Marquette University e-Publications@Marquette

Dissertations (2009 -)

Dissertations, Theses, and Professional Projects

Reaching Performance in Heathy Individuals and Stroke Survivors Improves after Practice with Vibrotactile State Feedback

Valay A. Shah Marquette University

Follow this and additional works at: https://epublications.marquette.edu/dissertations_mu

Part of the Biomedical Engineering and Bioengineering Commons

Recommended Citation

Shah, Valay A., "Reaching Performance in Heathy Individuals and Stroke Survivors Improves after Practice with Vibrotactile State Feedback" (2020). *Dissertations (2009 -)*. 916. https://epublications.marquette.edu/dissertations_mu/916

REACHING PERFORMANCE IN HEALTHY INDIVIDUALS AND STROKE SURVIVORS IMPROVES AFTER PRACTICE WITH VIBROTACTILE STATE FEEDBACK

by

Valay A. Shah, B.S.

A Dissertation Submitted to The Faculty of Graduate School, Marquette University, In Partial Fulfillment of The Requirements For The Degree of Doctor of Philosophy

Milwaukee, Wisconsin

May 2020

ABSTRACT

REACHING PERFORMANCE IN HEALTHY INDIVIDUALS AND STROKE SURVIVORS IMPROVES AFTER PRACTICE WITH VIBROTACTILE STATE FEEDBACK

Valay A. Shah, B.S.

Marquette University, 2020

Stroke causes deficits of cognition, motor, and/or somatosensory functions. These deficits degrade the capability to perform activities of daily living (ADLs). Many research investigations have focused on mitigating the motor deficits of stroke through motor rehabilitation. However, somatosensory deficits are common and may contribute importantly to impairments in the control of functional arm movement. This dissertation advances the goal of promoting functional motor recovery after stroke by investigating the use of a vibrotactile feedback (VTF) body-machine interface (BMI). The VTF BMI is intended to improve control of the contralesional arm of stroke survivors by delivering supplemental limb-state feedback to the ipsilesional arm, where somatosensory feedback remains intact.

To develop and utilize a VTF BMI, we first investigated how vibrotactile stimuli delivered on the arm are perceived and discriminated. We determined that stimuli are better perceived sequentially than those delivered simultaneously. Such stimuli can propagate up to 8 cm from the delivery site, so future applications should consider adequate spacing between stimulation sites. We applied these findings to create a multichannel VTF interface to guide the arm in the absence of vision. In healthy people, we found that short-term practice, less than 2.5 hrs, allows for small improvements in the accuracy of horizontal planar reaching. Long-term practice, about 10 hrs, engages motor learning such that the accuracy and efficiency of reaching is improved and cognitive loading of VTF-guided reaching is reduced. During practice, participants adopted a movement strategy whereby BMI feedback changed in just one channel at a time. From this observation, we sought to develop a practice paradigm that might improve stroke survivors' learning of VTF-guided reaching without vision. We investigated the effects of practice methods (whole practice vs part practice) in stroke survivors' capability to make VTF-guided arm movements. Stroke survivors were able to improve the accuracy of VTF-guided reaching with practice, however there was no inherent differences between practice methods. In conclusion, practice on VTF-guided 2D reaching can be used by healthy people and stroke survivors. Future studies should investigate long-term practice in stroke survivors and their capability to use VTF BMIs to improve performance of unconstrained actions, including ADLs.

ACKNOWLEDGEMENTS

Valay A. Shah, B.S.

I want to thank my parents, Anant and Hina, for their guidance, support, and love. I want to thank my sister, Sneha, for always being competitive with me and pushing me to pursue my PhD. I would also like to thank my friends, Carl, Dwani, and Michael for making my PhD fun along the way. I also want to thank the rest of my family and friends for their support and encouragement.

I am grateful to have had two great mentors, Dr. Robert A Scheidt and Dr. Leigh Ann Mrotek, who always looked out for my best interests and guided me through my PhD. Because of them, I feel I am a better scientist and set up for success as a researcher. Their mentorship and guidance has allowed me to make my PhD a great experience. I want to thank my committee members Dr. Scott Beardsley and Dr. Aaron Suminski, whose suggestions and guidance have strengthened my research. I am also grateful to Dr. Maura Casadio, my host in Italy and a committee member. Dr. Casadio provided me with tremendous support when I was doing my dissertation research overseas. Without her willingness to host me, I would never have had such a unique and exciting PhD experience. Along with Dr. Casadio, I want to thank her students, Giulia, Giorgia, Fabio, and Elisa, for welcoming to their lab and making my time in Italy enjoyable and memorable. I also want to thank the steering committee at the Whitaker International Program for believing in me and supporting my research endeavors in Italy.

I want to acknowledge the Biomedical Engineering department at Marquette University, Mrs. Mary Wesley, the Graduate School, my professors, my fellow graduate students, and my lab mates for their support.

Thank you to the National Institutes of Health (R15HD093086-01A1), The Whitaker International Program, and European Commission (Erasmus+ KA 107 action (USA-ITALY)) for providing funding and support for this dissertation research.

TABLE OF CONTENTS

ACKNOWLEDGEMENTS	i
LIST OF TABLES	iv
LIST OF FIGURES	.v

CHAPTERS

I.	MOTIVATION AND OBJECTIVES	1
II.	BACKGROUND	6
A B C D E F	 SENSORIMOTOR CONTROL AND FEEDBACK INTEGRATION	
III.	VIBRATION PROPAGATION ON THE SKIN OF THE ARM	
A B C D E	 INTRODUCTION MATERIALS AND METHODS RESULTS DISCUSSION CONCLUSIONS 	29 32 37 41 45
IV.	DISCRIMINATION OF VIBROTACTILE STIMULI ON THE ARM	47
A B C D E	 INTRODUCTION MATERIAL AND METHODS RESULTS DISCUSSION CONCLUSIONS 	47 52 58 64 74
V. VIB	IMPACT OF SHORT-TERM PRACTICE ON LEARNING TO USE ROTACTILE FEEDBACK TO GUIDE ARM MOVEMENTS	
A B C D E	 INTRODUCTION METHODS RESULTS DISCUSSION CONCLUSIONS 	
VI. TO	IMPACT OF INTERMEDIATE-TERM PRACTICE ON LEARNING USE VIBROTACTILE FEEDBACK TO GUIDE ARM MOVEMENTS	91
А	. INTRODUCTION	

B.	Methods	
C.	RESULTS	
D.	DISCUSSION	103
E.	CONCLUSIONS	107
VII. I	LONG-TERM PRACTICE RELATED CHANGES IN VIBROTACTILE	
FEED	BACK GUIDED REACHING BEHAVIOR	108
А	INTRODUCTION	108
B.	METHODS	111
C.	RESULTS	117
D.	DISCUSSION	126
E.	CONCLUSIONS	131
VIII.	LEARNING TO USE VIBROTACTILE FEEDBACK TO GUIDE	
REAG	CHING IN STROKE SURVIVORS	133
A.	INTRODUCTION	133
B.	Methods	137
C.	RESULTS	144
D.	DISCUSSION	152
E.	Conclusions	158
IX. C	CONCLUSIONS	159
A.	FUTURE EXPERIMENTS	161
X. I	REFERENCES	165

LIST OF TABLES

- Table 1: Examples of skills classified into their complexity and organization levels.
- Table 2: Subject Demographics showing age, height, weight, arm length and arm circumferences along the arm.
- Table 3: Vibration parameters as related input voltage. Frequency and Amplitude are reported from manufacturer specification sheet.
- Table 4: Description of task blocks: number of trials, block type, and feedback condition type.
- Table 5: Blocks that could be performed during each session.
- Table 6: Blocks that could be performed during each session by stroke survivors.
- Table 7: Clinical assessment scores for stroke participants meeting inclusion criteria in their respective groups. SS = stroke survivor identifier.

LIST OF FIGURES

- Figure 1: A simplified version of the motor control network of the human brain.
- Figure 2: A simplified view of the motor control loop in healthy humans.
- Figure 3: A) Anterior view of the arm. B) Equipment.
- Figure 4: Mean acceleration (across participants) at different distances from a source vibration, at various frequencies.
- Figure 5: Percentage of acceleration remaining decreases as distance from the source vibration increases.
- Figure 6: The dermatomes of the arm (the domains of origin of those projections) are labeled according to their target cord segment, and are marked by the shaded regions.
- Figure 7: A) Assessment of vibrotactile perception at dermatome C7 for a selected participant. B) Best-fit cumulative normal functions for the five testing locations for the same participant.
- Figure 8: Group results from Experiment 1. Mean (± 1 SEM) discrimination thresholds across the population were calculated for sequential vibrotactile stimuli presented within each of the five tested locations.
- Figure 9: Group results from Experiment 2. Mean (± 1 SEM) discrimination thresholds were calculated for sequentially (gray bars) and simultaneously delivered (white bars) vibrotactile stimuli at stimulus location pair.
- Figure 10: Experimental set up. Left Panel: participants sat in front of a computer screen that displayed targets and a cursor. Central Panel: a vibrotactile interface consisting of four vibrotactile motors was placed on the participant's non-dominant left arm. Right Panel: The Y+ tactor was activated when the cursor/hand was in the hemi-space above the center row of targets, whereas the X+ tactor was activated when the cursor/hand was to the right of the center column of targets.
- Figure 11: Task workspace showing sample reaching trajectories from one participant.
- Figure 12: Left: target capture error magnitude (cm). Right: target capture time (s).
- Figure 13: Vibrotactile interface (4 tactors) attached to the non-dominant, non-moving arm.

- Figure 14: This schematic describes the sequence of task blocks for each session.
- Figure 15: Average reaching error during the Rch task across five sessions.
- Figure 16: Average target capture time during the Rch task across five sessions.
- Figure 17: Sample reaching trajectories from a representative participant during RCH task under various feedback conditions.
- Figure 18: Vibrotactile interface made of four ERM motors attached to the non-moving arm while the moving arm works in a 5x5 reaching target grid
- Figure 19: Sample reaching trajectories from one representative participant during RCH task under various feedback conditions.
- Figure 20: Group reaching error during the RCH task using VTF to guide reaching, across the 20 sessions.
- Figure 21: Group Target capture time for the RCH task using VTF to guide reaching across the 20 sessions.
- Figure 22: Group Decomposition Index (DI) for the RCH task using VTF to guide reaching across the 20 sessions.
- Figure 23: Average reaching error during VTF-guided reaching.
- Figure 24: Average target capture time during VTF-guided reaching.
- Figure 25: Average choice reaction time during single CRT and CRT during DT.
- Figure 26: Schematic of a participant using the 2-joint robotic manipulandum.
- Figure 27: Stroke survivor reaching error averaged across experimental groups on the 2D reaching task.
- Figure 28: Stroke survivor target capture time averaged across experimental groups on the 2D reaching task.
- Figure 29: Stroke survivor DI averaged across experimental groups on the 2D reaching task.
- Figure 30: Stroke survivor reaching error across practice groups in the 2D VTF-guided reaching test.
- Figure 31: Stroke survivor target capture time across practice groups in the 2D VTFguided reaching test.

I. MOTIVATION AND OBJECTIVES

The objective of this dissertation is to examine the effects of practice duration and practice method on learning the sensorimotor control of upper extremity reaching movements with guidance from vibrotactile feedback (VTF). To successfully accomplish this objective, this dissertation aims to: 1) characterize how vibrations propagate across the skin of the arm; 2) extend understanding of how healthy human adults perceive vibrotactile stimuli applied to the arm; 3) examine the extent to which motor learning and practice duration can improve the ability to integrate VTF into the ongoing sensorimotor control of reaching movements in healthy people; and 4) examine how practice method influences VTF-guided reaching performance in stroke survivors. Ultimately, this research seeks to advance rehabilitative techniques and assistive devices that exploit supplemental vibrotactile feedback to improve arm control in stroke survivors.

The human brain can be affected by various neurological diseases and trauma (e.g., stroke, Parkinson's, Huntington's, Alzheimer's, Traumatic Brain Injury; (Purves 2012)). Stroke is one of the most prevalent diseases that affects humans. In the United States alone, there are more than 750,000 cases of stroke every year (Benjamin et al. 2018; Dobkin 2005). Stroke can cause multiple impairments, including movement, sensory, and cognitive deficits. The cost associated with stroke, within the next four decades, is expected to exceed \$2 trillion (Benjamin et al. 2018). Movement deficits are prominently visible. However, more than 50 percent of survivors of stroke have some form of sensory deficit, such as impaired proprioception (Carey 1995; Carey and Matyas 2011; Dukelow et al. 2010).

Proprioception is the ability to sense the position and orientation of our limbs and body. Proprioceptive deficits can lead to problems with movement, balance (Allum et al. 1998), and coordination (Sainburg, Poizner, and Ghez 1993). The scientific and clinical communities have primarily focused on motor rehabilitation after stroke, but there is also a need to lessen the impact of sensory (proprioceptive) deficits after stroke through sensory retraining (Schabrun and Hillier 2009). Motor rehabilitation is aimed towards relearning muscle and joint coordination as well as strengthening muscles (Carr and Shepherd 1987). However, for stroke survivors that have proprioceptive deficits, motor rehabilitation alone will not result in beneficial improvements to perform activities of daily living (ADLs) and to regain independence since they will not be able to perform coordinated movements without sufficient proprioceptive feedback.

Proprioception is crucial in movement planning and voluntary movement coordination (Sober and Sabes 2003). Proprioceptive deficits contribute largely to movement impairments and joint coordination (Sainburg et al. 1995) and hinder poststroke patients from adapting movements to novel mechanical loads (Scheidt and Stoeckmann 2007). Survivors often try to compensate for proprioceptive deficits by relying on visual feedback to make movements (Bonan et al. 2004). However, visual feedback takes longer to process and adds delays in detecting and correcting errors, leading to jerky and slow movements (Cameron, de la Malla, and Lopez-Moliner 2014; Sarlegna et al. 2006). Thus, it is imperative that we find alternative solutions that do not rely on vision to overcome proprioceptive deficits after stroke, as these deficits negatively impact movement control of the arm, ultimately leading to degraded ADLs and reduced independence. One technique that can be used to mitigate proprioceptive deficits is sensory augmentation. Sensory augmentation aims to replace impaired or lost sensations by providing relevant information via artificial stimulation of intact sensory "channels" or modalities (Bach-y-Rita and W. Kercel 2003). For example, people affected by vision loss can use tactile sensation of the skin to visualize words or objects they cannot see (White et al. 1970; Kaczmarek et al. 1985). For stroke survivors with proprioceptive deficits of the arm, it may be possible to supplement or replace impaired proprioception with another sense, such as tactile sensation (Molier et al. 2010). Sensory augmentation for proprioceptive deficits may help improve motor control over ADLs, leading to improved quality of life and independence in stroke survivors.

Of these alternate sensory modalities, tactile sensation appears to be the most viable option since visual feedback adds large delays (Cameron et al. 2014) and auditory feedback can interfere with social communication. Tactile feedback through vibration has been successfully used to provide augmented/substitutive feedback to the skin (Kaczmarek et al. 1991). More recently, Tzorakoleftherakis et al. (2015) utilized VTF to augment movement control after stroke. In their application, they utilized VTF to assist survivors in moving their arms towards a target. Stroke survivors with proprioceptive deficits were able to increase their accuracy in tracking targets with VTF. Krueger et al. (2017) showed that providing VTF on the less affected arm can improve performance of reaching and stabilization tasks performed with the more affected arm in stroke survivors. Moreover, the application of sensory augmentation via VTF shows promise for improving post-stroke movement control of the arm. The ultimate objective of this line of sensory augmentation research is to develop a novel biomedical device for post-stroke rehabilitation of the arm using VTF to replace and/or augment proprioception.

A barrier to the development and optimization of this technology is that we do not fully understand how humans perceive and integrate external VTF applied to one body part into the control of another body part nor do we understand how this might change with practice. The research in this dissertation seeks to enhance our understanding of how VTF is perceived and can be combined into existing healthy and stroke-impaired sensorimotor pathways to improve the control of movement performed with the arm. Additionally, influence of practice on learning to use VTF to control arm movements is also investigated.

Much of the previous research has focused on the initial use of VTF to guide movements (Bark et al. 2011; Kapur et al. 2010; Krueger et al. 2017; van der Linden, Schoonderwaldt, and Bird 2009; Risi et al. 2019). How exactly we progress our capability to use VTF to guide reaching movements and how this augmented control of movement can improve with practice is currently unknown. Amount and type of practice significantly impacts our capability to learn and retain new motor skills. Ericsson et al. (2008; 1993) have even concluded that to become an expert at a motor skill, long-term practice is required with some individuals needing up to 10 years of practice. Additionally, the information we use and the ways we alter performance changes as we increase practice of a new skill. In early practice, we see large improvements in performance, specifically in kinematic measures However, this does not mean we have become proficient and experts. We also need to display consistency and stability (low performance variability), adaptability (performance under varying task characteristics), and reduction in attentional demands (performance without conscious thinking; ability to multi-task). As we increase practice, performance improvements are more subtle, but more critical even though we are still learning (Magill and Anderson 2017). Additionally, practice can also be designed to have varying schemes. For example, learners can practice the task as a whole or break the task into parts to improve specific aspects of the task individually. The method of practice and how it changes our learning of using VTF to guide reaching should be investigated to advance BMIs that rely on VTF.

This dissertation has three main aims: 1) to investigate human perception and discrimination of external vibrotactile stimuli applied to the arm; 2) to identify effects of practice on using VTF to control arm movements; and 3) to explore different practice methods to improve learning of VTF-guided reaching in stroke survivors. The knowledge we gain from this study will ultimately improve sensory augmentation technologies for post-stroke motor rehabilitation of the arm and provide us with a better understanding of our ability to use VTF. In this dissertation, I will first set the background for sensorimotor control, stroke, stroke related sensorimotor deficits, sensory augmentation to mitigate sensorimotor deficits, sensorimotor learning, and how vibrations are sensed. I will then report the findings from the three main aims and their related investigations. I will end the dissertation with concluding remarks on future work that will further increase our understanding of VTF sensory augmentation and current limitations we face.

II. BACKGROUND

A. Sensorimotor Control and Feedback Integration

Sensorimotor control is a complex process that allows us produce voluntary movements to interact with our environment and manipulate objects (Magill and Anderson 2017; Rosenbaum 2010). Deficits of sensorimotor control can result in significant disabilities that affect the capability to perform ADLs, reduce independence, and decrease quality of life. Understanding how voluntary movements are controlled by the healthy brain and how movements are impacted by diseases such as stroke is critical in developing rehabilitation methods to improve motor capabilities (Crichton et al. 2016; Rafferty et al. 2017).

Voluntary movements are planned and executed by motor, sensory, and information processing brain regions (Purves 2012; Körding and Wolpert 2006; Todorov 2004). The motor control network is complex and involves both the central nervous system (CNS) and the peripheral nervous system (PNS). Goal-directed voluntary motor control can utilize two controller types for successful motor performance: a feedforward (FF) controller and a feedback (FB) controller (Scott 2004; Sober and Sabes 2003, 2005). These controllers are used for open-loop control of movements (when feedback is not needed or not available) and closed-loop control of movements (when feedback is required). Goal-directed voluntary movements often rely on the closed-loop control system (involving both FF and FB controllers) to produce precise and accurate movements and to adjust for mid-movement perturbations (Magill and Anderson 2017).

For goal-directed voluntary movements, the FF controller is used to initiate movements when external feedback is not available or when movements must be made in anticipation of some event. During FF movements, the motor plan (the desired movement intent) is created in the contralateral cortex using an internal representation of the body state and current sensory information. This plan travels through the descending motor pathways to execute the movement.



Figure 1: A simplified version of the motor control network of the human brain. Solid arrowed lines show descending connections and dashed arrowed lines show ascending connections. The motor plan for a goal directed movement originates in the cortex. This plan is then relayed to the basal ganglia for movement initiation and cerebellum for movement coordination. This information is relayed back to the cortex, which then forwards the motor command through the brainstem and spinal cord to the muscles. Muscles actuate the movement and sensory afferents send sensory feedback through the spinal cord and thalamus back to the cortex. The cerebellum also recieves a copy of the sensory feedback signal. This signal can be used to coordinate and plan corrective movements if necessary to reach the desired goal.

The motor plan created in the contralateral cortex crosses over to the ipsilateral side near the medulla to reach the corticospinal tract (Magill and Anderson 2017; Purves 2012). From the spinal cord, targeted motor units are activated to actuate the desired movement. In addition to traveling through the corticospinal tract, a copy of the motor plan is also sent to the cerebellum via the cortico-ponto-cerebellar pathway (efference copy). It is theorized that the efference copy is used to create an estimate of the expected sensory feedback from forward internal models of limb kinematics (Kawato 1999; Miall and Wolpert 1996; Pickering and Clark 2014). The expected sensory feedback is compared with actual sensory feedback to determine if the desired movements has been completed successfully (Ishikawa et al. 2016). Figure 1 depicts a simplification of the motor ontrol network in humans.

Once the initial movement is executed, the FB controller is used to correct movement errors due to internal planning errors or external disturbances. Sensory information from the produced movement travels from the sensory afferents, such as tactile sensors, muscle spindles, and Golgi tendons, to the spinal cord. The spinal cord relays this information to the thalamus. From the thalamus, the information is sent to the relevant sensorimotor cortices. The cerebellum also receives this sensory information through direct sensory inputs via the spinocerebellar tract or the sensorimotor cortices via the cortico-ponto- cerebellar pathway. This signal can be used to coordinate and plan corrective movements to reach the desired goal. The cerebellum functions to coordinate muscle activity to produce smooth, fast, and precise movements (Thach 1998). Figure 2 shows a simplified version of the closed-loop control system utilized to produce a goaldirected voluntary movement.



Figure 2: A simplified view of the motor control loop in healthy humans. The central nervous system (CNS) creates a motor plan (discrepancy signal) using sensory information from the peripheral nervous system (PNS) and the motor goal. The motor cortex relays this plan (feedforward) to the muscles to produce the desired movement. Sensory information from the produced movement is relayed back (feedback) to the CNS to identify if the desired movement is completed. The loop iterates as needed to achieve the desired movement.

The FF and FB controllers may correspond to a two-stage movement process during reaching. The FF controller allows us to plan an initial trajectory phase of movement, while the FB controller allows us to control the goal acquisition phase of movement (Scheidt and Ghez 2007; Scheidt and Stoeckmann 2007). The initial trajectory phase of movement is ballistic (single velocity curve), while the goal acquisition phase is slower (corrective) to bring the desired goal closer and closer (see Optimized Initial Impulse Model by Rosenbaum (2010)).

Additionally, current theories in sensorimotor control hypothesize that the brain selects motor plans based on "optimal performance" (Körding and Wolpert 2006; Todorov 2004). For optimal performance and control of goal-directed movements, Bayesian decision theory (Körding and Wolpert 2006) states that sensory feedback from different modalities receive different weightings (to reduce noise and remove unimportant information). These weightings are based on our own estimates (from the efference copy) and prior sensorimotor memories (Miall and Wolpert 1996). The Bayesian model allows for varying prioritization between our sensory feedback (i.e., between vision, proprioception, tactile feedback, and auditory feedback) that creates the most efficient movement to achieve the desired goal.

B. Stroke

Stroke is a cardiovascular disease that creates an excess of \$34 billion in annual care-related costs in the United States (Benjamin et al. 2018). There are two types of stroke that can occur: ischemic stroke (more prevalent in humans) and hemorrhagic stroke (Brainin and Heiss 2019; Kanyal 2015). Ischemic stroke occurs when cerebral blood supply is suddenly interrupted (due to blood clots or other particles). Hemorrhagic stroke occurs when a cerebral blood vessel bursts, leading to blood leakage and increased intercranial pressure in the brain. In both types of stroke, neurons in the brain experience trauma and/or cell death due to a lack of blood supply (oxygen and nutrient deficit) or physical trauma due to increased pressure and cell displacement (Kanyal 2015).

Stroke causes various impairments, depending on the injured brain regions. Examples of these deficits include loss of vision, audition, proprioception, or other sensation, as well as speech, balance, and motor capabilities (Carey 1995; Carey and Matyas 2011; Connell, Lincoln, and Radford 2008; Cumming, Marshall, and Lazar 2013; Hyndman and Ashburn 2003; Muren, Hütler, and Hooper 2008). Additionally, cognitive deficits can occur if information processing regions and networks suffer neuronal damage (Brainin and Heiss 2019). These deficits can significantly reduce patient independence and quality of life.

C. Sensorimotor Deficits of Stroke

Sensorimotor deficits caused by stroke significantly reduce survivors' ability to perform goal-directed, voluntary movements. The severity of reduction in motor control depends on the severity of the brain damage caused by stroke. The Middle Carotid Artery (MCA) supplies numerous regions in the brain, including the basal ganglia, motor cortex, somatosensory cortex, and parts of the thalamus (Teasell et al. 2016). Stroke in the MCA is also the one of the most common location of stroke that occurs, leading to a high prevalence of post-stroke sensorimotor deficits (Leys et al. 1992; Walcott et al. 2014).

Animal models in rodents have shown severe sensorimotor deficits caused by MCA strokes. Gharbawie et al. (2005) found dysfunctions in rat reaching behavior after induced MCA stroke. Rats with a damaged motor cortex due to stroke, showed excessive use of trunk and head musculature to assist reaching. Rats with MCA stroke showed additional deficits in sensory function as well as motor function. In another study, Gharbawie et al. (2005) showed that even if the motor cortex is spared after MCA stroke, its function involved in voluntary motor control is still disrupted. Conceivably, these motor issues are due to damage in intraneuronal connection between multiple motor planning regions. A review by Kleim et al. (2007) examined MCA stroke in rodents, citing major sensorimotor deficits as a result of stroke. These deficits can range from hemiparesis to impairments of complex task performance such as reaching for a reward. Furthermore, even motor learning (motor adaptation and skill task learning) was shown to be affected by MCA stroke.

In humans, sensorimotor deficits caused by stroke present similarly to those shown in rodent models. Major sensorimotor deficits in humans may present as hemiparesis (weakness), hemiplegia (paralysis), apraxia, sensory loss, visual perception deficits, visual neglect, or aphasia (Teasell et al. 2016). These deficits may be more or less severe and can present individually or concurrently as shown by numerous previous studies (Carey 1995; Dukelow et al. 2010; Kessner, Bingel, and Thomalla 2016; O'Sullivan, Schmitz, and Fulk 2014). Carey et al. (2011) examined the frequency of sensory deficits present in stroke survivors. In their cohort of patients (n = 51), 47% of survivors presented with tactile sensation deficits and 49% of patients also presented proprioceptive deficits on the contralateral (more affected) arm. Dukelow and colleagues (2010) assessed proprioception in the upper limb, showing that up to 66% of patients in their study had deficits. A review by Kessner et al. (2016) showed that sensory deficits can range from as low as $\sim 30\%$ to as high as $\sim 80\%$ across previously performed studies that examined sensorimotor function after stroke. These sensory deficits impede stroke survivors' ability to perform activities of living and limit motor rehabilitation after stroke since proprioception (limb sense) is necessary for motor performance in humans (O'Sullivan et al. 2014).

Most patients undergo motor relearning to some extent to regain the ability to use their more affected limbs (Carey 2012; Cirstea, Ptito, and Levin 2006). The capability this of motor learning also depends on the severity of proprioceptive deficits (Vidoni and Boyd 2009). Since the brain has neuroplastic capabilities even after stroke, sensory input is crucial for this motor relearning process to regain successful motor control of the body (Carey 2012; Magill and Anderson 2017). If proprioceptive sensory inputs are unavailable due to stroke, we must find another method to deliver sensory information to the brain to allow for successful motor relearning and post-stroke rehabilitation. In this dissertation research, I explored augmenting and substituting proprioceptive feedback in heathy people and stroke survivors.

D. Sensory Augmentation to Mitigate Sensory Deficits in the Arm

Recent efforts in the development of noninvasive body-machine-interfaces (BMIs) have sought to mitigate sensorimotor impairments (Casadio, Ranganathan, and Mussa-Ivaldi 2012; Mussa-Ivaldi and Miller 2003). In healthy individuals, proprioception is vital for closed-loop control of arm movements (Sober and Sabes 2003). Unfortunately, stroke can interrupt sensory feedback pathways that normally contribute to the coordination of arm movements leading to movements impairments (Carey 1995; Dukelow et al. 2010; Sainburg et al. 1995, 1993). Various approaches have been tried to develop BMIs to convey information that replaces or augments the impaired proprioceptive feedback. These BMIs have relied on using visual, tactile, or auditory stimuli to provide supplemental cues about movements (Casadio et al. 2012).

Visual feedback is necessary and valuable for exploring our environment and planning goal-directed movements, but it is disadvantageous for online control of arm movements as it adds large feedback delays compared to proprioceptive feedback, leading to jerky and slow movements (Cameron et al. 2014; Sarlegna et al. 2006). Auditory feedback is processed quicker than visual feedback and has been used successfully to guide movements in a controlled setting (Brown, Macpherson, and Ward 2011; Oscari et al. 2012). However, in a real-world setting, supplemental auditory feedback can hinder social communication. So, of these alternate sensory modalities, tactile feedback (specifically vibrotactile feedback (VTF)) may prove to be advantageous as it is an inexpensive and noninvasive way of conveying information to a user without taxing visual or auditory attention. For stroke survivors, VTF information can potentially augment or substitute for proprioceptive deficits, while off-loading visual attention needed to produce movements. This can enhance motor rehabilitation and limb use poststroke, ultimately leading to improved performance of ADLs and quality of life.

Previous work on VTF has shown successful uses of several forms of vibrotactile cues including: continuous error feedback, discrete error feedback (indicators of undesirable conditions; alerts), or continuous state feedback to indicate current state (Bark et al. 2011; Cuppone et al. 2016; Ferris and Sarter 2011; Krueger et al. 2017; Risi et al. 2019; Tzorakoleftherakis, Murphey, and Scheidt 2016). It is crucial that the design of VTF and the information it provides is based upon the executed task. Vibrotactile feedback can be provided to convey alerts, directional cues, or spatial orientation cues (for review see Prewett et al. (2012)). Prewett et al. concluded that successful use of VTF cues was dependent on the task being performed (i.e., task complexity) and the cueing method. In tasks where VTF cues replaced visual information, alerts elicited stronger performance than directional or spatial orientation cues. This difference in performance

between cue modalities was attributed the task being performed and the contextual conditions of the task. Spatial orientation cues were most helpful in tasks such as navigation. However, task performance and the extent to which VTF spatial orientation cues were used was impacted by the amount of daylight and weather conditions (Elliot et al. 2006; Elliott et al. 2007). Thus, we must select a method of VTF cues that can provide the task-related information in the most intuitive way in a real-world setting.

Error feedback can be used to produce goal-directed movements by reducing feedback as error towards the goal is reduced. Numerous previous studies have utilized VTF cues to provide error feedback in a movements control task (for a review of examples see Prewette et al. (2012); Jones and Sarter (2008)). Cuppone et al. (2016) used vibrotactile cues to provide error feedback about wrist movements. Vibrotactile feedback indicated deviation from the ideal wrist movement path. Feedback was provided on the contralateral or ipsilateral forearm using four vibration motors that changed intensity with error in the direction of movement, indicating error in wrist flexion/extension and ad/abduction. Up to two vibration motors could be activated at a single time to indicate a 2 degrees of freedom (DOF) movement. After a 3-day training regimen on wrist movements with error feedback, healthy users improved their wrist proprioceptive acuity. The VTF interface was intuitive enough that performance improvements in proprioceptive acuity were similar regardless of whether the feedback was applied on the contralateral or ipsilateral forearm. Cuppone et al. concluded from this study of healthy people, that motor training effects on the more affected arm can be achieved in people who have somatosensory deficits by providing supplemental feedback on the less affected arm. Bark et al. (2015) also used VTF to convey joint angle errors to during

motion guidance of the arm. Vibrotactile feedback cued repulsive motions, such that an increase in vibration intensity indicated an increase in the joint angle error and the user was required to move in the opposite direction to reduce vibration intensity. Feedback was provided on the ipsilateral arm using eight vibration motors, four motors mounted equidistantly around the wrist and four motor around the upper arm. Users performed arm movements displayed in a virtual reality headset, where movements were single DOF, 2 DOF, or 3 DOF motions of the forearm and upper arm. Regardless of DOF, only one vibration motor was activated at a single time. After a 4-day training regimen, healthy users' joint angle errors were reduced with VTF for the 1 DOF movements but not for 2 and 3 DOF movements. Bark et al. concluded that VTF could provide sufficient information to control joint angles for 1 DOF movements but for 2 and 3 DOF movements, a more intuitive feedback control system should be designed.

Krueger et al. (2017) used VTF to provide error feedback about hand movements in a 2D workspace. Error feedback was provided with VTF cues, indicating the error between the desired position (i.e., increasing distance between the hand and the target location equaled to increasing VTF intensity). When VTF intensity decreased, users were cued that they were near the desired hand position. Vibrotactile cues were continuously provided on the forearm with four vibration motors mounted on the contralateral forearm. After one day of training, healthy users improved their reaching performance with vibrotactile error feedback compared to reaching with intrinsic proprioception. Overall, multiple previous studies have successfully used error feedback in conveying information to users and to control movements.

Another method of delivering VTF cues for movements control is state feedback, where feedback represents the current state of the body or information regarding some event (e.g., grip force, limb position, body posture, gait cycle). An et al. (2011) used state feedback to convey force applied by a finger to a virtual object. Vibrotactile feedback provided information about the amount of normal force applied to the top of a virtual object. As the applied force increased, vibration intensity increased conveying to the users the applied force on the object. Vibrotactile feedback was continuously provided with one vibration motor attached to the upper arm. Users had to create a normal force on top of a virtual object to move the object from one location to another without dropping it (too little force) or crushing it (too much force). After a 4-day training regimen, healthy users significantly improved their ability to move the virtual object farther and faster without dropping or crushing the object. Users also indicated a reduction in task difficulty after multi-day training. Kreuger et al. (2017) also used VTF cues to provide hand kinematic state feedback, where VTF cue intensity was associated with the position and velocity of the hand in a 2D workspace. Vibrotactile feedback was continuously provided to the contralateral arm with four vibration motors mounted on the forearm. Vibrotactile feedback indicated the direction/state of the moving hand in the 2D workspace using a combination of hand position and velocity. The workspace was setup in a cartesian fashion such that users could move in X and Y directions individually or at the same time. The VTF cues indicated the directions of movements relative to the center of the cartesian workspace, such that up to two vibrations motors can be activated at the same time if users moved diagonally across the X and Y dimensions. After one day of training, healthy users improved reaching performance with state feedback and performance was

the best when vibrotactile feedback conveyed approximately 80% hand position and 20% hand velocity.

In a more recent study, Risi et al. (2019) utilized limb-state feedback to convey hand position in a 2D workspace. Vibrotactile feedback provided continuous state feedback of hand position through a multi-channel interface attached to the non-moving, contralateral arm. Four vibration motors were mounted across the upper arm and forearm and indicated the direction/state of the moving hand in the 2D workspace. The workspace was setup in a cartesian fashion such that users could move in X and Y directions individually or at the same time. Vibrotactile feedback indicated the position of the hand relative to the center of the cartesian workspace, such that up to two vibrations motors can be activated at the same time if the hand was located diagonally across the X and Y dimensions. After a 2-day training regimen, users were able to reach more accurately than with intrinsic proprioception. Overall, state feedback was successfully used to control movements and manipulate objects across varying experiments.

