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Doctoral Dissertation

Methods to bring focus to desired muscle patterns

By

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Abstract

Real-world motor skill learning is a complicated problem involving planning, execution, practice, and retention. One of the sub components in motor skill learning is the credit-assigment problem: how are errors during performance assigned to individual components involved in the task? This is not trivial since there are numerous processes and systems at play when making a movement. So, how do humans learn complex motor skills, and what methods are used to aid in the process?

A major source of inspiration for this work comes from the world of coaching where we see novices become elite-level athletes due to strategies, ranging from using motivation, sub tasking, iterative practice, tactile/visual aids, and visualization techniques. Coaches used these to modulate attention to task-relevant components. Two such sensory modulators of attention are vibratory feedback and visualization. My work is on understanding how these sensory modulators can create equivalent tasks by communicating percepts that are tactile, proprioceptive, or emotional in order to solve the credit-assignment problem.

Vibratory feedback has been widely used for rehabilitation purposes, and with success. Here its effects on muscle use was studied on real-world tasks as well as on a one-dimensional myocontrol task. It was found that scaled vibratory feedback augments sensory information by bringing selective focus to task-relevant components and increasing muscle use, while non scaled vibratory feedback does not have such an effect. An alternative theory of multi-muscle feedback cemented the importance of bringing selective focus via single-muscle vibration.

Visualization techniques have not received much attention in the motor Neuroscience community. One-dimensional and three-dimensional myocontrol tasks were designed to study its effects on performance and muscle use. Results showed that visualization brings selective focus by communicating non-visual sensations via some kind of task equivalence: substituting the body, task, or emotional context.

Both of these sensory methods were shown to help solve this complex credit-assignment problem by bringing selective focus directly to individual muscles or indirectly via movement sensations. Therefore, there is much room for the use of these techniques in motor skill learning.

Acknowledgements

My academic journey so far has been an incredible one, and I would not be here today without the support and encouragement of so many people.

I would like to first thank my advisor, Dr. Terence Sanger, for his guidance and mentorship to help me become the researcher I am today. And I thank him for giving me the opportunity to discover my strengths and weaknesses as an academic. I would also like to thank my doctoral committee members: Dr. Gisele Ragusa for her immense support and collaboration throughout the past two years, and Dr. Francisco Valero-Cuevas for his insightful comments and creative thinking. Drs. Nicolas Schweighofer and Maja Mataric, who were on my qualifying exam committee, were also very helpful in shaping my thesis work. And of course, all the professors, post doctoral researchers, staff, mentors, and experiment subjects at the University of Southern California and at the Georgia Institute of Technology who helped and inspired me in so many different ways. I have had a great set of friends and colleagues who helped me stay sane throughout this long and sometimes frustrating process, and I am so very thankful to them.

And now I come to family, the reason why I am here today. I am who I am because of my parents, Harischandra & Chandanie. My humble and unassumingly brilliant father instilled in me the value of higher studies, and paved the path for me to focus on my work with no other worries in mind. My caring and loving mother was there to talk to me every day, and helped me get through the darkest of days. My supportive and lovely sisters, Sandunie & Savindie, rejoiced in all my successes, and always kept me grounded. They gave me the space I needed to focus on my work while also ensuring I did not completely lose myself in it, and I thank them for all of their support. Additionally, I would like to thank my childhood hero, my great uncle, Prof. P.V.J. Jayasekera who told me to always question the norm. I am also blessed to have an incredible extended family who have always loved and supported me.

And last, but definitely not the least, I would like to thank my wonderful superman of a husband, Mevan, for his love, care, support, affection, and complete understanding. He has made me want to always reach for the stars, and know to expect the unexpected.

Contents

Chapter 1

A different approach to motor learning

1.1 Current perspectives in motor learning

The field of motor control and learning has developed numerous theories and perspectives in order to understand and predict the nature of human movement. Some of these theories describe concepts such as error-based learning, sensory-motor mappings, internal models, and equilibrium-point control (Haith and Krakauer, 2013; Kaas, 1991; Kawato, 1999; Latash et al., 2010; Shadmehr, 2010; Wolpert, Diedrichsen, and Flanagan, 2011). These theories have helped us understand, through human and animal laboratory experiments, how subjects adapt to different applied forces, learn to predict outcomes of self-motion, and move stably in the presence of perturbations (Dingwell, Mah, and Mussa-Ivaldi, 2002; Latash, 2010; Mussa-Ivaldi et al., 2011). Research in these areas is ongoing, and many new theories and associated experiments are under development to describe the mechanisms that lead to voluntary human movement.

While this research demonstrates promise and is of great importance within the field of Neuroscience, the theoretical premises associated with this work have not yet been successful in describing a model for teaching complex real-world skills associated with motor control that would be relevant outside the laboratory setting. This is perhaps most evident when we see that concepts fundamental to motor Neuroscience are mostly absent in literature on athletic coaching, strategies for learning to play musical instruments, and even in the language used by dancers. For example, we do not hear of coaches talking about internal models for teaching a tennis stroke, etc. This suggests that the field of Motor Neuroscience does not address the issues that are fundamental to successful learning of motor skills in real-world contexts.

Outside of the laboratory, we see novices with diverse levels of skill learning able to master specific motor skills, execute them under varying levels of stress and in diverse contexts, and do so repeatedly and with relative accuracy. These novices learn with greater efficiency via appropriate coaching and teaching. And so, it seems only reasonable to gain insights from the real world of motor learning in order to inform the design of motor Neuroscience experiments and to perhaps, in the long-term, expand its focus to study questions relevant to real-world motor learning. Success in such an endeavor could be particularly important for improving motor function in people with motor disabilities. This would be even more relevant in children for whom motor learning is an expected component of development.

Specifically, our interest was in understanding how humans solve the credit-assignment problem (Fu and Anderson, 2006). When we make a movement, how do we associate feedback with the choices and actions that brought about this movement? As shown on the block diagram for a control system in Figure 1.1, the error signal x^* is a result of z^*, which receives information from a variety of sources. The error signal needs to be associated with one or more of those incoming sensory signals. In order to solve this problem, it may be beneficial to see how it has been solved by experts in the real-world. And this is how we end up approaching the problem from a coaching perspective.

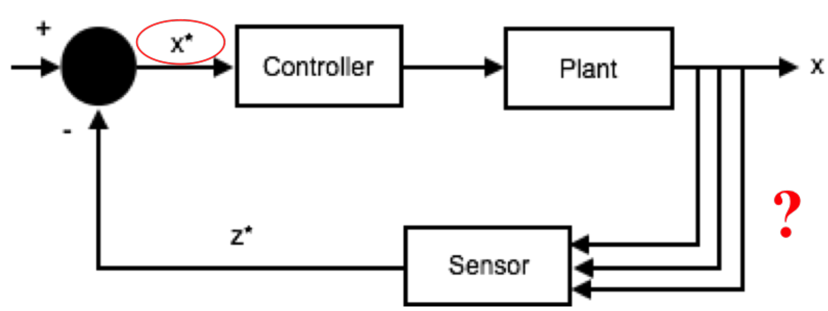

FIGURE 1.1: Control system block diagram showing the credit-assignment problem. The sensor receives numerous amounts of input based on the outcome of the plant, making it difficult to identify which choices resulted in the error signal x^*.

1.2 Perspectives in the world of coaching

Sports coaches have expertise and knowledge relevant to motor skill acquisition in real-world contexts. They have the ability to begin work with a novice athlete, teach them how to learn or perfect specific skilled movements, enable them to execute those movements under high levels of stress in competition and in different environments, and do so repeatedly and with maximal accuracy. Athletic coaching is an extensively studied field, with work being done to understand both the psychological and physical aspects involved in training athletes. Coaches analyze an athlete's performance in order to find methods by which suboptimal areas of performance can be effectively and efficiently modified (Annett, 1994). They use methods that resonate with an athlete's experiences because drawing parallels to what is known already is helpful in learning new techniques and performance-related strategies. If we can understand and model these processes, then it may be possible to discover new methods for re-training children with movement disorders.

Coaching offers methods to teach novel skills by focusing an athlete's attention to task relevant features, prioritizing goals, providing specific feedback to improve performance, and designing strategies for correction of errors. Research has indicated that goal-directed learning stimulated by coaches can enhance learning of gross motor skills (Platvoet et al., 2016). In a preliminary effort to discover best practices for effective and efficient coaching strategies and techniques, informal interviews with sports coaches at the University of Southern California (USC) were conducted. Coaches were asked what it was like to coach athletes at elite skill levels compared to novice athletes. The major difference between coaching a novice versus an expert, according to the interviewed coaches, was that experts were taught how to develop their own style and express themselves in a way that enabled them to distinguish themselves from others, and to provide them with a competitive edge. A novice needed to first learn the basics of making a movement or completing an athletic task, and therefore, expression/style would come after much practice and mastery of the basic task. However, coaches would not necessarily leave out methods used to teach elite level athletes when coaching novices. During training, coaches reported using various methods to communicate correct movement to athletes: demonstration (using visual aids such as pictures and movies or by asking athletes to imitate them or a famous athlete), tactile aids (guiding, pushing, creating altered environments), visualization techniques, iterative practice, and sub-tasking. They also constantly provided positive feedback during practice. In every interview that was conducted, mental imagery/visualization was highlighted as a tool that was used widely and with relative success. Coaches described visualization techniques as being useful in helping athletes understand the sequences of movements to be made, how those movements could be broken down, and how they could be perfected. Since visualization techniques and kinesthetic feedback were mentioned in these initial coaching interviews, we opted to dig deeper into coaching techniques involving these interventions in order to explore and understand them in greater detail.

