldiers are sometimes required to crawl. From an environmental perspective, Soldiers in moving ground vehicles are more likely to be subject to ongoing high vibrations and noise as opposed to

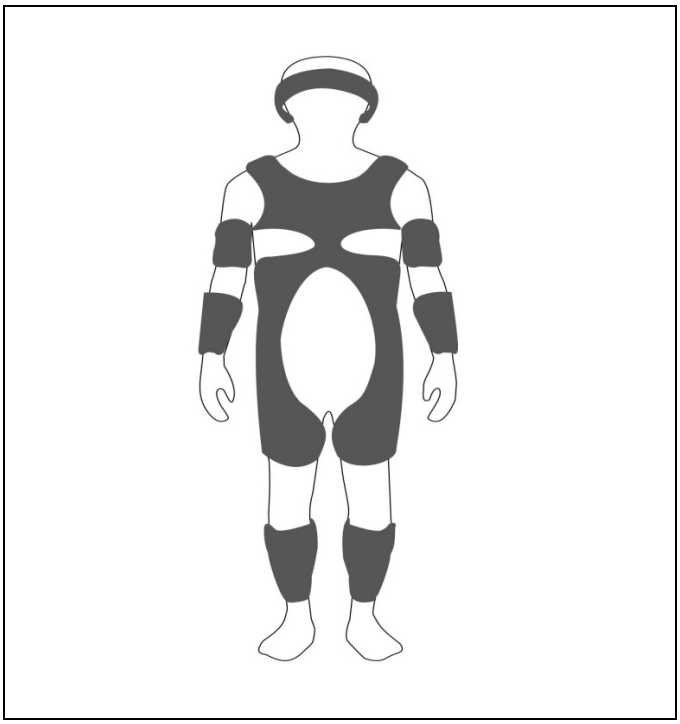

Figure 2. Placement areas for tactile display (Gemperle et al., 2003).

dismounted Soldiers (Van Erp and Self, 2008). The external vibrations of a moving ground vehicle can possibly interfere with vibrotactile perception (Van Erp and Self, 2008). It is therefore imperative that the mission requirements and operational environment be considered when identifying suitable body locations for vibrotactile stimulation. Tactile cues must be easily perceived under operating conditions (Elliott et al., 2009).

Tactile stimuli or cues can be provided as signals (i.e., a single discrete cue) or patterns. Signals are normally used to provide an alert or direction. The appropriate tactile stimuli type depends on the type of information that is being provided to the user. A pattern is normally used to communicate more complex communication or orientation information. Tactile patterns typically consist of multiple tactors firing one at a time or sequentially. Some useful dismounted applications of tactile cues include that of location cues (e.g., waypoint navigation, avoidance of terrain obstacles, off-limit area warnings, threat locations), attention management (e.g., alerts on command decision making), and critical communications (e.g., tactile commands as substitutes for visual arm and hand signals (Van Erp and Self, 2008; Pettitt et al., 2006). A number of research efforts have shown the potential of both tactile signals and tactile patterns with regard to dismounted Soldiers. These efforts will be described in the next few paragraphs.

4.1 Tactile Utility of Upper Limbs

There are a few tactile research efforts that utilize the upper limbs. Though none of these research efforts have focused specifically on the dismounted Soldier, their findings may be relevant to the dismounted Soldier. Most of these efforts have focused on mounted Soldiers.

4.1.1 Signals

In a laboratory investigation, Krausman et al. (2005) found that providing simple vibrotactile signals to the upper arm was helpful in alerting mounted platoon leaders of incoming messages. In a follow-on study, a vibrotactile cue paired with a visual cue was helpful in providing alerts to mounted platoon leaders as well (Krausman et al., 2007). In a multimodal experiment, tactile signals worn on the wrists have shown potential for improving operator performance on monitoring tasks in complex systems, such as control stations for unmanned aerial vehicles (Calhoun et al., 2002). Given the various dismounted Soldier maneuvers that specifically require movement of the arms, vibrotactile signals on the arm may be better suited for mounted or stationary applications.