In the laboratory setting, both error and state feedback seem to be feasible and healthy people are able to use them intuitively to control movements. However, error feedback may be less readily suited for real-world, goal-directed movements, since understanding a user's internal (unvoiced) goal or movement intent proves to be difficult without the use of invasive technology or cumbersome sensors (e.g., electroencephalography (EEG), electromyograph (EMG); (Chen, Zeng, and Yin 2017; Li et al. 2018; Shanechi et al. 2013)). Limb-state feedback may be more beneficial in the real-world as we can design the control system to use a reference point on the body from which states change (e.g., Krueger et al. (2017) and Risi et al. (2019) used the center of the workspace as the reference point) or inexpensive transducers to convey state information about the body (e.g., Afzal et al. (2015) used force transducers to determine the state of events during gait cycle). For successful development of a BMI that can augment or substitute proprioception through VTF, we need to further investigate how neurologically intact people and stroke survivors are able to use limb-state VTF to enhance reaching behavior in the absence of visual feedback. Additionally, the effects of practice and motor learning on using VTF to guide reaching must also be investigated. This will allow us to understand if long-term practice can improve use of VTF BMIs through motor learning.

E. Sensorimotor Learning and Practice

Sensorimotor learning is defined as the process of obtaining the capability to perform a skilled action (motor skills), as a result of practice and experience (Magill and Anderson 2017). Motor skills can be defined as movements or activities that have specific goals (goal directed movements). Motor skills can range from learning to coordinate and use large muscle movements (e.g., walking, jumping, running) to coordinating fine muscle movements (e.g., writing, typing, playing the violin). Since learning is an internal process, we infer that sensorimotor learning occurs through changes in behavioral performance. The learning process is a permanent change in the CNS that occurs as a result of practice. There are numerous theories that describe how motor learning potentially occurs and how specifically designed practice schemes aid in progressing motor learning of a skill.

Behavioral changes that are easily reversible or pass within minutes or hours are not considered signs of motor learning. Rather these changes are considered motor adaptations (Bastian 2008). Motor adaptations are the short-term modifications of a learned motor skill, based on the change in the motor skill parameters or external perturbations. Motor adaptations occur with short-term practice, over the course of minutes to hours. These adaptations can be de-adapted relatively quickly if needed (Bastian 2008; Scheidt and Stoeckmann 2007). For example, in a laboratory setting, when visual-motor rotations are applied, people adapt and de-adapt within the same session (Scheidt et al. 2000, 2005). In the real world, if someone has learned to use a particular sized bat when playing baseball and their bat breaks, then they have to adapt to a different sized/weight bat. They may make a few errors when trying to hit the ball initially, but they are quickly able to adapt to using the new bat. When the bat is replaced with one similar to the original, they only require a few extra swings to get back to their original performance.

In contrast, sensorimotor learning is the process of forming long-term and new motor patterns into well executed behaviors over the course of days to weeks to years (Schmidt and Lee 2005). These patterns change our overall behavior and are difficult to de-adapt (i.e., habits). Once we have learned a new motor skill, we have the capability to immediately create the needed motor plan or recall formed motor memories to perform that motor skill in the appropriate context. The process of motor learning is proposed to occur by various methods. One method involves continuously adapting and de-adapting a movement over a long period. For example, when a person learns to drive a manual transmission car when they already know how to drive an automatic car. The way we drive the car is the same, except for using the clutch to change the gear with the manual car. At the start, we may stall the car or get the sequencing of the clutch and brake wrong, but over time our CNS has the ability to learn and calibrate the adapted movement as its own skill (Martin et al. 1996). Another method of learning is de-novo motor learning. Here we learn to coordinate movements that we have not experienced in the past. For example, when we first learn to ride a bike, we have to coordinate our capabilities to balance the bike, steer the bike, and pedal the bike at the same time (Doyon and Benali 2005). The above methods of motor learning allow us to learn new motor skills, whether it is modifying a skill we already know or a brand-new skill.

Numerous theories and models have been proposed to conceptualize human sensorimotor learning as a process that occurs in distinct stages. Such models include Gentile's two stage model, Bernstein's seven phase model, and Fitts and Posner's three stage model. The commonality between these models is that sensorimotor learning occurs in stages and that we advance from one stage to the next via practice. Gentile's model proposes that motor learning occurs in two stages in context of the motor skill to be learned (Gentile 2000). In this model, the learner starts in the *initial stage* where the goal is to acquire a movements pattern based on the conditions of the environment where the movement is performed. The learner also has a goal of learning to discriminate between regulatory (important) and nonregulatory (irrelevant) conditions of the environment. For example, when learning to reach for a cup of water, in the initial stage the learner tries to understand the regulatory conditions (shape of the cup, amount of water in the cup, distance to the cup, etc.) and nonregulatory conditions (color of the cup, type of liquid in the cup, color of the table, etc.). As the learner practices the movements, there is progression towards the *later stages* of motor learning. During the later stages, the learner is focused on refining the movements and performing the movement efficiently. The

learner also gains the ability to adapt the movement to different regulatory and nonregulatory conditions of the environment and can perform the movement in these different conditions consistently.

Another model of motor learning is Bernstein's model which compares skill acquisition to solving a problem. In this model, learning occurs in seven *phases* (Bernstein 1996). The *first phase* consists of deciding which motor control system will be used to solve the problem. The *second* and *third phases* determine how to approach performing the skill (outside approach) and predict the relevant sensory feedback (i.e., how the skill should feel; inside approach). These first three phases are used for planning movements and require conscious effort towards understanding details of the motor skill. The *fourth phase* sees the transfer of the required conscious effort to a more subconscious process (i.e., movements starting to become automatic). The *fifth phase* is practicing this subconscious planning and performance of the motor skill. The *sixth phase* involves standardizing the automized skill such that corrections to external perturbations occur effortlessly at the level of joint reaction forces rather than with high effort as sensory corrections (inside approach) in the CNS. In the final seventh phase, the motor skill is stabilized against external disturbance such that the skill can be performed successfully under a variety of external conditions and perturbations.

In the context of this dissertation, I will focus on the Fitts and Posner model of motor learning and skill acquisition to examine motor learning of using supplemental VTF to control movements (Fitts and Posner 1967). The Fitts and Posner model is appropriate for the learned skill in this dissertation because we can infer motor learning through distinct changes in performance kinematics. In this model, motor learning and

22

skill acquisition occur in three distinct *stages*: the cognitive stage, the associative stage, and the autonomous stage. During the *cognitive stage*, the learner tries to acquire the movements for the skill, focusing on what to do and how to do it (requiring a high magnitude of cognitive resources). The learner is focused on instructions and relies heavily on external feedback of their movements (knowledge of results). In terms of behavior, during the cognitive stage we see numerous large errors in movements and movements are highly variable from one movements to the next (inconsistent movements). With practice (within minutes to hours), people are able to advance to the second stage, the *associative stage*. During this stage, the learner tries to associate specific environmental and sensory feedback cues with the movements. The learner is focused on refining movements, leading to reduced movement errors and reduced movement variability. After much practice (months to years), people advance to the third state, the autonomous stage. During this stage, the learner has achieved habituation (automaticity) of the skilled movement. They have formed enough motor memories during the transition from the associative stage that when they are required to perform the skill, they no longer have to consciously think about it. They are also able to successfully multi-task (showing reduced need for cognitive resources) and have very low variability between movement repetitions. It is possible that some people may never enter the autonomous stage, even after years of practice, if their practice is flawed. For example, someone who has been playing golf for years, yet they show no improvements in their swinging form or overall score. Their ability to play required concentration and is still cognitively demanding, where distractions will cause major mistakes. Thus, to

successfully advance through the different stages of motor learning, we must also consider the type of practice used.

The transition from one motor learning stage to the next and the rate at which this transition occurs is rather gradual. The transition between stages also depends on the individual differences between people as well as the amount and type of practice they receive. The type of practice can be selected based on skill complexity and movement organization. Skills can be practiced as a whole or in parts. Part practice is especially advantageous for learning very complex skills (Briggs and Waters 1958; Naylor and Briggs 1963) and skills that have low organization (multiple independent components). For a novice learner, a complex skill has many components and requires much attention (cognitive resources; (Magill and Anderson 2017)). Organization of a skill depends of the interconnectivity of its components (whether the components can be performed independently or needed to be performed sequentially). A skill is considered to have low organization of components are independent of each other. And conversely, skills with highly interdependent components are considered highly organized (Lee, Chamberlin, and Hodges 2001). Table 1 shows example skills classified into complexity and component organization. These example skills are classified based on the number of components in the skill and the organization of the temporal sequencing between those components. Designing the optimal practice paradigm is dependent on the complexity and temporal organization of the skill to be learned. Motor learning can be accelerated with the correct type of practice paradigm.

		Skill Organization	
		Low	High
Skill Complexity	Low	Combing hair	Walking
Skin Complexity	High	Reaching and gasping a cup	Riding a bike

Table 1: Examples of skills classified into their complexity and organization levels.

In this dissertation, I investigated the influence of practice on motor learning of skill acquisition in healthy people and stroke survivors. The skill to be acquired is using VTF to guide reaching movements, in the absence of visual feedback. I examined both short-term practice (in healthy people and stroke survivors) and long-term practice (in healthy people). Additionally, I explored the effect of changing the type of practice stroke survivors received.

F. Vibration Sensation

An important component of motor performance and motor control is sensory feedback. Even prior to executing movements, sensory information is used to create motor plans for movements. The CNS has many sensory inputs and it has to decide what inputs are important for interactions with our environment. Interacting with objects in our environment provides tactile sensory feedback. Tactile sensory feedback provides information regarding touch, force, vibration, pressure, and skin stretch.

Human skin has four main types of mechanoreceptors that detect tactile sensations: Merkel's disk, Meissner's Corpuscles (MCs), Ruffini endings, and Pacinian Corpuscles (PCs) (Burgess 1973; Hunt 1974; Johansson and Vallbo 1979). Merkel's disk sense touch and pressure, Ruffini endings detect skin stretch, and vibration is sensed by MCs and PCs (Bolanowski et al. 1988; Burgess 1973; Purves 2012). These mechanoreceptors are specialized neuronal endings that connect the PNS to the CNS. Tactile stimuli are sensed at the level of the mechanoreceptors and perceived at the level of the CNS. The receptors deliver sensory information to CNS via connections through the dorsal root ganglia (DRG) near the spinal cord. From the DRG, this information travels through the spinothalamic tract through the brainstem to the thalamus. The thalamus forwards this information to the appropriate location in the somatosensory cortex area. The somatosensory cortex is has moderate somatotropic organization, thus sensory information in the lower extremity is sent to the medial cortex regions whereas the upper extremity, hand, and face sent to the lateral cortex regions. This sensory information is also forwarded to the cerebellum via direct sensory inputs from the spinocerebellar tract or via the cortico-ponto-cerebellar pathway from the sensorimotor cortices.

The sensation of vibrations relies heavily on the density and distribution of MCs and PCs across skin. MCs are only found in glabrous skin (the hand or foot), whereas PCs are found in both glabrous and hairy skin (e.g., the arm, torso). The density, distribution, and receptive fields (area in which the receptor senses) of mechanoreceptors decreases as we move more proximal to the torso. This evolutionary design allows us to detect fine textures and changes in objects with which we interact. Thus, the fingers, which require the ability to detect fine detail, have many, densely-packed mechanoreceptors with small receptive fields), while the back, for example, has fewer receptors with large receptive fields. The perception of tactile stimuli in the CNS is dependent upon the size of the receptive field and the size of the brain territory allotted to the region of skin. In the somatosensory area the hands, feet, and face have large numbers of neurons and small receptive fields; as indicated above, perception of sensory feedback in these areas is precise and accurate. Conversely, the torso, neck, and back have smaller allotted brain regions and larger receptive fields; thus perception is poorer and diffuse (Eickhoff et al. 2007; Mancini et al. 2014; Penfield and Boldrey 1937; Purves 2012; Woolsey, Marshall, and Bard 1943).

Additionally, viscoelasticity properties of skin may also influence how vibrations might be sensed and perceived (Silver, Freeman, and DeVore 2001). If vibrations propagate on the skin, a vibration delivered to one location can excite the receptor fields of multiple mechanoreceptors, therefore altering sensation and perception (Jones and Held 2008; Sofia and Jones 2013). So, in our design of multi-channel VTF BMIs we should consider the location where VTF is delivered, mechanoreceptors targeted by VTF, and the effects of spatial-temporal characteristics of vibration (i.e., where and how vibrations are delivered) on VTF perception.

As glabrous skin of the hand and feet is the most densely rich in MCs and PCs, it would seem to be a good choice to deliver VTF. However, this would leave the hand hindered from interacting with the environment as it normally would (e.g., grasping objects, identifying textures, etc.). The torso would also seem to be a good choice for delivering VTF. However, the density of PCs in the torso is low and the receptive fields are large, reducing the amount of information that may be successfully sensed by PCs. Therefore, the arm has been used as a site to deliver VTF in numerous previous studies. These studies range from using VTF to improve grasp for prosthetic hand users to using VTF to guide arm movements (Bark et al. 2015; Cuppone et al. 2016; Kapur et al. 2010; Krueger et al. 2017; Risi et al. 2019; Stepp and Matsuoka 2012). To design VTF BMIs to be intuitive and easy to use, we must consider how and where VTF delivered, how it is
sensed, and how it is perceived. Successful use of VTF requires the user to sense vibration, decode the information it contains, and produce and assess a task-appropriate response (Haggerty et al. 2012).

In this dissertation, I investigated the interaction between multiple vibrotactile stimuli delivered on the arm to determine how vibrations propagate across the skin of the arm. I also determined how healthy people discriminate between two vibrotactile stimuli applied to various location on the arm. The results of these investigations were used to design the VTF BMI used in the investigations of VTF-guided reaching in this dissertation.

III. VIBRATION PROPAGATION ON THE SKIN OF THE ARM

Vibration sensation and perception is dependent on the site where vibration is applied. Perception of vibration is influenced by the type of mechanoreceptors that are stimulated, the number of mechanoreceptors stimulated, and the receptive fields that are activated by the vibration. To design a vibrotactile feedback body-machine interface (VTF BMI) that uses the arm as the stimulation site, we need to consider how vibration propagates on the skin of the arm and characterize the optimal distance between stimulation sites for a multi-channel VTF interface. This chapter has been published as a manuscript in *Applied Sciences* (Shah et al. 2019b).

A. Introduction

Four types of tactile mechanoreceptors mediate most of the sensation in human skin: Merkel's disks, Meissner's Corpuscles (MCs), Pacinian Corpuscles (PCs), and Ruffini endings (Burgess 1973; Hunt 1974; Johansson and Vallbo 1979). These mechanoreceptors allow for various haptic sensations such as touch and pressure by Merkel's disks, skin stretch by Ruffini endings, and vibration by Meissner's and Pacinian Corpuscles (Bolanowski et al. 1988; Burgess 1973; Purves 2012). Haptic perception (touch and vibration) has been studied widely, leading to development of body-machine interfaces (BMIs; (Casadio et al. 2012; Kaczmarek et al. 1991; Shull and Damian 2015)) that can stimulate the skin electrically (Kaczmarek et al. 1991), pneumatically (Sonar and Paik 2016), or tactilely to provide performance feedback to users (Jones and Sarter 2008; Shull and Damian 2015; White et al. 1970).

Tactile interfaces are by far the most popular, as they are relatively inexpensive to construct, non-invasive, and can be implemented at various locations on the body where

skin sensation remains intact. Tactile stimulation can be implemented using vibrating elements (An et al. 2011; Ariza et al. 2017; Cincotti et al. 2007; Cipriani, D'Alonzo, and Carrozza 2012; Krueger et al. 2017; Oakley et al. 2006; Weber et al. 2011), pressure (Caldwell, Tsagarakis, and Giesler 1999; Casini et al. 2015), or skin stretch (Bark et al. 2009; Hayward and Cruz-hernández 2000; Schorr et al. 2013). Interfaces that use vibrotactile stimulations target Meissner's Corpuscles by delivering low frequency stimulations (5-60 Hz) or Pacinian Corpuscles with higher frequency stimulations (60-400 Hz) (Hunt 1974; Mountcastle, LaMotte, and Carli 1972; Purves 2012; Ribot-Ciscar, Vedel, and Roll 1989). With this wide bandwidth of stimulation frequencies available, vibrotactile interfaces can provide a large range of performance feedback information to the user. Our long-term goal is to advance the development of inexpensive and noninvasive BMIs that use vibrotactile interfaces attached to the arm to provide performance feedback to users. Many of these interfaces rely on a multi-channel set up that often use the 2-point touch discrimination threshold (2-TDT) to determine the distance between two stimulation sites. However, this distance may not correctly represent the physical space needed between two vibrotactile stimuli because touch and vibration activate different mechanoreceptors (i.e., Merkel's disks and MCs/PCs, respectively).

The 2-point distance for vibrotactile stimuli applied to the hand and fingers has been previously investigated (Perez, Holzmann, and Jaeschke 2000; Tannan, Whitsel, and Tommerdahl 2006). Perez et al. found that the 2-point distance on the fingertip for high frequency stimulations (500 Hz, using piezoceramic vibrating pegs) was more than twofold higher at 0.5 cm than the 2-point distance for low frequency stimulations (25 Hz) at 0.2 cm. Tannan et al. found that at low frequency stimulations (25 Hz, using a single probe tip) 2-point distance for the hand dorsum was approximately 0.5 cm. Comparing the two studies, one can see that the 2-point distance changes with body location and vibration frequency. However, results of those studies are difficult to generalize to the skin of the forearm due to differences in mechanoreceptor densities between the glabrous skin of the hand and the hairy skin of the arm (Johansson and Vallbo 1979).

Cipriani et al. used rotating mass vibration motors to investigate the perception of relatively high frequency vibrotactile stimuli (122-156 Hz) on the volar forearm using three motors spaced 3 cm apart (Cipriani et al. 2012). Cipriani et al. found that errors in spatial discrimination of vibrotactile stimuli were greater when stimuli were delivered by two motors spaced 3 cm apart compared to motors spaced 6 cm apart. Cholewiak & Collins (2003) used inter-motor distances of 2.5 cm on the arm and found vibration localization accuracy as low as 46% (i.e. people were inaccurate in localizing vibration stimuli when the inter-stimulus distance was small). Cholewiak & Collins reported that the localization accuracy increased to 86% when the inter-stimulus site distance was increased to 5 cm. They concluded that interactions between the mechanical and physiological properties of the skin produced interference in vibrotactile localization. It is possible that mechanical propagation of vibration stimuli along the skin can negatively impact vibration perception as mechanoreceptors in the skin adjacent to the site of the vibration may also respond to the stimulus. Thus, space between vibration sites must be increased to reduce interference in vibration perception caused by propagation of vibration stimuli on the skin.

To understand propagation of vibration, Sofia & Jones (2013) measured surface wave propagation of vibrotactile stimuli on the volar forearm using rotating mass motors at ~100 Hz. These vibrotactile stimuli showed propagation of vibration to a distance of about 2.5 cm from the source of the vibration. If there is interference between two vibration stimuli due to mechanical propagation on the surface of the skin, then the perception of these vibration stimuli will be inaccurate (cf., Cipriani et al. (2012), Oakley et al. (2006), and Cholewiak & Collins (2003)). However, Sofia & Jones (2013) only studied vibration propagation at a vibration frequency of approximately 100 Hz, so how vibration propagates on the skin of the arm during higher frequency vibrations (>100 Hz) remains to be further investigated.

In this exploratory study, we sought to characterize the propagation of vibrotactile stimuli at multiple intensities delivered to the forearm (i.e., between 100-240 Hz). We classified vibration propagation by measuring acceleration across the skin of the arm at various distances from a source vibration of varying intensities. We analyzed changes in acceleration to determine the extent and frequency-dependence of propagation across the human arm. We expect the results will enhance the development of inexpensive BMIs and improve the perception of vibrotactile stimuli in multi-channel, high intensity vibrotactile feedback systems such as those utilized for hand position feedback for survivors of stroke (Krueger et al. 2017), grip force feedback for upper extremity amputees (An et al. 2011), or to reduce visual attention in people with spinal cord injury (Cincotti et al. 2007).

B. Materials and Methods

1. Participants

Six healthy participants (4 females) ranging in age from 19-62 years volunteered to participate in this study. Participants with no known cognitive or sensorimotor deficits

of the arm were recruited from the Marquette University community. All participants provided written informed consent to the experimental procedures, which were approved by a local Institutional Review Board in accord with the 1964 Declaration of Helsinki.

2. General Setup

Each participant completed a single experimental session lasting approximately 30 minutes. Participants were seated in an armchair with the right hand and arm relaxed on a table, supported by 1-inch thick foam pads. The arm was oriented to have 60 degrees of flexion at the elbow, 15 degrees of shoulder flexion, 0 degrees of shoulder ab/adduction, and the forearm was supinated. Several anthropometric variables (Table 2) were measured: arm circumference (Fig 3A: at each marker in dermatome C7 in), forearm length (from the lateral epicondyle of the humerus to the radial styloid process while the arm is supinated), and 2-point discrimination distances at the source vibration (Fig 3A: red marker). One 10 mm eccentric rotating mass (ERM) motor was used to deliver vibration stimuli (Precision Microdrives Ltd, Model # 310-117). These motors have an operational frequency range of approximately 60-250 Hz, coupled to an amplitude range of 0.5-2.4 G. For simplicity, we will refer to vibration intensity throughout this document in terms of frequency because the frequency and amplitude of vibration covary for these ERM motors.

The vibration motor was powered and controlled using custom drive circuitry that was interfaced to a portable laptop computer running a custom script within MATLAB R2017a computing environment (MathWorks Inc). Input voltage to the motor was provided through a Pulse Width Modulation signal. Vibration propagation was measured using an InvenSense MPU-6050 3-axis accelerometer with 16-bit resolution, a full-scale



Anterior Schematic View

Equipment

Figure 3: A) Anterior view of the arm. *Red marker* indicates the source vibration. *Gray markers* indicate the locations of acceleration measurements. Example distances from the source are shown as 4 cm in dermatome C7 and 8 cm in T1. B) Equipment. A 10mm vibration motor next to the MPU-6050 accelerometer mounted on a breakout board.

Table 2: Subject Demographics showing age, height, weight, arm length and arm circumferences along the arm.

Subject	Age (yrs)	Height (cm)	Weight (kg)	Sex	Arm length (cm)		2-TDT @ Source				
						Source	@ 4cm	@ 8cm	@ 12cm	@ 16cm	(cm)
1	21	178	83.9	m	26.70	27.90	27.90	26.60	24.10	20.30	3.50
2	18	185	70.3	m	27.90	26.70	26.00	26.00	23.20	19.40	3.75
3	31	157	68.0	f	21.60	25.40	25.40	24.10	20.30	17.80	3.50
4	42	157	52.2	f	22.90	22.20	22.20	21.00	17.80	15.60	2.50
5	23	164	45.5	f	24.40	19.90	18.60	17.30	15.20	13.60	4.50
6	62	157	72.6	f	21.60	25.10	24.80	21.00	17.80	15.90	3.75
Ave	32.83	166.33	65.42	-	24.18	24.53	24.15	22.67	19.73	17.10	3.58
SD	16.70	12.26	14.11	-	2.65	2.97	3.29	3.55	3.45	2.53	0.65

range set to \pm 2 G, a sampling rate of 1 kHz, and a digital lowpass filter implementing a lowpass cutoff frequency of 260 Hz. The accelerometer was interfaced with the laptop computer using I2C communication protocol.

3. Vibration Propagation Measurement

An ERM vibration motor was attached to the arm on dermatome C7 via "Transpore" medical tape (3M Inc). The motor was placed approximately 4 cm distal from the later epicondyle of the humerus. The accelerometer was similarly attached to the arm, with the Z-axis perpendicular to the arm and the Y-axis oriented along the lateral forearm. Measurements of vibration propagation were recorded at 7 different locations: at distances of 4, 8, 12, and 16 cm from the vibration motor along the lateral forearm (within dermatome C7); at 8 and 16 cm from the vibration motor along the medial forearm (dermatome T1); and on the ulnar head (UH, dermatome C8). Figure 3 shows the placement of the vibration motor (Fig 3A: red marker) and the locations where acceleration measurements were taken (Fig 3A: gray markers).

4. Vibration Stimuli

A total of 12 vibration intensities were tested at each location, with drive voltages ranging from 0.98 V (~100 Hz) up to 3.35 V (~240 Hz). Table 3 shows vibration characteristics for the 12 vibrotactile stimuli. The 12 vibration intensities were delivered consecutively to the same location, starting from the lowest intensity and ending with the highest intensity. Each vibration intensity was delivered to the testing location for 1000 ms and the interval between each vibration intensity was 1000 ms. An initial motor drive pulse of 5 ms at 5 V was used to overcome inertial effects of the ERM motor.

5. Data Analysis

Measured accelerations along the X, Y, and Z axes of the accelerometer were used to compute the total acceleration (i.e., the Euclidean norm; Equation 1):

[Eq 1]
$$a = \sqrt{(a_x^2 + a_y^2 + a_z^2)}$$

We compensated for gravity and variations in accelerometer orientation at each of the different measurement locations by subtracting the acceleration value recorded with the motor turned off. Gravity-adjusted acceleration values reported in the results section were

computed from the last 400 ms of stimulation (i.e., well after steady state vibration was reached).

Bit Value (Bits)	50	60	70	80	90	100	110	120	130	140	150	160
Duty Cycle (%)	19.7	23.6	27.6	31.5	35.4	39.4	43.3	47.2	51.2	55.1	59.1	63.0
Input (V)	0.98	1.18	1.37	1.57	1.77	1.96	2.16	2.36	2.55	2.75	2.95	3.15
Freq (Hz)	102.3	121.7	139.7	156.3	171.6	185.6	198.2	209.5	219.4	228.0	235.3	241.2
Amp (G)	0.45	0.65	0.85	1.05	1.20	1.40	1.55	1.75	1.90	2.15	2.25	2.35

Table 3: Vibration parameters as related input voltage. Frequency and Amplitude are reported from manufacturer specification sheet.

6. Statistical Testing

To characterize vibration propagation and the extent to which it attenuates with distance from the source, we used Bonferroni-corrected, one-tailed t-test to compare the acceleration at each measurement location to 0 G. We also used Bonferroni-corrected, one-tailed t-test to compare the acceleration at each measurement location to the vibrotactile intensity discrimination threshold defined in previously published work (see Chapter IV; (Shah et al. 2019a)); this analysis sought to infer the extent to which the propagation of vibratory stimuli could alter vibrotactile perception at each measurement distance. Finally, we used Pearson's correlation coefficient to determine the extent to which changes in the measured acceleration depend on participant anthropometrics, distance from the source vibration, and source vibration intensity. All analyses were

performed with SPSS Statistics 24 (IBM Corp). Statistical significance was set at a family-wise error rate of $\alpha = 0.05$.

C. Results

This study used an ERM vibration motor and accelerometers to quantify vibration propagation along the human arm. Acceleration on the arm of each participant was recorded during 12 different intensities of vibrotactile stimuli, at 7 different measurement locations. As expected, measured accelerations increased as vibration intensity increased, and they consistently decreased as distance from the source increased. Figure 4 shows the measured acceleration values at the 7 measurement locations for each tested vibration intensity.

1. Measured Acceleration as a Function of Source Intensity and Distance

At a distance of 4 cm from the source in dermatome C7, acceleration decreased by 73.3% on average at a vibration intensity of ~100 Hz and by 83.8% at ~240 Hz. At a distance of 8 cm in dermatome C7, acceleration decreased by 86.7% on average compared to the source at ~100 Hz, and by 96.2% at ~240 Hz. At distances of 12 cm and 16 cm in dermatome C7, acceleration at all tested vibration intensities decreased to ~0 G (i.e., less than the bit resolution of the accelerometer: 6.1×10^{-5} G). In dermatome T1, acceleration was also negligible across all vibration frequencies at a distance of 8 cm (a maximum 0.02 G at >230 Hz, a reduction of 99.2%) and decreased to 0 G at 16 cm for all vibration intensities. At the UH (i.e., a distance exceeding 18 cm from the source vibration in all participants), acceleration decreased to 0 G at all tested vibration intensities.



Figure 4: Mean acceleration (across participants) at different distances from a source vibration, at various frequencies. The *black dashed horizontal line* shows the amplitude value of the vibrotactile intensity discrimination threshold for dermatome C7. The *gray vertical bar* marks the highest intensity vibration (241 Hz) acceleration values. Error bars show SEM.

Compared to the ideal "no-propagation" value of 0 G, Bonferroni-corrected, onetailed t-test revealed significant differences between the measured accelerations at all vibration intensities for measurement distances of 4 and 8 cm in dermatome C7 and 8 cm in dermatome T1 ($p_{corrected} < 0.05$ in each case). There were no significant differences at 12 and 16 cm in dermatome C7, at 16 cm in dermatome T1, and at the UH ($p_{corrected} >$ 0.05 in each case). To determine the extent to which the vibration propagation might interfere with vibration perception, we compared accelerations measured at each location to the amplitude of the vibrotactile intensity discrimination threshold in either dermatome C7 (~0.35 G), dermatome T1 (~0.50G), or the UH (~0.40 G), respectively (derived from Shah et al. (2019a)). In dermatome C7, the measured acceleration at 4 cm was not significantly lower than 0.35 G for intensities greater than 156 Hz ($p_{corrected} > 0.05$).

This result was not a statistical artifact because the tests still showed nonsignificant differences for frequencies greater than 210 Hz when Bonferroni correction was removed. Measured accelerations were significantly lower than the C7 discrimination threshold at all vibration intensities at distances of 8, 12, and 16 cm ($p_{corrected} < 0.05$ in all cases). Measured accelerations were also lower than their respective discrimination thresholds at 8 and 16 cm in dermatome T1 and at the UH ($p_{corrected} < 0.05$ in all cases).

2. Acceleration Correlates with Distance

We regressed the acceleration data measured in dermatome C7 onto distance from the source vibration and found a negative correlation (r = 0.943, p < 0.05; Fig 5: gray shading). As the distance from the source increased, the measured acceleration decreased. By contrast, we found no correlation between measured acceleration and participant arm circumference, weight, or gender (p > 0.05 in all cases). Participant anthropometrics showed no influence on vibration propagation. Figure 5 shows the percent residual acceleration across the four measurement distances in dermatome C7 (i.e., the relative amount of acceleration that remains after accounting for the magnitude of the source vibration). We found that a decaying exponential function reasonably describes the change in acceleration y as a function of measurement distance x, shown in Equation 2:

[Eq 2]
$$y = a * e^{(-b*x)}$$

where *a* and *b* are constant scaling and rate coefficients, respectively. Across the 12 stimulus intensities, the average goodness of fit was high $[R^2 = 0.927 \pm 0.051 \text{ (mean } \pm$

SD); $a = 87.66 \pm 9.97$; $b = 0.360 \pm 0.041$]. The standard error of the non-linear model estimate was 1.29% at 4 cm, 0.84% at 8 cm, 0.45% at 12 cm, and 0.12% at 16 cm (i.e., Fig 4: gray shading).



Figure 5: Percentage of acceleration remaining decreases as distance from the source vibration increases. Data points represent remaining acceleration at the stimulation intensity. *Red line* indicates the non-linear fitted exponential curve, averaged cross the 12 vibration intensities. *Gray shaded region* indicates the SEM of the fit.

Finally, we regressed the percent residual acceleration at 4 cm and 8 cm onto source vibration intensity and found a significant correlation at both locations (4 cm: r = 0.911, p < 0.05; 8 cm: r = 0.991, p < 0.05). Because the relative amount of vibration

varies as a function of source intensity at 4 and 8 cm – even after normalizing (dividing) by the source intensity these results show that vibration propagation varies as a function of the source's frequency, and not just its magnitude.

D. Discussion

This study investigated the propagation of vibration within and across dermatomes on the hairy skin of the human arm. We measured acceleration on the surface of the arm at various distances from a source vibration, which applied stimuli of varying intensities. Whereas the measured acceleration was highly correlated to the distance between the source and measurement locations, measured accelerations did not covary with participant anthropometrics. Additionally, propagated vibrations were significantly attenuated by more than 95% at distances greater than 8 cm, both within and across dermatomes. At 4 cm and 8 cm testing locations in dermatome C7, the percentage of residual acceleration varied as a function of source stimulus intensity (frequency) even after accounting for differences in source vibration magnitude. Residual vibrations were lower than the amplitude of the vibrotactile intensity discrimination thresholds (Shah et al. 2019a) at each recording location greater than or equal to 8 cm from the source.

Our results confirm and extend the results of Jones & Held (2008) who measured vibration propagation on simulated skin (viscoelastic materials with properties similar to pig skin) and found that vibration stimuli were highly attenuated by 6 cm from the source and were reduced close to 0 m/s^2 at 8 cm (see their Fig 10; (Jones and Held 2008)). As we discuss below, our findings have important implications for the design of vibrotactile interfaces intended to convey multiple channels of information for use in bidirectional

body-machine interfaces (cf., An et al. (2011), Cincotti et al. (2007), Kreuger et al. (2017)).

1. Mechanisms of Perceptual Interference Between Stimulation Sites

Mechanical interference between two closely-space vibratory stimuli can negatively impact vibrotactile perception due to superposition (i.e., two vibration intensities can sum together via constructive or destructive interference to create higher or lower intensity vibrations, respectively).

Oakley et al. (2006) showed that during a discrimination task, vibration intensity can be perceived higher when three vibration motors provide synchronized (in-phase) stimulation in a small area, compared to when a single vibrating motor was activated at a similar frequency. It is also possible that multiple vibrating motors can produce destructive interference, wherein vibration amplitude is attenuated. This can result in lower perceived vibrotactile intensity (Cipriani et al. 2012). Based on the results of the current study, the confounding effects of mechanical interference can be mitigated by providing sufficient distance between two simultaneously activated sources. An interstimulus distance of 8 cm suffices to reduce mechanical interference to levels far below vibrotactile intensity discrimination thresholds previously reported in the literature (Shah et al. 2019a).

Physiological considerations such as the density and distribution of the different types of mechanoreceptive afferents found in skin also influence perception (cf., Johnson (2001), Muniak et al. (2007)). In a non-human primate study, Manfredi et al. (2012) investigated surface wave propagation of high frequency vibration (50-1000 Hz) on the glabrous skin of the primate digit. The investigators found that vibration propagated as far as 6.4 cm away from the source, and that the propagation also varied with vibration frequency. In that same study, the investigators modelled the response of Pacinian Corpuscles to vibratory stimuli and found that the estimated response (i.e., the number of recruited/activated mechanoreceptors) was almost two-fold larger for a 200 Hz stimulus than for a 20 Hz stimulus. Thus, the somatosensory response to vibrotactile stimuli is location- and frequency-dependent. A comparison of measured accelerations at ~100 Hz vs ~240 Hz at a distance of 4 cm in our study supports the idea that lower-intensity vibrations likely activate a lower number of mechanoreceptors because the vibration does not propagate as far as for higher-intensity vibrations (Fig 4). Our finding of significant correlations between source vibration intensity and percent residual acceleration at 4 and 8 cm confirms and extends the findings of Manfredi et al., who showed that vibration propagation depends on the vibration frequency.