1.3 Study on motor skill coaching

We designed two questionnaires on motor skill coaching that were sent to sports coaches at USC, as well as to coaches in the Special Olympics (SO) World Games, respectively. The questionnaires included specific questions about visualization, other methods for teaching motor skills, factors affecting coaching style, methods for tailoring coaching style to individual athletes, and the effects of psychological factors. The questionnaires differed slightly because of a more prominent focus on psychological factors in the Special Olympics questionnaire.

1.3.1 Methods

The University's Institutional Review Board approved the study protocol (UP-15-00252). Responses to this questionnaire were collected anonymously via a web link that was distributed in an email sent by the Athletics Department (to USC coaches) and Dr. Gisele Ragusa (to SO coaches). We provided the coaches with an electronic informational sheet that detailed the purpose of the study, participant involvement, the alternatives to participation, promise of confidentiality, and investigator contact information to the department that was distributed electronically along with the questionnaire link. The USC questionnaire was distributed to thirty-two head and assistant coaches, and we received thirteen responses. The SO questionnaire was sent to approximately 197 coaches, and we received 52 responses.

The questionnaire included both open-ended and multiple-choice questions. All the questions were optional, and respondents were allowed to move freely between questions so that they did not have to answer them in any specific order. This questionnaire was designed using Qualtrics© data collection platform (Qualtrics, Provo, Utah, U.S.A.), Version 06/2015, 2016. It was possible to complete this questionnaire using a computer or a mobile device. See Figure 1.2 for a snapshot of the questionnaire.

Qualitative analysis

NVivo qualitative data analysis software (QSR International Pty Ltd. Version 11.2.2, 2016) was utilized. This software facilitates thematic analysis of narrative and video qualitative data. Information was coded into nine descriptive categories or nodes. For some of the nodes, we created sub-nodes based on the responses to the questionnaire. In addition, we also enabled NVivo to auto-code the data, which created ten nodes based on the qualitative questions. Figure 1.3 shows the categories and sub-categories used in the analysis.

Coaching style/approach linked to experience

	How would you rate the importance of the following on defining your coaching style?		
	Not important	Somewhat important	Very important
Coaching training	○	○	○
Experience as a current/former athlete	○	○	○
Experience as coach	○	○	○
Educational/research articles on coaching	○	○	○
Understanding of biomechanics of sports	○	○	○

What types of observations about your student/athlete do you use to tailor your coaching style to each individual? Please describe.

Block 2

Which of the following methods do you use to teach a movement-related skill to your student/athlete? (Please check all that apply.)

- ☐ Learning by imitation
- ☐ Practice of same skill in a different context or sport i.e. cross-training
- ☐ Iterative practice of skill
- ☐ Task breakdown and iterative practice of individual parts of skill
- ☐ Iterative practice of skill on different body area
- ☐ Enhancement of mental imagery/visualization techniques related to learning a skill

Modes of feedback (we are interested in learning how different kinds of feedback can be more useful than others).

NOTE: Mental imagery/visualizations, refer to techniques that you use to help your athletes/students focus on:
(1) a specific part of the body (for example, you might say to an athlete: "imagine yourself crushing a watermelon with your stomach as you do a crunch"),
(2) the body completing an entire sequence (or "imagine what it's like to hit the perfect tennis stroke like a world class tennis player would"),
(3) the sensations involved in completing a sequence (or "imagine yourself being chased by wolves as you sprint").

	How effective are the following modes of feedback for a student/athlete who wants to improve his/her performance?		
	No effect	Somewhat effective	Very effective
Visual feedback (e.g. videos, mirrors)	○	○	○
Mental imagery/visualizations: Which of the 3 types mentioned in the note above do you use? Are there others as well? Please be as descriptive as possible.	○	○	○
Kinesthetic feedback (e.g. tactile, vibratory, pressure)	○	○	○
Auditory feedback	○	○	○

For mental imagery/visualizations, which of the 3 types mentioned on the note in the previous question do you use? Are there others as well? Please be as descriptive as possible.

FIGURE 1.2: A snapshot of the motor skill coaching questionnaire.

The nodes, or themes, we created resulting from the qualitative data collected via the questionnaire were aligned with our research questions, and included the following: Methods to teach & optimize skills, Feedback modes, Visualization techniques & their formation, Additional tools to go with visualization, How to ensure athletes followed instructions, Why visualization techniques not helpful, What do athletes look for in a coach, Can coaches modify psychological

Methods to teach & optimize skills	Feedback modes	Visualization techniques & their formation	Additional tools to go with visualization	How to ensure athletes followed instructions	Why visualization techniques not helpful	What do athletes look for in a coach	Can coaches modify psychological factors	Barriers to improving
Coaching training	Auditory	Images & related tools		Cannot determine				Athlete lacks motivation
Cross training	Kinesthetic	Positive feedback & clarity		Change in performance				Coaching limitations
Feedback from athlete	Visual	Practice with team		Coach views external changes				Intellectual challenges
Imitation & demonstration	Visualizations	Repetition		Verbal feedback from athlete				Need for recognition
Iterative practice of skill		Imitation						Reached athlete's biomechanical limits
Iterative practice on different body area		Type 1-focus on specific body part						Resources
Motivation		Type 2-body completing an entire sequence						Unrealistic expectations
Task breakdown		Type 3-sensations in completing sequence						
Visualization or mental imagery								
Written instructions								
Other items								

FIGURE 1.3: List of nodes and sub nodes created for qualitative data analysis.

factors, Barriers to improving. The sub nodes for each node are listed on Table 1. This listing and the associated sub nodes represent a comprehensive parsing of the data that accurately tells the story of the coaches' responses to the questions for our research. We also used NVivo to run coding and matrix coding queries, as well, to look at word frequencies displayed as word clouds.

Quantitative analysis

For the quantitative data collected via the coaches questionnaire, we used Matlab® R2013a software (Mathworks® Inc., Natick, MA, USA) for analysis.

1.3.2 Results

We combined both open-ended coaches' responses with closed set results to fully document the depth and breadth of the data collected and to provide interpretation of it in the context of our research questions. The following are the questionnaire results obtained from the USC coaches.

Factors affecting coaching style/approach

The coaches provided much information about the general styles and approaches they used to assist their athletes in improving performance. Coaching style and approach were defined by the participants through a number of factors: experience as a coach, coaching training, experience as a current/former athlete, understanding of biomechanics, and reading educational articles on coaching. Hence, we see that experience as a coach as well receiving training as a coach were of primary importance to the coaches.

Links between coaching style and individual athlete response

It is understood that for a coach to provide optimal guidance to an athlete, he/she must first assess and understand the athlete's skills, mindset, and the limits of his/her performance. Accordingly, we asked coaches to describe observations that they make to tailor coaching styles to their individual athletes' needs. Generally, salient observation types noted by the coaches included: figuring out what kind of learner (visual, auditory, repetition-based) the athlete is, athlete's motivation and passion for sport, movement adjustment resulting from real-time feedback, observation of skill progression, demonstrations of athletes' psychological well-being, observations of athletes' emergent trust between athlete and coach, and an athlete's particular physical capabilities and flexibility.

As an example of techniques using progressive skill mastery, one coach stated: "(I) Usually break skills down into components and work on the most basic until mastered (or as close as we can get), and then add more advanced skills," underscoring the importance of task analysis in coaching style. Another coach reported that trust was a major factor impacting his coaching style. He noted: "The first thing you need to do is earn their trust. It is like anything else, you have to find common ground, don't prove how much you know on day 1 or even 6 months in, just find ways to earn their trust and listen. Then once you have their trust, you can give them little nuggets to chew on that are more specific. I think too many coaches barge in and the kids tune you out because they don't think you are in it for the right reasons." This underscores the importance of relationship development between coaches and athletes as a precursor for task analysis in coaching and skill progression.

Type of methods used to teach movement-related skills to athletes

It can be expected that a number of different methods may be utilized to teach movement-related skills to athletes. We identified six approaches and asked respondents to choose all the methods they used. Coaches described imitation and enhancement of visualization techniques as useful in teaching motor skills. The responses to this question (by the USC coaches) are indicated in Figure 1.4 below. We added the "Motivation" bar to this chart because although it was not one of the options presented in the question, we saw it being highly emphasized throughout the questionnaire, and believed we should have included it as an influential factor. The results were similar in the SO questionnaire, and are thus, not included here. It is also evident from these results, as well as from the free-response sections that coaching requires the utilization of a "cocktail" of strategies to optimize athletes' performance.