4.1.2 Patterns

In a laboratory experiment, Piateski and Jones (2005) found that identification rates for vibrotactile patterns on the forearm were about 90%. However, due to spatial resolution issues, the arm may not provide the accuracy needed for military applications (Piateski and Jones, 2005). Providing tactile patterns to dismounted Soldiers can be difficult because patterns may be perceived incorrectly if the orientation of the arm changes. For example, a pattern that sweeps up the arm when the arm is positioned at the side of a person may be perceived as a downward sweep when the arm is raised. In this respect, unless an intelligent system that is capable of providing tactile patterns based on body or body part orientation is implemented, the arms would not be a feasible location for providing tactile patterns to dismounted Soldiers. Although uncommon for dismounted Soldiers, applications in which the arms remain stationary may be better suited for providing tactile patterns.

4.2 Tactile Utility of Torso

The torso has been utilized for tactile cueing more than any other body location on dismounted Soldiers. It has been determined to be a stable and an effective reception area for tactile cueing (Gilson et al., 2007; Van Erp, 2007). The torso is 3-D and body-centered (Van Erp, 2007). A belt worn around the torso that is made up of an array of tactors has been utilized for most dismounted research efforts. Cholewiak et al. (2004) also determined that a belt that is made up of an array of eight equally separated tactors yields optimal localization performance.

4.2.1 Signals

Research findings have shown the potential of providing tactile signals to the torso. An eight-tactor belt is particularly useful for providing directional cues for navigation and target

acquisition because the stimulation sites can be mapped to compass points. Van Erp (2007) and Cholewiak et al. (2004) found the torso to be a suitable location for tactile stimulation when the navel and the spine anchor points are included as stimulation sites within the tactile array. Research driven by Van Erp's Prenav theory has shown that tactors on the torso can aid in navigation tasks and reduce workload (Van Erp and Werkhoven, 2006). In one investigation that employed a tactile belt, participants were able to successfully navigate waypoints without any training (Van Erp et al., 2005). In another series of studies, dismounted Soldiers were able to successfully navigate with a tactile belt display during both day and night operations (Elliott et al., 2007).

4.2.2 Patterns

The torso has also been shown to be a feasible location to provide tactile patterns. Its large surface makes it particularly suitable for tactile patterns. A significant amount of this research as it pertains to the military has focused on assisting pilots in maintaining their spatial orientation during flight by providing vibrotactile patterns to the torso with a tactile vest. During an operational assessment, the TSAS was found to be effective in improving aircrew performance by reducing workload and improving situational awareness (Rupert et al., 2002). In a pilot investigation, another system known as the System for Tactile Reception of Advanced Patterns, investigators found that participants were able to learn a tactile grammar consisting of 56 tactile patterns in under 3.5 h (Fuchs et al., 2008). In regard to dismounted applications, in one study, Pettitt et al. (2006) utilized a tactile belt on the torso to provide vibrotactile patterns that were derived from conventional Army arm and hand signals. Dismounted Soldiers were able to receive, interpret, and respond to the tactile patterns faster than the conventional signals provided by a leader (Pettitt et al., 2006).

In a series of studies, Jones et al. (2006) provided participants with vibrotactile patterns using a geometrically symmetrical 4 × 4 matrix of tactors on the back. In a laboratory experiment, participants were able to identify patterns with 100% accuracy, and in a field experiment, participants were able to navigate with almost perfect accuracy (Jones et al., 2006). Krausman and White (2006a) performed an investigation to compare providing vibrotactile patterns with a 4 × 4 matrix of tactors on the back and an eight-tactor belt around the torso. Because the sample size was small, no significant differences were found between the two displays (Krausman and White, 2006a; Krausman and White, 2006b). Additional research should be conducted to highlight potential differences between the two torso display types. Table 2 contains a listing of the reviewed literature that employ tactile signals and patterns on the upper limbs and the torso. Though all of the literature in table 2 is not focused on dismounted applications, the findings may still be applicable.

Table 2. Body location × cue type.