2. Implications for Design of Vibrotactile Interfaces

Vibrotactile interfaces designed for BMIs often rely on a multi-channel set up, wherein multiple skin sites are stimulated with various frequencies of vibration, with each site encoding stimuli with different meanings (Ariza et al. 2017; Ferris and Sarter 2011; Lieberman and Breazeal 2007; Wang, Zhang, and Luo 2018). Some vibrotactile interfaces use the 2-point touch discrimination threshold (2-TDT) to determine the minimum inter-stimulus distance between two stimuli (Cholewiak and Collins 2003; Cipriani et al. 2012; Piateski and Jones 2005). The 2-TDT is defined as the distance needed to confidently distinguish between two simultaneous touch stimuli applied to the skin. For dermatomal regions of the arm and forearm, mean 2-TDT values range from 3.1 cm to 4.5 cm (Nolan 1982). However, the 2-TDT may not accurately represent the distance needed to distinguish between two simultaneous vibrotactile stimuli because different mechanoreceptors are involved in the perception of touch vs. vibratory stimuli (i.e., Merkel's disks for touch perception vs MCs/PCs for vibration perception; cf., Johnson (2001) and Cashin and McAuely (2017)). As shown in the current Figure 4, we observed mechanical propagation of vibrotactile stimuli across the hairy skin of the arm at distances up to approximately 8 cm. For high-intensity source stimuli, propagated vibrations could be expected to confound perceptual discrimination within a second stimulation channel applied 4 cm from the source. With an inter-site distance of 8 cm however, the magnitude of propagated vibration is just a small fraction of the vibrotactile discrimination threshold. Thus, vibrotactile interfaces that employ low-cost ERM vibrating motors can avoid potential perceptual errors caused by propagation of high intensity vibration stimuli if they ensure a minimum distance of 8 cm between two stimulation sources.

We have employed this kind of low-cost vibrotactile interface to mitigate proprioceptive deficits observed in stroke survivors. We attached a multi-channel feedback interface to the less affected arm, with inter-stimulus distances greater than 8 cm. The interface provided hand position feedback of the more affected arm to the nonmoving, less-affected arm (Krueger et al. 2017; Risi et al. 2019; Shah et al. 2018). While the system proved to be effective in improving the accuracy of simple, single-degree-offreedom movements (Tzorakoleftherakis et al. 2015), future work is focused on determining efficacy on multi-degree-of-freedom movements. Note that our system builds upon previous designs, which have utilized vibrotactile feedback to provide grip force feedback for upper extremity amputees (Witteveen, Rietman, and Veltink 2015) and to reduce visual attention needed to make movements in people with spinal cord injury (Cincotti et al. 2007). These vibrotactile interfaces could also be applied to other locations of the body if the tactile sense of the arm is affected by disease or injury. Therefore, future studies should look to investigate vibration propagation on skin of other body regions such as the chest, back, and legs.

3. Limitations

A limitation of our study derives from our use of inexpensive, off-the-shelf ERM vibration motors that have an operational bandwidth of 60-250 Hz. This bandwidth is smaller than the bandwidth of vibration perception for hairy skin, which ranges from 5-400 Hz (Hunt 1974; Mountcastle et al. 1972; Purves 2012; Ribot-Ciscar et al. 1989). Thus, we did not assess vibration propagation over the full range of frequencies perceptible by humans. Future studies should look to identify inexpensive vibration motors that have a larger operational bandwidth, thereby investigating propagation also at higher frequencies (e.g., between 250-400 Hz).

E. Conclusions

In this study, we measured the propagation of 100-240 Hz vibratory stimuli across the hairy skin of the human forearm. Propagation was well modeled as a decaying exponential function of distance from the source. At a distance of 8 cm, the magnitude of propagated vibration was reduced by at least 95% relative to the source at all tested frequencies and the intensity of propagated vibration was significantly lower than the vibrotactile discrimination threshold for each dermatome spanning the arm and hand. Additionally, vibration propagation was proportional to the source intensity at both 4 cm and 8 cm. From these results, we conclude that future BMIs that utilize vibrotactile interfaces should maintain a minimum of 8 cm separation between vibrotactile stimulation sites to avoid potential misperception of simultaneously applied stimuli.

IV. DISCRIMINATION OF VIBROTACTILE STIMULI ON THE ARM

In the previous chapter, I characterized propagation of vibration on the arm at various distances from a source vibration. When designing a multi-channel vibrotactile feedback body-machine interface (VTF BMI), we also need to consider people's capability to discriminate between two vibrotactile stimuli of different intensities. Perception of vibrotactile stimuli depends on where it is delivered, but also based on the temporal sequencing between stimuli. In this chapter, I investigated healthy people's capability to discriminate between two vibrotactile stimuli applied to various dermatomes of the arm, using the optimal distance between stimuli from the results of the previous chapter. This chapter has been published as a manuscript in *Experimental Brain Research* (Shah et al. 2019a).

A. Introduction

Even the simplest of actions – such as reaching out toward a coffee mug – typically require the central nervous system (CNS) to integrate information from multiple sensory modalities for planning and executing the motor commands required to accomplish the task (see Scott (2004)). In healthy individuals, vision (to locate the desired object relative to the hand) and intrinsic proprioception (to sense body configuration and movement) play key roles in these processes (Sober and Sabes 2003). Unfortunately, diseases such as Parkinson's Disease (Vaugoyeau et al. 2007), multiple sclerosis (Gandolfi et al. 2015), and neuromotor injury (e.g., spinal cord injury (Crewe and Krause 2009), stroke (Dukelow et al. 2010)) can interrupt sensory feedback pathways that normally contribute to the accuracy and coordination of movements (see Sainburg et al. (1995, 1993)). Recent efforts in the development of noninvasive body-machineinterfaces (BMIs) have sought to mitigate sensorimotor impairments due to disease and injury by using technology to compensate for the sensory and/or motor deficits (Mussa-Ivaldi and Miller 2003).

Various approaches to the development of sensory BMIs have included auditory, haptic, and electro-stimulation (Casadio et al. 2012; Mussa-Ivaldi and Miller 2003). Vibrotactile feedback is an inexpensive and noninvasive way of conveying supplemental information to a user without taxing visual or auditory attention. Common forms of vibrotactile cues include continuous state feedback (Ferris and Sarter 2011; Krueger et al. 2017; Risi et al. 2019), continuous error feedback relative to some goal (Cuppone et al. 2016; Tzorakoleftherakis et al. 2016; Wall et al. 2001), and indicators of undesirable conditions (i.e., alarms; (Ferris and Sarter 2011)). In each of these cases, the vibrotactile cues should be designed so that the encoded information is clearly perceptible. Moreover, the amount of information that can be encoded by vibrotactile stimuli will depend on the user's abilities to discriminate between different levels of stimulus intensity.

Vibrotactile perception has been studied widely and has advanced development of technologies for the presentation of vibrotactile stimuli (e.g., (Cholewiak 1999; Cholewiak and Collins 2003; Harris et al. 2006; Tannan, Dennis, et al. 2007; Tannan, Simons, et al. 2007; Verrillo 1985; Wentink et al. 2011)). Perception of vibrotactile stimuli depends on the location of stimulation, inter-stimulus timing, and cognitive ability of the user (Cholewiak 1999; Cholewiak and Collins 2003). Many of these prior studies have focused on the hand and digits as targets of stimulation (Harris et al. 2006; Morley and Rowe 1990; Post, Zompa, and Chapman 1994; Tannan, Dennis, et al. 2007; Verrillo 1985) because these locations have the highest density of tactile mechanoreceptors

(Burgess 1973; Hunt 1974). Because the hand and digits are regularly used for dexterous interaction with the environment, the arm may be a more appropriate site to apply vibrotactile cues. Few investigations have examined perception and discrimination of vibrotactile stimuli applied to the arm, especially for locations other than the volar forearm.

Our study builds upon prior studies of vibrotactile perception. Mahns et al. (2006) compared vibrotactile frequency discrimination in glabrous versus hairy skin. The discrimination threshold (quantification of discriminability) is defined as the just noticeable difference (JND) between two stimuli. Mahns et al. reported different discrimination thresholds between the glabrous skin of the fingertip (27.2 Hz) and the hairy skin of the forearm (33.9 Hz), for vibrotactile stimuli frequencies near 200 Hz. Other studies of vibrotactile perception have examined the volar forearm (Cholewiak and Collins 2003; Lamoré and Keemink 1988; Mahns et al. 2006; Morioka, Whitehouse, and Griffin 2008; Post et al. 1994), but other locations on the arm have rarely been studied (e.g., medial forearm, dorsal forearm, upper arm). Furthermore, it is difficult to generalize vibration perception of the hand and digits to that of the arm because the extent to which mechanoreceptor densities differ across the dermatomes of the arm is yet unknown.

Dermatomal representation within primary somatosensory cortex (S1) may also influence our ability to discriminate tactile stimuli. Non-human primate studies have shown that afferent signals from the different dermatomes of the body are projected onto S1 in a way that preserves the arrangement of the spinal segments (Werner and Whitsel 1968; Woolsey et al. 1943). Woolsey et al. found that cervical dermatomes C2-C8, which span the upper extremity and neck, are projected to large and overlapping areas of S1. By contrast, thoracic dermatomes T1-T12 are mapped onto a single, smaller area. Moreover, there is minimal overlap between the projections of cervical and thoracic dermatomes. This projection pattern may be similar to that in humans (Eickhoff et al. 2007; Penfield and Boldrey 1937). Consistent with this notion, human neuroimaging results show that the proximity of tactile stimulation, both in terms of body part (dermatomal proximity; hemispheric) and in time (i.e., whether the stimuli are presented simultaneously or sequentially), induces different levels of interaction between somatosensory evoked responses in primary and secondary (S2) somatosensory cortices (Hoechstetter et al. 2001). It is therefore possible that systematic variations in neural responses to tactile stimuli separated in space (Duncan and Boynton 2007) and time (Hoechstetter et al. 2001) may influence our ability to discriminate vibrotactile stimuli applied to different dermatomes in the arm and hand. In the present study, we sought to test this hypothesis by quantifying the ability of human subjects to discriminate pairs of vibrotactile stimuli of differing intensities when applied simultaneously and sequentially to various locations on the arm.

Perceptual decision making involves several central processes (including memory and attention) that contribute to the comparison of sensory stimuli (Heekeren, Marrett, and Ungerleider 2008). Discriminating between two sequential stimuli requires a neural representation of the first stimulus to be stored in working memory, which can later be accessed to compare against a second stimulus (Romo et al. 2002). Stimuli stored as neural responses are subject to noise and fading (forgetting), both of which can degrade the response and lead to worse discriminability (cf., Bernasconi et al. (2011) and Harris et al. (2002)). Focusing attention towards a sensory stimulus allows for less neuronal response variability (Mitchell, Sundberg, and Reynolds 2007). For accurate perception in the case of simultaneous stimuli, attentional resources must be divided between the two stimuli (Connell and Lynott 2012). Dividing attention across multiple sensory inputs increases neuronal variability (Mitchell et al. 2007) and introduces information leakage (from unimportant sensory stimuli) that can bias the decision-making process (Wyart, Myers, and Summerfield 2015). Thus, discrimination of two vibrotactile stimuli presented in different locations is influenced not only by the stimulation sites, but also by the relative timing of the stimuli (i.e., whether they are delivered sequentially or simultaneously).

In this study, we sought to describe how spatial and temporal features of vibrotactile stimuli influence their perception. Using an experimental setup wherein the amplitude and frequency of vibration covary, we performed a series of two-alternative forced-choice experiments that quantified discrimination of sequential and simultaneous vibrotactile stimulus intensities within and across dermatomes of the arm and hand. The experiments were designed to test two hypotheses. First, based on differences in mechanoreceptor density and cortical representation across dermatomes, we hypothesized that the acuity of vibration intensity discrimination differs across dermatomes of the arm. Second, based on the contributions of attention and working memory on perceptual decision making, we hypothesized that discrimination of vibrotactile stimuli is additionally influenced by inter-stimulus timing (i.e., sequential vs. simultaneous presentation). We analyzed the JNDs of vibrotactile stimulus intensities to determine the effects of stimulus location and inter-stimulus timing on the perception of vibrotactile

stimuli. We expect our results will enhance the utility of vibrotactile feedback in applications such as grip force feedback in the control of prosthetic hands (An et al. 2011), kinesthetic feedback for limb movement control in survivors of stroke (Krueger et al. 2017), and offloading of visual attention in spinal cord injury patients learning a brainmachine interface (Cincotti et al. 2007).

B. Material and Methods

1. *Participants*

Thirty neurologically intact participants (14 females; 16 males) with no known cognitive deficits or tactile deficits of the arm were recruited from the Marquette University community. Participants ranged in age from 19 to 29 years (22.9 ± 2.05 yrs, mean \pm SD; there was no significant age difference between the male and female subsets). Participants gave written, informed consent to participate in one of two experiments. All experimental procedures were approved by Marquette University's Institutional Review Board in full accordance with the Declaration of Helsinki.

2. *General Experimental Setup*

Participants were seated with their dominant arm (self-reported) supported by a one-inch thick memory foam pad on top of a table. The elbow was oriented at 90 degrees relative to the torso, with approximately 15 degrees of shoulder flexion, and no shoulder ab/adduction. The forearm was relaxed on the foam pad with the lateral forearm supinated such that the palm faced upward. Vibrotactile stimuli were delivered to the arm and hand via 10 mm eccentric rotating mass (ERM) vibration motors (Precision Microdrives Ltd, Model # 310-117) with an operational frequency range of approximately 60-240 Hz, which corresponded to an amplitude range of 0.5 G to 2.4 G.

For simplicity, we chose to represent vibrotactile stimulus intensity in terms of frequency even though the amplitude of vibration covaried with frequency in the ERM vibration motors (c.f. Hwang et al. (2013) for a description of how perception of vibration intensity changes as vibration frequency and amplitude change). The vibration motors were powered and controlled using drive circuitry that was interfaced to a portable laptop computer running a custom script within the MATLAB R2017a computing environment (MathWorks Inc., Natick MA). Vibration motors could be placed on five locations: dermatome C5, C7, C8, T1, or the ulnar head (UH), a boney prominence within the projection of dermatome C8. Figure 6 shows the dermatomes of the arm and the approximate locations of the testing sites. Vibration motors were fixed to the arm via Transpore tape (3M Inc).

3. Constant Stimuli Protocol

We conducted a series of two-alternative forced-choice experiments (2-AFC) using the method of constant stimuli (Gescheider 1997) to determine the JND of vibrotactile stimulus intensity for each participant under various testing conditions. The 2-AFC protocol presented participants with a series of 110 stimulus pairs, each comprised of a standard intensity that remained fixed throughout the experimental session, and a probe intensity that varied across stimulus pairs. The standard intensity for our experiments was set to a frequency (186 Hz), approximately in the middle range of the Pacinian Corpuscle's frequency sensitivity band (60-400 Hz; (Mountcastle et al. 1972; Ribot-Ciscar et al. 1989)). The probe intensity included five intensities below the standard, five intensities above the standard (ranging from 100-235 Hz; corresponding



Figure 6: The dermatomes of the arm (the domains of origin of those projections) are labeled according to their target cord segment, and are marked by the *shaded regions*. Mechanoreceptors within the arm and hand send afferent projections to one or more segments of the spinal cord through the Dorsal Root Ganglia. The *white shaded regions* are areas of major dermatomal overlap, i.e., more than 1 spinal cord segment can innervate that region. **A)** The anterior view of the arm, showing dermatomes, C5, C7, C8, and T1. **B)** The posterior view of the arm, showing dermatomes and the Ulnar Head. The *gray markers* indicate the placement of the vibration motor motors on the arm in experimental 1 and 2. The *white marker* indicates the placement of the second vibration motor during the C7-C7 pair of experimental 2. Adapted from Lee et al. (2008).

amplitude of 0.45-2.25 G) and the standard intensity itself (186 Hz; corresponding amplitude of 1.40 G).

For experiment 1, a single vibration motor was used to present two sequential vibrations at each one of five different locations. We asked participants to verbally indicate which stimulus, first or second, was perceived to be of greater intensity. For experiment 2, two vibration motors were used to present pairs of vibrations (sequentially

or simultaneously) across pairs of stimulation sites. In this case, we asked participants to verbally indicate the location of the stimulus perceived to be of greater intensity.

4. Presentation of Stimuli

Sequential: During the sequential presentation of stimuli, the first vibrotactile stimulus was delivered for 750 ms, followed by a 750 ms pause, and then the second stimulus was presented for 750 ms. **Simultaneous**: During the simultaneous presentation of stimuli, both vibrotactile stimuli were presented at the same time for a duration of 750 ms. This presentation method was only used for experiment 2, wherein two vibration motors delivered vibrotactile stimuli to several location pairs.

5. Experiment 1: Discrimination Thresholds for Sequential Stimulations in Dermatomes of the Arm and Hand

Fifteen participants (6 females) volunteered to participate in three experimental sessions, lasting approximately 60 minutes each, spaced at least 24 hours apart. Each session consisted of five blocks of 2-AFC trials. During each block, one vibration motor was attached to the arm at one of five arm locations: C5, C7, C8, T1, or UH (Fig 6: gray markers). The vibrotactile discrimination threshold was tested using sequential stimuli presentation as described in *Constant Stimuli Protocol* above.

Participants completed 110 trials during each block (11 probe stimuli repeated 10 times each), wherein they verbally indicated which of the two stimuli they perceived to be more "intense", regardless of whether they interpreted stimulus intensity to refer to stimulus amplitude or frequency (which were coupled by the ERM motors used in these experiments). Each trial lasted about 2-4 seconds depending on participant response time; between each trial there was a 2-3 second rest period. The ordering of standard and probe stimuli presentation (i.e., which stimulus was presented first) was pseudorandomized

across trials. Testing locations were also pseudorandomized across participants and sessions to minimize potential order effects.

6. Experiment 2: Sequential versus Simultaneous Stimulation Within and Across Dermatomes

Fifteen participants (8 females) volunteered to participate in a single experimental session lasting approximately 90 minutes. The session consisted of eight blocks of 2-AFC trials. During each block, one of four dermatomal pairs were tested using either sequential or simultaneous presentations: within a dermatome (C7-C7) and across dermatomes (C7-C5, C7-UH, and C7-T1). One vibration motor was always placed on dermatome C7 at the location marked by the gray C7 marker in Figure 6. A second vibration motor was attached to the other indicated location. We performed a pilot study (Shah et al. 2019b) that used a vibration motor and a 3-axis accelerometer to measure the propagation of vibrations across the arm; we found that interference across stimulation sites was negligible with motor separations greater than 8 cm (see Chapter III; see also Cipriani et al. (2012), Krueger et al. (2017)). The two vibration motors were therefore always placed at least 8 cm apart.

The vibrotactile discrimination threshold was tested using sequential or simultaneous stimuli presentation as described in Constant Stimuli Protocol above. Participants completed 110 trials during each block, where they verbally indicated which of the two tested locations received the more "intense" stimulation. The ordering of standard and probe stimuli (i.e., which stimulus was presented at which location) was pseudorandomized across trials. Each trial lasted about 2-4 seconds depending on participant response time and between each trial there was a 2-3 second rest period. Block presentation order (i.e., the eight combinations of stimulation delivery method (sequential/simultaneous) and sites (dermatomal pairs)) were also pseudorandomized across participants and blocks to minimize potential order effects.

7. Data Analysis

Verbal responses were converted into probabilities of indicating each probe intensity as greater than the standard intensity. For each participant and each testing block, psychometric functions were fit to the probability data as a function of probe stimulus intensity (represented by frequency) using the cumulative normal distribution in Equation 3:

[Eq 3]
$$F(x) = \frac{1}{2} \left[1 + erf\left(\frac{x-\mu}{\sigma\sqrt{2}}\right) \right]$$

where, F(x) is the predicted probability, x is the probe intensity, μ is the mean of the underlying decision process modelled as a normal distribution, σ is the standard deviation of that normal distribution, and the *erf* is the cumulative normal function. Curve fitting was performed using the MATLAB function (fminsearch) to find the μ and σ values that minimized the sum of squared error between the predicted and actual response probabilities. The vibrotactile intensity discrimination threshold was defined as one standard deviation of the underlying normal distribution (i.e., the σ found by fminsearch). This discrimination threshold (i.e., the JND) was defined as a measure of uncertainty in comparing vibration intensities near the standard intensity of 186 Hz. For probe stimuli either much greater than or much less than the standard stimulus, we expect people to be relatively accurate in discriminating the probe and standard stimulus intensities. As we found no significant effect of sessions for experiment 1, discrimination thresholds were averaged across the three sessions for each tested location, to yield one discrimination threshold per participant per condition. For both experiments 1 and 2, we report the mean discrimination threshold averaged across participants within blocks.

8. Statistical Hypothesis Testing:

Motivated by the observation that the density of cutaneous mechanoreceptor varies across the body (Hunt, 1974), we first sought to test the extent to which discrimination thresholds for vibrotactile stimuli might vary across locations of the arm and hand (Experiment 1). Specifically, we used two-way ANOVA and post-hoc, Bonferroni-corrected, paired samples t-test to compare mean vibrotactile discrimination thresholds (the dependent variable) across sessions and across locations on the arm and hand.

Motivated by the consideration that discrimination of sequential vibrotactile stimuli involves aspects of working memory and attention, which might be limited resources and divided for simultaneously presented stimuli, we sought to test the hypothesis that discrimination thresholds would vary between sequential and simultaneously presented stimuli, both within and across dermatomes (Experiment 2). We used two-way ANOVA and post-hoc, Bonferroni-corrected, paired samples t-test to compare mean discrimination thresholds (the dependent variable) across delivery methods (sequential or simultaneous) and across location of stimulus delivery (within or across dermatomes). All analyses were performed with SPSS Statistics 24 (IBM Corp, Armonk, NY). Statistical significance was set at the family-wise error rate of $\alpha = 0.05$.

C. Results

This study used eccentric rotating mass (ERM) vibration motors to examine the psychophysics of vibrotactile perception within and across dermatomes of the arm and

hand in 30 neurologically healthy participants. All participants were attentive throughout their experimental session, and all responded to stimuli in a timely fashion.

1. Experiment 1: Discrimination Thresholds for Sequential Stimuli Applied at Single Locations in Dermatomes of the Arm and Hand

In the first set of experiments, we tested the extent to which difference thresholds for vibrotactile intensity vary across dermatomes of the arm and hand. Figure 7A depicts response probabilities calculated from a single block of discrimination trials performed by one participant (dermatome C7). As expected, when the probe intensity was markedly lower than that of the standard, the participant reliably identified the standard as more intense than the probe [i.e., P (probe > standard) was close to 0]. By contrast, when the probe intensity was markedly higher than that of the standard, the participant was much more likely to identify the probe as more intense. When the probe intensity was close to that of the standard, the participant was less reliable in correctly identifying which stimulus was more intense.

We fit the cumulative normal function (Eq 1) to the observed likelihood data in order to obtain estimates of μ and σ from the underlying normal model of the perceptual decision process. Figure 7B presents the psychometric curves obtained from all five testing locations from the same participant. Dermatome C5 is traced by the blue curve (174.27 ± 35.87 Hz; $\mu \pm \sigma$ of the underlying normal distribution), dermatome C7 by the red curve (186.38 ± 19.01 Hz), dermatome C8 by the orange curve (193.09 ± 46.69 Hz), dermatome T1 by the green curve (189.29 ± 64.42 Hz), and the ulnar head by the purple curve (181.16 ± 34.95 Hz). Here, the psychometric curve for dermatome C7 had the steepest slope (smallest σ). Thus, this participant was better at discriminating between



Figure 7: A) Assessment of vibrotactile perception at dermatome C7 for a selected participant. *Gray Squares* indicate the observed fraction of trials at each probe frequency where the participant indicated that she perceived the probe stimulus as more intense than the standard stimulus. *Black sigmoid curve*: the psychometric (cumulative normal) function that was fit to the observed probability data. *Gray Shaded Region:* the discrimination threshold defined as one estimated standard deviation (here, ± 19.01 Hz) from the estimated mean (186.38 Hz) of the underlying normal distribution. The upper bound of the box crosses the sigmoid at approximately P(Probe > Standard) = 0.84 (*Gray dotted line*). *Gray Dashed Line:* the point of subjective equality (i.e., P(Probe > Standard) = 0.5). **B)** Best-fit cumulative normal functions for the five testing locations for the same participant. Dermatome D7 has the best discrimination threshold, while dermatome T1 has the worst.

vibrotactile stimuli intensity presented sequentially on dermatome C7 than the same stimuli presented on dermatome T1. Discrimination thresholds for sequential stimuli applied to dermatomes C5, C8, and the ulnar head fell between the bounds established by dermatomes C7 and T1.

The results presented in Figure 7 were representative of the study population (Fig 8). Two-way ANOVA found that vibrotactile discrimination thresholds differed significantly across stimulation sites ($F_{4,56} = 6.801$, p = 0.0002), but not across session ($F_{2,28} = 1.212$, p = 0.313). Post-hoc testing revealed that this effect was due to better vibrotactile discrimination on dermatome C7 [32.78 ± 4.73 Hz (mean \pm SEM)] vs.



Figure 8: Group results from Experiment 1. Mean (\pm 1 SEM) discrimination thresholds across the population were calculated for sequential vibrotactile stimuli presented within each of the five tested locations. Dermatome C7 is significantly better at discriminating vibrotactile stimuli than dermatome T1.

dermatome T1 (43.25 \pm 5.48 Hz, t₁₄ = 5.22, p = 0.0001). Vibrotactile discrimination thresholds on dermatomes C5 (36.88 \pm 4.23 Hz), C8 (37.96 \pm 4.58 Hz), and the Ulnar

Head (34.70 ± 4.03 Hz) did not differ significantly from each other or from those on dermatomes C7 or T1 (p > 0.05 in all cases). Across participants, the average difference in discrimination thresholds between dermatomes C7 and T1 was 10.47 ± 1.48 Hz. We also calculated the average slopes of the psychometric functions at its inflection point within each of the tested dermatomes (Slopes: C5 = 0.0159 ± 0.0032 (mean ± SEM), C7 = 0.0240 ± 0.0057, C8 = 0.0182 ± 0.0055, UH = 0.0234 ± 0.0058, T1 = 0.0125 ± 0.0016). It can be shown by differentiating Equation 3 with respect to *x* that the slope of the psychometric function at the inflection point (i.e., when $x = \mu$) is a reciprocal function of the discrimination threshold σ . Despite this nonlinearity, the slopes of the fitted psychometric functions exhibited a high degree of negative correlation with discrimination thresholds over the range of the experimentally observed thresholds (R = -0.926).

2. Experiment 2: Sequential versus Simultaneous Stimulation Within and Across Dermatomes

In the second set of experiments, we examined two factors having the potential to impact how the CNS processes vibrotactile information in support of perceptual decision making: concurrency of stimuli (i.e., whether working memory and attention are required to support the decision) and somatotopy of stimulus delivery (i.e., whether the two stimuli are provided within the same dermatome or across different dermatomes). Participants performed 8 blocks of 2-AFC trials wherein they discriminated between two vibrotactile stimuli delivered either sequentially or simultaneously at each of four location pairs on the arm or hand; each permutation of this 2x4 experimental design was tested in separate blocks. As per Experiment 1, we fitted Eq 1 to the observed response likelihood data from each block to obtain separate estimates of the mean (μ) and standard deviation (σ) of the normal model of the perceptual decision process underlying each testing condition. Two-way ANOVA found that vibrotactile discrimination thresholds varied systematically by delivery method (F_{1, 113} = 13.01, p = 0.0004), but did not vary significantly across paired stimulation sites (F_{3, 113} = 1.124, p = 0.343). Participants



Figure 9: Group results from Experiment 2. Mean (± 1 SEM) discrimination thresholds were calculated for sequentially (gray bars) and simultaneously delivered (white bars) vibrotactile stimuli at stimulus location pair. Sequential vibrotactile stimuli (C7-C5: 46.32 \pm 6.29 Hz; C7-C7: 40.94 \pm 3.70 Hz; C7-T1: 41.74 \pm 3.60 Hz; C7-UH: 53.75 \pm 6.51 Hz) allowed for better discriminability than simultaneous stimuli (C7-C5: 62.63 \pm 7.62 Hz; C7-C7: 65.38 \pm 9.17 Hz; C7-T1: 57.06 \pm 8.04 Hz; C7-UH: 70.96 \pm 10.56 Hz).
demonstrated better discriminability of vibrotactile stimuli with sequential delivery $(45.57 \pm 3.92 \text{ Hz} \text{ (mean} \pm \text{SEM}))$ than with simultaneous delivery $(64.14 \pm 6.54 \text{ Hz}; \text{Fig} 9)$. Across participants, the difference in discrimination thresholds between delivery methods averaged $18.57 \pm 7.83 \text{ Hz}$. The main effect found in experiment 1 did not differ significantly from the main effect found in experiment 2 (2-sample t test, $t_{28} = 1.0167$, p = 0.318).

D. Discussion

This study investigated vibration intensity discrimination when stimuli were applied either sequentially or simultaneously to various dermatomes on the arm and hand (C5, C7, C8, T1). Based on reports of differing densities of mechanoreceptors in the hand and varying dermatomal representations in the primary (S1) and secondary somatosensory cortex (S2), we hypothesized that the discrimination threshold for vibrotactile stimuli would vary across dermatomes. In support of this hypothesis, we observed that vibrotactile intensity discrimination threshold in dermatome C7 was on average approximately 10 Hz lower than the threshold for dermatome T1. However, the dermatomal effect is only a small fraction of the JND for each dermatome (ranging from 23% in dermatome T1 to 31% in dermatome C7). Thus, this fractional difference is well below the perceptible change in vibration intensity. The current study also tested the hypothesis that discrimination thresholds of vibrotactile stimuli depend on whether the stimuli are delivered sequentially or simultaneously. Our results showed that the discriminability of sequentially delivered stimuli was better than that of simultaneously delivered stimuli.

1. Discrimination Across Dermatomes – Possible Mechanisms

It is possible that the difference in discrimination thresholds between dermatome C7 and T1 are attributable to differences in the cortical representation of dermatomal projections onto the somatosensory cortex (i.e., the number of neurons responsible for sensing a stimulus). In non-human primates, the cortical representation area is much larger for dermatome C7 than T1 (Woolsey et al. 1943). Dermatomal representations in the somatosensory cortex of the human brain likely follow a similar pattern (Eickhoff et al. 2007; Penfield and Boldrey 1937), suggesting a possible mechanism for the different discrimination levels we found for dermatomes C7 and T1 in experiment 1. Duncan and Boynton (2007) showed that in humans, the extent of cortical representation of the index finger is much larger than that of the little finger, and that the cortical representation correlates with tactile acuity in the two fingers. In our study, discrimination thresholds in the cervical dermatomes were indistinguishable, whereas dermatomes C7 and T1 differed significantly in a way that could reflect greater cortical representation of the cervical dermatomes. Future neuroimaging work is needed to test whether cortical representation can explain the differences in discrimination observed in this study.

A second possibility relates to potential differences in mechanoreceptor density across the arm. Pacinian Corpuscles (PCs) are much sparser and their location is also much deeper in the epidermis of hairy skin relative to glabrous skin (Burgess 1973). Johansson & Vallbo (1979) showed that the density of PCs is higher towards the lateral side (index finger and thumb) of the hand compared to the medial side (little finger). This lateral to medial difference in mechanoreceptor density may also hold true for the forearm. Desensitization of dermatome T1 (medial arm) may also occur due to frequent interactions with objects in the environment (e.g., resting the arm on a chair or a table). To our knowledge, no studies to date have compared mechanoreceptor density or sensitivity across the dermatomes of the arm or other body locations, which could provide valuable insights into differences in discrimination acuity across the dermatomes of the body.

2. Discrimination Across Time – Influence of Working Memory and Attention

A comparison of two studies from Romo and colleagues provides insight into the neural correlates of vibrotactile stimulus discrimination when two stimuli are presented sequentially, as in the present study. In a first study, Romo et al. (1999) recorded from neurons in the prefrontal cortex (PFC) of non-human primates. Here, activations reflected the contribution of working memory to the discrimination of two sequential vibrotactile stimuli. During the delay period between the two stimuli, neuronal responses to the first stimulus were maintained within the PFC throughout the delay period. Moreover, the neuronal responses in the PFC within the last 200 ms of the delay period persisted at levels consistent with neuronal responses recorded in the primary (S1) and secondary (S2) somatosensory cortices during the first stimulus. By contrast, little to no delay period activations were observed in either S1 or S2 in their later study (Romo et al. 2002). Whereas neuronal responses to the first stimulus depended only on its frequency of vibration in both S1 and S2, neuronal responses to the second stimulus were proportional to the difference in the vibration frequency of the two stimuli (f2-f1) in about 20% of the recorded S2 neurons (but not in S1). Within this subset, Romo and colleagues, through the analysis of trials wherein the monkeys made erroneous choices, found that neuronal responses reflected the actual choice the monkey would ultimately

make rather than strictly adhering to the (f2-f1) relationship (see their Fig 7a). This was true for responses recorded even within the first 300 ms of the second stimulus, well before the motor response to the decision was performed. If the mechanism of stimulus encoding, recall, and discrimination described by Romo and colleagues also holds true for vibrotactile discrimination in humans, then the decreased acuity we observed during the discrimination of simultaneous stimuli may be due to timing constraints that preclude the engagement of working memory systems located within PFC ((Braver et al. 1997; Lara and Wallis 2015); for review see Curtis and D'Esposito (2003)).

Wu and Liu (2008) have compared the structure of information processing within the CNS to computer networking structures, where regions such as the PFC, S1 and S2 act as *servers* that are connected to each other through *routers* (neural pathways). In this queuing-network model, Wu and Liu conceptualized that sensory information is processed and routed through multiple servers that comprise different perpetual, cognitive, and motor subnetworks. Whereas simultaneous sensory stimuli can be perceived and stored at the same time in the perceptual subnetwork, one stimulus must be processed before the second within the cognitive subnetwork because each stimulus must pass serially through the same *server*. While the memory of one stimulus is waiting to be processed by the cognitive network, noise in the form of neuronal response variability can degrade the stored representation (Bernasconi et al. 2011). By contrast, each of two sequential stimuli can be processed immediately by the cognitive network if the time between two stimuli exceeds some minimum time required to process a single stimulus. In our study, the inter-stimulus interval of 750 ms evidently exceeded that minimum because the acuity of vibrotactile discrimination was systematically lower for sequential

vs. simultaneous stimuli. A future study of vibrotactile discrimination should manipulate the duration of the inter-stimulus interval to identify the time-course and effects of memory encoding, recall and forgetting on vibrotactile perceptual acuity ((Berglund, Berglund, and Ekman 1967; Gallace et al. 2008; Harris et al. 2002)).

Variations in attention also likely impact the acuity of vibration intensity discrimination. Attentional resources available for the comparison of vibrotactile stimuli likely follow the capacity sharing model proposed by Pashler (1994). In that model, attention is a limited capacity resource. Attentional capacity that is shared or divided across multiple stimuli reduces the capacity available for perception of each individual stimulus. When attention towards a stimulus decreases, higher variability in neuronal responses can increase neuronal noise (Mitchell et al. 2007). Noise in the representation of a vibrotactile stimulus can also increase due to leakage of information from other sensory modalities (e.g., audition, vision) that may or may not provide a signal consistent with the vibrotactile stimulus (Mozolic et al. 2008; Wyart et al. 2015).