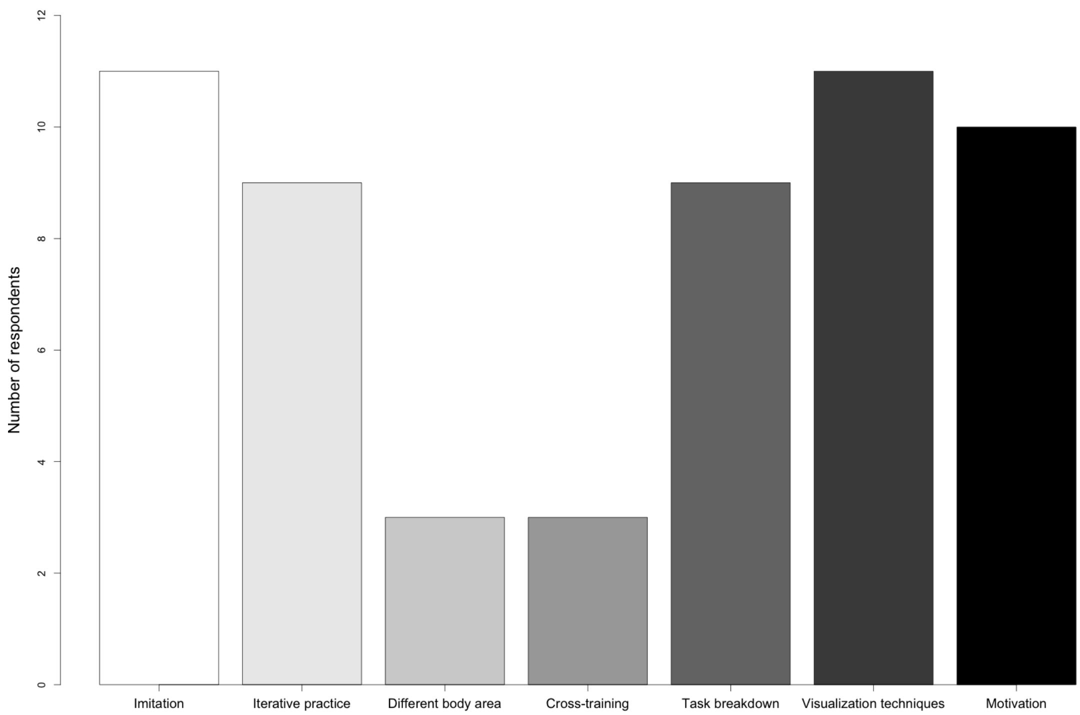

FIGURE 1.4: Methods used by USC coaches to teach movement-related skills.

We also asked the coaches to designate the single most important tool necessary to teach a movement-related skill. Respondents said visual aids, imitation, and practice were most important.

Effectiveness of different forms of feedback

To assess the relative degree of use of different forms of feedback that coaches reported providing to their athletes, we identified four discrete types: visual, auditory, visualization/mental imagery, kinesthetic. We queried the coaches as to whether each of these feedback types could be considered to have varying levels of effect on athletic performance and relative improvement. Every respondent believed visual feedback was very effective, followed by both kinesthetic feedback and visualizations.

Visualization as a tool to teach and optimize skills

Our study results indicate that the participating coaches believed visualization techniques were effective in teaching and optimize athletic skills, and as such, we wished to determine what in particular this signified to the coaches. There was complete agreement by the coaches that there was a relationship between visualization and athletic performance outcomes, thus exhibiting the relative importance of this coaching approach. Accordingly, to determine the particularity of such visualization techniques, we parsed the data into three discrete categories described as follows to the participants, via the questionnaire: Mental imagery and visualizations refer to techniques that are used to help athletes focus on: (1) a specific part of the body (2) the body completing an entire sequence and (3) the sensations involved in completing a movement sequence. Since this categorization may not have been as easy to understand by the respondents, we provided an example for each type of visualization of how a coach might assist his/her athletes/students with focus. For type 1, we noted: “imagine yourself crushing a watermelon with your stomach as you do a crunch”, for type 2, “imagine what it’s like to hit the perfect tennis stroke like a world class tennis player would”, and for type 3, we stated: “imagine yourself being chased by wolves as you sprint.”

We instructed the participating coaches to indicate which of the three categories they used with their athletes. Some of the respondents indicated that they used two or more of the three types of visualization. In a related remark, a coach identified that:

“You can improve almost any skill through visualization because the body does not realize that you are not actually executing the skill physically.”

One coach stressed the importance of being flexible and inclusive in the use of imagery. This coach responded:

"I think the moment you leave out an imagery technique, you have just limited yourself as a coach. You want to be open to all ways of learning because each kid is different."

Psychological factors

In the SO questionnaire, with regards to psychological well-being, coaches emphasized the importance of motivation, positive feedback, constant encouragement, and making sure the athletes were enjoying themselves. Coaches placed a strong level of importance in identifying any and all psychological factors that may influence motor performance since they deemed it vital to training and learning. They believed in the importance of building long-lasting relationships with their athletes, and teaching the game correctly so that "the athlete learns to love and enjoy the game". They cautioned, however, that modifying psychological factors was dependent on an individual athlete's intellectual capacities and abilities. Hence, of the 23 respondents to the question on importance of psychological factors for athletic success, 12 said they were extremely important, 10 said they were very important, and only 1 respondent said that these factors were not too important.

As shown in Figure 1.5, we predict (based on the questionnaire results) that psychological factors need to always be acknowledged during motor skill acquisition. Motivation gives an athlete the will-power to even want to learn. This is the first step. Then, this will-power causes the athlete to be open to coaching strategies and interventions i.e. the "coachability" improves. Finally, this results in improved performance. However, it does not stop here because coaches need to always keep paying attention to the psychological factors since learning and motivation go hand-in-hand.

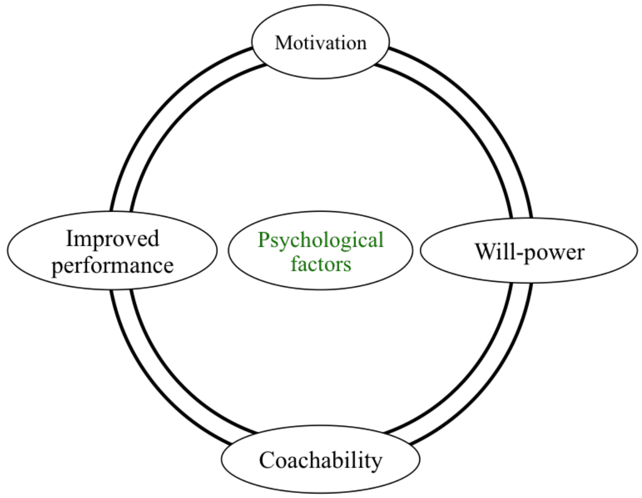

FIGURE 1.5: Prediction of the effects of psychological factors on motor skill learning in athletes.

1.3.3 Discussion

The goal of these questionnaires was to identify the methods used by coaches to teach motor skills, in order to begin to understand the implications of their expertise for motor Neuroscience and for retraining children with motor disabilities. Certain coaching strategies, including imitation, task breakdown, and visualization techniques can all be applied to teach motor skills to children with disabilities. We learned that the training method need not be linear i.e. imitation followed by task breakdown, etc., and that the moment one leaves out a technique, one might be losing out. There was consensus among the coaches in the belief that there is a positive relationship between use of visualization techniques and motor performance. Coaches also believed kinesthetic feedback was very effective in teaching motor skills. This supports the use of various biofeedback techniques, including wearable devices (Sanger, 2007), skin taping, and practice in altered mechanical environments. From our prior work, as well as from the results of this research, it is evident that a mix of selective methods should be utilized in order to teach motor skills.

This work was focused on coaching perspectives, and we are planning to send a revamped version of this questionnaire to gain athletes' perspectives as well. It would be useful to understand what strategies mentioned by coaches are most popular with athletes, and also to find out what they think of visualization and kinesthetic feedback. In addition, we were constantly reminded of the importance of psychological factors on motor skill learning, and believe this is an undervalued yet extremely important missing piece in motor control theory.

The methods identified by coaches do not correspond to questions currently being studied by most researchers in motor Neuroscience. This disparity suggests that Neuroscience could have greater impact and be more effective in modifying real-world skill learning if concepts, including visualization, kinesthetic feedback, and motivation could be operationalized and quantified in a way that could be studied in the laboratory. This would be particularly important if we could develop models to predict the relative effectiveness of different training interventions in people with brain injury or developmental disorders of motor control. There has been some early success in such research, including our own work showing the role of EMG-based scaled vibratory feedback changing muscle use and upper extremity function in children with cerebral palsy, and also how visual feedback can reduce co-contraction in these groups (Bertucco and Sanger, 2015; Bloom, Przekop, and Sanger, 2010; Liyanagamage et al., 2017; Young, Doornik, and Sanger, 2011).

Thus, coaches have found strategies to modulate attention in their athletes. These perspectives inspired in the development of a model for studying the effects of two sensory methods (visualization and vibratory feedback) on motor skill learning.

1.4 How visualization and vibratory feedback affect motor skill acquisition

Credit assignment requires identifying the behavior that corresponds to a specific outcome. In a complex system of muscles working together to create a movement, such an identification is fairly difficult and perhaps even impossible. Therefore, in learning new motor skills, sensory interventions that help solve this problem are of great importance. Just as coaches talked about the use of attention modulators, such as visualization techniques and kinesthetic feedback, neuroscientists have also studied the role of attention on performance, and to changes in brain regions (Sarter, Givens, and Bruno, 2001; Lu, 2008; Jeannerod, 1994). Therefore, providing selective attention to task-relevant components by creating task equivalence and/or augmenting sensory information is most helpful.

Seen this way, we predict vibratory feedback brings selective focus to specific muscles, and thus, allows one to change muscle use by focusing on task-relevant components. In Figure 1.1, we showed the credit-assignment problem, and in Figure 1.6 below we show how vibratory feedback provides a solution. The red modulator box in the control system represents how the incoming signals are filtered in order to bring selective focus to task-relevant components, and improving performance. Feedback correlated to muscle activity is acting as an attention modulator.