	Upper Limbs	Torso	
Simple Signals	Calhoun et al. (2005)	Asseman et al. (2008)	Krausman & White (2008)
	Calhoun et al. (2002)	Brill et al. (2004)	Lindeman et al. (2003)
	Calhoun et al. (2003)	Carlander & Eriksson (2006)	Lindeman et al. (2005)
	Calhoun et al. (2004)	Chen & Terrence (2007)	McKinley et al. (2005)
	Dobbins & Samways (2002)	Chen & Terrence (2008)	Merlo et al. (2006)
	Ferris & Sarter (2008)	Cholewiak et al. (2004)	Mohebbi et al. (2009)
	Ferris et al. (2006)	Davis (2006)	Oskarsson et al. (2008)
	Jones et al. (2009)	Davis (2007)	Redden et al. (2006)
	Krausman et al. (2005)	Diamond et al. (2002)	Savick et al. (2008)
	Krausman et al. (2007)	Dorneich et al. (2006)	Smets et al. (2008)
	Sklar & Sarter (1999)	Elliott et al. (2006)	Tan et al. (2003)
	Tilak (2008)	Elliott et al. (2007)	Terrence et al. (2005)
		Elliott et al. (in prep)	Van Erp (2000)
		Gilson et al. (2007)	Van Erp (2007)
		Glumm et al. (2006)	Van Erp (2008)
		Glumm et al. (2007)	Van Erp et al. (2005)
		Haas & Stachowiak (2007)	White et al. (2009)
		Haas et al. (2009a)	
		Haas et al. (2009b)	
Patterns / Rhythms	Brewster & King (2005)	Bles (2008)	Van Erp et al. (2002)
	Brown et al. (2006)	Brill et al. (2006)	Van Erp et al. (2006)
	Jones et al. (2009)	Craig et al. (2004)	Van Erp et al. (2007)
	Piateski & Jones (2005)	Fuchs et al. (2008)	
	Rothenberg et al. (1977)	Gilson et al. (2007)	
		Hoggan & Brewster (2007)	
		Jones et al. (2006)	
		Jones et al. (2009)	
		Krausman & White (2006a)	
		Krausman & White (2006b)	
		McGrath et al. (2004)	
		Merlo et al. (2008)	
		Pettitt et al. (2006)	
		Piateski & Jones (2005)	
		Rupert et al. (2002)	
		Van Erp & Self (2008)	

5. Conclusions

Research has indicated the feasibility of vibrotactile communications for dismounted Soldiers. However, due to the complexity of the skin and dismounted Soldier mission requirements, researchers must carefully examine the appropriate tactile cue types and body locations in order to maximize the benefits of vibrotactile communications for dismounted Soldiers. Vibrotactile communications can be utilized in combination with other sensory communications and as an alternate sensory communication with other sensory channels that may be limited or lost (Gilson et al., 2007). If implemented properly, vibrotactile communications can reduce cognitive overload and performance degradation. Consequently, Soldiers will be provided with critical information that is essential for improving situational awareness and survivability on the battlefield.

Tactile stimuli can either be provided as signals or patterns depending on the type of information that is being provided to the user. Although a number of research efforts have shown the success of vibrotactile signals, research that employs vibrotactile patterns to communicate complex messages is very limited. Most Army-relevant vibrotactile research has focused on the upper limbs and the torso. Based on the reviewed literature, the torso is the most feasible body location to provide dismounted Soldiers with vibrotactile stimulation. It is stable, body-centered, and 3-D (Gilson et al., 2007; Van Erp, 2007). The torso has shown promise in receiving simple signals as well as more complex patterns. In regard to dismounted Soldiers, the use of vibrotactile patterns on the torso should be further explored.

In military environments, some signals or messages may need to be encoded with some level of urgency. Urgency can be encoded by manipulating parameters such as frequency, amplitude, and duration (Brewster and Brown, 2004; Van Erp, 2002; Van Erp and Van Den Dobbelsteen, 1998). Research has shown significance in the perceived urgency of auditory signals by varying parameters. In one study, interpulse intervals had a consistent effect on the perceived urgency of auditory signals, in that signals with shorter interpulse intervals and higher sound pressure levels were rated as more urgent (Haas and Edworthy, 1996). Similarly, varying interstimulus intervals in vibrotactile patterns may also be a possible method of displaying urgency. The findings of another study that employed “tactons” that were created from a combination of spatial location, rhythm, and roughness suggest that varying tactor intensity may also be a feasible alternative for displaying urgency (Brown et al., 2004). One area that future work should focus on is the perceived urgency of vibrotactile patterns. Pairing urgency with more complex tactile messages can potentially aid dismounted Soldiers in making better decisions by enabling them to prioritize tasks within their overall mission.