Signal detection theory predicts that the accuracy of discrimination will be degraded by the presence of noise, whatever its source (Green and Swets 1966; Wickens et al. 2015). Attention can act as a filter during the perception of stimuli by attenuating noise (Mozolic et al. 2011) thereby reducing variability in the neuronal response (Bernasconi et al. 2011; Mitchell et al. 2007). Thus, division of attention may have contributed to the systemic increase in discrimination thresholds observed during simultaneous presentation of vibrotactile stimuli in experiment 2.

3. Implications for Vibrotactile Sensory Augmentation

By developing an understanding of vibrotactile perception, vibrotactile feedback can be used more effectively in applications such as sensory augmentation (Bach $\Box y \Box$ Rita 1967; Cuppone et al. 2016; Risi et al. 2019; Shull and Damian 2015; Witteveen et al. 2015). Sensory augmentation is a technique where one sensory modality is enhanced or replaced through the application of stimuli to another sensory modality. The use of vibrotactile feedback in sensory augmentation has been investigated since the 1960s. Previous studies have utilized the tactile sense to augment several other senses. For example, Witteveen et al. (2015) demonstrated that it is possible to improve the control of grip force and hand aperture in prosthetic users by providing feedback of these variables via vibrotactile cues. Cuppone et al. (2016) enhanced performance of wrist movements by supplementing proprioceptive practice with error-based vibrotactile feedback provided on either forearm. In our earlier works (Krueger et al. 2017; Risi et al. 2019), we also investigated the use of vibrotactile sensory augmentation for upper extremity motor control. We encoded limb state or performance error information about the moving arm within vibrotactile feedback applied to the other (non-moving) arm. With both forms of information encoding, the use of vibrotactile feedback led to significant improvements in the performance of reaching and stabilization behaviors.

One reason for choosing the arm as a location for vibrotactile feedback is allowing the user to manipulate objects with both hands (e.g., using the non-dominant hand to hold a bottle while the dominant hand opens it) without obstructing the hand and digits with the vibration motors. Another factor to consider when choosing a location for vibrotactile stimulation is the ease of interpretation of the stimuli. All previous studies involving vibrotactile feedback have selected sites that are in some sense intuitive or relevant to the specific application under examination. For example, we have previously shown the intuitiveness of using vibrotactile feedback applied to the arm to successfully guide reaching (Krueger et al. 2017; Risi et al. 2019). Wall et al. (2001) demonstrated a reduction in body sway during quiet standing in healthy users who were provided vibrotactile feedback to the trunk. In that case, the stimuli conveyed information about head tilt. Sienko et al. (2008) expanded that work by providing vibrotactile error feedback of trunk sway to users with vestibular sensation loss. Doing so successfully reduced body sway. Our current study advances the development of sensory augmentation applications by providing a better understanding of vibration intensity perception on various locations of the arm. The methods described in this study could be used in the future to quantify vibrotactile perception at other body locations suitable for other potential applications (e.g., providing feedback of ankle angle on the thigh to mitigate foot drop).

The current results also provide insight into the maximum amount of information that can be encoded by VTF-based BMIs. The results of our first experiment characterized the minimum intensity difference between two vibrotactile stimuli required to accurately distinguish between them. Given that the bandwidth of human vibration perception via PCs is limited (i.e., 80-500 Hz), the number of discretely perceptible stimuli within that range is determined by the smallest resolvable difference between two stimuli in that range (i.e., the JND). Thus, while all of the tested dermatomes on the arm and hand could serve as viable sites of vibrotactile stimulation for a practical BMI, future applications of vibrotactile sensory augmentation on the arm may consider using dermatomes C5, C7, or C8 (UH) as stimulation sites because they have indistinguishable discrimination thresholds, while potentially avoiding dermatome T1, which has a slightly elevated discrimination threshold. The results of our second experiment showed that sequential delivery outperforms simultaneous delivery. The implication is that the number of independent vibrotactile channels that can be used to simultaneously convey useful information may be limited, at least upon initial exposure in untrained individuals, as tested here. Future applications using multichannel vibrotactile stimulation may consider limiting the extent to which attention must be divided across multiple simultaneous stimuli either through the minimization of distractions, or through the promotion of autonomous sensory integration via long-term practice.

Finally, the tactile sensory modality also plays a role in body representation and influences proprioception (Kuling, Brenner, and Smeets 2016; Lee et al. 2013; Weerakkody et al. 2007). Weerakkody et al. (2007) showed that stimulating the cutaneous mechanoreceptor through vibrotactile stimuli decreased perception of proprioceptive changes, leading to decreased detection of movements. The work of Weerakkody and colleagues focused on detection of movements in the digits of the hand while this same area was also stimulated with vibration; how their findings may generalize to hairy skin of the body is yet unknown. To provide the best utility and experience for the user of novel technology that employs supplemental vibrotactile stimuli, it therefore will be important to consider where on the body the cues are to be applied, what information they will provide, and whether the cueing may interfere with other intrinsic modes of somatosensation (e.g., proprioception).

4. Limitations

There are several potential limitations of the present study. One limitation might arise from differences in contact force/pressure between vibration motors attached to different stimulation sites. We mitigated this concern by having the same experimenter attach the motors to the skin using medical grade tape, taking care to ensure that the length of tape (~4 cm) and tension were consistent across testing sites and participants. We also counter-balanced the presentation of standard and probe stimuli across the two locations through pseudorandomization to reduce any systematic effects of differences in contact force/pressure.

Another limitation may arise from our use of inexpensive ERM vibration motors rather than more expensive devices that can decouple the frequency of vibration from its amplitude. While the selection of vibrating actuators might affect perception of vibration (see Lee et al. (2013)), it is unlikely that the factors contributing to the spatiotemporal variations in vibrotactile acuity described in this study would be the result of variations in sensitivity to just one of these parameters (frequency, amplitude) but not the other, and so the overall pattern of results we describe should not depend on the choice of vibration motor technology. Additionally, studies by Choi & Kuchenbecker (2013), Hwang et al. (2013), and Morley & Rowe (1990) have shown that perception of vibration intensity depends both on the frequency and amplitude of vibration. Counterintuitively, Hwang et al. showed that at certain frequencies of simulation, the perceived intensity of vibration can decrease even as the amplitude of vibration increases. Thus, the coupling of vibration magnitude and frequency is a beneficial feature of the low-cost ERM motors in our study. Indeed, as exemplified by the data provided in Figure 7, the perceived intensity of vibration increased monotonically as a function of motor activation in all subjects in the current study over the range of frequencies stimulated by the selected ERM motors. Therefore, the low-cost ERM vibration motors are well-suited for use in VTF applications.

Other limitations might arise from our choices to include only healthy, young participants in this study, to test using only a single standard stimulus, and to test using only a single stimulus duration. Aging has been shown to be a factor in perception of vibrotactile stimulations (Cholewiak and Collins 2003; Lin et al. 2015; Verrillo 1980) and so discrimination thresholds might vary if we conduct the same experiments in an older population. Additionally, the mechanical propagation of vibrations through soft tissues in the arm and hand is frequency dependent (cf., Chapter III, Manfredi et al. (2012), Sofia and Jones (2013)). Thus, the number of receptors activated by a given stimulus will be frequency-dependent, as will be also the magnitude of discrimination thresholds (see Francisco et al. (2008)). Finally, because vibrotactile perception also appears to depend on stimulus presentation time for short stimuli less than 1 second in duration (Berglund et al. 1967), we would also expect the magnitude of discrimination thresholds to vary slightly as a function of stimulus duration. In all of these cases, however, we would not expect the observed variations in perception across dermatomes and across temporal patterns of stimulation to change as a result of arbitrary choices in standard stimulus frequency, stimulus duration, and participant population. Future experiments of vibrotactile perception could be performed to verify these assumptions.

E. Conclusions

We conclude, therefore, that while all of the tested dermatomes on the arm and hand could serve as viable sites of vibrotactile stimulation for a practical BMI, implementations should ideally account for small differences in perceptual acuity across dermatomes. Moreover, the maximum amount of information that can effectively be encoded will be constrained by at least two factors: limitations in vibrotactile perceptual acuity that differ slightly between dermatomes, and limitations in the amount of information that can be simultaneously presented across multiple stimulation sites. Future applications using multichannel vibrotactile stimulation may consider limiting the extent to which attention must be divided across multiple simultaneous stimuli either through the minimization of distractions, or through the promotion of autonomous sensory integration via long-term practice.

V. IMPACT OF SHORT-TERM PRACTICE ON LEARNING TO USE VIBROTACTILE FEEDBACK TO GUIDE ARM MOVEMENTS

Utilizing the results of the previous two chapters, we designed a vibrotactile interface that was attached to one arm on users and conveyed limb-state information of the other hand. In this chapter, we investigated sensorimotor learning of vibrotactile feedback (VTF) to guide reaching in the absence of visual feedback, after a small bout of practice. If we see signs of initial motor learning, developing an intuitive and useful VTF body-machine interface (BMI) would seem promising. This chapter has been published as a manuscript in the proceeding of the *EuroHaptics Conference* (Shah et al. 2018).

A. Introduction

Body-machine interfaces (BMI) establish bidirectional information transfer between devices and their users (Casadio et al. 2012). Vibrotactile feedback (VTF) is a popular choice for noninvasive informational interfaces for many BMIs. These interfaces do not load visual attention and they can be implemented inexpensively. Vibrotactile feedback has previously been used with BMIs to replace lost sensation or to augment intact sensory modalities such as sight (Bach y Rita 1967; Kaczmarek et al. 1985; White et al. 1970), balance (Dozza et al. 2007; Lee et al. 2012), and proprioception (Tzorakoleftherakis et al. 2016; Witteveen et al. 2015). Lam et al. (Lam et al. 2008) and Kapur et al. (2009, 2010) have investigated vibrotactile technologies for post-stroke motor rehabilitation. Lam et al. (2008) showed that cued activation of specific elbow and shoulder muscles can improve upper extremity motor control in this population. Lieberman and Breazeal (2007) developed a wearable device that provided VTF to multiple locations on the hand, arm, and torso. They asked people to use this device to learn a new motor skill, and their results show that upper extremity motor skill acquisition can improve with VTF in naïve users. However, these prior applications of VTF all conveyed information about performance using error feedback. Error feedback is difficult to implement as it requires timely estimation of the user's intent, and the translation of that intent into signals that can be used to drive the user's behavior toward some goal. By contrast, it is also possible to encode information about limb state in a way that is not referenced to some desired movement pattern (e.g., by encoding hand position, joint angular position, or velocity using off-the shelf sensor technologies (Krueger et al. 2017)).

Recently, Risi and colleagues (2019) have demonstrated that limb-state VTF can be used effectively to provide real-time feedback such that movement accuracy in neurologically intact individuals improves beyond limits imposed by proprioceptive uncertainty. In their study, two days of VTF-guided reach practice improved target capture accuracy toward the limits of vibrotactile perception but increased time needed to complete the movement by two-fold. Given that VTF-guided reaching took approximately two times longer to perform than movements without VTF, it is likely that the use of online VTF to plan and control movements imposes additional cognitive loads sufficient to degrade movement timing. Based on these results and other previous studies, we believe the successful use of VTF requires the user to sense vibration, decode the information it contains, and produce a task-appropriate response (Haggerty et al. 2012; Lin et al. 2015; Risi et al. 2019). Thus, using real-time VTF to assist in performing simultaneous tasks, such as reaching for a glass of water while reading or talking, may be difficult until the use of VTF becomes automatic. We investigated the ability of neurologically intact participants to dual-task VTFguided reaching while performing a secondary choice reaction time task. We sought to understand if divided attention negatively affects performance of VTF-guided reaching, and to investigate if short-term practice with VTF can reduce the negative impact of simultaneous VTF-guided reaching and secondary task performance. We also sought to investigate the extent to which VTF-guided reaching can move beyond the first stage of motor learning (Fitts and Posner 1967) within a single session of practice, and whether any performance enhancement transfers to the dual-task condition. We hypothesized that performance benefits provided by short-term practice with limb state VTF are not susceptible to interference by dual-tasking. Our results indicate that healthy participants are indeed able to use VTF to guide goal-directed reaching in a dual-task situation and suggest that performance of VTF-guided reaching is robust against dual-task interference.

B. Methods

1. Participants

Eleven neurologically-intact participants (7 female) ranging in age from 23-27 years (24.63 yr ± 1.15 yr), with no known tactile or cognitive deficits were recruited from the University of Genoa community (Genoa, Italy). Ten participants self-reported as right-hand dominant and one participant reported as left hand dominant. Ten of the 11 participants were naïve to the use of vibrotactile feedback for movement control and all were naïve to the experimental objectives. In accord with the 1964 Declaration of Helsinki, all participants volunteered for the study, and all provided written consent to the experimental procedures, which were approved by local Institutional Review Boards serving the University of Genoa (ASL3 Genovese) and Marquette University.

2. General Procedures

Each participant completed a single experimental session, lasting approximately 90 min. Participants grasped the handle of a custom, planar manipulandum (Fig 10, left panel; see Ballardini et al. (2018) for details) and made reaching movements in the horizontal plane with their dominant hand (Reach Task; described below). The manipulandum has a parallel structure and its handle position is determined by the output of two potentiometers (Vishay Intertechnology Inc, Model # 132-0-202). A computer screen (23.6" Samsung B2430L) was located directly in front of the participant and was used to display a grid of 25 reach targets and a cursor, which corresponded to the instantaneous position of the manipulandum's handle (Fig 11). Subjects rested their nondominant arm on a rigid support structure with the index, middle and ring fingers resting gently above the numeric keys of a standard computer keyboard. Three of the keys were used to record subject responses during a secondary choice reaction time task (Button Press Task; described below). The manipulandum and dominant arm were blocked from view. Subjects wore noise-cancelling headphones to minimize auditory cues during the experimental tasks.

3. Visual Stimuli and Vibrotactile Interface

Visual stimuli were created in PsychToolbox (MatLab 2017a). Reach targets (5 mm diameter circles) were arranged in a 5x5 grid on the computer screen (Fig 10, right panel), with corresponding nearest-neighbor distances on the screen equal to 2.85 cm. Note that this inter-target distance is approximately equal to the range of uncertainty within proprioceptive perception of limb position (2.5 ± 0.2 cm), as derived using joint angular uncertainty values reported by Fuentes and Bastian (2009).



Figure 10: Experimental set up. Left Panel: participants sat in front of a computer screen that displayed targets and a cursor. Cursor location was controlled via the manipulandum held in the participant's right hand. Central Panel: a vibrotactile interface consisting of four vibrotactile motors was placed on the participant's non-dominant left arm. Right Panel: The Y+ tactor was activated when the cursor/hand was in the hemi-space above the center row of targets, whereas the X+ tactor was activated when the cursor/hand was to the right of the center column of targets. The participant also used the non-dominant hand to make key presses corresponding to the color of the target during the dual-task trials. The manipulandum and the dominant arm were blocked for the participant's view, although the occlusion screen is not shown here to facilitate visualization of the setup.

A vibrotactile interface was attached to the non-dominant (stationary) arm (Fig 10, central panel) as described by Krueger et al. (2017). The interface was comprised of four miniature, eccentric-rotating-mass ERM "tactors" (Precision Microdrives Ltd, Model # 310-117), attached to the arm at four locations. Over their operational range, the tactors have monotonic relationships between activation voltage and both vibration frequency and vibration amplitude such that vibration frequency and amplitude are coupled. The tactors were powered and controlled from a customized microcontroller circuit that interfaced to the Matlab computing environment (version 2017a; the MathWorks Inc.) using the Matlab Arduino Support Package. When activated in the current study, the tactors operated between 60 Hz to 250 Hz. At their peak vibration frequency, the tactors produce a peak vibrational amplitude of 2.8 G, which corresponds

to maximal forearm-plus-hand accelerations ranging between 0.53 m/s^2 and 0.77 m/s^2 , depending on participant anthropometrics (Krueger et al. 2017).

We calibrated the vibrotactile interface such that a hand displacement of 1.10 cm (i.e., a little less than half of the distance between adjacent targets) corresponded to a change in tactor frequency of 33 Hz. The origin of the vibrotactile interface was set to the center of the grid (VTF was set to 0 Hz). To overcome internal friction within the motors, tactor excitation increased discontinuously from 0 Hz to 60 Hz when the hand moved 0.6 cm from the center of the origin. Tactor excitation increased linearly with displacement such that vibration frequency was about 135 Hz at one target distance from the center and 230 Hz at two target distances from the center. If the cursor moved outside of the grid by 0.5 cm, VTF increased to its maximum frequency (>250 Hz); participants were informed that maximum vibration was only reached when they had left the desired workspace. Near the middle of their operating range, the tactors elicit vibrotactile sensations that depend on which dermatome was stimulated, with dermatome C7 on the lateral forearm being the most sensitive to changes in tactor frequency (a just noticeable difference (JND) of 33 Hz), and dermatome T1 on the medial forearm being the least sensitive (with a JND of 43 Hz, (Shah et al. 2019a)). In any case, participants needed to move at least two vibrotactile JNDs to reach from one target to an adjacent target under the guidance of VTF

4. Task Procedures

During the session, participants completed a total of 12 blocks of 25 trials each (Table 4). Blocks 1–3 familiarized the subjects to the workspace, the individual reaching and choice reaction time tasks, and allowed assessment of baseline performance in both

tasks without VTF. Block 4 familiarized subjects to VTF-guided reaching by also providing visual feedback of cursor motion. Block 5 allowed assessment of pre-practice dual-task performance in the absence of visual cursor feedback. Blocks 6–10 consisted of VTF-guided reach practice. Blocks 11 and 12 allowed for assessment of post-practice dual-task and reach performance. Participants were allowed a five-minute rest before and after VTF practice in Blocks 6–10. Table 4 shows the task and feedback condition of each block. All participants completed the blocks in the same order. Because the focus of this study was on the impact of VTF practice on dual-task performance, and because it was imperative to compare pre- and post-practice dual-task performances without intervening experiences unrelated to practice, we did not counterbalance the presentation order of Blocks 11 and 12 across subjects.

Block	Trials	Task	Feedback	Туре
1	25	Reach	V+T-	Baseline
2	25	Reach	V-T-	Baseline
3	25	Button press	N/A	Familiarization
4	25	Reach	V+T+	Familiarization
5	25	Dual	V-T+	Pre-practice
6–10	25 each block	Reach	V-T+	Practice
11	25	Dual	V-T+	Post-practice
12	25	Reach	V-T-	Post-practice

Table 4: Description of task blocks: number of trials, block type, and feedback condition type.

Participants were instructed to reach to the visual target as soon as it appeared on screen (Reach Task). After moving, participants verbally indicated they had reached the target. Participants were then given visual cursor feedback and were instructed to correct any target capture errors so that the next trial could start. During movement, participants

could be provided with one of four combinations of visual and VTF feedback of hand position: (i) only visual feedback of the cursor (V+T-); (ii) only VTF (V-T+); (iii) both forms of feedback (V+T+); (iv) no feedback, i.e., neither visual feedback of the cursor nor VTF (V-T-). In the choice reaction time task, participants were instructed to press 1 of 3 color-coded keys when they saw a colored target change shape (Button Press Task). The target could be 1 of 3 colors: red, blue, or green. The target first appeared as a hollow ring. After a variable amount of time (350 ms to 850 ms), the target switched from a hollow ring to a filled circle of the same color, cueing the participant to press the corresponding button; the target did not move.

During the dual task, participants completed the Reach Task and the Button Press Task simultaneously. Changes in target location were used to cue dominant hand movements as in the Reach Task. Changes in a colored target's shape were used to cue non-dominant hand key presses as in the Button Press Task. Participants were instructed to begin reaching to the hollowed ring as soon as it appeared, and then press the color corresponding button when the hollowed ring changed shape into a filled circle.

5. Data Acquisition and Statistical Hypothesis Testing

In the Reach Task, we computed target capture error as our primary measure of performance. Target capture error was defined as the Euclidean distance between the actual target location and the final location of the cursor at the end of the movement. We sought to address the hypothesis that performance benefits provided by short-term practice with supplemental VTF of hand position information are robust against dual-task interference. We used repeated measures ANOVA and post hoc, Bonferroni-corrected, one-tailed, paired samples t-tests to test the statistical significance of changes in capture

error between the first and final blocks of practice as well as the error of pre- and postpractice dual tasking. We sought to verify that VTF practice would indeed result in improved performance in the reach task. If the beneficial effects of reach practice are robust against dual-task interference, we would anticipate that practice dependent improvements in reaching performance would also be evident in the dual-task testing condition. Our secondary measure of performance was target capture time, defined as the time difference between reach trial start and participant indication of target capture. We used repeated measures ANOVA with post hoc, Bonferroni-corrected, one-tailed, paired samples t-tests to analyze the target capture time (time difference between trial start to participant stating they have reached the target). We expect to see practice dependent improvements in target capture time in the dual-task testing as well as the first and final blocks of practice.

In the Button Press Task, we computed the number of correct button presses in the experimental blocks wherein this task was performed (Blocks 5, 11). Based on the Capacity Sharing Model (Pashler 1994), we anticipated that reduced interference due to practice related improvements in reach performance might result in better Button Press Task performance. Here, we used a one-tailed, paired samples t-test to evaluate the statistical significance of changes in the percentage of correct responses pre- to postpractice. Statistical significance was set at the family-wise error rate of $\alpha = 0.05$.

C. Results

In this study, participants grasped the handle of an instrumented manipulandum with their dominant hand and practiced performing a horizontal planar Reaching Task guided by vibrotactile stimuli that encoded real-time information about the location of the moving hand. We hypothesized that performance benefits provided by short-term practice with supplemental vibrotactile feedback would be robust against interference by a secondary choice reaction task that increased cognitive loading. All subjects were attentive throughout their experimental sessions and all were able to understand and complete each task. Figure 11 shows the reaching trajectories from a typical participant. Using separate one-way repeated measures ANOVA, we found significant differences in reaching error ($F_{(8,80)} = 2.89$, p < 0.05) and target capture time ($F_{(8,80)} = 3.94$, p < 0.05) across reaching trial Blocks 2 through 11. Post-hoc analyses exploring these main effects are discussed in the following paragraphs.



Figure 11: Task workspace showing sample reaching trajectories from one participant. Twentyfive black circles depict the workspace and possible target locations. Green circle: start location; red circle: the goal target (the only visible cue). Thick blue and red lines: unseen trajectories. Purple stars: the location where the participant indicated (s)he had reached the goal. Thin Purple line: Euclidean reach error.

1. Immediate Effects of Vibrotactile Feedback Practice

With visual feedback of the cursor but no vibrotactile feedback (Fig 12, Block 1; V+T–), reaching error was minimal at 0.12 ± 0.01 cm (mean \pm SEM) and subjects required 1.99 ± 0.14 s to complete and report the reach. In the absence of both visual and vibrotactile feedback, target capture error averaged 2.25 ± 0.16 cm and target capture time was 2.50 ± 0.25 s (Block 2; V–T–). Thus, upon removing visual feedback of performance (V–T–), movement accuracy degraded greatly relative to the baseline V+ feedback condition ($t_{10} = 13.76$, p < 0.05) and movements required a longer amount of time ($t_{10} = 3.53$, p < 0.05).

Participants improved their reach accuracy over a short period of practice, involving only 125 movements spanning approximately 30 min. Target capture error in the first block of VTF practice (Block 6) averaged 2.09 ± 0.14 cm, whereas error in the last block of VTF practice (Block 10) averaged 1.76 ± 0.14 cm. By the end of practice, target capture errors approached the limit of performance expected from projecting an estimate of vibrotactile sensory acuity in the arm, as described by our earlier work (Shah et al. 2019a), onto the plane of hand movement. Across participants, we found the decrease in target capture error from the start to end of practice to be statistically significant ($t_{10} = 3.04$, p < 0.05). Mean target capture time at the beginning of practice (5.84 ± 1.75 s, Block 6) did not significantly differ ($t_{10} = 0.801$, p > 0.05) the end of practice (4.93 ± 1.08 s, Block 10).

2. Effect of Practice on Dual Task Performance

Consistent with a transition from the cognitive phase of motor learning to the associative phase (Fitts and Posner 1967), we found that the learning achieved through

VTF practice in the simple reaching task was transferred to the dual-task condition. Whereas target capture errors in the pre-practice dual-task averaged 2.22 ± 0.18 cm (Block 5), errors in the post-practice dual-task averaged 1.89 ± 0.14 cm (Block 11).



Figure 12: Left: target capture error magnitude (cm). Right: target capture time (s). Grey bars: reaching only trial blocks that include VTF (T+); White bars: reaching only trial blocks without VTF (T–). Blue bars: dual-task trial blocks that include VTF (T+). V+: concurrent visual feedback; V–: no visual feedback during movement. Horizontal black lines with endcaps: statistical comparisons that reached significance (p < 0.05). Horizontal red lines: the magnitude of movement corresponding to 1 vibrotactile JND for two selected dermatomes (C7 and T1) under the mapping used to project hand position into the vibrotactile interface. ITD indicates the intertarget distance of 2.85 cm. Error bars: mean ± SEM.

This change reflects a significant decrease in target capture error as a result of VTF practice in the simple reach task ($t_{10} = 2.44$, p < 0.05). By contrast, a comparison of mean target capture time pre-practice (Block 5: 4.91 ± 1.00 s) vs. post-practice (Block 11: 4.52 ± 0.84 s) did not find a significant decrease ($t_{10} = 0.62$, p > 0.05),

suggesting that the use of VTF had not yet moved beyond the associative phase toward automaticity.

3. Secondary Task Performance

We also examined participants' performance of the Button Press Task during preand post-practice dual-task. Prior to practice, participants pressed the correct button 93.6 \pm 2.1% of trials. After practice, participants continued to perform at a similar rate of success (97.0 \pm 0.8% of trials). Participants did not show any improvement in the untrained secondary task (t₁₀ = 1.93, p > 0.05 after Bonferroni correction), demonstrating that practice effects due to reach practice with VTF were specific to the trained task.

D. Discussion

This study tested the extent to which reductions in target capture error resist dualtask interference from a choice reaction task that increased cognitive load. Our results indicate that healthy participants can indeed use VTF to complete goal-directed reaches in a dual-task situation, and that practice-dependent performance gains are preserved while performing a simultaneous cognitively demanding task. We also observed no aftereffects of VTF-guided reach practice when VTF was removed. Therefore, the performance improvements reported here were due specifically to the real-time use of VTF for ongoing control of reaching, rather than a general performance improvement due to, for example, improved calibration of proprioceptive sensation.

We also found that VTF-guided reaching required increased target capture time. This finding was consistent across all trial blocks involving VTF. In contrast to the practice-induced improvements in the target capture error, we found no significant improvements in the target capture time after VTF-guided reach practice. Taken together, these findings demonstrate that participants began to transition between the cognitive and associative phases of learning (Fitts and Posner 1967; Rosenbaum 2010) within a single short bout of practice on the VTF-guided reaching task.

By contrast, performance on the Button Press Task did not improve following reach practice, suggesting that practice-dependent improvement in reach performance did not result from increased automaticity of vibrotactile control during reaching. We base this conclusion on the Capacity Sharing Model of attentional resources (Pashler 1994), which states that attention is a finite resource shared across tasks, and that if two or more tasks are performed simultaneously, each task can access less attentional capacity than if it were performed individually, which can lead to degraded performance. If practicedependent improvement in reach performance did originate from increased automaticity of control, we would have expected the Button Press Task to then gain access to additional attentional capacity released by the automatization of VTF-guided reaching. Because we observed no improvement in performance of the secondary task, we conclude that a short bout of VTF practice did not reduce the attentional resources required by VTF-guided reaching.

Vibrotactile feedback was easy to learn in the sense that our subjects were not told how the vibration frequency encoded their movements, yet within one practice session (125 trials) they were able to improve their ability to use VTF to reach accurately. Thus, our participants learned to use novel information (vibrotactile feedback) to complete a goal-directed reaching task, with ease and without explicit instruction, in the absence of visual feedback. Intuitiveness and automaticity are important when considering the use of VTF for sensory augmentation or substitution especially for individuals with somatosensory impairment on a portion of their body (e.g., some stroke survivors), who may also present with cognitive deficits that can reduce their ability to correctly interpret novel sensory stimuli and integrate them into the ongoing control of movement. In this study, we have shown that within a single day of practice, participants experience motor learning through parts of the cognitive and associative stages but have not yet reached the autonomous stage (Fitts and Posner 1967; Rosenbaum 2010). Future studies should repeat the current study with participation in a long-term VTF-based practice program to determine the extent to which VTF-guided reaching can become autonomous with practice, thereby enabling improved dual-task performance on secondary tasks requiring visual attention or other forms of cognitive load.

Because vibration frequency and amplitude are coupled in the ERM tactors used in this study, our vibrotactile interface is limited in the way it can encode information about the moving limb. We cannot, for example, encode independent X- and Y-axis motions along the coupled dimensions of vibration frequency and amplitude, nor could we use frequency and amplitude of vibration to encode hand position and velocity, respectively. This is not a concern in the present study because we used separate vibrotactile channels to encode hand position along X- and Y-axis motions within a Cartesian reference frame centered on the target workspace. This choice of reference frame was one of convenience, due to our use of the planar manipulandum to track hand motion. Future studies should explore other limb state encoding schemes that might be more easily implemented using existing wearable motion sensors, as well as the kinematic and cognitive impact of adding additional channels to the vibrotactile interface to simultaneously encode, for example, the 3D position of the hand and grasp force.

E. Conclusions

This pilot study investigated the extent to which the learned ability to use VTF to guide reaching is impacted by simultaneous performance of a secondary task. We found that VTF practice can induce performance improvements of reaching but did not improve performance of a choice reaction time task. The improvements in reaching error during dual tasking indicates that VTF can be used while multi-tasking. Due to the efficacy of the short practice bout described here, we conclude that a single short bout of practice sufficed for participants to begin the transition between the cognitive and associative phases of learning for the integration of VTF into the planning and ongoing control of reaching movements. Future studies should explore the impact of long-term (multi-day) practice on the accuracy, stability, and automaticity of VTF-guided reaching.

VI. IMPACT OF INTERMEDIATE-TERM PRACTICE ON LEARNING TO USE VIBROTACTILE FEEDBACK TO GUIDE ARM MOVEMENTS

In this chapter, we investigated the effects of five ¹/₂ hour practice sessions (2.5 hours total practice) on learning to use vibrotactile feedback (VTF) to guide reaching. In the previous chapter, we found that healthy participants started to show kinematic improvements in movement accuracy but not efficiency after a single practice session. If learning in our task follows the three stage Fitts and Posner Model (Fitts and Posner 1967), we expect that increasing the amount of practice over several session will lead to improvements in performance of VTF-guided reaching by increasing both reaching accuracy and efficiency.

A. Introduction

Body-machine interfaces (BMIs) are devices that allow for transfer of information and control of devices (Casadio et al. 2012; Choi and Kuchenbecker 2013; Mussa-Ivaldi, Casadio, and Ranganathan 2013). Vibrotactile feedback (VTF) has been a popular choice to provide relevant feedback to the user through the skin (Dozza et al. 2007; Kaczmarek et al. 1991; Kapur et al. 2010; Lee et al. 2013; Tzorakoleftherakis et al. 2016). The skin has mechanoreceptors that allows humans to sense numerous intensities of vibrations (Burgess 1973; Hunt 1974; Purves 2012). We previously showed that multiple vibrations applied to the arm can be discriminated with just ~33 Hertz difference (Shah et al. 2019a). This perceptual capability makes vibrotactile feedback a very feasible method to transfer information to users from a BMI (Kapur et al. 2010; Krueger et al. 2017; Lam et al. 2008; Tzorakoleftherakis et al. 2016; Witteveen et al. 2015). In addition, VTF has the potential to off-load visual attention (Ho, Reed, and Spence 2006), it is non-invasive, and it can be implemented inexpensively (Broccard et al. 2014).

However, VTF is cognitively demanding as it requires the user to sense the vibration, decode the provided information, and produce a response related to the conveyed information (Gallace et al. 2008; Haggerty et al. 2012; Risi et al. 2019). Thus, for successful implementation of VTF in BMIs used by patients with cognitive deficits, it is important that we understand the attentional demands of this feedback and whether the relevant attentional load (Pashler 1994) can be reduced through practice.

In our previous work, we studied how one session of practice affects healthy people's capability to use VTF to guild reaching (Shah et al. 2018). We found that one 30-minute session of practice resulted in improvements of reaching accuracy but came at a cost of increased target reaching time. Additionally, we found no significant improvements to perform a secondary task while also using VTF to guide a reaching movement. We concluded that more practice is required for sensorimotor learning to occur during VTF guided reaching (Fitts and Posner 1967).

Based on our previous work, we hypothesize that increased practice on using VTF to guide movements will lead to a reduction in cognitive resources needed to use VTF information and thus performance enhancements provided by practice will not be susceptible to interference from a secondary task (i.e., practice improves performance in both a primary VTF task and secondary, attentionally demanding task). We tested this hypothesis by using a dual-task scenario, where participants must perform VTF-guided reaching and a choice reaction time task simultaneously before and after receiving practice of the use of VTF.

B. Methods

1. Participants

Fifteen neurologically-intact participants (9 female) ranging in age from 21-29 years (26.3 yr ± 6.2 yr), with no known tactile or cognitive deficits were recruited from the University of Genoa community (Genoa, Italy). Fourteen participants self-reported as right-hand dominant and one participant reported as left hand dominant. All participants were naïve to the use of vibrotactile feedback for movement control and all were naïve to the experimental objectives. In accord with the 1964 Declaration of Helsinki, all participants volunteered for the study, and all provided written consent to the experimental procedures, which were approved by local Institutional Review Boards serving the University of Genoa (ASL3 Genovese) and Marquette University.

2. General Procedures

Each participant completed five experimental sessions, lasting approximately 30-90 mins each. Sessions were spaced at least 6 hours apart. Participants grasped the handle of a custom, planar manipulandum (see Ballardini et al. (2018) for details) and made reaching movements in the horizontal plane with their dominant hand. A computer screen (23.6" Samsung B2430L) was located directly in front of the participant and was used to display a 5x5 target grid of 25 targets and a cursor which corresponded to the instantaneous position of the manipulandum's handle (Fig 13; also see Fig 10). Subjects rested their non-dominant arm on a rigid support structure with the index, middle and ring fingers resting gently above the numeric keys of a standard computer keyboard. Three keys were used to record participant responses during a secondary choice reaction time task. The manipulandum and dominant arm were blocked from view.



Figure 13: Vibrotactile interface (4 tactors) attached to the non-dominant, non-moving arm. The dominant arm controlled a manipulandum handle to make reaching movements on a grid in the task space made of a 5x5 target grid.

Subjects wore noise-cancelling headphones to minimize auditory cues during the experimental tasks.

3. Visual Stimuli and Vibrotactile Interface

Visual stimuli were created in PsychToolbox (MatLab 2017a). Reach targets (0.50 cm diameter) were arranged in a 5x5 grid with corresponding nearest-neighbor distances on the screen equal to 2.85 cm. Note that this inter-target distance is approximately equal to the range of uncertainty within proprioceptive perception of limb position (2.5 ± 0.2 cm), as derived using joint angular uncertainty values reported by Fuentes and Bastian (2009).