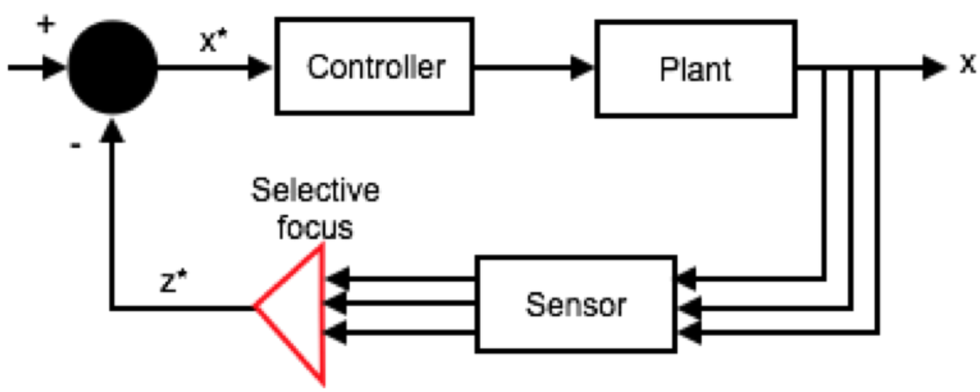

FIGURE 1.6: Predicted model of how vibratory feedback modulates attention by bringing focuse to task-relevant components.

Visualization brings selective focus to movement sensations via task equivalence. Figure 1.7 shows the plant and sensor as red dotted boxes, while the controller stays the same. Visualization allows one to answer the credit-assignment problem by finding the equivalent control system that predicts the errors most closely. Therefore, this is another attention modulator that brings focus to task-relevant non-visual sensations.

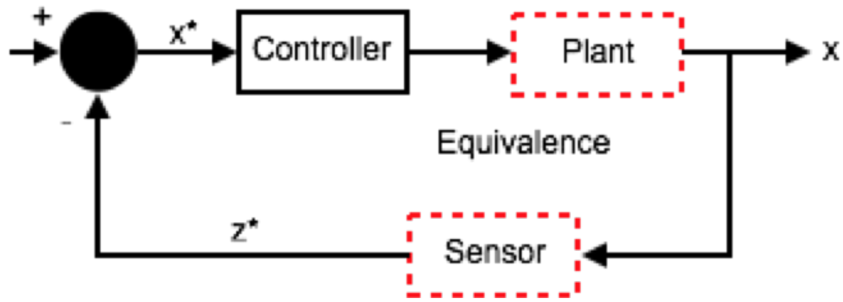

FIGURE 1.7: Predicted model of how visualization modulates attention via task equivalence.

These models can be better explained using an example scenario. If one is asked to walk without slouching, the idea is to bring attention to one's posture. If vibratory feedback is provided to the back muscles, there is increased focus on a specific area, allowing one to correct one's posture. Thus, vibratory feedback is modulating the signals that are constantly coming into the system by augmenting the signals necessary to help solve the problem. Similarly with visualization, one may be asked to walk as if holding a book steady on one's head. This naturally helps one straighten up by holding the head up high, and shoulders out. Thus, an equivalent system is created, which helps in solving the same problem using a different method.

In our work thus far, we have use the term "visualization" to refer to the techniques coaches utilize to communicate non-visual perceptions to their athletes. These perceptions may be proprioceptive, tactile, or emotional, and can be accomplished by creating an imagined task has the same motor action but different associated sensations. Vibratory feedback can also be used to communicate a perception that is tactile, and in some cases, even proprioceptive. The techniques for communicating these non-visual perceptions may be categorized as such: (1) substituting the task, (2) substituting the body, and (3) substituting the emotional context.

(1) Substituting the task: if the task is to do a crunch, one may be asked to imagine crushing a watermelon between the thighs and abdomen, which would be expected to activate the abdominal muscles fast and forcefully (see Figure 1.8).

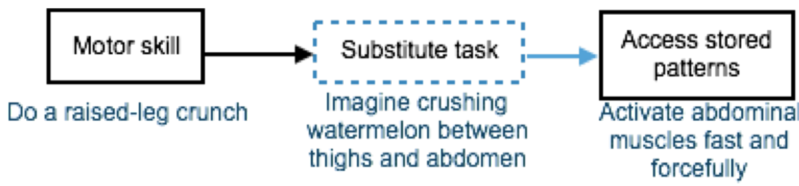

FIGURE 1.8: Model of substituting the task.

(2) Substituting the body: if the task is to hit a tennis serve like a tennis professional (for example, Roger Federer), one would most likely first imagine how he would do this, and then try to get a "feel" for what it would be like to be in Federer's shoes. This is not to say that one would necessarily *know* what it feels like to be in a differnt body of course, but that the mental image would elicit sensations associated with the elements required to hit up a tennis serve like Federer (see Figure 1.9).

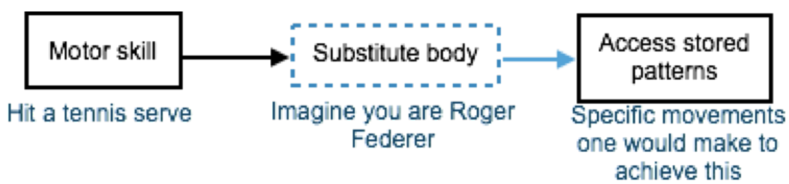

FIGURE 1.9: Model of substituting the body.

(3) Substituting emotional context: if the task is to sprint to the finish line, then, one may be asked to imagine running while being chased by wolves. This would evoke the sensation of maximal emotional effort, and should provide an extra motivation to complete the task (see Figure 1.10).

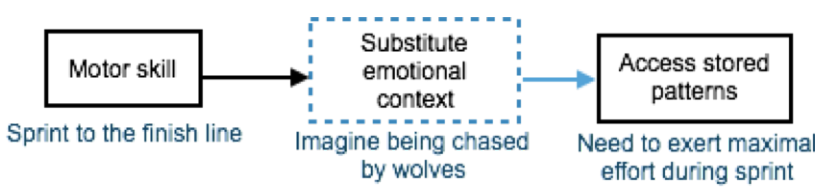

FIGURE 1.10: Model of substituting the emotional context.

Chapter 2

Vibratory feedback as a mode of communication to bring focus to task-relevant components

Sections of the following chapter are adapted from my published work in the Journal of Child Neurology on the effects of vibratory feedback on motor skill learning via changes in muscle use (Liyanagamage et al., 2017).

2.1 Relevance of vibratory feedback

The efficacy of augmented sensory feedback for rehabilitation purposes has been widely studied using visual, auditory, and tactile modes of feedback to understand how they affect performance (Robert et al., 2013; Sigrist et al., 2013; Young, Doornik, and Sanger, 2011). Among different biofeedback modalities, the use of vibratory feedback in stroke rehabilitation, and its effects on muscle activation and cortical excitability have been studied extensively, but mostly in adults (Kossev et al., 2001; Marconi et al., 2011; Paoloni et al., 2014; Rosenkranz and Rothwell, 2003; Bock, Pipereit, and Mierau, 2007; Conrad, Scheidt, and Schmit, 2011). We were interested in how vibratory feedback could be used in a special population group: children with dystonia.

Dystonia is a movement disorder characterized by involuntary sustained or intermittent muscle contraction, overflow of electromyography (EMG) activity, and co-contraction of antagonistic muscles, leading to repetitive movements and abnormal postures (Sanger, 2004; Bertucco and Sanger, 2015). Primary dystonia is mostly genetically-derived, and presents no structural brain abnormalities, while secondary dystonia is a result of degenerative processes or injury, such as seen in children with cerebral palsy (Geyer and Bressman, 2006). While dystonia can occur in both adults and children, most of the research in this field has been conducted to understand how dystonia affects adults (Hallett, 2006; Zeuner et al., 2002). Sensory deficits are common in secondary dystonia due to dyskinetic cerebral palsy (Sanger and Kukke, 2007), and along with motor deficits, can result in reduced skill acquisition and poor motor performance. We believed these effects were even more pronounced in children since the inability to acquire new motor skills during early stages of development may further exacerbate their motor disability and limit their social development. Constraint-induced movement therapy and deep brain stimulation are tools that have been used to improve movement (Bertucco and Sanger, 2015; Gordon et al., 2011; Bhanpuri et al., 2014). Furthermore, transcranial direct current stimulation (tDCS) of motor cortex has been used with mixed results (Bhanpuri et al., 2015; Young, Bertucco, and Sanger, 2014; Young et al., 2013). While these treatments are helpful to reduce the symptoms of dystonia, there is an unmet clinical need for solutions that would promote sensorimotor learning. Therefore, it is worthwhile exploring whether augmented sensory information can ameliorate sensory deficits, and thus improve motor skill acquisition.

2.1.1 Mechanistic explanation

Augmented sensory feedback in the form of vibration is able to direct attention to specific areas of the body, possibly resulting in a more efficient selection of sensory inputs, and causing an increase in behavioral impact (Rosenkranz and Rothwell, 2012). This selective attention while performing a motor task enables one to change muscle patterns, and potentially improve performance due to the intermediate feedback provided. Vibratory feedback is thus aiding with the credit-assignment problem. This is not to say that we do not pay attention to our bodies when making a movement; instead, vibratory feedback aids with providing selective attention to a specific muscle (Refer to Figure 1.6).