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Appendix. Pressure Sensitivity, Two-Point Discrimination, and Point Localization Thresholds*

* The figures in this appendix were reprinted with permission from Weinstein, S. Intensive and Extensive Aspects of Tactile Sensitivity as a Function of Body Part, Sex, and Laterality. In *The Skin Senses;* Kenshalo, D. R., Ed.; Charles C. Thomas: Springfield, IL, 1968; pp 195–222. Copyright 1968 Charles C. Thomas.

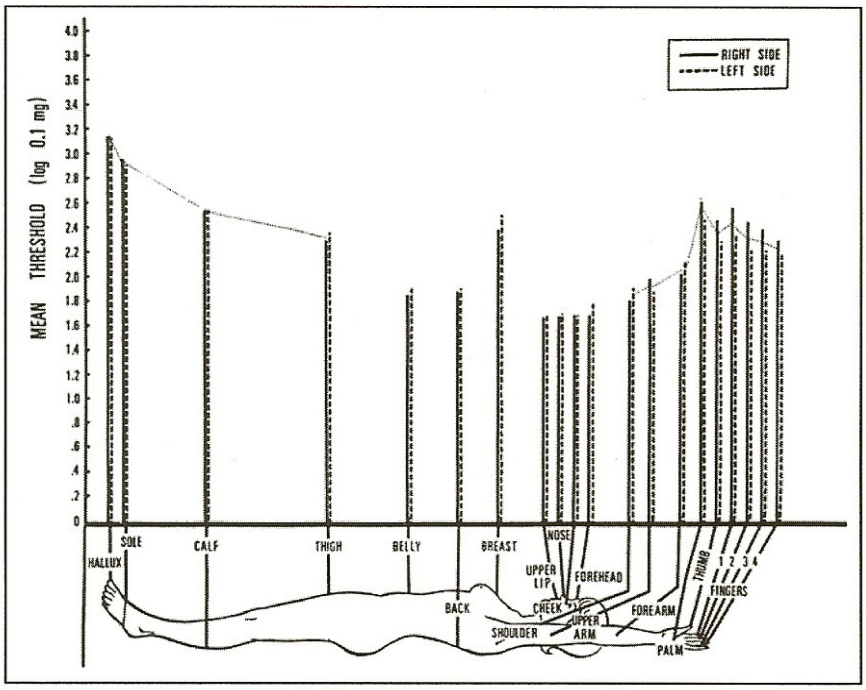

Figure A-1. Pressure sensitivity thresholds for females.

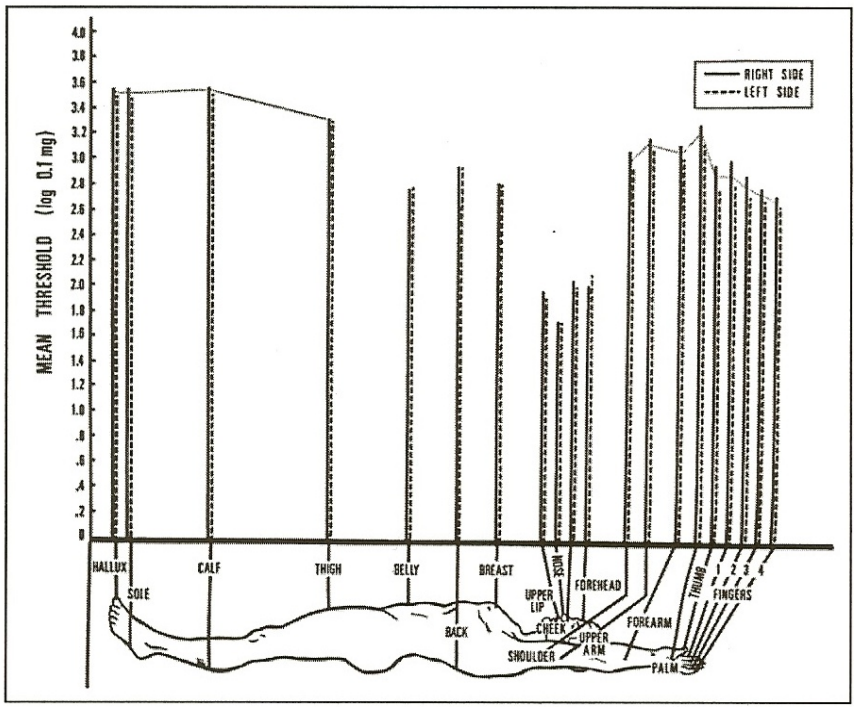

Figure A-2. Pressure sensitivity thresholds for males.