A vibrotactile interface was attached to the non-dominant (non-moving) arm (Fig 13). The interface was comprised of four miniature, eccentric-rotating-mass (ERM) "tactors" (Precision Microdrives Ltd, Model # 310-117). The tactors were powered and controlled from a customized microcontroller circuit that interfaced to the Matlab computing environment (version 2017a; the MathWorks Inc.) using the Matlab Arduino Support Package. The tactors operated between 60 Hz to 250 Hz. At their peak vibration frequency, the tactors produce a peak vibrational amplitude of 2.8 G.

Vibrotactile feedback was provided as limb-state feedback, such that the vibration intensity increased as the hand diverged from the center of the grid. Near the center of the grid the intensity was set to 0 Hz; moving 1 target away from the center increased the vibration to 135 Hz in the affiliated tactor; and at 2 targets away, the intensity was increased to 230 Hz. Inter-target distance was 2.85 cm, so a change in hand position of ~1 cm, produced a change of about 33 Hz in the tactors (just noticeable difference (JND) of ~33 Hz for dermatome C7 on the lateral forearm (Mahns et al. 2006; Shah et al. 2019a)). Participants needed to move at least two vibrotactile JNDs in the workspace to reach from one target to an adjacent target under the guidance of VTF. If the cursor moved outside of the grid by 0.5 cm, VTF increased to its maximum frequency (>250 Hz); participants were informed that maximum vibration was only reached when they had left the desired workspace.

4. Task Blocks

Participants completed up to 12 blocks per experimental session. The task schematic in Figure 14 shows the blocks completed during each session. Participants performed a primary reaching (Rch) task alone and concurrently with a secondary cuedchoice reaction time (CRT) task as a dual-task (DT). Rch was performed under three feedback conditions: Visual Feedback Only (Vis, T-); No Feedback Condition (NoVis, T-); VTF Only (NoVis, T+). During Rch, participants were instructed to reach as accurately and quickly as possible. Participants verbally indicated when they believed they reached the goal target. During practice, participants performed 125 VTF (NoVis, T+) guided reaching trials (approx. 30 mins), resulting in 2.5 hours of total practice after five experimental sessions. The DT was performed prior to practice on session 1, postpractice on session 3, and post-practice on session 5.

5. Sequence of Events During One Dual-Tasking Trial

During DT, participants performed the Rch task and the CRT task simultaneously in each trial. A trial started with a ring-shaped target appearing at one of the target locations. The color of target could be red, blue, or green and each color was assigned a key on the keyboard under the non-moving hand. Participants were instructed to begin



Figure 14: This schematic describes the sequence of task blocks for each session. On session 1, participants performed 25 trials of Visual Feedback Only (*Vis*) reaching, followed by No Feedback Condition (*NoVis*) reaching. They then performed the dual task (*Pre*). After this, they received 125 trials of practice on VTF-guided reaching (*Prc*), followed by post-practice assessment of DT (*Post*). Sessions 2-5 consisted of practicing 125 trials of VTF-guided reaching (*Prc*). On the 3rd and 5th session, post-practice DT (*Post*) was also performed.

reaching to the target (VTF on) as soon as they saw the ringed target appear. After 350-850 ms, the target changed from ring-shaped to a solid circle (at the same location and filled with the same color as the ring). Participants were instructed to press the color corresponding keyboard key as soon as they saw the change in the target shape, even while moving towards the target. Participants were instructed to continue reaching towards the target while pressing the keys. Participants verbally indicated when they reached the target, marking the end of the trial. After 1-2 s, a new ring-shaped target appeared marking the start of the next trial.

6. Statistical Hypothesis Testing

We sought to address the hypothesis that practice on VTF-guided reaching leads to reduced cognitive load required to integrate VTF information into motor control of the arm and thus performance enhancements provided by practice will not be susceptible to interference from a secondary task. We used repeated measures ANOVA and post hoc, Bonferroni-corrected, one-tailed, paired samples t-tests to test the statistical significance of changes in performance after practice.

In the Rch Task (single or during DT), we computed target capture error as our primary measure of performance. Target capture error was defined as the absolute distance between the actual target location and the final location of the cursor at the end of the movement. Our secondary measure of performance was target capture time, defined as the time difference between reach trial start and participant indication of target capture. We sought to verify that VTF practice would indeed result in improved kinematic performance in the Rch task. If the beneficial effects of reach practice are robust against DT interference, we would anticipate that practice dependent improvements in reaching performance would also be evident in the DT. Reaching errors and target capture times were averaged across practice blocks (average of 125 trials per session) for VTF-guided reaching, for each participant. Reaching errors and target capture times were averaged across 25 trials for non-practice blocks for each participant. Statistical analysis was completed using participant averages for the data measures (df = 14), allowing us to compare within subject effects of practice.

In the CRT Task, we computed the number of correct key presses (choice accuracy) and choice reaction time. Based on the Capacity Sharing Model (Pashler 1994), we anticipated that reduced interference due to practice related improvements in reach performance might result in better CRT task performance during DT. Here, we used a one-tailed, paired samples t-tests to evaluate performance during the CRT task during DT after practice. All analyses were performed with SPSS Statistics 24 (IBM Corp). Statistical significance was set at a family-wise error rate of $\alpha = 0.05$.

C. Results

In this study, participants grasped the handle of a planar manipulandum with their dominant hand and practiced performing a horizontal planar reaching task guided by vibrotactile stimuli that encoded real-time limb-state feedback of the moving hand. We hypothesized that practice on VTF leads to reduced cognitive load needed to use VTF information and thus performance enhancements provided by practice will not be susceptible to interference from a secondary task. Figure 15 shows a representative participant's reaching trajectories pre- and post-practice. Figure 16 shows the sample population results of the average reaching error and figure 17 shows the sample population results of the average target capture time for task blocks in each session.

1. Kinematic Performance During VTF-guided Reaching Improves with Practice

Figure 16 shows the sample population results of the average reaching error and figure 17 shows the sample population results of the average target capture time. Visually guided reaching produced minimal reaching errors (0.11 ± 0.01 cm, mean \pm SEM) and the fastest times to capture the target (2.08 ± 0.19 s). When no feedback was provided and participants relied on intrinsic proprioception, reaching errors significantly increased



Figure 15: Sample reaching trajectories from a representative participant during RCH task under various feedback conditions. Blue trajectory indicated visually guided reaching. The red trajectory shows no external feedback reaching (no vision, no VTF). Purple and green trajectories show pre- and post-practice VTF-guided reaching trajectories, respectively. Cyan dots indicate end of the reach.

to 2.67 ± 0.09 cm (t₁₄ = 30.7, p < 0.05, Fig 16: black asterisk) along with significantly longer target capture times (2.67 ± 0.22 s; t₁₄ = 2.93, p < 0.05, Fig 17: black asterisk). rmANOVA (Greenhouse–Geisser adjusted for sphericity) showed that target capture
error changed significantly over the five sessions of practice ($F_{GG(2.61,36.5)} = 5.83$, p < 0.05). During the first bout of practice, average reaching error for VTF-guided movements (2.50 ± 0.08 cm) decreased compared to the no feedback condition, but not



Figure 16: Average reaching error during the Rch task across five sessions. Colored asterisks (*black, red , blue, green*) show significant differences between reaching error. T+ and T- indicate VTF on and off, respectively. *Black* bars indicate the DT condition, *Gray* and *white* bars indicate the single Rch task. Error bars indicate \pm SEM.

yet significantly ($t_{14} = 1.61$, p = 0.067). Reaching error decreased significantly (2.17 ± 0.10 cm) after five sessions of practice for VTF-guided reaching, compared to the no

feedback condition and during the first session of practice ($t_{14(no feedback)} = 4.50$, p < 0.05, Fig 16: red asterisk; $t_{14(1st session)} = 3.19$, p < 0.05, Fig 16: blue asterisk).

During the first bout of practice, the average target capture time for VTF-guided reaches (4.17 \pm 0.51 s) was significantly higher than reaching with no feedback (t₁₄ = 3.85, p < 0.05, Fig 17: magenta asterisk). After five sessions of practice, average target capture time decreased to 3.40 \pm 0.40 s compared to reaching during the first practice session (t₁₄ = 2.21, p < 0.05, Fig 17: blue asterisk). However, target captures times did not become as efficient (i.e., remained significantly higher) as reaching under no feedback (t₁₄ = 2.00, p < 0.05, Fig 17: red asterisk) after five sessions of practice. Overall, practice resulted in improvements to VTF-guided reaching performance in both reaching accuracy and target capture time, although target capture times never became similar to those of reaching with no feedback.

2. Dual-Tasking Retains Performance Improvements after Practice

While dual-tasking, average reaching errors decreased as a result of practice ($F_{(3,42)} = 8.376$, p < 0.05) and followed the same trend as the single Rch task. The average DT reaching error during the first session (2.74 ± 0.15 cm) was reduced significantly after the fifth session of practice (reduced to 2.20 ± 0.13 cm; $t_{14} = 4.54$, p < 0.05, Fig 16: green asterisk). At the end of five sessions, reaching error during the single Rch task and during DT was not significantly different ($t_{14} = 0.24$, p = 0.812). Dual-tasking target capture times saw a similar trend across the five sessions as the single VTF-guided Rch task. However, rmANOVA did not find any significant differences across sessions ($F_{(3,42)} = 1.27$, p = 0.30). Average DT target capture time during the first session was 3.95 ± 0.76 s and decreased to 3.28 ± 0.42 s during the fifth session. At the end of five sessions, target



Figure 17: Average target capture time during the Rch task across five sessions. Colored asterisks (*black, red, magenta, blue*) show significant differences between capture time. T+ and T- indicate VTF on and off, respectively. *Black* bars indicate the DT condition, *Gray* and *white* bars indicate the single Rch task. Error bars indicate \pm SEM.

Participants were accurate in their choice during the secondary CRT task prior to practice (91.6 ± 3.30). After five session of practice, CRT task choice accuracy increased significantly to 99.1 ± 0.045 % ($t_{14} = 2.25$, p < 0.05). Participants also reduced their choice reaction times for CRT. Participants started had a reaction time of 2096 ± 554 ms prior to practice VTF-guided reaching. After five sessions of practice, reaction times significantly reduced to 960 ± 204 ms ($t_{14} = 2.40$, p < 0.05).

D. Discussion

This study examined the extent to which kinematic performance improves with increased practice with VTF to guide reaching. Participants used a multi-channel vibrotactile interface attached to the non-moving arm to guide and control movements of the dominant arm. The VTF provided limb-state information of the moving hand in the workspace grid. Our results indicate that healthy participants can use VTF to guide reaches in the absence of visual feedback and this performance benefit persists during DT. Practice related performance gains are preserved while performing a concurrent cognitively demanding task. In our previous study (Shah et al. 2018), we identified improvements in reaching accuracy after just one bout of VTF guided reaching practice, yet people did not become significantly faster in capturing the target. In this study, we extended the sessions of practice, which resulted in participants becoming more efficient in their capability to reach using VTF, but not to the level of reaching with intrinsic proprioception.

1. Vibrotactile Feedback Improves Reaching Accuracy Beyond That of Intrinsic Proprioception

When visual feedback of movement was provided, participants could reach to targets with accuracy, precision, and efficiency. Reaching accuracy degraded and

movements became highly variable and slower when visual feedback of movements were removed. This degradation in reaching performance is likely due to accumulating errors caused by noise inherent to the sensory and motor signals used for updating estimates of limb position (Wolpert, Ghahramani, and Jordan 1995; Wolpert, Goodbody, and Husain 1998). When limb-state VTF was provided in place of visual feedback of movements, movements started to become more accurate after one bout of practice but movement times increased significantly. This increase in movement time likely resulted because more time was required to sense, process, and integrate VTF into the ongoing control of movements (Haggerty et al. 2012). At the end of 2.5 hours of practice, participants could reach with increased accuracy and faster target capture times under the guidance of VTF compared but movements were not yet efficient (target capture times were still higher than reaching with intrinsic proprioception).

The results of the current study are in line with our previous studies (Risi et al. 2019; Shah et al. 2018), where we found that people are indeed able to use VTF guide movements after short-term practice. In the present study, we also found that these performance enhancements gained through extended practice allow for better performance during a secondary task, where we see improvements in reaction times and choice accuracy. Dupin et al. (2015) have also shown that showed that people can successfully integrate proprioceptive information from a moving limb with haptic information from a nonmoving limb. This integration forms a similar percept to when making single limb movements while interacting with the environment. Within our study, it seems that healthy participants have the capability to integrate VTF into the ongoing control of goal directed movements in the absence of visual feedback.

2. Short-Term Practice Displays Cognitive Phase Characteristics of Fitts and Posner Motor Learning Model

Humans have the capability to adapt to new movements relatively quickly (Scheidt et al. 2000, 2005). However, motor learning is necessary for the long-term acquisition of a skill and mastery of movements (Ericsson et al. 1993; Magill and Anderson 2017). The Fitts and Posner motor learning model (Fitts and Posner 1967) theorizes that learning occurs in three distinct stages. Practice of a motor skill advances the learner through the three stages of learning. In the first stage of learning, the cognitive stage, the learner tries to acquire the movements for the skill, focusing on what to do and how to do it (requiring cognitive resources). The learner is focused on instructions and relies heavily on external feedback of their movements (knowledge of results). In terms of behavior in using VTF to guide movement, during the cognitive stage we see numerous errors in reaching (low accuracy), high movement variability (low precision), and low efficiency in movements (higher target capture times). In our experimental design, the participants were able to see their movements error after the reaching trial ended, thus able to use knowledge of results to improve reaching performance. Additionally, the VTF was on during this time and participants could associate the intensity and combination of ERM motors activated at the correct target location/hand position. This allowed participants to be actively aware of their movement errors and begin the learning process to integrate VTF into ongoing movement control.

With practice (in our experimental design after 2.5 cumulative hours of practice) people are able to advance towards the second stage, the associative stage. During this stage, the learner tries to associate specific environmental and sensory feedback cues with the movements. The learner is focused on refining movements, leading to reduced

movement errors and movement variability. In terms of behavior in VTF guided reaching, our results show that participant movements become more accurate. However, we can infer from our results that participants are not yet in the associative phase since their movement are not yet efficient (VTF-guided reaches are still significantly slower than reaching with intrinsic proprioception).

3. Vibrotactile Feedback Guided Movements Become Decomposed

Participants also adopted a new movement strategy and continued to use this strategy throughout practice, where movements were made along the cardinal axis of the VTF interface and the target workspace (decomposition; (Risi et al. 2019)). Figure 15 shows this decomposition in reaching trajectory from a representative participant in the VTF-guided movements. Vibrotactile feedback requires numerous steps for its integration into the motor control pathway of limb movements. It requires the user to sense the vibration, decode the provided information, and produce a response related to the conveyed information (Gallace et al. 2008; Haggerty et al. 2012; Risi et al. 2019). In our previous work (Shah et al. 2019a), we showed that people are better at perceiving sequentially delivered vibrotactile stimuli rather than simultaneous vibrotactile stimuli. Perhaps as a strategy to better perceive the provided VTF information, participants choose to move along one axis of the VTF interface first and then the other.

The representative participant shown in Figure 15 moves along the horizontal axis prior moving in along the vertical axis to reach the target when moving under the guidance of VTF. Can this decomposition strategy be returned to normal, single velocity peak, straight-line movements with further practice or as people enter the associative

stage of motor learning? Future studies should investigate the effects of long-term practice on the use of VTF to guide and coordinate hand movements.

E. Conclusions

In this study, we asked participants to make targeted reaching movements using VTF when visual feedback was removed. Through extended short-term practice, participants successfully used VTF to improve their reaching accuracy, but their movements were still inefficient and took longer than moving using intrinsic proprioception. Participants also showed a capability to dual-task after practice with increased choice accuracy and reaction times of the secondary task while maintaining movement accuracy in the VTF-guided reaching task. However, participants strategized their movements by moving along the cardinal axis of the vibrotactile interface, likely in order to enhance their perception and discrimination of VTF. Future studies should investigate long-term practice on the use of VTF to guide reaching movements to identify if decomposed movements become normalized or if this strategy is remains throughout.

VII. LONG-TERM PRACTICE RELATED CHANGES IN VIBROTACTILE FEEDBACK GUIDED REACHING BEHAVIOR

In the previous two chapters we concluded that short-term practice (less than 2.5 cumulative hours) results in some performance improvements in reaching accuracy during vibrotactile feedback (VTF) guided reaching. However, neurologically intact people are still inefficient reaching under the guidance of VTF because their reaching movements take longer to complete compared to reaching with no visual feedback (using proprioceptive feedback). Could this inefficiency be reduced as we increase time spent practicing? In this chapter, we investigated the outcomes of long-term practice on using VTF to guide reaching and motor learning.

A. Introduction

The human brain has the capability to integrate multiple senses, such as vision and proprioception, to control body movements (Scott 2004; Sober and Sabes 2003). Neurodegenerative diseases such as stroke (Carey and Matyas 2011; Dukelow et al. 2010), spinal cord injury (Crewe and Krause 2009; Morrison et al. 2018), and multiple sclerosis (Gandolfi et al. 2015; Nelson, Fabio, and Anderson 1995) can negatively impact the brain's capability to integrate sensory feedback, leading to impaired human motor control. Impaired motor control makes it more difficult to perform activities of daily living and increases overall healthcare costs for patient populations (Katan and Luft 2018; Morrison et al. 2018; Mozaffarian et al. 2016). Improving motor ability and successful performance of activities of daily living can significantly improve independence and quality of life in patients (Gulick 1997; Haghgoo et al. 2013; Muren et al. 2008). Body-machine interfaces (BMIs) have shown promise in improving quality of life through rehabilitation of motor control (Mussa-Ivaldi et al. 2013; Pierella et al. 2014).

Recent advances in BMIs have demonstrated that external stimuli can be substituted for sensory modalities impaired by neurodegenerative diseases or to augment intact sensory modalities, leading to improved motor control of the body (Broccard et al. 2014; Casadio et al. 2012; Pierella et al. 2014). These BMIs allow for bidirectional sensory information transfer between devices and their users (Broccard et al. 2014; Casadio et al. 2012; Mussa-Ivaldi and Miller 2003). BMIs have utilized vibrotactile feedback (VTF) as a common method for non-invasive interface of information (An et al. 2011; Ariza et al. 2017; Cipriani et al. 2012; Ferris and Sarter 2011; Ho et al. 2006; Kaczmarek et al. 1985). Vibrotactile feedback has been applied to substitute for lost sensations such as sight (Kaczmarek et al. 1985), balance (Dozza et al. 2007; Sienko et al. 2008; Wall et al. 2001), and proprioception (Cuppone et al. 2016; Krueger et al. 2017). Augmentation of intact senses has also proven to be promising (e.g., alarming doctors (Ferris and Sarter 2011), improving driving (Ho et al. 2006), or increasing reaching performance (Risi et al. 2019)).

In our recent work (Krueger et al. 2017; Risi et al. 2019; Shah et al. 2018), we investigated limb-state VTF used to enhance motor control of the arm in a 2D workspace. Our results showed improved motor performance in healthy individuals while using VTF to guide reaching in the absence of visual feedback. Additionally, users adopted a strategy where they decomposed their movements along the axes of the workspace and VTF interface (Risi et al. 2019). This strategy may have been the result of two factors: by the relative increase in cognitive resources required to process simultaneous vibrotactile

stimuli on the skin (Haggerty et al. 2012; Wu and Liu 2008), and/or by the empirically observed advantage in the perceptual acuity of vibrotactile stimuli delivered sequentially over those delivered simultaneously (Shah et al. 2019a). Given that subjects were instructed to maximize accuracy in reaching, both of these factors could have motivated subjects to maximize VTF acuity by moving first along one VTF channel and then along the other.

Practicing the use of VTF to guide reaching can potentially lead to a decrease in cognitive resources needed to process and integrate this VTF into the motor control system of the brain (Shah et al. 2018). If motor learning of VTF-guided reaching follows the Fitts and Posner motor learning theory (Fitts and Posner 1967), then cognitive resources needed to process and integrate supplemental VTF into motor control pathways should be reduced with extended practice. If the decomposition of VTF-guided reaching is driven by a bottleneck in the cognitive processing of simultaneous vs. sequential vibrotactile stimuli (Haggerty et al. 2012; Pashler 1994; Shah et al. 2019a; Wu and Liu 2008), then well-practiced VTF-guided reaching may revert to the straight-line movements seen during visually guided or proprioceptively guided reaching as subjects transition through the associative stage of skill acquisition.

We therefore sought to understand the effects of long-term practice on motor performance during VTF-guided reaching. We hypothesized that VTF-guided reaching follows classical motor learning (Fitts and Posner 1967) such that reaching performance improvements accrue in a way that is resistant to Dual-Task (DT) interference. Cognitive resources needed to perform VTF-guided reaching will be reduced after long-term practice, leaving more cognitive resources available to increase performance of a concurrent, secondary task (during DT). Through testing our hypothesis, we will determine if long-term practice will advance people out of the first phase of motor learning, and whether this leads to a decrease in movement decomposition during VTF-guided reaching.

To test our hypothesis, we asked healthy, young adults to practice using VTF to guide their reaching in a 2D workspace. We analyzed reaching performance before, during, and after participants received approximately 10 hours of practice on using VTF to guide reaching. Our results showed motor learning of VTF-guided reaching through a decrease in reaching error and target capture time but movements remained decomposed. Additionally, we saw improvements in DT performance. We expect our results will improve our understanding of the extent to which people need to be trained to induce motor learning and successfully use VTF for sensory augmentation/substitution. This will enhance our use of VTF to provide performance feedback in BMIs for patients with sensorimotor deficits caused by neurodegenerative diseases.

B. Methods

1. Participants

Fifteen neurologically healthy participants (8 females) ranging in age from 23-28 years $(23.3 \pm 1.4 \text{ yrs})$ with no known cognitive deficits or tactile deficits of the arm volunteered from the University of Genoa community (Genoa, Italy). Eleven participants self- identified as right-handed, 4 self-identified as left-handed. All participants were naïve to vibrotactile feedback and the experimental objectives and provided written consent to the experimental procedures, which were approved by Institutional Review

Boards serving the University of Genoa and Marquette University, in accordance with the Declaration of Helsinki.

2. Experimental Setup

Visual stimuli were created using PsychToolbox for MatLab (Mathworks Inc). Reaching targets (0.50 cm diameter) were arranged in a 5x5 grid on a visual display (LG Inc, Model: 23EA63V-P), with inter-target distance of 2 cm (below the range of proprioceptive uncertainty of limb position $(2.5 \pm 0.2 \text{ cm})$; cf., Fuentes and Bastian (2010)). A passive, 2D manipulandum was used to move an onscreen cursor to reach targets (for design specification see Ballardini et al. (2018)). A vibrotactile interface was created using four eccentric rotating mass vibration motors (ERM; Precision Microdrives Inc, Model: 310-117). The vibration motors were powered and controlled using drive circuitry that was interfaced to a portable laptop computer running a custom script within the MATLAB R2017a computing environment (MathWorks Inc., Natick MA). The vibrotactile interface was calibrated such that a hand displacement of one target from the center (2 cm) resulted in a vibration change of ~ 60 Hz (almost two-fold of the prepractice just noticeable difference (JND) reported for the volar forearm by Shah et al. (2019a)). The interface operated in a piecewise fashion: at the center of the grid, vibration was turned off up to a distance of 0.6 cm; from 0.6 cm to 4 cm (just outside of the center target to outer targets) vibration ranged from ~120-245 Hz; at distances >4 cm, vibration was set to maximum at >255 Hz. Figure 18 shows a schematic of the grid workspace and the vibrotactile interface attached to the arm.



Figure 18: Vibrotactile interface made of four ERM motors attached to the non-moving arm while the moving arm works in a 5x5 reaching target grid.

3. Experimental Procedure

Each participant was asked to complete 20 experimental sessions, spaced at least 6 hours apart. Experimental session duration ranged from 30-90 minutes, depending on the number of task blocks completed. During each session, participants were required to reach to targets on a screen using the handle of a planar manipulandum placed in front of them (see Fig 10). Reaching movements were completed in the horizontal plane using the dominant hand under various cursor feedback conditions. During each session, participants received ~30 mins of practice on VTF-guided reaching, totaling ~10 hours at the end of the final session. A vibrotactile interface attached to the non-moving arm

provided limb-state VTF. The non-moving arm rested on a rigid support structure (Fig 18). The index, middle, and ring fingers of the non-moving arm were used to perform concurrent button presses on a standard computer keyboard during the dual-tasking blocks. The view of the reaching arm was occluded and noise-cancelling headphones played white noise to minimize auditory cues/distractors.

4. Experimental Tasks

The experiment consisted of two tasks: A primary ReaCHing task (RCH) and a secondary Choice Reaction Time task (CRT). These tasks were performed individually or concurrently as a Dual-Task (DT). RCH was performed under three cursor feedback conditions: Visual feedback (V+T-), VTF (V-T+), or no feedback (V-T-). During each trial of RCH, participants were instructed to reach to a visual target presented on the screen as quickly and accurately as possible. Participants verbally indicated when they had reached the target, ending the trial. At the end of the trial, participants were given visual feedback of the cursor and were required to center the cursor to the correct target

Block	Trials	Task	Feedback	Session	Туре
1	25	RCH	V+T-	1	Baseline
2	25	RCH	V-T-	1	Baseline
3	<u>></u> 25	CRT	N/A	1,10,20	Familiarization
4	<u>></u> 25	RCH	V+T+	1-20	Familiarization
5	25	DUAL	V-T+	1	Pre-Practice
6-10	25/block	RCH	V-T+	1-20	Practice
11	25	DUAL	V-T+	1,10,20	Post-Practice

Table 5: Blocks that could be performed during each session.

location, which was the starting location for the next reaching trial. CRT was performed concurrently with RCH during DT. During CRT, participants were instructed to press a button on a standard computer keyboard as quickly as possible after the colored circle target appeared. The onscreen target started as a white ring that changed to a color-filled target after some random time (350-850 ms). The targets could be one of three colors: red, blue, or green. Participants used their index, middle, and ring fingers of the non-moving arm to press the color-corresponding buttons. The DT was performed as a test of divided attention. Participants were asked to perform RCH and CRT at the same time during DT. RCH during DT was performed with VTF.

5. Experimental Blocks

Participants performed trials of RCH, CRT, and DT in blocks during each session. Each block consisted of 25 trials. Table 5 shows the blocks along with the task type, the feedback used during the block, and the block classification. Participants received practice (blocks 6-10) during all 20 sessions, while the post-practice assessment of DT (block 11) was measured during the 1st, 10th, and 20th session.

6. Data Analysis

To assess reaching performance, we computed reaching error, target capture time, and decomposition index (DI) during RCH. Reaching error was defined as the absolute distance between the target location and the final position of the onscreen cursor. Target capture time was computed as the time difference between the start of the trial and after participant hand speed fell below 10% of maximum hand speed. The DI was calculated as defined by Risi et al. and was an indicator of movement straightness (see Risi et al. (2019) for full details). Equation 4 below shows the equation for DI as defined by Risi et al. (2019):

[Eq 4]
$$DI = \sum_{n=2}^{N} \left\{ \frac{1}{2} \left| \frac{x(n) - x(n-1)}{x(N) - x(1)} \right| \left| \frac{\dot{y}_{\max} - \dot{y}(n)}{\dot{y}_{\max}} \right| + \frac{1}{2} \left| \frac{y(n) - y(n-1)}{y(N) - y(1)} \right| \left| \frac{\dot{x}_{\max} - \dot{x}(n)}{\dot{x}_{\max}} \right| \right\}$$

where N corresponds to the maximum number of data samples within a given trajectory, n corresponds to the sample number in that trajectory, and \dot{x}_{max} and \dot{y}_{max} correspond to the peak hand speeds along each of the cardinal axes. Decomposition index is defined as the extent to which hand paths move parallel to the cardinal axes (x, y) of the workspace. Values of DI close to 0.24 indicate nearly straight-line off-axis, single velocity peak movements while values greater than 1.0 indicate a path with on-axis, multi-velocity peak movements along the cardinal axes of the VTF.

CRT performance was analyzed using choice accuracy and the participant reaction time to make their choice (trials where participant pressed the button ahead of the cue or did not press the button were recorded as errors). Reaching errors and target capture times were averaged across practice blocks (average of 125 trials per session) for VTF-guided reaching, for each participant. Reaching errors and target capture times were averaged across 25 trials for non-practice blocks for each participant. Statistical analysis was completed using participant averages for the data measures (df = 14), allowing us to compare within subject effects of practice.

7. Statistical Testing

To test our hypothesis that practice with VTF-guided reaching accrues motor learning related improvements, we used repeated measures ANOVA and post hoc, Bonferroni-corrected, one-tailed, paired samples t-tests to compare reaching performance before, during (at session #10), and after (at session #20) long-term practice on VTFguided reaching. The dependent variables were average reaching error, average target capture time, and average DI. The independent factor was session number. We used repeated measures ANOVA and post-hoc, Bonferroni-corrected, one-tailed, paired samples t-tests to compare DT performance before, during, and after long-term practice on VTF-guided reaching. The dependent variables were CRT reaction time and choice accuracy. The independent factor was session number. All analyses were performed with SPSS Statistics 24 (IBM Corp). Statistical significance was set at a family-wise error rate of $\alpha = 0.05$.

C. Results

This study used a 2D, planar manipulandum to evaluate improvements in reaching performance due to VTF-guided reach practice. We hypothesized that VTF-guided reaching follows classical motor learning model (Fitts and Posner 1967) such that reaching performance improvements accrue in a way that is resistant to DT interference. We evaluated reaching and dual-tasking performance in 15 healthy, young adults. All participants were able to understand the reaching task and were able to use the VTF to guide their movements. Figure 19 shows sample reaching trajectories from a representative participant under various feedback conditions and reaching trajectories after practice. Figure 20 shows the sample population results of the average reaching error. Figure 21 shows the sample population results of the average target capture time.

1. Reaching Performance During VTF-guided RCH Improves with Practice

Visually guided reaching produced minimal average reaching errors (0.087 \pm 0.001 cm, mean \pm SEM) and the fastest times to capture the target (1.88 \pm 0.068 s). When



Figure 19: Sample reaching trajectories from one representative participant during RCH task under various feedback conditions. *Blue* trajectory indicated visually guided reaching. The *red* trajectory shows no external feedback reaching (no vision, no VTF). *Purple* and *green* trajectories show pre- and post-practice VTF-guided reaching trajectories, respectively. *Cyan* dots indicate end of the reach.

no feedback was provided and participants relied in intrinsic proprioception, average reaching errors significantly increased to 1.85 ± 0.096 cm ($t_{14} = 18.2$, p < 0.05, Fig 20: black asterisk) along with longer target capture times (2.79 ± 0.27 s; $t_{14} = 3.85$, p < 0.05, Fig 21: black asterisk). Reaching performance was assessed before, during, and after 20 sessions (10 hours) of VTF-guided reach practice. rmANOVA concluded that reaching error ($F_{(19,266)} = 20.7$, p < 0.05) significantly changed with respect to amount of practice completed. With VTF-guided reach practice, average reaching error became significantly lower than the no feedback condition during the first practice session ($1.63 \pm .076$ cm; t = 2.18, p < 0.05, Fig 20: red asterisk). After 10 practice sessions, reaching error continued to decrease (1.14 ± 0.094 cm; $t_{14} = 6.80$, p < 0.05, Fig 20: blue asterisk) and further

decreased to 0.97 ± 0.065 cm (t₁₄ = 9.69, p < 0.05, Fig 20: magenta asterisk) after 20 practice sessions. Overall, with practice reaching error decreased until the error was near the JND of VTF (0.89 cm) and performance gains in reaching error during RCH seemed to plateau around 15 practice sessions.



Figure 20: Group reaching error during the RCH task using VTF to guide reaching, across the 20 sessions. The *red* horizontal line indicates pre-practice JND of the VTF in relation to the workspace (0.89 cm). Colored asterisks (*black, red, blue, magenta*) indicated significant differences between sessions. Error bars indicate SEM.

Target capture times also showed significant changes throughout the practice sessions ($F_{(19,266)} = 5.08$, p < 0.05). During the first bout of practice, average target capture time with VTF (4.53 ± 0.66 s; t₁₄ = 3.36, p < 0.05, Fig 21: black asterisk) was significantly higher than the no feedback condition. At 10 practice sessions, average

target capture time during VTF-guided reaching $(3.36 \pm 0.52 \text{ s})$ decreased such that it was no longer significantly different than target capture time during no feedback reaching (t₁₄ = 1.10, p = 0.15) and continued to decrease to 2.78 ± 0.34 s (t₁₄ = 0.013, p = 0.50) after 20 practice sessions. After practice, the time needed to perform the vibrotactile feedback



Figure 21: Group Target capture time for the RCH task using VTF to guide reaching across the 20 sessions. Colored asterisks (*black, red, blue, magenta*) indicated significant differences between sessions. The *gray* band shows the similarity in capture times between no feedback reaching and VTF reaching as a result of practice. Error bars indicate SEM.

guided reaching task was similar to the time needed to reach while using only proprioception.

Figure 22 shows the sample population results of the average DI. Decomposition index showed no significant changes as a result of extended practice ($F_{(19,266)} = 0.69$, p =

0.83). Decomposition index for visually guided reaching was 0.90 ± 0.01 . During the no feedback condition, DI was 0.92 ± 0.03 . There was no change in DI when between visually guided reaching and no feedback reaching ($t_{14} = 0.70$, p = 0.25). During the first bout of practice, VTF-guided movements became significantly more decomposed compared to the no feedback condition (1.53 ± 0.14 ; $t_{14} = 5.09$, p < 0.05, Fig 22: black asterisk). At 10 practice sessions, movements continued to be decomposed (1.60 ± 0.31 ; $t_{14} = 2.19$, p < 0.05, Fig 22: red asterisk). This decomposition was present even after 20 practice sessions (1.47 ± 0.15 ; $t_{14} = 3.55$, p < 0.05, Fig 22: blue asterisk).



Figure 22: Group Decomposition Index (DI) for the RCH task using VTF to guide reaching across the 20 sessions. Colored asterisks (*black, red, blue*) indicated significant differences between sessions. Error bars indicate SEM.



Figure 23: Average reaching error during VTF-guided reaching. *Blue* bars indicate reaching errors for single RCH performed with VTF. *Gray* bars indicate reaching errors for VTF-guided reaching during DT. Practice (after 20 sessions) allows users to transfer performance improvements from the single RCH task to the DT. The *red* horizontal line indicates the pre-practice JND of the VTF in relation to the workspace. Error bars indicate SEM.



Figure 24: Average target capture time during VTF-guided reaching. *Blue* bars indicate target capture times for single RCH performed with VTF. *Gray* bars indicate target capture times for VTF-guided reaching during DT shows improvements during DT. Practice (after 20 sessions) allows users to transfer performance improvements from the single RCH task to the DT. Error bars indicate SEM.



Figure 25: Average choice reaction time during single CRT and CRT during DT. *Blue* bar indicates average reaction time during single CRT. *Gray* bars indicate average reaction times of CRT during DT. Practice (after 20 sessions) reduces reaction time of CRT during DT. Colored asterisks (*black, red, blue, magenta*) indicate significant differences between sessions. Error bars indicate SEM.

2. Dual-Tasking Performance Improves After VTF-guided RCH Practice

Figure 23 shows the average reaching error during DT and the single RCH task.