2.1.2 Effects of vibratory feedback on motor skill learning

Type 1 errors usually occur when there is not enough information about errors, thus making it difficult to change undesired movements. The work here focuses on type 1 errors due to sensory deficits, and how vibratory feedback can be used to ameliorate these deficits by creating awareness of the activity of individual muscles, without giving a specific goal to achieve. Since vibratory feedback can be used to bring selective attention to muscles most responsible for movement errors, subjects can train and learn to improve their movement patterns.

It has been shown that figure-8 drawings by healthy children result in traces that can be seen at the level of the fingertip, wrist, elbow, as well as the shoulder, while the traces in children with dystonia were not recognizable at the more proximal joints (Casellato et al., 2011). This suggests that while proximal joint motion assists with distal motion in healthy children, proximal joint motion does not necessarily assist in children with dystonia. This may be a result of the brain injury, which resulted in inappropriate motor patterns being learned over time. It is possible that proximal joint motion may require compensation by distal joints to reduce noise derived from the proximal joints.

Hence, it can be hypothesized that vibratory feedback of proximal muscles improves overall motor performance and distal muscle control due to increase in selective attention.

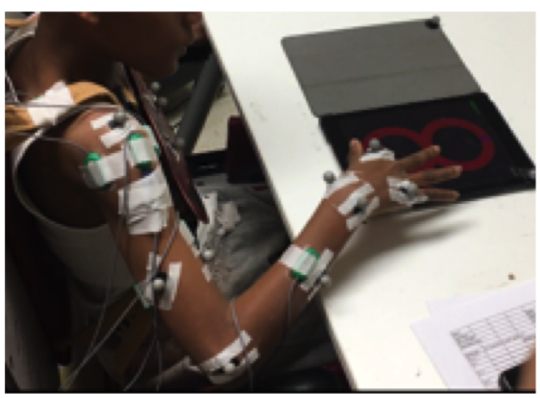

FIGURE 2.1: A subject completing a figure-8 trace on the iPad, with vibratory feedback applied to the lateral deltoid.

In order to study this theory, two tasks were designed in the Sanger Lab (University of Southern California, Los Angeles, CA, U.S.A.) and the Near Lab (Politecnico di Milano, Milan, Italy). The first was a figure-8 tracing task where subjects would trace a figure-8 on an iPad to the beat of a metronome (Figure 2.1). There were three metronome speeds being tested, and subjects were trained over a 5-day period without vibratory feedback, and another 5-day period with vibratory feedback. Testing was done only on days 1 and 5.

The figure-8 task was special because the remporal frequency of its horizontal and vertical movemenet components had a 2:1 ratio, which allowed the contribution of individual muscles to be directly linked to the task by calculating power in the Fourier spectrum. Therefore, it would be possible to determine how vibratory feedback has affected muscle patterns over time. The second task was a spoon task emulating self-feeding, and was done after the figure-8 task on each of the 5-day periods. Here, subjects were asked to move a spoon containing a marble in-between two targets as fast as possible. We tested subjects on three spoons of varying depths, in order to follow a Fitts' paradigm (which provides a speed-accuracy tradeoff). One of the primary outcome measures was a change in the speed-accuracy tradeoff i.e. higher speed for the same accuracy or higher accuracy for the same speed.

This study is ongoing, and we have had some promising results so far on two subjects with dystonia. Figure 2.2 below shows that performance (as measured by decrease in average movement times across targets) change between day 5 of the week without vibratory feedback (bf^-) and day 5 of the week with vibratory feedback (bf^+) is statistically significantly ($P < 0.05$). While subjects were able to perform better at the end of the 5-day period for each of the bf^+ (from 2.874 s $\pm$ 1.179 s on day 1 to 2.192 s $\pm$ 1.179 s) and bf^- (from 3.548 s $\pm$ 3.548 s to 1.179 s to 2.865 s $\pm$ 1.179 s) interventions, subjects performed better with bf^+ comparatively. Therefore, vibratory feedback has the ability to bring attention to task-relevant components and improve performance (and also solve the credit-assignment problem) in children with dystonia.

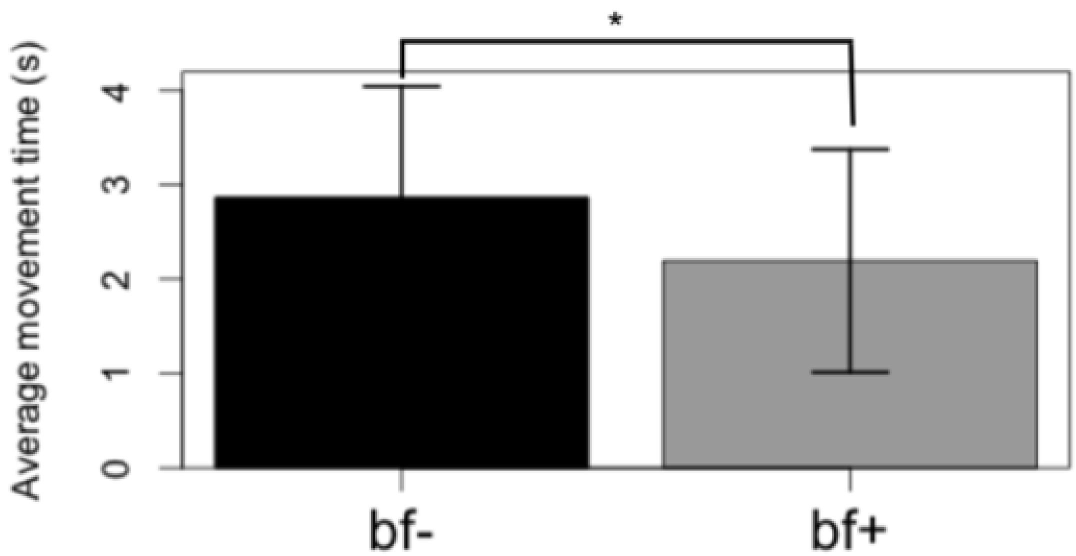

FIGURE 2.2: Movement time across targets is significantly ($P < 0.05$) less on day 5 after vibratory feedback (bf^{+}), signifying improved performance.

While this work is ongoing, a different question arose: what is it about vibratory feedback that is augmenting performance and chaning muscle patterns? Would the credit-assignment problem be answered by the provision of any kind of vibratory feedback, or is there something specific about the type of feedback that is causing these changes?

2.2 Effect of different kinds of vibratory feedback on muscle use

In this work, we aimed to understand how (and in which situations) vibration affects motor behavior and muscle use in childhood dystonia. We hypothesized that scaled feedback (i.e. feedback that is directly or inversely proportional to EMG) could provide task-relevant information, thereby enabling changes in muscle activation based on how the added sensory information is utilized. In particular, we compared effects of scaled vs. non-scaled forms of vibratory feedback to evaluate our primary hypothesis that scaled vibration augments sensory awareness and would produce a wider range of behaviors in a multi-muscle task with numerous solutions. We did not expect non-scaled vibration (i.e. feedback that is either constant or random, and not correlated to EMG) to cause similar behaviors because it would not provide task-relevant sensory information. These types of vibration would act like background noise that the system would ignore. According to Brooks, when a previously relevant stimulus turns out to be irrelevant, neurons in the temporal cortex stop responding to it, resulting in subject habituation (Brooks, 1986). We predict that scaled vibration would be provinding focused attention to one muscle, while non-scaled vibration would perhaps only be bringing attention to an entire limb. We also expected scaled vibration to benefit children with dystonia more so than healthy controls because the latter group already has an intact sensorimotor system.

In order to test our hypotheses, we designed a one-dimensional bimanual myocontrol task that provided enough redundancy to allow for limited exploration, but also had a set of optimal (and efficient) solutions. We derived the basis for this task from previous work by Latash et al. (Latash, Scholz, and Schoner, 2002; Kang et al., 2004). A myocontrol task was designed because it allowed us to measure the effects of vibratory feedback at the level of muscle activation. Task performance was measured using the speed-accuracy trade-off, formulated by Fitts' Law (Fitts, 1954; Lunardini et al., 2015b; Bertucco and Sanger, 2014). Such a paradigm provided the opportunity to study how well one could modulate muscle contraction (both amplitude and duration), before and after vibratory feedback. In this study, we measured task performance with four kinds of vibratory feedback: scaled (proportional and reverse) and non-scaled (constant and random).

2.2.1 Materials and Methods

Subjects

We recruited eleven children (eight males, three females; age 16.7 $\pm$ 3.0) affected by either primary or secondary dystonia in at least one of their upper limbs, and fourteen healthy control children (nine males, five females; age 15.5 $\pm$ 3.2).

The subjects with dystonia were recruited from the Children's Hospital of Los Angeles, and all had sufficient cognitive and verbal ability to understand the instructions. The upper extremity components of the Barry-Albright Dystonia (BAD) scale were used to assess level of motor skill and differences between arms (Barry, VanSwearingen, and Albright, 1999). The more impaired arm was used for vibration (in control subjects, the non-dominant arm was used for vibration). The University of Southern California Institutional Review Board approved the study protocol. All children and their parents gave informed written assent/consent for participation. Authorization for analysis, storage, and publication of protected health information was obtained from parents according to the Health Information Portability and Accountability Act (HIPAA). This study was performed in accordance with the Declaration of Helsinki.