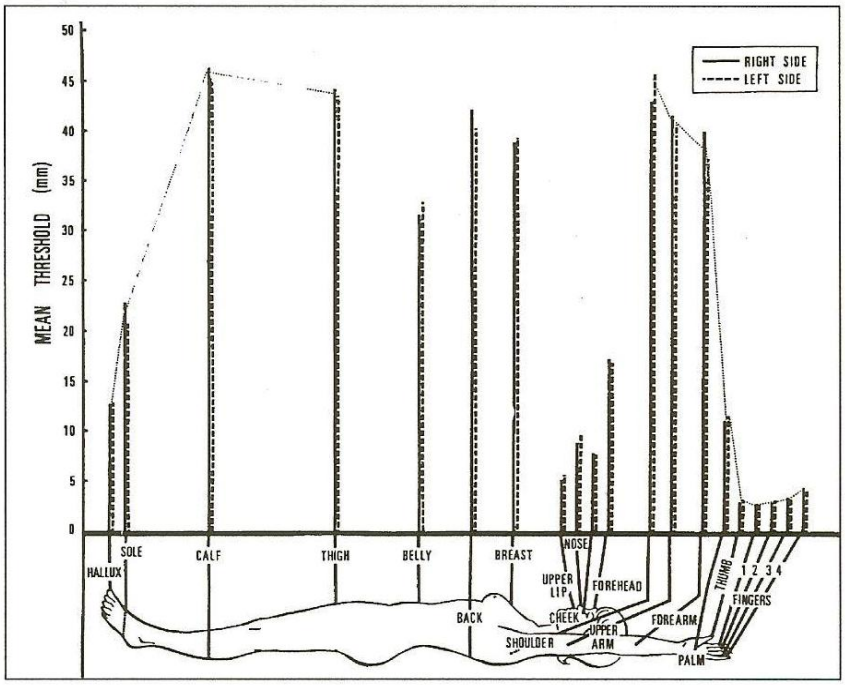

Figure A-3. Two-point discrimination thresholds for females.

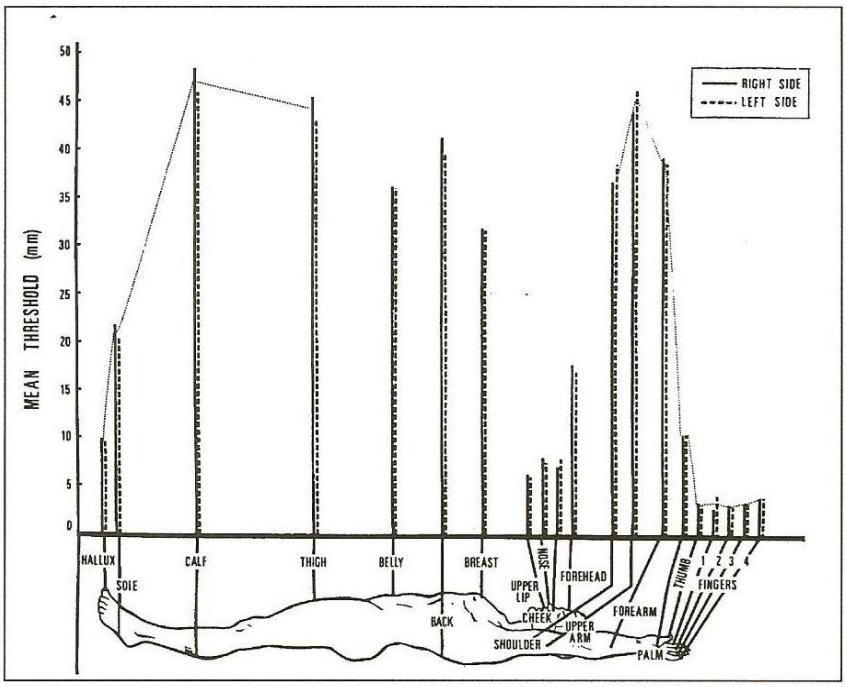

Figure A-4. Two-point discrimination thresholds for males.