While dual-tasking, reaching error decreased significantly as a result of practice ($F_{(3,42)}$ =

32.9, p < 0.05). Pre-practice reaching error during DT (1.98 \pm 0.14 cm) decreased, but not

significantly, after one bout of practice $(1.75 \pm 0.11 \text{ cm}; t_{14} = 1.41, p = 0.090)$. However,

reaching error during DT decreased significantly after 10 practice sessions $(1.15 \pm 0.06 \text{ cm}, t_{14} = 5.93, \text{ p} < 0.05)$ and continued to decrease after 20 practice sessions $(0.98 \pm 0.06 \text{ cm}, t_{14} = 6.85, \text{ p} < 0.05)$. After 20 practice sessions, DT reaching error was not significantly different than reaching error of RCH with VTF, suggesting carry-over of performance improvements from single task to DT.

Figure 24 shows average DT target capture times. Target capture time during DT $(6.08 \pm 0.92 \text{ s})$ decreased significantly $(5.32 \pm 0.69 \text{ s}, t_{14} = , p < 0.05)$ after one bout of practice. Average target capture time during DT decreased significantly after 10 sessions $(4.12 \pm 0.46 \text{ s}, t_{14} = 3.05, p < 0.05)$ and continued to decrease after 20 sessions $(3.72 \pm 0.35 \text{ s}, t_{14} = 2.98, p < 0.05)$. However, post-practice target capture time during DT was still significantly higher than target capture time for the single RCH with VTF ($t_{14} = 5.23$, p < 0.05), most likely as a result of the additional time needed to perform CRT.

Participants were fairly accurate in their choice during pre-practice CRT (97.2 \pm 1.05 %) and did not change significantly after one bout (97.2 \pm 1.05 %), 10 sessions (98.3 \pm 0.68 %), or 20 sessions (98.9 \pm 0.49 %) of practice. Figure 25 shows the average reaction times of CRT across session. Normal choice reaction time for participants averaged at 754 \pm 45 ms. During DT, choice reaction time pre-practice increased to 1843 \pm 247 ms and reduced after one bout of practice (1275 \pm 183 ms, t₁₄ = 2.74, p < 0.05, Fig 25: red asterisk). Choice reaction time continued to decrease significantly after 10 practice sessions (1142 \pm 214 ms, t₁₄ = 3.74, p < 0.05, Fig 25: blue asterisk) and after 20 sessions (1154 \pm 229 ms, t₁₄ = 3.15, p < 0.05, Fig 25: magenta asterisk). However, after 10 practice sessions, choice reaction time plateaued and did not change from the 10th session to the 20th session (t₁₄ = 0.147, p = 0.89).

D. Discussion

This study tested the extent to which kinematic performance improves with longterm practice on using vibrotactile feedback (VTF) to guide reaching in the absence of vision. Our results indicate that healthy participants can indeed learn to efficiently use VTF to guide reaches in the absence of visual feedback and this performance persists even while dual-tasking (DT). Performance benefits gained through long-term practice are preserved over spaced practice sessions and while concurrently performing a cognitively demanding task. In our previous studies, we found improvements in reaching accuracy after short-term practice of VTF guided reaching and saw minor improvements in target capture times (Risi et al. 2019; Shah et al. 2018). In this study, we increased the sessions of practice to provide approximately 10 hours of cumulative practice. This resulted in participants becoming more efficient in their ability to reach using VTF to the extent that they were reaching significantly more accurately than and as fast as reaching with intrinsic proprioception (no vision).

1. VTF-guided Reaching Becomes More Efficient with Long-Term Practice

Participants could reach to targets with accuracy, precision, and efficiency with visual feedback. When visual feedback was removed, reaching accuracy degraded and movements became slow. Reaching performance degradation during proprioceptive reaching is likely caused by sensory and motor noise in signals used for updating estimates of limb position (Wolpert et al. 1995, 1998). When VTF was provided to substitute for visual feedback and augment proprioception, movements started to become more accurate after just one bout of practice but movement times increased significantly to account for this accuracy. After completing 20 sessions of practice (about 10 hours),

participants were able to use VTF to reach with exceptional accuracy and efficiency. In fact, reaching accuracy increased to the levels of the pre-practice JND of VTF (0.89 cm) and target capture times decreased to the same levels as reaching with intrinsic proprioception. This result is promising in that it shows the viability of using VTF to guide movements in healthy individuals and the limiting factor may be the resolution of the vibrotactile interface.

Through the long-term practice provided here, we may also be inherently training the sensory capabilities of participants. As participants are learning to use VTF, their acuity in VTF discrimination may also improve beyond the vibrotactile JNDs reported in Chapter IV, allowing for better perception, decoding, and integration VTF into the motor control networks. Previous studies have shown positive effects of sensory training on human and non-human primates capability to perceive sensory stimuli (Byl, Nagajaran, and McKenzie 2003; Crist et al. 1997; Kerr et al. 2008; Wright and Sabin 2007). One study concluded that long-term sensorimotor training provided through Tai Chi improved tactile acuity in adults compared to adults who did not practice Tai Chi (Kerr et al. 2008). Another study examined the extent of practice needed to accrue learning and improve capabilities to discriminate auditory stimuli and showed practice related improvements in perceptual capabilities after a multi-day training regimen (Wright and Sabin 2007). Thus, the practice provided on VTF-guided reaching may be improving VTF perception capabilities in participants which contribute to the exhibited reaching performance improvements.

2. *VTF-guided Movements Remain Decomposed Along the Axis of The VTF Interface*

Consistent with our previous studies (see Chapter V and VI) participants adopted a new movement strategy and continued to use this strategy after long-term practice. We expected that this strategy would resolve with practice and participants would regain the ability to make straight-line movements, but decomposition did not reduce. Even while participants were becoming efficient and accurate in their reaches guided by VTF, participants continued to use the decomposition strategy (Fig 22). This strategy involved moving the hand along the cardinal axis of the VTF interface and the target workspace. Figure 19 shows decomposed movement trajectories from a representative participant. We see that with visual feedback and proprioceptive feedback (no feedback), movements are fairly straight-line towards the target. When VTF is added, movements become decomposed during the first bout of practice and remain decomposed at the end of the 20th practice session.

It appears participants are resistant to leave this decomposition strategy and switch to a more cognitively demanding strategy of moving in a straight line. We originally thought that this strategy may have been the result of two factors: 1) the relative increase in cognitive resources required to process simultaneous vibrotactile stimuli (Haggerty et al. 2012; Pashler 1994; Wu and Liu 2008), and 2) increased perceptual acuity for vibrotactile stimuli delivered sequentially over those delivered simultaneously (Shah et al. 2019a). With the improvements in capability to DT after practice, the persistent decomposition strategy is likely due participants trying to monitor changes in multiple channels of VTF interface. We have shown that people are better at discriminating sequentially delivered vibrotactile stimuli rather than simultaneous vibrotactile stimuli (see Chapter IV). This difference in stimuli perception leads participants choose a decomposition strategy wherein they to move along one axis of the VTF interface first and then the other. It is also likely that this strategy was adopted consequent to the instructions we provided the participants: "reach as accurately and fast as possible". In trying to reach as accurately as possible, participants chose to move along one axis of the VTF interface first and then the other. Moving in such a fashion allows for better acuity of VTF discrimination since we can better discriminate sequential stimuli (see Chapter IV). If we provided different instruction such as "reach as straight to the target as possible", we hypothesize that subjects would decrease decomposition after long-term practice, although other aspects of the movements such as accuracy or efficiency may be sacrificed because participants may be focused on the movement trajectory rather than target capture.

3. Long-Term Practice Provides Performance Enhancements That are Characteristic of The Associative Stage of Fitts and Posner Motor Learning Model

The results of the current study expand the findings of our previous studies (see Chapter V and VI), where we found that people are indeed able to use VTF guide movements after short-term practice. In the present study, long-term practice allows participants to enhance their reaching behavior in the absence of vision. We also found that these performance enhancements from long-term practice result in improved dualtasking performance. During DT, we found that VTF-guided reaching performance improvements gained through practice are maintained at the same levels. Additionally, performance also improves in the secondary Choice Reaction Time task (CRT). We see that choice accuracy improves even when participants only practice VTF-guided RCH. CRT reaction times also become faster with practice on RCH alone (although there is a plateau after the 10th session).

Based on our kinematic performance results, we can infer that motor learning is taking place as a result of the long-term practice. Cognitive resources needed to perform VTF-guided reaching are reduced after long-term practice, leaving more cognitive resources available to increase performance of concurrent, secondary task during DT. As movements guided by VTF are more accurate, more efficient, and allow for successful dual-tasking, participants have entered the second, associative stage of the Fitts and Posner (1967) motor learning theory. While movements guided by VTF remain decomposed after long-term practice, perhaps motor learning of VTF-guided reaching benefits from this strategy. Participants have yet to reach the last, autonomous stage of motor learning, as evidence shows that this takes months to years of practice to achieve (Ericsson 2008). Future studies should consider altering practice to identify if performance of VTF-guided reaching can be enhanced faster. Practice can be designed based on classification of VTF-guided reaching in Gentile's taxonomy (Adams 1999; Gentile 2000) and can be completed as a whole or in parts (Magill and Anderson 2017; Murray 1981; Naylor and Briggs 1963).

4. Limitations

There are two possible limitations of the present study. The first limitation is that participants might have chosen to focus on reaching accuracy rather than speed based on the provided instructions. We instructed the participants to "reach as accurately and fast as possible". It is possible that due to accurately being stated first, participants chose to focus their efforts towards improving reaching accuracy, thereby contributing to relatively long target capture times, even for visually guided reaches. However, based on the Fitts and Posner motor learning model, we expected to see initial performance improvements in reaching accuracy rather than reaching efficiency. So, our instructions likely did not significantly affect the outcomes of the experiments, especially with VTFguided reaching.

Another limitation may arise from not having a continuous DT. The DT asked participants to reach while pressing a button at the same time. However, the button pressing was a discrete, one-time event per DT trial. We instructed the participants to "start reaching as soon as the reaching target appears as a white ring and make the choice when the target changes color". Participants were also instructed to "reach as accurately and fast as possible". It is possible that some participants chose to perform the primary RCH task and the secondary CRT task in a sequence rather than concurrently as instructed. Even if the two tasks were sequenced, participants were still likely required to divide their attention when they planned their reach and the button press at the start of the trial. They simply chose to execute the plans sequentially rather than concurrently. So practice related performance improvements may have reduced cognitive resources necessary for planning VTF-guided reaching, making these resources more readily available to also plan the secondary button pressing task. Future experiments can use a dual-tasking scenario where the secondary task is continuously performed to avoid task sequencing.

E. Conclusions

In this study, we asked participants to make goal-directed reaching movements using VTF to replace visual feedback. Through long-term practice, participants

131

successfully used VTF to improve their reaching accuracy and were able to move efficiently at the end of practice. Participants also showed a capability to DT after practice with increased choice accuracy and reaction times of the secondary task while maintaining movement accuracy and efficiency in the VTF-guided reaching task. Participants strategized their movements by moving along the cardinal axis of the vibrotactile interface, likely in order to enhance their perception and discrimination of VTF. Even while decomposing their movements, participants were able to reach more accurately than and as efficiently as reaching with intrinsic proprioception (no vision). Future studies should investigate long-term practice on the use of VTF to guide reaching movements to identify if decomposed movements become normalized or if this strategy is a lower JND (< 0.89 cm) vibrotactile interface and should consider changing the type practice to identify if performance of VTF-guided reaching can be enhanced faster than 10 hours of practice.

VIII. LEARNING TO USE VIBROTACTILE FEEDBACK TO GUIDE REACHING IN STROKE SURVIVORS

In the previous chapters, we determined the effects of practice duration on performance improvements of vibrotactile feedback (VTF) guided reaching in healthy people. We found that long-term practice is needed to achieve beneficial kinematic performance improvements and reduce cognitive resources needed to use VTF to guide arm movements. We also found that people adopted a movement strategy wherein they decomposed their movements along the axes of the VTF interface. It is possible that the decomposition strategy is a self-selected method of part practice for VTF-guided movements. Could constraining stroke survivors to practice decomposed movements improve their capability to use VTF to guide movements of their more affected arm? In this chapter, we investigated the effects of practice method on stroke survivors' capability to learn to use VTF to guide reaching with their contralesional arm. This chapter will be submitted for publication as a manuscript.

A. Introduction

Stroke is a cardiovascular disease that effects millions of people worldwide. In the United States alone, stroke accrues an additional \$34 billion per year in healthcare related costs (Benjamin et al. 2018; Katan and Luft 2018; Mozaffarian et al. 2016). Stroke causes various impairments, depending on the injured brain regions. Examples of these deficits include loss of processing capabilities for vision, audition, proprioception, or other sensation, as well as speech, balance, and motor capabilities (Carey 1995; Carey and Matyas 2011; Connell et al. 2008; Cumming et al. 2013; Hyndman and Ashburn 2003; Muren et al. 2008). Additionally, cognitive deficits occur if information processing

regions and networks suffer neuronal damage (Brainin and Heiss 2019). Sensorimotor and cognitive deficits of stroke can result in significant disabilities that alter the capability to perform activities of daily living (ADLs), reduce independence, and decrease quality of life (Crichton et al. 2016; Rafferty et al. 2017).

Movement deficits are prominent after stroke. However, more than 50 percent of survivors of stroke have some form of sensory deficit, such as impaired proprioception or tactile sensation (Carey 1995; Carey and Matyas 2011; Dukelow et al. 2010). Current research and clinical efforts related to post-stroke arm rehabilitation focus primarily on motor retraining, with limited focus on the impact of somatosensory deficits on motor function (Schabrun and Hillier 2009). This is not surprising given that arms are not very useful without volitional movement. However, somatosensory (proprioceptive) feedback is crucial for volitional movement planning and coordination (Sober and Sabes 2003).

Proprioceptive deficits are common in the contralesional arm and may contribute importantly to deficits in the control of functional movement (Carey 1995; Sainburg et al. 1995). Survivors often try to compensate these deficits by heavily relying on their vision to make movements (Bonan et al. 2004). Yet, movements are jerky and slow when vision is used because processing visual information requires longer times, thus adding delays in detecting and correcting errors (Cameron et al. 2014; Herter, Scott, and Dukelow 2019; Sarlegna et al. 2006). Therefore, it is imperative that we find alternative solutions that do not rely on vision to overcome proprioceptive deficits after stroke, especially since proprioceptive deficits negatively impact movement control of the arm, ultimately leading to degraded ADLs and reduced independence. One technique that can be used to mitigate proprioceptive deficits is sensory augmentation. Sensory augmentation aims to replace impaired or lost sensations by providing relevant information via artificial stimulation of intact sensory "channels" or modalities (Bach-y-Rita and W. Kercel 2003). For stroke survivors with proprioceptive deficits of the arm, it may be possible to augment the damaged proprioception with another sense, such as vision, auditory feedback, or tactile sensation (Molier et al. 2010). Of these alternate sensory modalities, tactile sensation appears to be the most viable option since visual feedback adds large delays (Cameron et al. 2014) and auditory feedback can interfere with social communication. Tactile feedback through vibration has been successfully used to provide augmented/substitutive feedback to the skin to substitute for vision (Kaczmarek et al. 1991), augment balance (Lee et al. 2012, 2013; Sienko et al. 2008), improve control of prosthetic devices (Cipriani et al. 2012; Witteveen et al. 2015), and increase upper extremity movement control (Krueger et al. 2017; Risi et al. 2019; Shah et al. 2018).

In our previous work, we utilized vibrotactile feedback (VTF) to supplement proprioception in the absence of vision in healthy participants (Krueger et al. 2017; Risi et al. 2019). Krueger et al. (2017) also found that VTF on the less affected arm improves performance of reaching and stabilization tasks performed with the more affected arm. In some stroke survivors, these investigations show promise in the initial use of VTF to augment proprioceptive feedback in stroke survivors and healthy people.

However, VTF is cognitively demanding and complex because it requires multiple steps to integrate into motor control networks. Users must sense the vibration, decode the provided information, and produce a response related to the conveyed
information (Gallace et al. 2008; Haggerty et al. 2012; Risi et al. 2019). This complexity leads to a strategy of moving where people used one channel of the VTF interface at a time (decomposition) as reported by Risi et al. (2019) and verified in the previous chapter. Some stroke survivors with cognitive deficits in addition to proprioceptive deficits may have reduced capability to understand information provided by VTF and have difficulties to integrate VTF into the ongoing control of movements. For the longterm use of VTF to guide movements, it would be useful to design a practice paradigm that maximizes stroke survivors capability to integrate VTF into motor planning (Adams 1999; Gentile 2000). Due to the high complexity of the VTF-guided reaching task, it may be beneficial to consider simplifying the practice environment.

Skills can be practiced as a whole or in parts. Part practice is especially advantageous for learning very complex skills (Briggs and Waters 1958; Naylor and Briggs 1963). For a novice learner, a complex skill has many components and requires much attention (cognitive resources; (Magill and Anderson 2017)). Part practice can be categorized in three ways: simplification, segmentation, and fractionization. Simplification involves reducing skill difficulty during practice so success requires less proficiency. An example is using a wider bat to hit a baseball. Segmentation involves separating the skill into parts and practicing one part first, then practicing that part together with the next. Such as practicing the parts of a dance routine individually prior to combining them. Fractionization involves practicing coordination tasks where individual limb movements are practiced before performing them together. For example, practicing the left and right hands separately while learning to play a piece on the piano. Designing the optimal practice paradigm can accelerate learning of a new skill and reduce the needed cognitive demand. It is possible that the decomposition strategy reported in the previous chapters is a method of self-selected part practice for the learning the use of VTF-guided movements. Could guiding stroke survivors to practice decomposed movements improve their capability to use VTF to guide movements of their more affected arm?

In this study, we sought to understand the impacts of whole and part practice on motor performance of VTF-guided movement in stroke survivors. We hypothesized that simplification and segmentation part practice will allow for increased performance improvements in VTF-guided reaching compared to whole practice. We asked stroke survivors to practice using VTF to guide movements over two sessions. Survivors were placed in one of three groups to use whole practice, simplification part practice, or a combination of segmentation and simplification part practice. Our results showed improvements in reaching performance across all three experimental practice groups. We expect our results will improve our understanding of how VTF-guided reaching can be better learned by stroke survivors. This will enhance the development of VTF bodymachine interfaces (BMIs) for stroke survivors.

B. Methods

1. Participants

Twenty-three stroke survivors ranging in age from 28-79 years were recruited from the greater Milwaukee area (Wisconsin, USA). Nineteen participants (8 females) $(59.6 \pm 12.9 \text{ yrs}, \text{mean} \pm \text{SD})$ met the experimental inclusion criteria (see below). Ten participants presented with their right arm more affected by stroke and nine had their left arm more affected by their stroke. All participants were naïve to vibrotactile feedback, objectives of the experiment, and provided written consent to the experimental procedures, which were approved by Institutional Review Boards serving Marquette University, in accordance with the Declaration of Helsinki.

Inclusion criteria for participants included sufficient shoulder and elbow range of motion in the more affected arm, the capability to sit and use the arm of a robotic manipulandum for up to one hour, the capability to transfer to the chair for the robotic manipulandum. Exclusion criteria included the inability to understand task instructions (assessed during participant screening) and inability to use the robotic manipulandum. We did not exclude participants based on recent or concurrent botulinum neurotoxin therapy in the involved limb.

2. Experimental Setup

Visual targets were created using MatLab (Mathworks Inc). Reaching targets (1 cm diameter) were arranged in a 5x5 grid with inter-target distance of 2 cm (below the range of normal proprioceptive uncertainty of limb position $(2.5 \pm 0.2 \text{ cm})$; cf., Fuentes and Bastian (2010)). Reaching targets were projected onto a horizontal screen. Additionally, a cursor was projected onto the screen to covey hand position. A robotic, 2-joint, horizontal planar manipulandum was used to move the onscreen cursor to reach targets (for design specification see Scheidt et al. (2010)). Figure 26 shows the robotic manipulandum. The manipulandum consists of two brushless DC torque motors (M-605-A Goldline; Kollmorgen, Inc. Northampton, MA) attached to a handle via a 2-joint arm. It allowed movements only within the horizontal plane. Handle location was resolved within 0.038 mm using joint angular position data from two 17-bit encoders (A25SB17P180C06E1CN; Gurley Instruments Inc). Data collection and control were



Figure 26: Schematic of a participant using the 2-joint robotic manipulandum. Participants sat on a chair with vision of their arm occluded from the shoulder down. The horizontal occlusion was used to display visual targets for reaching (left panel). The vibrotactile interface was attached to their less-affected (non-moving) arm and conveyed limb-state information about the moving hand in the grid workspace. The highlighted cyan row and column of targets indicate the targets used for the part practice blocks. The participants used their more-affected arm to grasp the handle of the manipulandum (right panel).

performed at 1000 sample/s.

A vibrotactile interface was created using four vibration motors (VMs; Precision Microdrives Inc, Model: 308-102). The VMs were powered and controlled using drive circuitry that was interfaced to a host computer running a custom script within the MatLab environment. The vibrotactile interface was calibrated such that a hand displacement of 1 cm resulted in a vibration change of ~72.5 Hz (greater than two-fold of the just noticeable difference reported for the volar forearm by Shah et al. (2019a)). The interface operated such that at the center of the grid, vibration was turned off up to a distance of 0.5 cm (0 Hz); from 0.5 cm to 4 cm (just outside of the center target to outer targets) vibration ranged from ~60-350 Hz; at distances >4 cm, vibration was set to maximum at >360 Hz. Figure 26 shows a schematic of the grid workspace and the vibrotactile interface attached to the arm.

3. Experimental Procedure

Each participant was asked to complete two experimental sessions, spaced at least 24 hours apart. Each experimental session duration ranged from 90-120 minutes. In the first session participants completed the clinical assessments (see below) as well as familiarization, practice, and testing blocks on the VTF-guided reaching task. In the second session participants participated in further practice and testing blocks on the VTF-guided reaching task.

Participants were comfortably seated in a high-backed chair in front of the horizontal planar robotic arm that was blocked from view with a horizontal surface (Fig 26). They used the more affected hand to grasp the vertically oriented cylindrical handle of the robotic arm. If a participant had a weak grasp, their hand was secured to the handle using medical wrap. The grid of reaching targets was displayed on the horizontal surface just above the robotic arm. An interface of four vibrotactile motors was adhered to the less affected arm (which rested on a rigid support structure; see Fig 26 for VTF interface attachment). Noise-cancelling headphones were used to play white noise to minimize auditory cues/distractions.

4. Experimental Groups

To test our hypothesis of practice paradigms, participants were pseudorandomly placed into one of three groups. One group practiced with whole practice and the two other groups received a variation of part practice. Participants were placed into one of three experimental groups: whole practice group (2D), simplification part practice group (1DSim), or the segmentation part practice group (1DSeg). Each group received a specific type of VTF-guided reaching practice. All participants performed a pre-practice

VTF-guided reaching test in the 2D workspace. The 2D group practiced the whole task, where they performed 100 trials of the 2D VTF-guided reaching per session. For this group pre- and post-practice test blocks and practice blocks were the same 2D VTFguided reaching task. The 1DSim group practiced 50 trials of reaching in the individual dimensions of the 2D workspace (simplification part practice). They first practiced reaching to targets that were all in the same row, then practiced reaching to targets that were all in the same column, completing a total for 100 practice trials (see Fig 26; cyan highlights). The 1DSeg group received sensory training (segmentation part practice) during the first session, where they attended to VTF as their arm was moved for them. The arm was moved by the robot; each movement had a bell-shaped velocity profile and movement duration was set to three seconds. Hand speeds depended on the distance to be moved over the three second movement duration. During the second session, participants completed the same practice as the 1DSim group such that they first actively moved to targets within a row and then actively moved to targets within a column. For the 1DSeg group, we separated the sensory component from the movement component between sessions. Overall, each experimental group received 200 trials of practice by the end of the second session in addition to the pre-practice block, post-practice block and familiarization time.

5. Experimental Task

During each session, participants were instructed to use the more affected hand to reach to targets on a screen as quickly and accurately as possible using the handle of the horizontal planar robotic manipulandum. Across both sessions participants received a total of \sim 1 hour of practice on VTF-guided reaching; practice time was equally

distributed across the sessions by equating number of practice trials. Table 6 shows the task blocks and the feedback conditions used during the VTF-guided reaching task familiarization, practice, and testing blocks.

Planar reaching was performed under three cursor feedback conditions: Visual feedback of movements (V+T-), VTF of movements (V-T+), or no external feedback (V-T-). During each trial, when participants were required make movements, participants were shown a target and they moved to that location and then verbally indicated when they had reached the target, ending the trial. At the end of the trial, participants were given visual feedback of the cursor and were required to center the cursor to the correct endpoint target location, which marked the starting location for the next reaching trial.

Block	Session	Feedback	Туре	Trials
1	1	V+T-	Baseline	25
2	1	V-T-	Baseline	25
3	1,2	V+T+	Familiarization	<u>NA</u>
4	1,2	V-T+	Pre-Practice 2D Test	25
5-8	1,2	V-T+	Practice	100 (25/block)
9	1,2	V-T+	Post-Practice 2D Test	25

Table 6: Blocks that could be performed during each session by stroke survivors.

If the participants were receiving VTF during the block they continued to receive that feedback during the error correction phase.

6. Clinical Assessments

Prior to performing the experimental tasks, participants underwent a battery of clinical assessments by a licensed physical therapist to characterize their stroke and

deficits. Clinical assessments included: the Montreal cognitive assessment score (MoCA; (Nasreddine et al. 2005)), which quantifies the memory and information processing aspects of cognition in a score between 0-30 wherein a score of 25 of greater considered normal. The upper extremity Fugl-Meyer Assessment (Fugl-Meyer et al. 1975; Sullivan et al. 2011) which includes motor capability (FMM) scored between 0-66 where 66 indicates no clinical deficit and a light touch/proprioception Fugl-Meyer assessment (FMS), provides a score for limb sensation at the thumb, wrist, elbow, and shoulder. Each joint measured with the test is scored between 0-2; with 2 indicating no presence of sensory deficit. Scores at each joint were added, therefore this test is scored between 0-12 where 12 indicates no clinical deficit is measured. The modified Ashworth scale (MAS) was used to quantify the level of spasticity and muscle tone the upper limb at the wrist, elbow, and shoulder (Bohannon and Smith 1987). Each joint is scored between 0-4 and tested both in extension and flexion; with 0 indicating no presence of spasticity. This test is scored by summing the scores of each joint, therefore the total ranges from 0-24 with 24 indicating increased stroke related spasticity and muscle tone. A vibration tuning fork test (128 Hz) was used to characterize vibration sensation on the less affected arm. The more affected arm was not tested because we were only applying the VTF to the less affected arm. Participants were asked if they could sense the vibration at the thumb, wrist, and elbow. Table 7 shows the participant demographics and clinical assessment data.

7. Data and Statistical Analysis

To assess reaching performance, we computed reaching error, target capture time, and decomposition index (DI) during reaching. Reaching error was defined as the absolute distance between the target location and the final position of the onscreen cursor. Target capture time was computed as the time between start of trial and when participant hand velocities reach 5% of peak hand velocity near the end of the target. The DI was calculated using Equation 4 shown in the previous chapter and was an indicator of offaxes movements. These kinematic data measures were averaged across 25 trials for each participant during the pre-practice 2D VTF-guided reaching task and post-practice 2D VTF-guided reaching task.

To test our hypothesis that part practice provides better performance improvements than whole practice, we used a one-way ANCOVA on the post-practice performance results, with the pre-practice performance results as the covariate to adjust for differences in the baseline levels of participants between groups. We used one-tailed, independent t-tests to compare changes in post-practice performance between groups. We used one-tailed, paired samples t-test to compare changes in performance within groups. All analyses were performed with SPSS Statistics 25 (IBM Corp). Statistical significance was set at a family-wise error rate of $\alpha = 0.05$.

C. Results

This study used a 2-joint robotic manipulandum to measure reaching performance during VTF-guided reaching by stroke survivors. We hypothesized that part practice of VTF-guided reaching provides larger improvements to reaching performance than whole practice. We evaluated reaching performance in three groups of stroke survivors, where each group received a different method of practice. All participants were able to understand the reaching task and were able to use the VTF to guide their movements.

Vibration Time Tuning Lesion/ MoCA FMM **FMS** MAS since Exp Age SS Fork Group (yrs) (30) (66) (12) (24) Stroke Location Sensation (yrs) (Y/N) 3 48 27 62 11 2 Y 4 Left MCA 5 66 21 21 12 8 Y 1 Right MCA 2D 9 51 22 66 12 0 Y 16 Left MCA 7 5 5 13 27 21 Y **Right MCA** 64 16 74 25 55 10 0 Y 3 **Right PCA** -60.6 24.4 45 10.4 3 6 Ave -1 4 Y 3 58 27 51 6 Right MCA 4 20 65 12 0 Y 7 Brainstem 63 8 Y N/A 59 24 37 10 8 12 1DSim 0 Y 3 N/A 10 67 24 32 6 17 57 25 41 12 8 Y 1 Left MCA 20 Y 72 24 62 12 1 1 **Right MCA** 22 65 24 60 12 0 Y 1 Left MCA 63 24 49.7 10 3 4 -Ave --2 27 63 10 3 Y 2 Left BG 35 7 59 29 64 12 0 Y 10 Left MCA 39 Y 11 50 24 2 14 10 **Right MCA** 8 Y 1DSeg 15 68 22 59 12 1.5 Brainstem 19 28 2 10 Y 2.5 **Right MCA** 28 26 Y 21 70 25 63 12 8 2.5 Pons Left & 23 79 26 50 12 0 Y 1.5 Right MCA 8.9 4.3 _ 55.6 25.6 52.3 6.1 Ave --

Table 7: Clinical assessment scores for stroke participants meeting inclusion criteria in their respective groups. SS = stroke survivor identifier, MCA = middle cerebral artery, BG = basal ganglia, Y = yes, N = no, N/A = Not Available.

Clinical scores (Table 7) showed that stroke survivor distribution was fairly heterogenous across the groups.



Figure 27: Stroke survivor reaching error averaged across experimental groups on the 2D reaching task. Colored asterisks (*black, red, blue*) show significant differences between reaching error. Error bars indicate \pm SEM.

1. Clinical Scores Show Even Distribution of Participant Between Practice Groups

One-way ANOVA showed that each clinical score and age were not significantly different between the three practice groups ($F_{Age(2,15)} = 0.57$, $F_{MoCA}(2,15) = 0.45$, $F_{FMM}(2,15)$

= 0.75, $F_{FMS(2,15)}$ = 0.34, $F_{MAS(2,15)}$ = 0.73, p > 0.05 for all clinical tests). Overall, the pseudorandomization of stroke survivors across the practice groups resulted in each group having a similar heterogenous distribution of participants.



Figure 28: Stroke survivor target capture time averaged across experimental groups on the 2D reaching task. Colored asterisks (*black, red, blue*) show significant differences between capture times. Error bars indicate \pm SEM.

2. Reaching Performance Improves with Short-Term Practice

Figure 27 shows the sample population reaching error results, averaged across groups. Figure 28 shows the sample population target capture time results, averaged across groups. Visually guided reaching produced minimal average reaching errors across all participants (0.30 ± 0.08 cm, mean \pm SEM) and the fastest target capture times (3.76 ± 0.76 s). When visual feedback was removed and participants relied on intrinsic proprioception, reaching errors increased significantly (1.61 ± 0.14 cm, $t_{18} = 10.4$, p < 0.05, Fig 27: black asterisk) and target capture times became significantly longer (5.13 ± 0.64 s, $t_{18} = 2.26$, p < 0.05, Fig 28: black asterisk). Prior to practice, the initial use of VTF to guide reaching resulted in a decrease in reaching accuracy (2.04 ± 0.19 cm, $t_{18} = 1.9$, p < 0.05, Fig 27: red asterisk). After engaging in practice for two sessions, across groups (i.e., regardless of method of practice), overall average reaching accuracy improved from the initial attempts with VTF (1.78 ± 0.17 cm, $t_{18} = 4.21$, p < 0.05, Fig 27: blue asterisk). However, reaching accuracy with VTF after two sessions of practice was not significantly better than reaching accuracy with no feedback ($t_{18} = 0.83$, p = 0.21).

Prior to practice, target capture times of VTF-guided movements increased significantly compared to the no feedback condition $(7.32 \pm 0.76 \text{ s versus } 5.13 \pm 0.64 \text{ s}, t_{18} = 5.31, p < 0.05$, Fig 28: red asterisk). After participating in practice for two sessions, across groups (i.e., regardless of method of practice), overall average target capture time still remained higher, as expected, than the no feedback condition $(6.82 \pm 0.80 \text{ s}, t_{18} = 2.82, p < 0.05, Fig 28$: blue asterisk). Overall, VTF-guided reaching target capture times remained higher with the short-term practice stroke survivors performed.

Figure 29 shows the sample population DI results, averaged across groups. Decomposition index was the lowest during visually guided reaching (1.40 ± 0.32) . When visual feedback was removed and participants relied on intrinsic proprioception, DI increased, but not significantly $(3.09 \pm 1.33, t_{18} = 1.29, p = 0.11)$. Prior to practice, the initial use of VTF to guide reaching resulted in no significant change in DI (4.66 ± 3.23, $t_{18} = 0.44, p = 0.33$). After participating in two practice sessions, across groups (i.e., regardless of method of practice), overall average DI during VTF-guided reaching did not improve significantly ($1.04 \pm 0.20, t_{19} = 1.11, p = 0.14$). DI with VTF after two session of practice was also no better than with no feedback ($t_{18} = 1.54, p = 0.07$). The highly variable nature of the DI stems from some stroke survivors searching for the target with VTF more than others or a strategy where some survivors went to the center and then moved to the target.

3. Whole practice provides better performance improvements in reaching accuracy than part practice

A between group comparison using a one-way ANCOVA on post-practice 2D reaching error with the pre-practice reaching error as a covariate showed a significant difference between groups ($F_{(2,15)} = 7.76$, p < 0.05). Figure 30 shows the between groups pre- and post-practice reaching error. Pre-practice reaching error was used as a covariate in order to adjust for differences between participant baseline capability. Independent samples, two-tailed t-test revealed a significant difference between the 2D (whole practice) group and the two part practice groups (1DSim and 1DSeg; Fig 30: blue asterisk). Whole practice resulted in significantly less reaching error ($p_{(1DSeg)} < 0.05$) than both the simplification part practice and segmentation part practice. Simplification part practice did not result in significantly different reaching



Figure 29: Stroke survivor DI averaged across experimental groups on the 2D reaching task. Error bars indicate ± SEM.

errors compared to segmentation part practice (p = 0.21). A paired samples, one-tailed t-test within the whole practice (2D) group revealed that, on average, reaching error decreased significantly with practice (reduction of 0.46 ± 0.15 cm (t₄ = 3.00, p < 0.05), Fig 30: black asterisk). Simplification part practice (1DSim) also decreased average reaching error significantly (average reduction of 0.29 ± 0.077 cm, t₆ = 3.72, p < 0.05, Fig 30: red asterisk). However, segmentation part practice (1DSeg with the passive practice trials) did not provide significant improvements in reaching error.



Figure 30: Stroke survivor reaching error across practice groups (panel A) and individual participants in each group (panel B) for the 2D VTF-guided reaching test. Colored asterisks (*red, black, blue*) show significant differences between reaching errors. Error bars indicate ± SEM.