Experimental setting

We designed a bimanual myocontrol task where the activation and relaxation of the left and right biceps muscles, via elbow joint flexion, controlled the vertical position of a single red line on the computer screen. The modified sum of the EMG amplitudes from the two biceps muscles controlled the movement of the red line (i.e. the cursor position) as such:

$$Cursor\ position = [EMG_{left\ biceps}^{1/1.2} + EMG_{right\ biceps}^{1/1.2}]^{1.2} \tag{2.1}$$

Position on the screen thus corresponded to muscle activity, and the position was scaled so that the top of the screen corresponded to 100% of maximal voluntary contraction (MVC).

Custom software was developed to create the interface for the task (Visual Studio 6.0, Microsoft, Redmond, WA, USA). According to the Fitts' Law paradigm (Fitts, 1954), we designed five virtual targets, represented by a blue bar with a specific width and vertical position. We used 3 bar widths (0.1, 0.2, 0.3% MVC), and 3 bar positions (vertical height) (0.25, 0.5, 0.75% MVC). Index of difficulty (ID) was calculated according to Fitts' Law:

$$Index\ of\ Difficulty\ (ID) = log_2\left(\frac{2 * Height}{Width}\right) \tag{2.2}$$

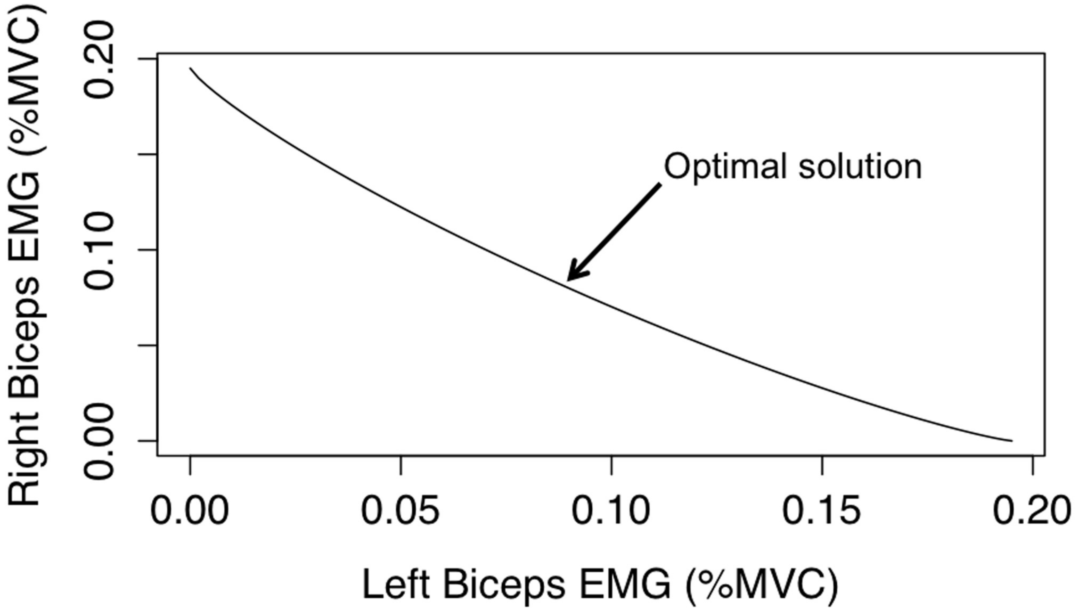

FIGURE 2.3: The possible solutions for each target can be represented as a function of how activation of each biceps muscle contributes to control of the line on computer screen. Here we show the solution space for one of the indices of difficulty (ID 4). An optimal solution always exists i.e. equal use of both biceps muscles.

The range of indices of difficulty was 1.32-3.32 bits.

The task was designed in a manner where the most energetically efficient strategy to reach each target was achieved by activating both of the biceps muscles equally, in the sense that this solution minimizes the sum of squared muscle activations. The specific exponent values in Equation 2.1 were chosen to make the task difficult but not impossible, based on data collected during pilot experiments. This is explained in Figure 2.3, where it can be seen how modulation of the two muscles allows for task success (i.e. reaching the target). The energetically favorable solution was always to flex both muscles equally.

We placed surface EMG electrodes (DE-2.1 electrodes with Bagnoli-8 amplifier, Delsys Incorporated, Boston, MA, USA) with 20-450 Hz band-pass filter and 1000x amplification over the left and right biceps muscle bellies. The EMG signals were sampled at 1KHz (Power 1401, Cambridge Electronic Design Limited, Cambridge, UK) using custom data acquisition software. The EMG signals from each muscle were processed online in the following manner: a high-pass Butterworth filter (fourth order, 1 Hz cutoff) followed by a Bayesian filter (Sanger, 2007), and then a low-pass Butterworth filter (second order, 5 Hz cutoff). A round 2-inch gel ground electrode (PainRX Store, Fountain Valley, CA, USA) was placed on the right hip. Maximum voluntary contraction (MVC) was obtained at the beginning of each experiment set by asking subjects to flex each of their biceps muscles maximally during a period of 32 s. The EMG trace during this period was broken into segments of equal length, and the signal in each bin was averaged to obtain a value. The maximum of each of the bins was determined to be the MVC.

In order to provide vibration, we first attached a surface EMG sensor (Biometrics Ltd, Newport, UK) next to the electrode on the more dystonic/non-dominant arm. Input from the sensor was processed at 1 KHz by an electromyograph (DataLOG MWX8, Biometrics Ltd, Newport, UK) that then wirelessly sent the data to a program (on Visual Studio 6.0), which controlled the type and amount of vibration to be applied via a portable vibrating unit (designed and developed by Dr. Terence Sanger; patent number: US 8,311,623 B2). The vibrating unit sensor was placed directly on top of the electrode on the more dystonic/non-dominant arm that was used to control the red line. It must be noted that the vibrating unit had the functionality to both measure EMG signals and provide vibratory output scaled proportionally to EMG levels; however, we used the device on slave mode so that we could control the vibration pattern. The ground electrode for the DataLOG system was embedded in a cloth bracelet that we tightened around the non-vibrated arm's wrist.

Task

Subjects were seated in front of a table with the computer screen placed at eye-level. They were asked to place their arms, with palms facing up, on the chair's armrest. We strapped their wrists onto the armrests using wrist straps to ensure isometric muscle contractions during the elbow joints flexion. Subjects were asked to activate both the left and right biceps muscles in order to move the red line into the blue target bar on the screen (each target appeared on the screen for 3s per trial). They were asked to do this as fast as possible, using any combination of the two muscles as they saw fit. Task success was achieved when the color of the bar turned from blue to cyan (this occurred when a subject stabilized the red line within the target bar for at least 500ms), at which point they could relax their muscles in order to return the line back to the bottom of the screen Figure (2.4).

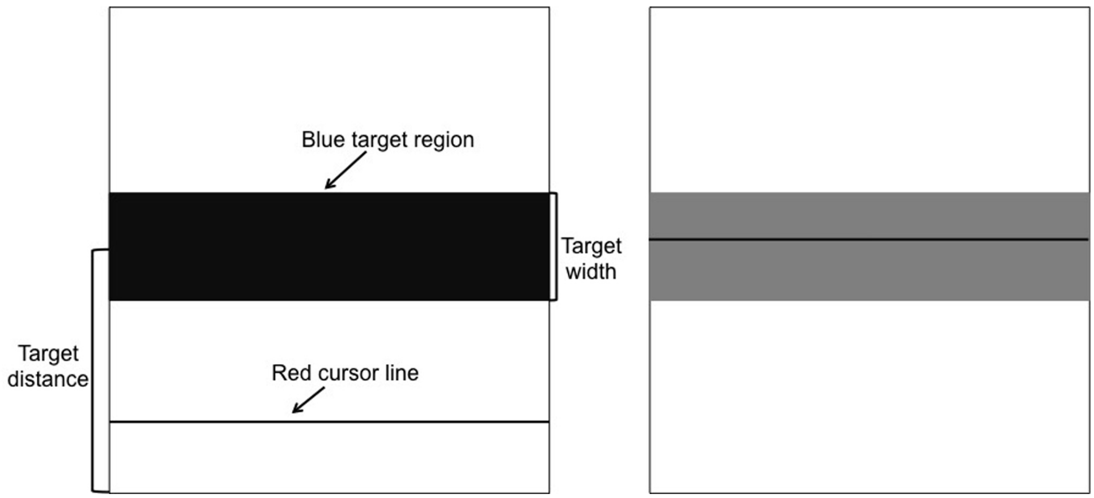

FIGURE 2.4: Each target appears on the computer screen as a blue bar (shown here in black) with a specific width and distance from bottom of the screen. The black line on the bottom of the screen is controlled via a specific combination of left and right biceps activation. Successful task completion was signified by the blue bar changing color to cyan (black to gray in this figure), as shown on the screen to the right.

The experiment was divided into 4 blocks (AABA design), each containing 15 trials, with the 5 different IDs presented in a pseudorandom order within each trial. In block 3, one of the 4 modes of vibration was applied. We tested four types of vibration in a pseudorandom order: 1) Proportional: vibration was provided at a level proportional to the measured EMG, 2) Constant: vibration was provided at a constant level (50% of the power generated by the motor), 3) Random: vibration levels were generated, via a random number generator, between 0 and 100% of the power of the motor, 4) Reverse: vibration was provided at a level inversely proportional to the measured EMG. The vibration was applied to the more dystonic arm (assessed using BAD scale) in children with dystonia, and to the non-dominant arm in controls. Each block lasted approximately 8 minutes. Subjects came in on 4 separate days to complete the experiment for each of the four modes of vibration. Two of the 14 controls only completed proportional and constant types of vibration.