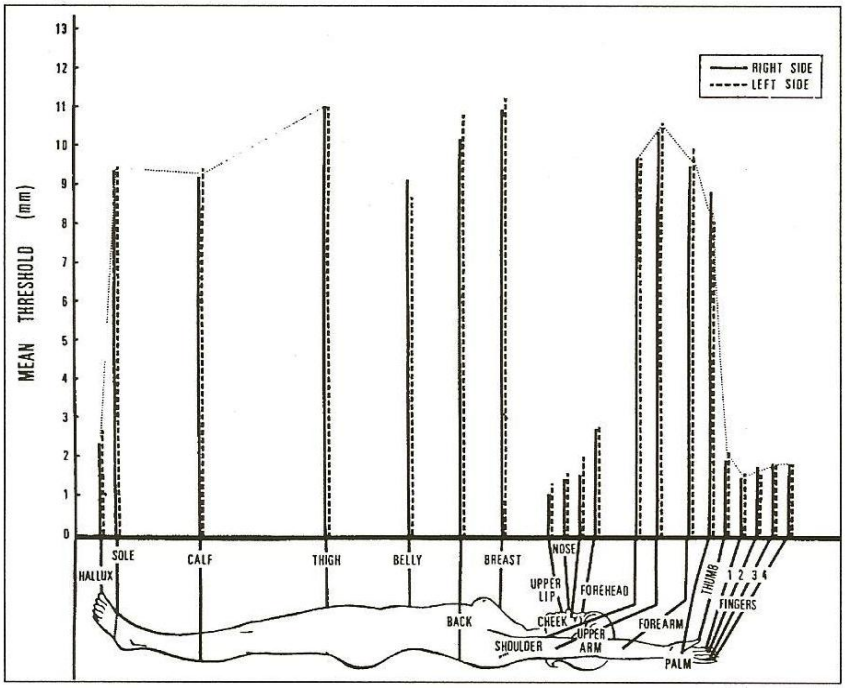

Figure A-5. Point localization thresholds for females.

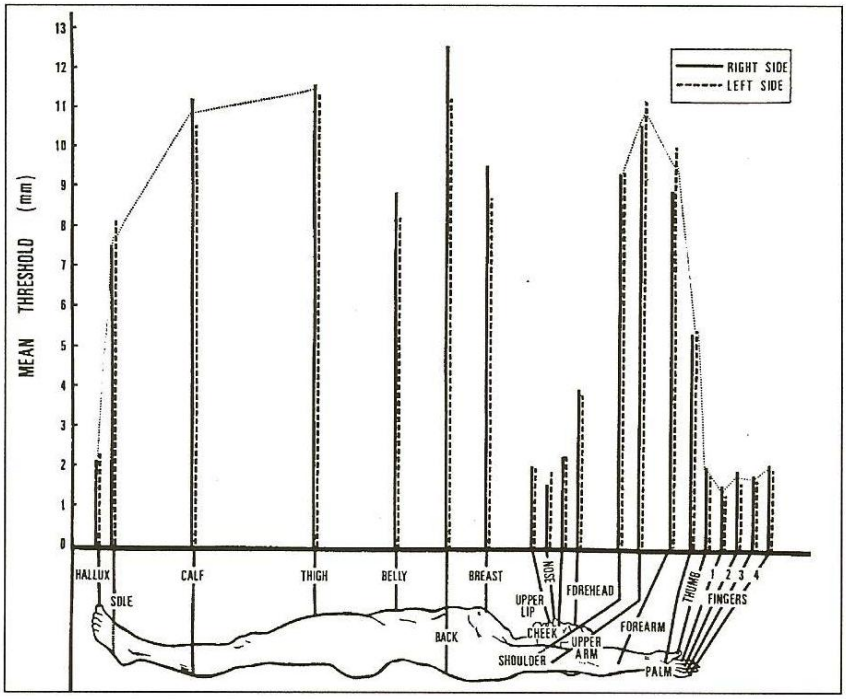

Figure A-6. Point localization thresholds for males.

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