One-way ANCOVA on post-practice 2D target capture time (adjusted using prepractice 2D target capture times as a covariate), resulted in no significant difference between groups ($F_{(2,15)} = 1.82$, p = 0.20). Figure 31 shows the between groups pre- and post-practice target capture time. This is expected as our previous results in healthy people showed that short-term practice did not improve target capture times (see chapter V, VI, and VII; target capture time results). Paired samples, one-tailed t-test within whole (2D) practice revealed that target capture time did not improve significantly after practice. Target capture time trended to a non-significant increase after segmentation part (1DSeg) practice (average time increase of 0.86 ± 1.25 s). Simplification part (1DSim) practice however did improve average target capture time (average time reduction of 1.73 ± 0.89 s, t₆ = 1.95, p < 0.045, Fig 31: black asterisk). One-way ANCOVA on postpractice DI (adjusted with pre-practice DI), compared between groups, resulted in no significant differences between groups ($F_{(2,15)} = 0.161$, p = 0.85).

D. Discussion

This study examined the extent to which stroke survivors' kinematic performance differs during 2D VTF-guided reaching when varied practice methods are used. Stroke survivors used a multi-channel VTF interface attached to their less-affected arm to guide their more-affected arm in a 2D workspace. Stroke survivors practiced using VTF with one of three methods: whole practice, simplification part practice, or segmentation part practice. Our results indicate that stroke survivors can indeed improve reaching performance with short-term practice, regardless of the method of practice. The performance improvements in VTF-guided reaching were only present for reaching



Figure 31: Stroke survivor target capture time across practice groups (panel A) and individual participants in each group (panel B) for the 2D VTF-guided reaching test. *Black* asterisks show significant differences between capture times. Error bars indicate \pm SEM.

accuracy and target capture times and DI did not improve (in line with previous results; see chapter VII; DI results).

1. Reaching Accuracy Improvements are Present Across Practice Groups

Short-term practice provided performance improvements in 2D VTF-guided reaching accuracy, which is in line with our previous results (see Chapter VI, and VII). Performance improvements in the experimental groups partially confirmed our hypothesis that part practice would provide increased performance gains compared to whole practice. Participants engaging in whole (2D) practice showed the largest improvement in reaching error, followed by modest improvements for users of segmentation (1DSeg) part practice. Simplification (1DSim) part practice did not provide any significant performance improvements. In the case of 2D VTF-guided reaching, practicing the task as a whole task seems to prove the best for accuracy-related performance improvements.

Target capture times (i.e., movement efficiency) only saw modest benefits from simplification part practice. Neither whole practice nor segmentation part practice provided any significant improvements in target capture times. As we saw in the previous chapters, after two practice sessions, participants likely remain in the initial stage of motor learning, such that improvements to movement efficiency are not yet displayed.

We originally classified VTF-guided reaching as a complex task, requiring users to sense the vibration, decode the provided information, and produce a response related to the conveyed information (Gallace et al. 2008; Haggerty et al. 2012; Risi et al. 2019). However, we did not consider the highly organized nature of VTF-guided reaching. There is a large amount of dependence between the various components (i.e., VTF cannot be used to produce a movement response until it is decoded and it cannot be decoded until it is sensed). Previous theories have identified that part practice is advantageous for learning very complex skills (Briggs and Waters 1958; Naylor and Briggs 1963) and skills that have low organization (multiple independent components). For a novice learner, a complex skill has many components and requires much attention (i.e., cognitive resources; (Magill and Anderson 2017)). Organization of a skill depends on the interconnectivity of its components. A skill is considered to have low organization of components are independent of each other. And conversely, skills with highly interdependent components (components can only be executed in some order) are considered highly organized (Lee et al. 2001). For future use of VTF BMIs for stroke survivors, we should classify VTF as highly organized and highly complex. Thus a prediction of the most successful practice paradigms may switch.

2. Practice Paradigms Should Be Customized to Stroke Survivors

The purpose of this study was to in part to identify if part practice can be used by stroke survivors to learn VTF-guided movements. We therefore did not assign participants to experimental groups using criteria based on their clinical scores. In this study, we pseudorandomly assigned each stroke survivor to an experimental practice group. Perhaps this also caused a lack of performance improvements in part practice groups compared to whole practice. Although the experimental groups had a fairly heterogenous sample, some survivors might have benefitted more from part practice than others in the same experimental group. Previous studies have shown that stroke affects survivors through a variety of deficits even while having the stroke in the same brain regions (Connell et al. 2008; Tatemichi et al. 1994). So even with a heterogenous sample

across experimental groups, it is possible that each participant had varying levels of deficits and this affected their ability to learn VTF-guided movements, regardless of the method of practice. Thus, future applications of VTF BMIs to guide movements in stroke survivors should consider individualizing practice based on the individual's stroke and the related deficits. Additionally, a subjective questionnaire that records survivors' comments on the usability and helpfulness of VTF would give insight into which type of stroke survivors might benefit from this technology.

Stroke survivors' capability to learn VTF-guided reaching may also be influenced by organization of practice and practice specificity. In addition to whole vs part practice, the organization and specificity of practice also affect learning (for a review see Merbah and Meulemans (2011)). Practice can be scheduled into blocked or random practice. Blocked practice involves practicing the same skilled movement repetitively before moving onto practicing a different variation of the movement (i.e., low movement variance). Random practice requires that the same skilled movements never be practiced sequentially, resulting in higher variance between movements. Blocked practice is more advantageous during skill acquisition, whereas random practice promotes better retention of the skill and our ability to generalize the skill across varying external conditions (i.e., learning (Braun et al. 2009; Shea and Morgan 1979; Wilde, Magnuson, and Shea 2005)). Practice specificity is defined as the degree of similarity between the practice movements and the actual movement condition. If the practiced movement is the same as the actual movement, specificity is high (Magill and Anderson 2017; Schmidt and Lee 2005).

We organized our practice paradigms to use blocked practice. The whole practice group was instructed to practice blocked movements, with high specificity since practiced reaching trials were the same as in the 2D reaching test blocks. The part practice groups also practiced movements with blocked schedules, however practice specificity was moderate for the 1DSim group and low for the 1DSeg group. The 1DSim group practiced moving in one dimension of the 2D workspace prior to practicing exclusively in the other dimension (i.e., they practiced X dimension movements prior to Y dimension movements). The 1DSeg group practiced VTF-perception first and then practiced movements of the 2D workspace where movements were blocked into individual workspace dimensions (i.e., they received sensory training first, then practiced the X dimension movements, and finally the Y dimension movements). We considered the specificity of practice for the 1DSim group as moderate since participants we actively using VTF to guide their movements for the whole duration of practice. The 1Dseg group was classified to have low practice specificity since practiced movements differed significantly than the tested 2D reaching movements as half the practice duration involved sensory training. A portion of practice trials for the 1DSeg group involved participants not actively producing movements (the robotic manipulandum moved participants' hands). The high practice specificity and blocked organization of practice may be the reason for consistent performance improvements seen in the whole practice group compared to the part practice groups (Shea and Morgan 1979).

Previous studies have also shown that performance improvements during acquisition occur at a faster rate with blocked practice compared to random practice (see Shea et al. (1990); for a review see Merbah and Meulemans (2011)). However, for learning the skilled movement and becoming an expert, random practice is more beneficial as acquisition utilizes greater contextual interference. Therefore, future designs of practice paradigms should consider practice schedules and practice specificity to maximize skill learning.

E. Conclusions

In this study, we asked stroke survivors to make targeted reaching movements in a 2D workspace using VTF in the absence of visual feedback. Stroke survivors were pseudorandomly placed into practice groups. Through two sessions of practice, survivors showed the capability to use VTF to guide reaching movements. The results partially confirmed our hypothesis, in that some participants benefitted from whole practice whereas some benefitted from part practice. We saw modest improvements in reaching accuracy as a result of two practice sessions, while movements remained inefficient (higher target capture times). The current experiment did not take into consideration clinical assessment scores when placing survivors into experimental groups. Future studies should try and constrain the method of practice survivors experience based on their current capabilities (i.e., customized practice paradigm). We also identified that VTF-guided reaching is a highly complex and a highly organized task. So, it is possible that for some participants part practice might not be the correct practice method. However, we need future studies to investigate the influence of long-term whole practice and part practice on stroke survivors' capability to learn VTF-guide reaching movements, so that we can identify how the rate of learning is affected by practice method.

IX. CONCLUSIONS

In this dissertation, I investigated how sensorimotor control of upper extremity reaching movements can be improved through supplemental vibrotactile feedback (VTF) and if this VTF can be used improve motor control of the arm in stroke survivors. This dissertation extended our understanding of how healthy human adults perceive vibrotactile stimuli applied to the arm (Chapters III and IV), how this VTF can be used to supplement proprioceptive feedback during reaching through how motor learning (Chapters V, VI, and VII), and how the method of practice (whole vs part practice) influences stroke survivor's capability to integrate this external feedback into ongoing motor control of movements (Chapter VIII).

In the first set of experiments, we measured vibration propagation across the skin of the arm. We measured the propagation of 100-240 Hz vibratory stimuli across the hairy skin of the human forearm. At a distance of 8 cm, the magnitude of propagated vibration was reduced by at least 95% relative to the source at all tested vibration intensities (Fig 4). From these results, we conclude that future VTF BMIs should maintain a minimum 8 cm separation between vibrotactile stimulation sites to avoid potential misperception of simultaneously applied stimuli.

We used these results to characterize perception and discrimination of vibrotactile stimuli at multiple locations on dermatomes of the arm when stimuli are delivered sequentially or simultaneously. We conclude that while all of the tested dermatomes on the arm and hand could serve as viable sites of vibrotactile stimulation for a practical BMI, implementations should ideally account for small differences in perceptual acuity across dermatomes. Moreover, the maximum amount of information that can effectively be encoded will be constrained by at least two factors: limitations in vibrotactile perceptual acuity that differ slightly between dermatomes (Fig 8), and limitations in the amount of information that can be simultaneously presented across multiple stimulation sites (Fig 9).

We used our findings of perceptual acuity and the characterized vibrotactile JNDs to design a multi-channel vibrotactile interface with ERM motors (Fig 10). We attached this interface to the non-moving arm of healthy people and supplemented their intrinsic proprioception with limb-state feedback. Healthy people successfully used this limb-state feedback to perform VTF-guided reaching. Short-term practice (<2.5hrs) induced performance improvements of reaching accuracy (Fig 12; Fig 15) but movements were not yet efficient (higher target capture times; Fig 12; Fig 16). We concluded that, with short-term practice, healthy participants are still likely in the first stage of learning VTF-guided reaching movements.

Long-term practice (~10 hrs) induced performance improvements of reaching accuracy (Fig 20) and movements became more efficient than reaching with intrinsic proprioception (Fig 21). Participants strategized their movements where they used one channel of the VTF interface and then the other, moving along the cardinal axis of the vibrotactile interface (Fig 19; Fig 22). This behavior likely stemmed from participants trying to enhance movement accuracy by maximizing acuity of VTF discrimination. Even while decomposing their movements, participants were able to reach more accurately than and as efficiently as reaching with intrinsic proprioception. We concluded that after long-term practice, healthy participants have advanced to the second stage of learning VTF-guided reaching movements.

It is possible that the decomposition strategy by healthy people is a method of self-selected part practice to increase the learning of VTF-guided movements. We investigated the effects of practice method on stroke survivors' capability to learn to use VTF to guide reaching with their contralesional arm. We established that, with short-term practice, stroke survivors have the capability to use VTF to guide reaching movements of their more affected arm in absence of visual feedback. Both whole practice and segmentation part practice improved stroke survivors' reaching performance (Fig 27; Fig 30). In line with the kinematic performance results of healthy people, VTFguided reaching movements were not yet efficient with short-term practice (regardless of practice method). Part practice might function better for some stroke survivors whereas others might benefit more from whole practice, depending largely on the deficits caused by their stroke (Hanlon 1996). This may especially hold true for survivors with moderate to severe cognitive deficits as their capability to learn new skills might be hindered. Additionally, there is evidence that stroke survivors' capability to learn motor skills depends on the severity of proprioceptive deficits. The more severe the deficit, the lower performance improvements in learned motor skills (Vidoni and Boyd 2009). There may be an interaction between proprioceptive and cognitive deficits on survivor's capability to learn and the amount improvements that accrue through practice.

A. Future Experiments

Based on our results, I propose two future experiments to continue to examine the use of VTF to improve motor control of the more affected arm in stroke survivors. It would be interesting to examine the effects of long-term practice in stroke survivors. Does their stroke increase the amount of practice needed compared to healthy people?

Within this research question one could also determine performance improvements that might be gained through sensory training (segmentation part practice) on performing 2D VTF-guided reaching. If we can further characterize stroke survivors' use of VTF in a 2D workspace, we can advance towards using VTF to help improve performance of ADLs.

1. Long-Term Practice on VTF-guided Reaching in Stroke Survivors

In our long-term practice experiment (Chapter VII), we found that healthy participants were able to learn the use of VTF to guide their arm movements in the absence of visual feedback. With long-term practice, participants improved their reaching accuracy, their movements became more efficient, and their ability to dual-task improved. The participants gained these improvements while choosing to adopt a strategy of where they used one channel of the VTF interface and then the other, moving along the cardinal axis of the vibrotactile interface (Fig 19; Fig 22).

Ultimately, we would want stroke survivors to become as efficient as possible in using VTF to control their more affect arm. To determine this, I propose a similar experiment to that of Chapter VII, wherein stroke survivors undergo 20 sessions (~10 hrs) of VTF-guided reach practice. Additionally, it would be interesting to identify performance improvements provided by sensory training alone. I suggest these experiments have two groups of stroke survivors: one which performs whole practice on the 2D VTF-guided reaching task, and the other which receives sensory training (segmentation part practice) for first half of the practice sessions and then performs whole practice during the second half of the session. I suspect that motor learning will take place through this long-term practice (in line with the Fitts and Posner motor learning model (1967)). It is likely that we will see similar trend (perhaps a slower trend

if survivors present with cognitive deficits) in performance gains in stroke survivors as we have seen in healthy people.

2. Using VTF to Control Movements of ADLs

The successful use of VTF to guide constrained movements in a laboratory and research environment has been established through our investigations (Chapter V, VI, VIII, and VIII). But we still face a challenge in designing and implementing a VTF interface that can be used to help stroke survivors perform ADLs. Previous studies, although still in a controlled setting, have shown the feasibility of VTF BMIs to help perform real-life actions. For example, to augment balance (Lee et al. 2012, 2013; Sienko et al. 2008), to improve control of upper extremity prostheses (Cipriani et al. 2012; Witteveen et al. 2015), or to alarm unfavorable conditions (Ferris and Sarter 2011).

Our ultimate goal is to help improve motor performance of the contralesional arm in stroke survivors who retain motor capability but are hindered by their proprioceptive deficits. The motor improvements that stroke survivors gain through an assistive device or rehabilitation should pertain transfer into improving their capability to perform ADLs and regain independence. Stroke adds an additional \$34 billion per year due to healthcare related costs and loss of work. If some stroke survivors are able to regain their independence, even partially, we can aim to reduce some of this economic burden.

To determine the feasibility of a VTF BMI to improve ADL performance, I propose an investigation where we use a VTF interface designed to provide limb-state information referenced from an arm joint (e.g., the shoulder, elbow, or wrist). In the laboratory setting, limb-state feedback is referenced to the center of the workspace, but what if we change this to a joint on the arm? Would VTF still be intuitive to use when

performing ADLs? Stroke survivors should undergo practice in using this VTF interface while performing ADLs like, reaching for items in front of the body, combing hair, brushing teeth, or buttoning a shirt. I expect that VTF-guided ADL performance would be feasible but likely requires long-term practice, as movements are not constrained to the 2D workspace and occur in 3D.

X. REFERENCES

- Adams, Deborah L. 1999. "Develop Better Motor Skill Progressions with Gentile's Taxonomy of Tasks." *Journal of Physical Education, Recreation & Dance* 70(8):35–38.
- Afzal, Muhammad Raheel, Min-Kyun Oh, Chang-Hee Lee, Young Sook Park, and Jungwon Yoon. 2015. "A Portable Gait Asymmetry Rehabilitation System for Individuals with Stroke Using a Vibrotactile Feedback." *BioMed Research International* 2015:e375638. Retrieved April 15, 2020 (https://www.hindawi.com/journals/bmri/2015/375638/).
- Allum, J. H. J., B. R. Bloem, M. G. Carpenter, M. Hulliger, and M. Hadders-Algra. 1998. "Proprioceptive Control of Posture: A Review of New Concepts." *Gait & Posture* 8(3):214–42.
- An, Q., Y. Matsuoka, and C. Stepp. 2011. "Multi-Day Training with Vibrotactile Feedback for Virtual Object Manipulation." Pp. 1–5 in 2011 IEEE International Conference on Rehabilitation Robotics.
- Ariza, O. J., M. Lange, F. Steinicke, and G. Bruder. 2017. "Vibrotactile Assistance for User Guidance towards Selection Targets in VR and the Cognitive Resources Involved." Pp. 95–98 in 2017 IEEE Symposium on 3D User Interfaces (3DUI).
- Bach□y□Rita, Paul. 1967. "Sensory Plasticity." *Acta Neurologica Scandinavica* 43(4):417–26.
- Bach-y-Rita, Paul, and Stephen W. Kercel. 2003. "Sensory Substitution and the Human-Machine Interface." *Trends in Cognitive Sciences* 7(12):541–46.
- Ballardini, Giulia, Giorgio Carlini, Psiche Giannoni, Robert A. Scheidt, Ilana Nisky, and Maura Casadio. 2018. "Tactile-STAR: A Novel Tactile STimulator And Recorder System for Evaluating and Improving Tactile Perception." *Frontiers in Neurorobotics* 12.
- Bark, K., J. Wheeler, G. Lee, J. Savall, and M. Cutkosky. 2009. "A Wearable Skin Stretch Device for Haptic Feedback." Pp. 464–69 in World Haptics 2009 - Third Joint EuroHaptics conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems.
- Bark, Karlin, Emily Hyman, Frank Tan, Elizabeth Cha, Steven A. Jax, Laurel J. Buxbaum, and Katherine J. Kuchenbecker. 2015. "Effects of Vibrotactile Feedback on Human Learning of Arm Motions." *IEEE Transactions on Neural Systems and Rehabilitation Engineering* 23(1):51–63.

- Bark, Karlin, Preeya Khanna, Rikki Irwin, Pulkit Kapur, Steven A. Jax, Laurel J. Buxbaum, and Katherine J. Kuchenbecker. 2011. "Lessons in Using Vibrotactile Feedback to Guide Fast Arm Motions." Pp. 355–60 in 2011 IEEE World Haptics Conference.
- Bastian, Amy J. 2008. "Understanding Sensorimotor Adaptation and Learning for Rehabilitation." *Current Opinion in Neurology* 21(6):628–33.
- Benjamin, Emelia J., Salim S. Virani, Clifton W. Callaway, Alanna M. Chamberlain, Alexander R. Chang, Susan Cheng, Stephanie E. Chiuve, Mary Cushman, Francesca N. Delling, Rajat Deo, Sarah D. de Ferranti, Jane F. Ferguson, Myriam Fornage, Cathleen Gillespie, Carmen R. Isasi, Monik C. Jiménez, Lori Chaffin Jordan, Suzanne E. Judd, Daniel Lackland, Judith H. Lichtman, Lynda Lisabeth, Simin Liu, Chris T. Longenecker, Pamela L. Lutsey, Jason S. Mackey, David B. Matchar, Kunihiro Matsushita, Michael E. Mussolino, Khurram Nasir, Martin O'Flaherty, Latha P. Palaniappan, Ambarish Pandey, Dilip K. Pandey, Mathew J. Reeves, Matthew D. Ritchey, Carlos J. Rodriguez, Gregory A. Roth, Wayne D. Rosamond, Uchechukwu K. A. Sampson, Gary M. Satou, Svati H. Shah, Nicole L. Spartano, David L. Tirschwell, Connie W. Tsao, Jenifer H. Voeks, Joshua Z. Willey, John T. Wilkins, Jason Hy Wu, Heather M. Alger, Sally S. Wong, Paul Muntner, and American Heart Association Council on Epidemiology and Prevention Statistics Committee and Stroke Statistics Subcommittee. 2018. "Heart Disease and Stroke Statistics-2018 Update: A Report From the American Heart Association." Circulation 137(12):e67-492.
- Berglund, Birgitta, Ulf Berglund, and Goesta Ekman. 1967. "Temporal Integration of Vibrotactile Stimulation." *Perceptual and Motor Skills* 25(2):549–60.
- Bernasconi, Fosco, Marzia De Lucia, Athina Tzovara, Aurelie L. Manuel, Micah M. Murray, and Lucas Spierer. 2011. "Noise in Brain Activity Engenders Perception and Influences Discrimination Sensitivity." *Journal of Neuroscience* 31(49):17971–81.
- Bernstein, N. A. 1996. "On Dexterity and Its Development." Pp. 1–244 in Dexterity and its development, Resources for ecological psychology, edited by M. L. Latash and M. T. Turvey. Mahwah, N.J: L. Erlbaum Associates.
- Bohannon, Richard W., and Melissa B. Smith. 1987. "Interrater Reliability of a Modified Ashworth Scale of Muscle Spasticity." *Physical Therapy* 67(2).
- Bolanowski, S. J., G. A. Gescheider, R. T. Verrillo, and C. M. Checkosky. 1988. "Four Channels Mediate the Mechanical Aspects of Touch." *The Journal of the Acoustical Society of America* 84(5):1680–94.
- Bonan, Isabelle V., Alain P. Yelnik, Florence M. Colle, Carole Michaud, Emanuelle Normand, Benedicte Panigot, Philippe Roth, Jean P. Guichard, and Eric Vicaut.
 2004. "Reliance on Visual Information after Stroke. Part II: Effectiveness of a Balance Rehabilitation Program with Visual Cue Deprivation after Stroke: A

Randomized Controlled Trial." *Archives of Physical Medicine and Rehabilitation* 85(2):274–78.

- Brainin, M., and W. D. Heiss, eds. 2019. *Textbook of Stroke Medicine*. Third edition. Cambridge, United Kingdom; New York, NY: Cambridge University Press.
- Braun, Daniel A., Ad Aertsen, Daniel M. Wolpert, and Carsten Mehring. 2009. "Motor Task Variation Induces Structural Learning." *Current Biology* 19(4):352–57.
- Braver, Todd S., Jonathan D. Cohen, Leigh E. Nystrom, John Jonides, Edward E. Smith, and Douglas C. Noll. 1997. "A Parametric Study of Prefrontal Cortex Involvement in Human Working Memory." *NeuroImage* 5(1):49–62.
- Briggs, George E., and Lawrence K. Waters. 1958. "Training and Transfer as a Function of Component Interaction." *Journal of Experimental Psychology* 56(6):492–500.
- Broccard, Frédéric D., Tim Mullen, Yu Mike Chi, David Peterson, John R. Iversen, Mike Arnold, Kenneth Kreutz-Delgado, Tzyy-Ping Jung, Scott Makeig, Howard Poizner, Terrence Sejnowski, and Gert Cauwenberghs. 2014. "Closed-Loop Brain–Machine–Body Interfaces for Noninvasive Rehabilitation of Movement Disorders." Annals of Biomedical Engineering 42(8):1573–1593.
- Brown, David, Tom Macpherson, and Jamie Ward. 2011. "Seeing with Sound? Exploring Different Characteristics of a Visual-to-Auditory Sensory Substitution Device:" *Perception*.
- Burgess, P. R. 1973. Cutaneous Mechanoreceptors. Vol. 3. edited by E. C. Carterette and M. P. Friedman. New York: Academic Press.
- Byl, Nancy N., Srikantan Nagajaran, and Alison L. McKenzie. 2003. "Effect of Sensory Discrimination Training on Structure and Function in Patients with Focal Hand Dystonia: A Case Series 1." Archives of Physical Medicine and Rehabilitation 84(10):1505–14.
- Caldwell, D. G., N. Tsagarakis, and C. Giesler. 1999. "An Integrated Tactile/Shear Feedback Array for Stimulation of Finger Mechanoreceptor." Pp. 287–92 vol.1 in Proceedings 1999 IEEE International Conference on Robotics and Automation (Cat. No.99CH36288C). Vol. 1.
- Cameron, B. D., C. de la Malla, and J. Lopez-Moliner. 2014. "The Role of Differential Delays in Integrating Transient Visual and Proprioceptive Information." *Front Psychol* 5(50).
- Carey, L. M. 2012. *Stroke Rehabilitation Insights from Neuroscience and Imaging*. New York: Oxford University Press.

- Carey, L. M., and T. A. Matyas. 2011. "Frequency of Discriminative Sensory Loss in the Hand after Stroke in a Rehabilitation Setting." *Journal of Rehabilitation Medicine* 43:257–263.
- Carey, Leeanne M. 1995. "Somatosensory Loss after Stroke." Critical Reviews™ in *Physical and Rehabilitation Medicine* 7(1).
- Carr, Janet H., and Roberta B. Shepherd. 1987. *A Motor Relearning Programme for Stroke*. 2nd ed., US ed. Oxford : Rockville, Md: Heinemann Medical Books ; Aspen Publishers.
- Casadio, M., R. Ranganathan, and F. A. Mussa-Ivaldi. 2012. "The Body-Machine Interface: A New Perspective on an Old Theme." *Journal of Motor Behavior* 44(6):419–433.
- Cashin, Aidan G., and James H. McAuley. 2017. "Measuring Two-Point Discrimination Threshold with a Caliper." *Journal of Physiotherapy* 63(3):186.
- Casini, Simona, Matteo Morvidoni, Matteo Bianchi, Manuel Catalano, Giorgio Grioli, and Antonio Bicchi. 2015. "Design and Realization of the CUFF Clenching Upper-Limb Force Feedback Wearable Device for Distributed Mechano-Tactile Stimulation of Normal and Tangential Skin Forces." Pp. 1186–1193 in 2015 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS). IEEE.
- Chen, Xing, Yan Zeng, and Yuehong Yin. 2017. "Improving the Transparency of an Exoskeleton Knee Joint Based on the Understanding of Motor Intent Using Energy Kernel Method of EMG." *IEEE Transactions on Neural Systems and Rehabilitation Engineering* 25(6):577–88.
- Choi, S., and K. J. Kuchenbecker. 2013. "Vibrotactile Display: Perception, Technology, and Applications." *Proceedings of the IEEE* 101(9):2093–2104.
- Cholewiak, Roger W. 1999. "The Perception of Tactile Distance: Influences of Body Site, Space, and Time." *Perception* 28(7):851–75.
- Cholewiak, Roger W., and Amy A. Collins. 2003. "Vibrotactile Localization on the Arm: Effects of Place, Space, and Age." *Perception & Psychophysics* 65(7):1058–77.
- Cincotti, Febo, Laura Kauhanen, Fabio Aloise, Tapio Palomäki, Nicholas Caporusso, Pasi Jylänki, Donatella Mattia, Fabio Babiloni, Gerolf Vanacker, Marnix Nuttin, Maria Grazia Marciani, and José del R. Millán. 2007. "Vibrotactile Feedback for Brain-Computer Interface Operation." *Computational Intelligence and Neuroscience* 2007(Article ID 48937):12.
- Cipriani, C., M. D'Alonzo, and M. C. Carrozza. 2012. "A Miniature Vibrotactile Sensory Substitution Device for Multifingered Hand Prosthetics." *IEEE Transactions on Biomedical Engineering* 59(2):400–408.

- Cirstea, C., A. Ptito, and M. Levin. 2006. "Feedback and Cognition in Arm Motor Skill Reacquisition After Stroke." *Stroke* 37(5): 1237-1242.
- Connell, LA, NB Lincoln, and KA Radford. 2008. "Somatosensory Impairment after Stroke: Frequency of Different Deficits and Their Recovery." *Clinical Rehabilitation* 22(8):758–67.
- Connell, Louise, and Dermot Lynott. 2012. "When Does Perception Facilitate or Interfere with Conceptual Processing? The Effect of Attentional Modulation." *Frontiers in Psychology* 3.
- Crewe, N. M., and J. S. Krause. 2009. *Spinal Cord Injury*. Athens, USA: Elliott & Fitzpatrick, Inc.
- Crichton, Siobhan L., Benjamin D. Bray, Christopher McKevitt, Anthony G. Rudd, and Charles D. A. Wolfe. 2016. "Patient Outcomes up to 15 Years after Stroke: Survival, Disability, Quality of Life, Cognition and Mental Health." *Journal of Neurology, Neurosurgery, and Psychiatry* 87(10):1091–98.
- Crist, Roy E., Mitesh K. Kapadia, Gerald Westheimer, and Charles D. Gilbert. 1997. "Perceptual Learning of Spatial Localization: Specificity for Orientation, Position, and Context." *Journal of Neurophysiology* 78(6):2889–94.
- Cumming, Toby B., Randolph S. Marshall, and Ronald M. Lazar. 2013. "Stroke, Cognitive Deficits, and Rehabilitation: Still an Incomplete Picture." *International Journal of Stroke* 8(1):38–45.
- Cuppone, Anna Vera, Valentina Squeri, Marianna Semprini, Lorenzo Masia, and Jürgen Konczak. 2016. "Robot-Assisted Proprioceptive Training with Added Vibro-Tactile Feedback Enhances Somatosensory and Motor Performance." *PLOS ONE* 11(10):e0164511.
- Curtis, Clayton E., and Mark D'Esposito. 2003. "Persistent Activity in the Prefrontal Cortex during Working Memory." *Trends in Cognitive Sciences* 7(9):415–23.
- Dobkin, Bruce H. 2005. "Rehabilitation after Stroke." *New England Journal of Medicine* 352(16):1677–84.
- Doyon, Julien, and Habib Benali. 2005. "Reorganization and Plasticity in the Adult Brain during Learning of Motor Skills." *Current Opinion in Neurobiology* 15(2):161–67.
- Dozza, Marco, Conrad Wall, Robert J. Peterka, Lorenzo Chiari, and Fay B. Horak. 2007. "Effects of Practicing Tandem Gait with and without Vibrotactile Biofeedback in Subjects with Unilateral Vestibular Loss." *Journal of Vestibular Research: Equilibrium & Orientation* 17(4):195–204.

- Dukelow, Sean P., Troy M. Herter, Kimberly D. Moore, Mary Jo Demers, Janice I.
 Glasgow, Stephen D. Bagg, Kathleen E. Norman, and Stephen H. Scott. 2010.
 "Quantitative Assessment of Limb Position Sense Following Stroke." Neurorehabilitation and Neural Repair 24(2):178–87.
- Duncan, Robert O., and Geoffrey M. Boynton. 2007. "Tactile Hyperacuity Thresholds Correlate with Finger Maps in Primary Somatosensory Cortex (S1)." *Cerebral Cortex* 17(12):2878–91.
- Dupin, Lucile, Vincent Hayward, and Mark Wexler. 2015. "Direct Coupling of Haptic Signals between Hands." *Proceedings of the National Academy of Sciences* 112(2):619–24.
- Eickhoff, Simon B., Christian Grefkes, Karl Zilles, and Gereon R. Fink. 2007. "The Somatotopic Organization of Cytoarchitectonic Areas on the Human Parietal Operculum." *Cerebral Cortex* 17(8):1800–1811.
- Elliot, Linda R., Elizabeth S. Redden, Rodger A. Pettitt, Christian B. Carstens, Jan van Erp, and Maaike Duistermaat. 2006. *Tactile Guidance for Land Navigation:* Fort Belvoir, VA: Defense Technical Information Center.
- Elliott, Linda R., Maaike Duistermaat, Elizabeth S. Redden, and Jan Van Erp. 2007. *Multimodal Guidance for Land Navigation*. Army Research Lab Aberdeen Proving Ground MD Human Research and Engineering
- Ericsson, K. Anders. 2008. "Deliberate Practice and Acquisition of Expert Performance: A General Overview." *Academic Emergency Medicine* 15(11):988–94.
- Ericsson, K. Anders, Ralf T. Krampe, and Clemens Tesch-Römer. 1993. "The Role of Deliberate Practice in the Acquisition of Expert Performance." *Psychological Review* 100(3):363–406.
- Ferris, Thomas K., and Nadine Sarter. 2011. "Continuously Informing Vibrotactile Displays in Support of Attention Management and Multitasking in Anesthesiology." *Human Factors* 53(6):600–611.
- Fitts, P. M., and M. I. Posner. 1967. *Human Performance*. Belmont, CA: Brooks/Cole Pub.
- Francisco, E., V. Tannan, Z. Zhang, J. Holden, and M. Tommerdahl. 2008. "Vibrotactile Amplitude Discrimination Capacity Parallels Magnitude Changes in Somatosensory Cortex and Follows Weber's Law." *Experimental Brain Research* 191(1):49.
- Fuentes, Christina T., and Amy J. Bastian. 2009. "Where Is Your Arm? Variations in Proprioception Across Space and Tasks." *Journal of Neurophysiology* 103(1):164–71.