Data analysis and statistics

Data were analyzed using Matlab® R2013a software (Mathworks® Inc., Natick, MA, USA). The movement time (MT) of the cursor was calculated as the time interval between appearance of the target and successful task completion. We analyzed performance by measuring overall throughput (TP) values before and after vibration was provided ("Card, English, and Burr (1978)–25 years later"). TP (bits/s) was calculated as:

$$TP = \frac{1}{N}\sum_{i=1}^{N} ID_i/MT_i \tag{2.3}$$

where N=5 is the number of ID conditions.

In order to assess how vibration affected muscle use, we determined the average ratio of EMG in the vibrated muscle to non-vibrated muscle for each subject. We assessed how this ratio changed during vibration ($Ratio_{2,3}$) and post-vibration ($Ratio_{2,4}$) by comparing to the ratio in the pre-vibration phase (baseline). A positive ratio meant that the biceps of the vibrated arm had higher activation than that of the non-vibrated arm.

$$R = \frac{EMG_{vibrated\ arm}}{EMG_{non\ vibrated\ arm}} \tag{2.4}$$

$$Ratio_{2,3} = \frac{R_{Block3} - R_{Block2}}{R_{Block3} + R_{Block2}} \tag{2.5}$$

$$Ratio_{2,4} = \frac{R_{Block4} - R_{Block2}}{R_{Block4} + R_{Block2}} \tag{2.6}$$

These ratios were calculated for two stages of the task: the feedforward stage and the stabilization stage. We defined the feedforward stage to be the first 100ms post appearance of a bar, based on work by (Milner and Franklin, 2005). The stabilization stage was defined as the period in which the subject had to maintain the line inside a bar for 500 ms in order to successfully complete the task. All EMG signals were normalized to the previously measured MVC values before analysis. Positive ratio values indicated increased use of the vibrated arm (with respect to block 2), while negative values showed the opposite.

In order to test Fitts' Law, we performed linear regressions on average movement time across subjects within each type of vibration via the method of least squares. The correlation coefficient indicated the goodness of fit of movement time in successful trials as a function of ID.

Statistical analysis was performed using RStudio® version 0.98.977 (RStudio Inc.®, Boston, MA, USA). We used a linear mixed effects model (R-package lme4, version 1.1-7) to determine interactions and effects of four factors (ID, block, subject type, vibration type) on outcome measures i.e. the dependent variables. We created linear mixed effects models using maximum likelihood (R-package lme4, version 1.1-7) to analyze effects on a dependent variable. For the analysis of movement time, the variables ID (5 levels), block (4 levels), vibration type (4 levels), and subject type (2 levels) were set up as fixed effects, while the intercepts for subjects were random effects. This is the model for movement time:

$$Movement\,Time \sim Subject\,type + Vibration\,type + Block + ID + (1 + ID|Subject) \tag{2.7}$$

In order to analyze effects of block, vibration type and subject type on throughput, we created the following model:

$$Throughput \sim Subject\ type + Vibration\ type + Block + (1|Subject) \tag{2.8}$$

For analyzing the effects on the vibrated arm, we created the following model:

$$EMG_{vibrated\ arm} \sim Subject\,type + Vibration\,type + Block + ID + (1 + ID|Subject) \tag{2.9}$$

After creating these models, we tested the significance of each of the fixed effects on the dependent variable by comparing the model (full) against reduced models (null) in which one of the fixed effects was removed each time. Afterwards, we looked at the interaction between fixed effects by testing a model with interaction against one without it. In order to compare the significance between models and to find the model that best fit our data, we ran one-way ANOVA to obtain P values and the Akaike information criterion (AIC) values (Akaike, 1974). A lower AIC value in the model with interaction, as well as P <

0.05 indicated that a significant interaction between the tested factors existed. To determine significance of the different levels in a factor on the dependent variable, we ran post-hoc analyses on the data by running pairwise Tukey's tests on reduced models.

2.2.2 Results

Fitts' Law

Both groups of subjects followed behavioral patterns described by Fitts' Law during the experiments i.e. the movement times were longer for the higher IDs, as expected (Figure 2.5). Movement time showed a significant linear regression on ID for both subject groups in all 4 types of vibration. In patients, the Pearson's correlation coefficients were 0.930 [$t(18)=10.707$, $P < 0.001$], 0.911 [$t(18)=9.369$, $P < 0.001$], 0.959 [$t(18)=14.351$, $P < 0.001$], 0.962 [$t(18)=15.024$, $P < 0.001$] for proportional, constant, random, and reverse types of vibration respectively. In controls, the correlation coefficients for the same four vibration types were: 0.964 [$t(18)=15.394$, $P < 0.001$], 0.950 [$t(18)=12.931$, $P < 0.001$], 0.898 [$t(18)=8.671$, $P < 0.001$], 0.963 [$t(18)=15.131$, $P < 0.001$]. In patients, the coefficient of determination varied from 0.816-0.989 across the different types of vibration; in controls, it varied between 0.662 and 0.976. There was no significant difference in the R-squared values ($P=0.989$) and the slopes of the linear fits ($P=0.708$) between patients and controls.

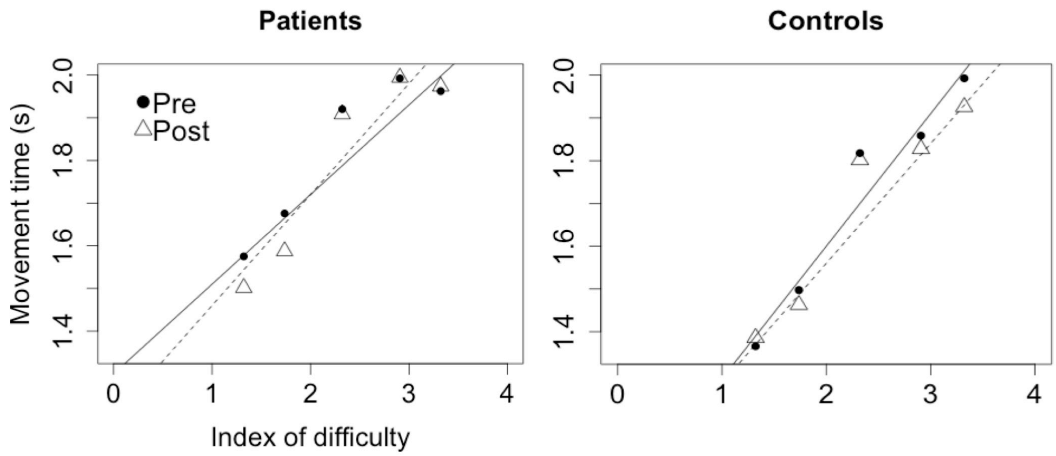

FIGURE 2.5: Subjects generally followed Fitts' Law in the task both pre and post vibration. The graphs here show this relationship for proportional vibration (R^2 in patients: pre-0.816, post-0.898; R^2 in controls: pre-0.939, post-0.924). This relationship persists for all other types of vibration as well. The solid line represents regression in the pre vibration data, and dashed line represents the regression on post vibration data.

Linear mixed effects modeling showed that these factors had significant effects on movement time during the target stabilization period: subject type (AIC_{full}=-69.368; AIC_{null}=-56.449; $P < 0.001$), vibration type (AIC_{full}=-69.368; AIC_{null}=-55.329; $P < 0.001$), block (AIC_{full}=-69.368; AIC_{null}=-59.672; $P < 0.01$), ID (AIC_{full}=-69.368; AIC_{null}=7.274; $P < 0.001$). Movement time in subjects with dystonia was 0.173 ± 0.0406 seconds higher than in controls, as expected. Overall, across all subjects, movement time was lowest for random (1.699 ± 0.0267 s), followed by constant (1.701 ± 0.0261 s), then reverse (1.731 ± 0.0265 s), and finally proportional vibration (1.752 ± 0.0261 s).

We saw a significant interaction between subject and vibration type (AIC_{full}=-78.084; AIC_{null}=-69.368; P<0.01), implying that the effect of different kinds of vibration was different for the two subject groups. During constant, random, and reverse vibration, controls moved significantly faster: 0.162 ± 0.0446s (P=0.0163) , 0.230 ± 0.0457s (P=0.0002) and 0.189 ± 0.0452s (P=0.0031) respectively. Movement time was lowest during the vibration block (mean: 1.698 ± 0.0262s) when compared to other blocks. However, it was not significantly lower than that in the block before it.

Throughput

We ran a linear mixed effects model to determine effects of subject type, vibration type and block on throughput (TP). We found subject type (AIC_{full}=1269.3; AIC_{null}=1276.8; $P < 0.01$) and vibration type (AIC_{full}=1269.3; AIC_{null}=1274.3; $P < 0.05$) to have significant effects on TP, while block (AIC_{full}=1269.7; AIC_{null}=1269.3; P=0.129) did not. There were also no significant interactions between any of the factors in the model. Using the Tukey test, we found that overall TP of subjects with dystonia was 0.127 ± 0.0391 bits/s (P=0.0031) lower than in controls, thus showing that control subjects performed significantly better on the task (as shown in Figure 2.6). With regards to effects of vibration type on TP, we found the only significant difference to be between proportional and random vibration, with TP being 0.0744 ± 0.0233 bits/s (P=0.0079) higher in the case of random vibration.