- Fuentes, Christina T., and Amy J. Bastian. 2010. "Where Is Your Arm? Variations in Proprioception Across Space and Tasks." *Journal of Neurophysiology* 103(1):164–171.
- Fugl-Meyer, Axel R., L. Jääskö, Ingegerd Leyman, Sigyn Olsson, and Solveig Steglind. 1975. "The Post-Stroke Hemiplegic Patient. 1. a Method for Evaluation of Physical Performance." *Scandinavian Journal of Rehabilitation Medicine* 7(1):13–31.
- Gallace, Alberto, Hong Z. Tan, Patrick Haggard, and Charles Spence. 2008. "Short Term Memory for Tactile Stimuli." *Brain Research* 1190:132–42.
- Gandolfi, Marialuisa, Daniele Munari, Christian Geroin, Alberto Gajofatto, Maria Donata Benedetti, Alessandro Midiri, Fontana Carla, Alessandro Picelli, Andreas Waldner, and Nicola Smania. 2015. "Sensory Integration Balance Training in Patients with Multiple Sclerosis: A Randomized, Controlled Trial." *Multiple Sclerosis Journal* 21(11):1453–62.
- Gentile, Ann M. 2000. "Skill Acquisition: Action, Movement, and Neuromotor Processes." Pp. 111–87 in *Movement science : foundations for physical therapy in rehabilitation*, edited by J. H. Carr and R. B. Shepherd. Rockville, MD: Aspen.
- Gescheider, G. 1997. *Psychophysics: The Fundamentals*. 3rd ed. Mahwah, NJ: Lawrence Erlbaum Associates Inc.
- Gharbawie, O. A., C. L. R. Gonzalez, P. T. Williams, J. A. Kleim, and I. Q. Whishaw. 2005. "Middle Cerebral Artery (MCA) Stroke Produces Dysfunction in Adjacent Motor Cortex as Detected by Intracortical Microstimulation in Rats." *Neuroscience* 130(3):601–10.
- Gharbawie, Omar A., Claudia L. R. Gonzalez, and Ian Q. Whishaw. 2005. "Skilled Reaching Impairments from the Lateral Frontal Cortex Component of Middle Cerebral Artery Stroke: A Qualitative and Quantitative Comparison to Focal Motor Cortex Lesions in Rats." *Behavioural Brain Research* 156(1):125–37.
- Green, D. M., and J. A. Swets. 1966. *Signal Detection Theory and Psychophysics*. New York: John Wiley and Sons Inc.
- Gulick, Elsie E. 1997. "Correlates of Quality of Life Among Persons With Multiple Sclerosis." *Nursing Research* 46(6):305.
- Haggerty, Stephanie, Liang-Ting Jiang, Andrzej Galecki, and Kathleen H. Sienko. 2012. "Effects of Biofeedback on Secondary-Task Response Time and Postural Stability in Older Adults." *Gait & Posture* 35(4):523–528.
- Haghgoo, Hojjat Allah, Elmira Saed Pazuki, Ali S. Hosseini, and Mehdi Rassafiani.
 2013. "Depression, Activities of Daily Living and Quality of Life in Patients with Stroke." *Journal of the Neurological Sciences* 328(1):87–91.
- Hanlon, Robert E. 1996. "Motor Learning Following Unilateral Stroke." Archives of Physical Medicine and Rehabilitation 77(8):811–15.
- Harris, Justin A., Ehsan Arabzadeh, Adrienne L. Fairhall, Claire Benito, and Mathew E. Diamond. 2006. "Factors Affecting Frequency Discrimination of Vibrotactile Stimuli: Implications for Cortical Encoding." *PLOS ONE* 1(1):e100.
- Harris, Justin A., Carlo Miniussi, Irina M. Harris, and Mathew E. Diamond. 2002. "Transient Storage of a Tactile Memory Trace in Primary Somatosensory Cortex." *Journal of Neuroscience* 22(19):8720–25.
- Hayward, Vincent, and Juan Manuel Cruz-hernández. 2000. "Tactile Display Device Using Distributed Lateral Skin Stretch." Pp. 1309–1314 in Vol. 69(2). ASME.
- Heekeren, Hauke R., Sean Marrett, and Leslie G. Ungerleider. 2008. "The Neural Systems That Mediate Human Perceptual Decision Making." *Nature Reviews Neuroscience* 9(6):467–79.
- Herter, Troy M., Stephen H. Scott, and Sean P. Dukelow. 2019. "Vision Does Not Always Help Stroke Survivors Compensate for Impaired Limb Position Sense." *Journal of NeuroEngineering and Rehabilitation* 16(1):129.
- Ho, Cristy, Nick Reed, and Charles Spence. 2006. "Assessing the Effectiveness of 'Intuitive' Vibrotactile Warning Signals in Preventing Front-to-Rear-End Collisions in a Driving Simulator." *Accident Analysis & Prevention* 38(5):988– 96.
- Hoechstetter, Karsten, André Rupp, Andrej Stančák, Hans-Michael Meinck, Christoph Stippich, Patrick Berg, and Michael Scherg. 2001. "Interaction of Tactile Input in the Human Primary and Secondary Somatosensory Cortex—A Magnetoencephalographic Study." *NeuroImage* 14(3):759–67.
- Hunt, Carlton C. 1974. The Pacinian Corpuscle. Boston, MA: Springer US.
- Hwang, I., J. Seo, M. Kim, and S. Choi. 2013. "Vibrotactile Perceived Intensity for Mobile Devices as a Function of Direction, Amplitude, and Frequency." *IEEE Transactions on Haptics* 6(3):352–62.
- Hyndman, D., and A. Ashburn. 2003. "People with Stroke Living in the Community: Attention Deficits, Balance, ADL Ability and Falls." *Disability and Rehabilitation* 25(15):817–22.
- Ishikawa, Takahiro, Saeka Tomatsu, Jun Izawa, and Shinji Kakei. 2016. "The Cerebro-Cerebellum: Could It Be Loci of Forward Models?" *Neuroscience Research* 104:72–79.

- Johansson, R. S., and A. B. Vallbo. 1979. "Tactile Sensibility in the Human Hand: Relative and Absolute Densities of Four Types of Mechanoreceptive Units in Glabrous Skin." *The Journal of Physiology* 286(1):283–300.
- Johnson, Kenneth O. 2001. "The Roles and Functions of Cutaneous Mechanoreceptors." *Current Opinion in Neurobiology* 11(4):455–61.
- Jones, L. A., and D. A. Held. 2008. "Characterization of Tactors Used in Vibrotactile Displays." *Journal of Computing and Information Science in Engineering* 8(4):044501.
- Jones, Lynette A., and Nadine B. Sarter. 2008. "Tactile Displays: Guidance for Their Design and Application." *Human Factors* 50(1):90–111.
- Kaczmarek, K. A., J. G. Webster, P. Bach-y-Rita, and W. J. Tompkins. 1991.
 "Electrotactile and Vibrotactile Displays for Sensory Substitution Systems." *IEEE Transactions on Biomedical Engineering* 38(1):1–16.
- Kaczmarek, K., P. Bach-Y-Rita, W. J. Tompkins, and J. G. Webster. 1985. "A Tactile Vision-Substitution System for the Blind: Computer-Controlled Partial Image Sequencing." *IEEE Transactions on Biomedical Engineering* BME-32(8):602–8.
- Kanyal, Neema. 2015. "The Science of Ischemic Stroke: Pathophysiology & Pharmacological Treatment."
- Kapur, P., M. Jensen, L. J. Buxbaum, S. A. Jax, and K. J. Kuchenbecker. 2010. "Spatially Distributed Tactile Feedback for Kinesthetic Motion Guidance." Pp. 519–26 in 2010 IEEE Haptics Symposium.
- Kapur, P., S. Premakumar, S. A. Jax, L. J. Buxbaum, A. M. Dawson, and K. J. Kuchenbecker. 2009. "Vibrotactile Feedback System for Intuitive Upper-Limb Rehabilitation." Pp. 621–22 in World Haptics 2009 - Third Joint EuroHaptics conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems.
- Katan, Mira, and Andreas Luft. 2018. "Global Burden of Stroke." *Seminars in Neurology* 38(2):208–211.
- Kawato, Mitsuo. 1999. "Internal Models for Motor Control and Trajectory Planning." *Current Opinion in Neurobiology* 9(6):718–27.
- Kerr, Catherine E., Jessica R. Shaw, Rachel H. Wasserman, Vanessa W. Chen, Alok Kanojia, Thomas Bayer, and John M. Kelley. 2008. "Tactile Acuity in Experienced Tai Chi Practitioners: Evidence for Use Dependent Plasticity as an Effect of Sensory-Attentional Training." *Experimental Brain Research* 188(2):317–22.

- Kessner, Simon S., Ulrike Bingel, and Götz Thomalla. 2016. "Somatosensory Deficits after Stroke: A Scoping Review." *Topics in Stroke Rehabilitation* 23(2):136–46.
- Kleim, Jeffrey A., Jeffery A. Boychuk, and DeAnna L. Adkins. 2007. "Rat Models of Upper Extremity Impairment in Stroke." *ILAR Journal* 48(4):374–85.
- Körding, Konrad P., and Daniel M. Wolpert. 2006. "Bayesian Decision Theory in Sensorimotor Control." *Trends in Cognitive Sciences* 10(7):319–26.
- Krueger, Alexis R., Psiche Giannoni, Valay Shah, Maura Casadio, and Robert A. Scheidt. 2017. "Supplemental Vibrotactile Feedback Control of Stabilization and Reaching Actions of the Arm Using Limb State and Position Error Encodings." *Journal of NeuroEngineering and Rehabilitation* 14(1):36.
- Kuling, Irene A., Eli Brenner, and Jeroen B. J. Smeets. 2016. "Proprioceptive Localization of the Hand Changes When Skin Stretch around the Elbow Is Manipulated." *Frontiers in Psychology* 7.
- Lam, Paul, Debbie Hebert, Jennifer Boger, Hervé Lacheray, Don Gardner, Jacob Apkarian, and Alex Mihailidis. 2008. "A Haptic-Robotic Platform for Upper-Limb Reaching Stroke Therapy: Preliminary Design and Evaluation Results." *Journal of NeuroEngineering and Rehabilitation* 5(1):15.
- Lamoré, P. J. J., and C. J. Keemink. 1988. "Evidence for Different Types of Mechanoreceptors from Measurements of the Psychophysical Threshold for Vibrations under Different Stimulation Conditions." *The Journal of the Acoustical Society of America* 83(6):2339–51.
- Lara, Antonio H., and Jonathan D. Wallis. 2015. "The Role of Prefrontal Cortex in Working Memory: A Mini Review." *Frontiers in Systems Neuroscience* 9.
- Lee, Beom-Chan, Jeonghee Kim, Shu Chen, and Kathleen H. Sienko. 2012. "Cell Phone Based Balance Trainer." *Journal of NeuroEngineering and Rehabilitation* 9(1):10.
- Lee, Beom-Chan, Bernard J. Martin, Allison Ho, and Kathleen H. Sienko. 2013. "Postural Reorganization Induced by Torso Cutaneous Covibration." *Journal of Neuroscience* 33(18):7870–76.
- Lee, M. W. L., R. W. McPhee, and M. D. Stringer. 2008. "An Evidence-Based Approach to Human Dermatomes." *Clinical Anatomy* 21(5):363–73.
- Lee, T., C. Chamberlin, and N. Hodges. 2001. "Practice." in *Handbook of sport psychology*, edited by R. Singer, H. Hausenblas, and C. Janelle. New York: John Wiley.

- Leys, D., J. P. Pruvo, O. Godefroy, P. Rondepierre, and X. Leclerc. 1992. "Prevalence and Significance of Hyperdense Middle Cerebral Artery in Acute Stroke." *Stroke* 23(3):317–24.
- Li, Min, Guanghua Xu, Jun Xie, and Chaoyang Chen. 2018. "A Review: Motor Rehabilitation after Stroke with Control Based on Human Intent." *Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine* 232(4):344–60.
- Lieberman, J., and C. Breazeal. 2007. "TIKL: Development of a Wearable Vibrotactile Feedback Suit for Improved Human Motor Learning." *IEEE Transactions on Robotics* 23(5):919–26.
- Lin, Chia-Cheng, Susan L. Whitney, Patrick J. Loughlin, Joseph M. Furman, Mark S. Redfern, Kathleen H. Sienko, and Patrick J. Sparto. 2015. "The Effect of Age on Postural and Cognitive Task Performance While Using Vibrotactile Feedback." *Journal of Neurophysiology* 113(7):2127–36.
- van der Linden, Janet, Erwin Schoonderwaldt, and Jon Bird. 2009. "Good Vibrations: Guiding Body Movements with Vibrotactile Feedback." Pp. 13–18 in. Cambridge, UK.
- Magill, Richard A., and David Anderson. 2017. *Motor Learning and Control: Concepts and Applications*. Eleventh edition. New York, NY: McGraw-Hill Education.
- Mahns, D. A., N. M. Perkins, V. Sahai, L. Robinson, and M. J. Rowe. 2006. "Vibrotactile Frequency Discrimination in Human Hairy Skin." *Journal of Neurophysiology* 95(3):1442–50.
- Mancini, Flavia, Armando Bauleo, Jonathan Cole, Fausta Lui, Carlo A. Porro, Patrick Haggard, and Gian Domenico Iannetti. 2014. "Whole-Body Mapping of Spatial Acuity for Pain and Touch." *Annals of Neurology* 75(6):917–24.
- Manfredi, Louise R., Andrew T. Baker, Damian O. Elias, John F. Dammann Iii, Mark C. Zielinski, Vicky S. Polashock, and Sliman J. Bensmaia. 2012. "The Effect of Surface Wave Propagation on Neural Responses to Vibration in Primate Glabrous Skin." PLOS ONE 7(2):e31203.
- Martin, T. A., J. G. Keating, H. P. Goodkin, A. J. Bastian, and W. T. Thach. 1996.
 "Throwing While Looking through Prisms: II. Specificity and Storage of Multiple Gaze--Throw Calibrations." *Brain* 119(4):1199–1211.
- Merbah, Sarah, and Thierry Meulemans. 2011. "Learning a Motor Skill: Effects of Blocked Versus Random Practice a Review." *Psychologica Belgica* 51(1):15–48.
- Miall, R. C., and D. M. Wolpert. 1996. "Forward Models for Physiological Motor Control." *Neural Networks* 9(8):1265–79.

- Mitchell, J. F., K. A. Sundberg, and J. H. Reynolds. 2007. "Differential Attention-Dependent Response Modulation across Cell Classes in Macaque Visual Area V4." *Neuron* 55, 131–41.
- Molier, Birgit I., Edwin H. F. Van Asseldonk, Hermie J. Hermens, and Michiel J. A. Jannink. 2010. "Nature, Timing, Frequency and Type of Augmented Feedback; Does It Influence Motor Relearning of the Hemiparetic Arm after Stroke? A Systematic Review." *Disability and Rehabilitation* 32(22):1799–1809.
- Morioka, Miyuki, Darren J. Whitehouse, and Michael J. Griffin. 2008. "Vibrotactile Thresholds at the Fingertip, Volar Forearm, Large Toe, and Heel." *Somatosensory* & *Motor Research* 25(2):101–12.
- Morley, J. W., and M. J. Rowe. 1990. "Perceived Pitch of Vibrotactile Stimuli: Effects of Vibration Amplitude, and Implications for Vibration Frequency Coding." *The Journal of Physiology* 431(1):403–16.
- Morrison, Sarah A., Douglas Lorenz, Carol P. Eskay, Gail F. Forrest, and D. Michele Basso. 2018. "Longitudinal Recovery and Reduced Costs After 120 Sessions of Locomotor Training for Motor Incomplete Spinal Cord Injury." Archives of Physical Medicine and Rehabilitation 99(3):555–562.
- Mountcastle, V. B., R. H. LaMotte, and G. Carli. 1972. "Detection Thresholds for Stimuli in Humans and Monkeys: Comparison with Threshold Events in Mechanoreceptive Afferent Nerve Fibers Innervating the Monkey Hand." *Journal* of Neurophysiology 35(1):122–36.
- Mozaffarian, Dariush, Emelia J. Benjamin, Alan S. Go, Donna K. Arnett, Michael J. Blaha, Mary Cushman, Sandeep R. Das, Sarah de Ferranti, Jean-Pierre Després, Heather J. Fullerton, Virginia J. Howard, Mark D. Huffman, Carmen R. Isasi, Monik C. Jiménez, Suzanne E. Judd, Brett M. Kissela, Judith H. Lichtman, Lynda D. Lisabeth, Simin Liu, Rachel H. Mackey, David J. Magid, Darren K. McGuire, Emile R. Mohler, Claudia S. Moy, Paul Muntner, Michael E. Mussolino, Khurram Nasir, Robert W. Neumar, Graham Nichol, Latha Palaniappan, Dilip K. Pandey, Mathew J. Reeves, Carlos J. Rodriguez, Wayne Rosamond, Paul D. Sorlie, Joel Stein, Amytis Towfighi, Tanya N. Turan, Salim S. Virani, Daniel Woo, Robert W. Yeh, and Melanie B. Turner. 2016. "Heart Disease and Stroke Statistics— 2016 Update." *Circulation* 133(4):38–360.
- Mozolic, Jennifer L., Christina E. Hugenschmidt, Ann M. Peiffer, and Paul J. Laurienti. 2008. "Modality-Specific Selective Attention Attenuates Multisensory Integration." *Experimental Brain Research* 184(1):39–52.
- Mozolic, Jennifer L., Ashley B. Long, Ashley R. Morgan, Melissa Rawley-Payne, and Paul J. Laurienti. 2011. "A Cognitive Training Intervention Improves Modality-Specific Attention in a Randomized Controlled Trial of Healthy Older Adults." *Neurobiology of Aging* 32(4):655–68.

- Muniak, Michael A., Supratim Ray, Steven S. Hsiao, J. Frank Dammann, and Sliman J. Bensmaia. 2007. "The Neural Coding of Stimulus Intensity: Linking the Population Response of Mechanoreceptive Afferents with Psychophysical Behavior." *Journal of Neuroscience* 27(43):11687–99.
- Muren, Marie Almkvist, Matthias Hütler, and Julie Hooper. 2008. "Functional Capacity and Health-Related Quality of Life in Individuals Post Stroke." *Topics in Stroke Rehabilitation* 15(1):51–58.
- Murray, Joseph F. 1981. "Effects of Whole vs Part Method of Training on Transfer of Learning." *Perceptual and Motor Skills* 53(3):883–89.
- Mussa-Ivaldi, Ferdinando A., Maura Casadio, and Rajiv Ranganathan. 2013. "The Body– Machine Interface: A Pathway for Rehabilitation and Assistance in People with Movement Disorders." *Expert Review of Medical Devices* 10(2):145–47.
- Mussa-Ivaldi, Ferdinando A., and Lee E. Miller. 2003. "Brain–Machine Interfaces: Computational Demands and Clinical Needs Meet Basic Neuroscience." *Trends in Neurosciences* 26(6):329–34.
- Nasreddine, Ziad S., Natalie A. Phillips, Valérie Bédirian, Simon Charbonneau, Victor Whitehead, Isabelle Collin, Jeffrey L. Cummings, and Howard Chertkow. 2005. "The Montreal Cognitive Assessment, MoCA: A Brief Screening Tool For Mild Cognitive Impairment: MOCA: A BRIEF SCREENING TOOL FOR MCI." Journal of the American Geriatrics Society 53(4):695–99.
- Naylor, James C., and George E. Briggs. 1963. "Effects of Task Complexity and Task Organization on the Relative Efficiency of Part and Whole Training Methods." *Journal of Experimental Psychology* 65(3):217–24.
- Nelson, Susan R., Richard P. Di Fabio, and John H. Anderson. 1995. "Vestibular and Sensory Interaction Deficits Assessed by Dynamic Platform Posturography in Patients with Multiple Sclerosis." *Annals of Otology, Rhinology & Laryngology* 104(1):62–68.
- Nolan, Michael F. 1982. "Two-Point Discrimination Assessment in the Upper Limb in Young Adult Men and Women." *Physical Therapy* 62(7):965–69.
- Oakley, I., Yeongmi Kim, Junhun Lee, and Jeha Ryu. 2006. "Determining the Feasibility of Forearm Mounted Vibrotactile Displays." Pp. 27–34 in 2006 14th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems.
- Oscari, Fabio, Riccardo Secoli, Federico Avanzini, Giulio Rosati, and David J. Reinkensmeyer. 2012. "Substituting Auditory for Visual Feedback to Adapt to Altered Dynamic and Kinematic Environments during Reaching." *Experimental Brain Research* 221(1):33–41.

- O'Sullivan, Susan B., Thomas J. Schmitz, and George D. Fulk. 2014. *Physical Rehabilitation*. 6th ed. Philadelphia: F.A. Davis Co.
- Pashler, Harold. 1994. "Dual-Task Interference in Simple Tasks: Data and Theory." *Psychological Bulletin* 116(2):220–244.
- Penfield, Wilder, and Edwin Boldrey. 1937. "SOMATIC MOTOR AND SENSORY REPRESENTATION IN THE CEREBRAL CORTEX OF MAN AS STUDIED BY ELECTRICAL STIMULATION." *Brain* 60(4):389–443.
- Perez, C. A., C. A. Holzmann, and H. E. Jaeschke. 2000. "Two-Point Vibrotactile Discrimination Related to Parameters of Pulse Burst Stimulus." *Medical and Biological Engineering and Computing* 38(1):74–79.
- Piateski, E., and L. Jones. 2005. "Vibrotactile Pattern Recognition on the Arm and Torso." Pp. 90–95 in *First Joint Eurohaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems. World Haptics Conference.* IEEE.
- Pickering, Martin J., and Andy Clark. 2014. "Getting Ahead: Forward Models and Their Place in Cognitive Architecture." *Trends in Cognitive Sciences* 18(9):451–56.
- Pierella, Camilla, Farnaz Abdollahi, Ali Farshchiansadegh, Jessica Pedersen, David Chen, Ferdinando A. Mussa-Ivaldi, and Maura Casadio. 2014. "Body Machine Interfaces for Neuromotor Rehabilitation: A Case Study." Pp. 397–401 in 2014 36th Annual International Conference of the IEEE Engineering in Medicine and Biology Society.
- Post, L. J., I. C. Zompa, and C. E. Chapman. 1994. "Perception of Vibrotactile Stimuli during Motor Activity in Human Subjects." *Experimental Brain Research* 100(1):107–20.
- Prewett, M. S., L. R. Elliott, A. G. Walvoord, and M. D. Coovert. 2012. "A Meta-Analysis of Vibrotactile and Visual Information Displays for Improving Task Performance." *IEEE Transactions on Systems, Man, and Cybernetics, Part C* (Applications and Reviews) 42(1):123–32.

Purves, Dale, ed. 2012. Neuroscience. 5th ed. Sunderland, Mass: Sinauer Associates.

- Rafferty, Miriam R., Peter N. Schmidt, Sheng T. Luo, Kan Li, Connie Marras, Thomas L. Davis, Mark Guttman, Fernando Cubillos, and Tanya Simuni. 2017. "Regular Exercise, Quality of Life, and Mobility in Parkinson's Disease: A Longitudinal Analysis of National Parkinson Foundation Quality Improvement Initiative Data." *Journal of Parkinson's Disease* 7(1):193–202.
- Ribot-Ciscar, E., J. P. Vedel, and J. P. Roll. 1989. "Vibration Sensitivity of Slowly and Rapidly Adapting Cutaneous Mechanoreceptors in the Human Foot and Leg." *Neuroscience Letters* 104(1):130–35.

- Risi, Nicoletta, Valay Shah, Leigh A. Mrotek, Maura Casadio, and Robert A. Scheidt. 2019. "Supplemental Vibrotactile Feedback of Real-Time Limb Position Enhances Precision of Goal-Directed Reaching." *Journal of Neurophysiology* 122(1):22–38.
- Romo, Ranulfo, Carlos D. Brody, Adrián Hernández, and Luis Lemus. 1999. "Neuronal Correlates of Parametric Working Memory in the Prefrontal Cortex." *Nature* 399(6735):470.
- Romo, Ranulfo, Adrián Hernández, Antonio Zainos, Luis Lemus, and Carlos D. Brody. 2002. "Neuronal Correlates of Decision-Making in Secondary Somatosensory Cortex." *Nature Neuroscience* 5(11):1217.
- Rosenbaum, David A. 2010. *Human Motor Control*. 2nd ed. Amsterdam ; Boston, MA: Elsevier Inc.
- Sainburg, R. L., M. F. Ghilardi, H. Poizner, and C. Ghez. 1995. "Control of Limb Dynamics in Normal Subjects and Patients without Proprioception." *Journal of Neurophysiology* 73(2):820–35.
- Sainburg, R. L., H. Poizner, and C. Ghez. 1993. "Loss of Proprioception Produces Deficits in Interjoint Coordination." *Journal of Neurophysiology* 70(5):2136–47.
- Sarlegna, Fabrice R., Gabriel M. Gauthier, Christophe Bourdin, Jean-Louis Vercher, and Jean Blouin. 2006. "Internally Driven Control of Reaching Movements: A Study on a Proprioceptively Deafferented Subject." *Brain Research Bulletin* 69(4):404– 15.
- Schabrun, SM, and S. Hillier. 2009. "Evidence for the Retraining of Sensation after Stroke: A Systematic Review." *Clinical Rehabilitation* 23(1):27–39.
- Scheidt, Robert A., Michael A. Conditt, Emanuele L. Secco, and Ferdinando A. Mussa-Ivaldi. 2005. "Interaction of Visual and Proprioceptive Feedback During Adaptation of Human Reaching Movements." *Journal of Neurophysiology* 93(6):3200–3213.
- Scheidt, Robert A., and Claude Ghez. 2007. "Separate Adaptive Mechanisms for Controlling Trajectory and Final Position in Reaching." *Journal of Neurophysiology* 98(6):3600–3613.
- Scheidt, Robert A., Kyle P. Lillis, and Scott J. Emerson. 2010. "Visual, Motor and Attentional Influences on Proprioceptive Contributions to Perception of Hand Path Rectilinearity during Reaching." *Experimental Brain Research* 204(2):239– 54.
- Scheidt, Robert A., David J. Reinkensmeyer, Michael A. Conditt, W. Zev Rymer, and Ferdinando A. Mussa-Ivaldi. 2000. "Persistence of Motor Adaptation During

Constrained, Multi-Joint, Arm Movements." *Journal of Neurophysiology* 84(2):853–62.

- Scheidt, Robert A., and Tina Stoeckmann. 2007. "Reach Adaptation and Final Position Control Amid Environmental Uncertainty After Stroke." *Journal of Neurophysiology* 97(4):2824–36.
- Schmidt, Richard A., and Timothy Donald Lee. 2005. *Motor Control and Learning: A Behavioral Emphasis.* 4th ed. Champaign, IL: Human Kinetics.
- Schorr, S. B., Z. F. Quek, R. Y. Romano, I. Nisky, W. R. Provancher, and A. M.
 Okamura. 2013. "Sensory Substitution via Cutaneous Skin Stretch Feedback." Pp. 2341–46 in 2013 IEEE International Conference on Robotics and Automation.
- Scott, Stephen H. 2004. "Optimal Feedback Control and the Neural Basis of Volitional Motor Control." *Nature Reviews Neuroscience* 5(7):532.
- Shah, Valay A., Maura Casadio, Robert A. Scheidt, and Leigh A. Mrotek. 2019a. "Spatial and Temporal Influences on Discrimination of Vibrotactile Stimuli on the Arm." *Experimental Brain Research* 237(8):2075–86.
- Shah, Valay A., Maura Casadio, Robert A. Scheidt, and Leigh A. Mrotek. 2019b. "Vibration Propagation on the Skin of the Arm." *Applied Sciences* 9(20):4329.
- Shah, Valay A., Nicoletta Risi, Giulia Ballardini, Leigh Ann Mrotek, Maura Casadio, and Robert A. Scheidt. 2018. "Effect of Dual Tasking on Vibrotactile Feedback Guided Reaching – A Pilot Study." Pp. 3–14 in *Haptics: Science, Technology, and Applications, Lecture Notes in Computer Science*, edited by D. Prattichizzo, H. Shinoda, H. Z. Tan, E. Ruffaldi, and A. Frisoli. Springer International Publishing.
- Shanechi, Maryam M., Ziv M. Williams, Gregory W. Wornell, Rollin C. Hu, Marissa Powers, and Emery N. Brown. 2013. "A Real-Time Brain-Machine Interface Combining Motor Target and Trajectory Intent Using an Optimal Feedback Control Design" edited by W. Zhan. *PLoS ONE* 8(4):e59049.
- Shea, Charles H., Robert Kohl, and Catherine Indermill. 1990. "Contextual Interference: Contributions of Practice." *Acta Psychologica* 73(2):145–57.
- Shea, John B., and Robyn L. Morgan. 1979. "Contextual Interference Effects on the Acquisition, Retention, and Transfer of a Motor Skill." *Journal of Experimental Psychology: Human Learning and Memory* 5(2):179.
- Shull, Peter B., and Dana D. Damian. 2015. "Haptic Wearables as Sensory Replacement, Sensory Augmentation and Trainer – a Review." *Journal of NeuroEngineering* and Rehabilitation 12(1):59.

- Sienko, K. H., M. D. Balkwill, L. I. E. Oddsson, and C. Wall. 2008. "Effects of Multi-Directional Vibrotactile Feedback on Vestibular-Deficient Postural Performance during Continuous Multi-Directional Support Surface Perturbations." *Journal of Vestibular Research: Equilibrium & Orientation* 18(5–6):273–85.
- Silver, Frederick H., Joseph W. Freeman, and Dale DeVore. 2001. "Viscoelastic Properties of Human Skin and Processed Dermis." *Skin Research and Technology* 7(1):18–23.
- Sober, Samuel J., and Philip N. Sabes. 2003. "Multisensory Integration during Motor Planning." *Journal of Neuroscience* 23(18):6982–92.
- Sober, Samuel J., and Philip N. Sabes. 2005. "Flexible Strategies for Sensory Integration during Motor Planning." *Nature Neuroscience* 8(4):490–97.
- Sofia, K. O., and L. Jones. 2013. "Mechanical and Psychophysical Studies of Surface Wave Propagation during Vibrotactile Stimulation." *IEEE Transactions on Haptics* 6(3):320–29.
- Sonar, Harshal Arun, and Jamie Paik. 2016. "Soft Pneumatic Actuator Skin with Piezoelectric Sensors for Vibrotactile Feedback." *Frontiers in Robotics and AI* 2.
- Stepp, C. E., and Y. Matsuoka. 2012. "Vibrotactile Sensory Substitution for Object Manipulation: Amplitude Versus Pulse Train Frequency Modulation." *IEEE Transactions on Neural Systems and Rehabilitation Engineering* 20(1):31–37.
- Sullivan, Katherine J., Julie K. Tilson, Steven Y. Cen, Dorian K. Rose, Julie Hershberg, Anita Correa, Joann Gallichio, Molly McLeod, Craig Moore, Samuel S. Wu, and Pamela W. Duncan. 2011. "Fugl-Meyer Assessment of Sensorimotor Function After Stroke: Standardized Training Procedure for Clinical Practice and Clinical Trials." *Stroke* 42(2):427–32.
- Tannan, V., R. G. Dennis, Z. Zhang, and M. Tommerdahl. 2007. "A Portable Tactile Sensory Diagnostic Device." *Journal of Neuroscience Methods* 164(1):131–38.
- Tannan, V., S. Simons, R. G. Dennis, and M. Tommerdahl. 2007. "Effects of Adaptation on the Capacity to Differentiate Simultaneously Delivered Dual-Site Vibrotactile Stimuli." *Brain Research* 1186:164–170.
- Tannan, Vinay, Barry L. Whitsel, and Mark A. Tommerdahl. 2006. "Vibrotactile Adaptation Enhances Spatial Localization." *Brain Research* 1102(1):109–16.
- Tatemichi, T. K., D. W. Desmond, Y. Stern, M. Paik, M. Sano, and E. Bagiella. 1994. "Cognitive Impairment after Stroke: Frequency, Patterns, and Relationship to Functional Abilities." *Journal of Neurology, Neurosurgery & Psychiatry* 57(2):202–7.

- Teasell, Robert, Norhayati Hussein MBBS MRehabMed, Ricardo Viana, Sarah Donaldson BHSc, and Mona Madady. 2016. "Stroke Rehabilitation Clinician Handbook 2016." 27.
- Thach, William T. 1998. "What Is the Role of the Cerebellum in Motor Learning and Cognition?" *Trends in Cognitive Sciences* 2(9):331–37.
- Todorov, Emanuel. 2004. "Optimality Principles in Sensorimotor Control." *Nature Neuroscience* 7(9):907–15.
- Tzorakoleftherakis, E., M. C. Bengtson, F. A. Mussa-Ivaldi, R. A. Scheidt, and T. D. Murphey. 2015. "Tactile Proprioceptive Input in Robotic Rehabilitation after Stroke." Pp. 6475–81 in 2015 IEEE International Conference on Robotics and Automation (ICRA).
- Tzorakoleftherakis, Emmanouil, Todd D. Murphey, and Robert A. Scheidt. 2016. "Augmenting Sensorimotor Control Using 'Goal-Aware' Vibrotactile Stimulation during Reaching and Manipulation Behaviors." *Experimental Brain Research* 234(8):2403–14.
- Vaugoyeau, M., S. Viel, C. Assaiante, B. Amblard, and J. P. Azulay. 2007. "Impaired Vertical Postural Control and Proprioceptive Integration Deficits in Parkinson's Disease." *Neuroscience* 146(2):852–63.
- Verrillo, Ronald T. 1980. "Age Related Changes in the Sensitivity to Vibration." Journal of Gerontology 35(2):185–93.
- Verrillo, Ronald T. 1985. "Psychophysics of Vibrotactile Stimulation." *The Journal of the Acoustical Society of America* 77(1):225–32.
- Vidoni, Eric D., and Lara A. Boyd. 2009. "Preserved Motor Learning after Stroke Is Related to the Degree of Proprioceptive Deficit." *Behavioral and Brain Functions* 5(1):36.
- Walcott, Brian P., Jennifer C. Miller, Churl-Su Kwon, Sameer A. Sheth, Marc Hiller, Carolyn A. Cronin, Lee H. Schwamm, J. Marc Simard, Kristopher T. Kahle, W. Taylor Kimberly, and Kevin N. Sheth. 2014. "Outcomes in Severe Middle Cerebral Artery Ischemic Stroke." *Neurocritical Care* 21(1):20–26.
- Wall, C., M. S. Weinberg, P. B. Schmidt, and D. E. Krebs. 2001. "Balance Prosthesis Based on Micromechanical Sensors Using Vibrotactile Feedback of Tilt." *IEEE Transactions on Biomedical Engineering* 48(10):1153–61.
- Wang, Feng, Wanna Zhang, and Wei Luo. 2018. "An Empirical Evaluation on Vibrotactile Feedback for Wristband System." *Mobile Information Systems* 2018(Article ID 4878014):8.

- Weber, B., S. Schätzle, T. Hulin, C. Preusche, and B. Deml. 2011. "Evaluation of a Vibrotactile Feedback Device for Spatial Guidance." Pp. 349–54 in 2011 IEEE World Haptics Conference.
- Weerakkody, N. S., D. A. Mahns, J. L. Taylor, and S. C. Gandevia. 2007. "Impairment of Human Proprioception by High-Frequency Cutaneous Vibration." *The Journal of Physiology* 581(3):971–80.
- Wentink, E. C., A. Mulder, J. S. Rietman, and P. H. Veltink. 2011. "Vibrotactile Stimulation of the Upper Leg: Effects of Location, Stimulation Method and Habituation." Pp. 1668–71 in 2011 Annual International Conference of the IEEE Engineering in Medicine and Biology Society.
- Werner, G., and B. L. Whitsel. 1968. "Topology of the Body Representation in Somatosensory Area I of Primates." *Journal of Neurophysiology* 31(6):856–69.
- White, Benjamin W., Frank A. Saunders, Lawrence Scadden, Paul Bach-Y-Rita, and Carter C. Collins. 1970. "Seeing with the Skin." *Perception & Psychophysics* 7(1):23–27.
- Wickens, C. D., J. G. Hollands, S. Banbury, and R. Parasuraman. 2015. *Engineering Psychology and Human Performance*. 4th ed. New York: Psychology Press.
- Wilde, Heather, Curt Magnuson, and Charles H. Shea. 2005. "Random and Blocked Practice of Movement Sequences." *Research Quarterly for Exercise and Sport* 76(4):416–25.
- Witteveen, Heidi JB, Hans S. Rietman, and Peter H. Veltink. 2015. "Vibrotactile Grasping Force and Hand Aperture Feedback for Myoelectric Forearm Prosthesis Users." *Prosthetics and Orthotics International* 39(3):204–12.
- Wolpert, D. M., Z. Ghahramani, and M. I. Jordan. 1995. "An Internal Model for Sensorimotor Integration." *Science* 269(5232):1880–82.
- Wolpert, Daniel M., Susan J. Goodbody, and Masud Husain. 1998. "Maintaining Internal Representations: The Role of the Human Superior Parietal Lobe." *Nature Neuroscience* 1(6):529–33.
- Woolsey, Clinton N., Wade H. Marshall, and Philip Bard. 1943. "Note on the Organization of the Tactile Sensory Area of the Cerebral Cortex of the Chimpanzee." *Journal of Neurophysiology* 6(4):287–91.
- Wright, Beverly A., and Andrew T. Sabin. 2007. "Perceptual Learning: How Much Daily Training Is Enough?" *Experimental Brain Research* 180(4):727–36.
- Wu, Changxu, and Yili Liu. 2008. "Queuing Network Modeling of the Psychological Refractory Period (PRP)." *Psychological Review* 115(4):913–54.

Wyart, Valentin, Nicholas E. Myers, and Christopher Summerfield. 2015. "Neural Mechanisms of Human Perceptual Choice Under Focused and Divided Attention." *Journal of Neuroscience* 35(8):3485–98.