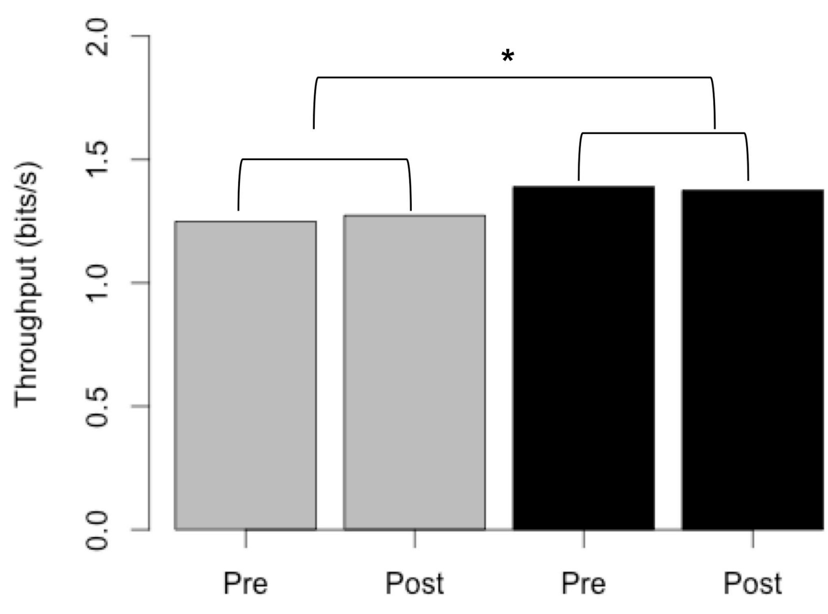

FIGURE 2.6: Throughput does not significantly change post vibration in either patients (grey) or controls (black). However, there is a significant ($P < 0.01$) difference in the throughput values across subject groups.

Muscle use during stabilization period

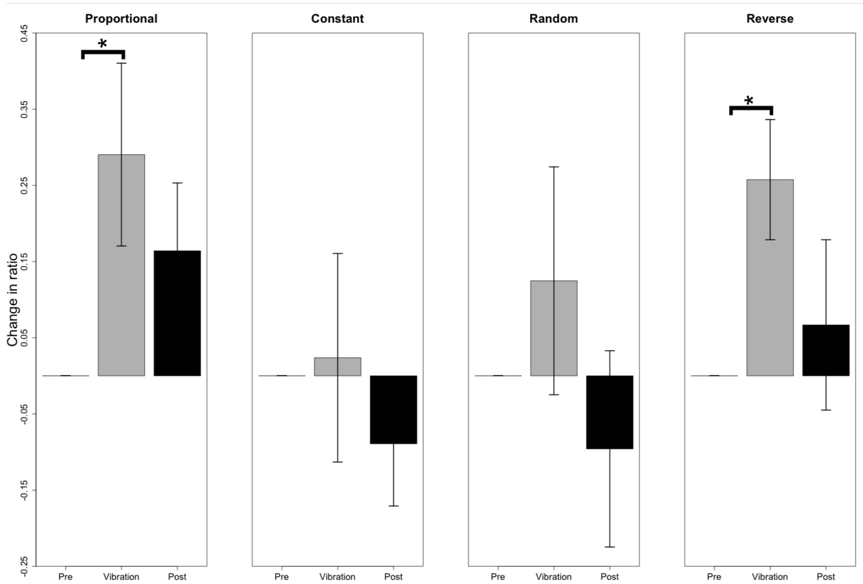

FIGURE 2.7: In patients, vibrated arm use increased significantly ($P < 0.05$) when provided with proportional or reverse-scaled vibration, as shown by the increase in the ratio from block 2 (pre vibration) to block 3 (vibration provided). However, this significance did not persist post vibration. Also, there was no statistical significance at all in the constant and random vibration cases. Standard error bars shown.

For the linear mixed effects model on EMG of vibrated arm, we found block (AIC_{full}=-6701.1; AIC_{null}=-6676.8; $P < 0.001$) and ID (AIC_{full}=-7112.8; AIC_{null}=-6701.1; $P < 0.001$) were the only factors that had significant effects, while subject type and vibration type did not. There were significant interactions between subject type and block, vibration type and block, and subject type and vibration type. The model that best fit (i.e. had the lowest AIC) the data included all factors, along with interaction between subject and vibration type (AIC_{full}=-7135.4; AIC_{null}=-7112.8; $P < 0.001$). We saw significant ($P < 0.0001$) decreases in EMG levels between blocks 1 and 3 (0.0105 ± 0.00213), and blocks 2 and 3 (0.0121 ± 0.00212), and a significant ($P<0.0001$) increase (0.0101 ± 0.00212) in EMG levels between blocks 3 and 4.

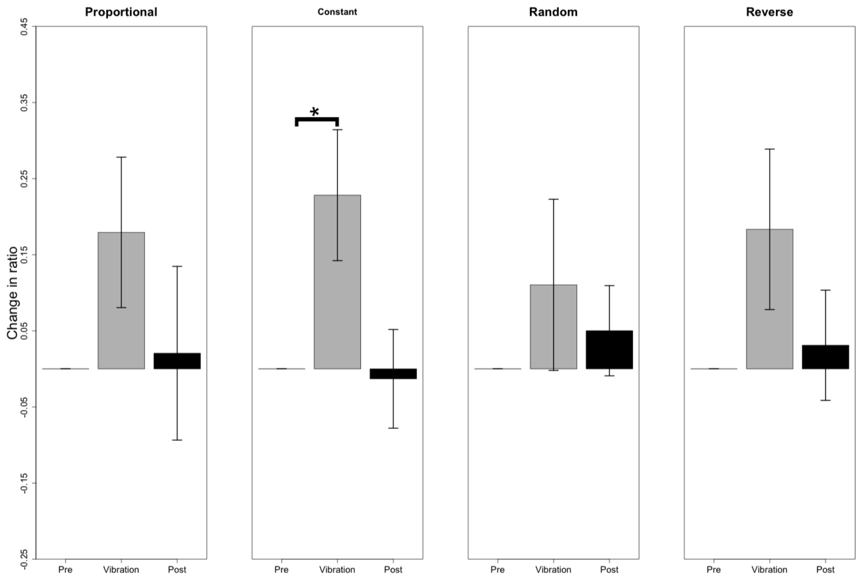

FIGURE 2.8: In controls, vibrated arm use increased significantly (P < 0.05) only when provided with constant vibration, as shown by the increase in the ratio from block 2 (pre vibration) to block 3 (vibration provided). This increase did not persist post vibration.

Figures 2.7 and 2.8 shows a significant increase in $Ratio_{2,3}$ for patients during proportional and reverse vibration, and for controls during constant vibration, but no statistically significant changes during other blocks or conditions. Patients were able to increase use of their vibrated arm 73% of the time during proportional vibration, and 90% of the time with reverse vibration. For the control subjects during constant vibration, their vibrated arm use increased for 72% of trials.

We found that $Ratio_{2,4}$ was not significant for any of the vibration types. However, in patients, the average of this ratio is positive only for the scaled forms of vibration; hence, increased vibrated arm use only persists when vibration is scaled to muscle activity, and not when patients are provided with either constant or random vibration. In addition, more than 50% of subjects reported they believed they utilized the vibrated arm more during vibration (as seen on the raw EMG traces). This signifies that subjects truly had an increased awareness of their body during that period.

Muscle use during feedforward stage

We conducted similar mixed effects modeling to analyze how the previously studied factors affected vibrated arm use during the feedforward phase (the first 100 ms post appearance of a target). We found these factors had significant effects on vibrated arm use during the feedforward stage: block (AIC_{full}=-8972.6; AIC_{null}=-8896.5 ; $P < 0.001$), vibration type (AIC_{full}=-8896.5; AIC_{null}=-8891.7; $P < 0.05$), and ID (AIC_{full}=-9013.4; AIC_{null}=-8972.6; $P < 0.001$). Subject type was not significant. There were significant interactions between subject type and vibration type (AIC_{full}=-8931.9; AIC_{null}=-8896.5; $P < 0.001$), subject type and block (AIC_{full}=-9018.7; AIC_{null}=-8967.5; $P < 0.001$), and vibration type and block (AIC_{full}=-9029.6; AIC_{null}=-8972.5; $P < 0.001$). There was a significant ($P < 0.0001$) decrease in vibrated muscle use between blocks 2 and 3 and a significant ($P < 0.0001$) increase in vibrated muscle use between blocks 3 and 4. We found subjects had significantly (P=0.042) higher vibrated muscle use during random vs. proportional vibration, and significantly (P=0.0148) higher muscle use during random vs. reverse vibration.

In patients, $Ratio_{2,3}$ was significantly higher than baseline during proportional and reverse vibration (Figure 2.9), similar to that which is seen during the target stabilization phase. These increases are more pronounced than in the stabilization phase i.e. the increases in vibrated arm use were seen 82% of the time during proportional vibration, and 100% of the time during reverse vibration. In controls, $Ratio_{2,3}$ showed significant increases in both constant and random vibration (Figure 2.10). This was seen 100% and 71% of the time, respectively. Generally, the ratio was unchanged in the scaled modes of vibration for controls.

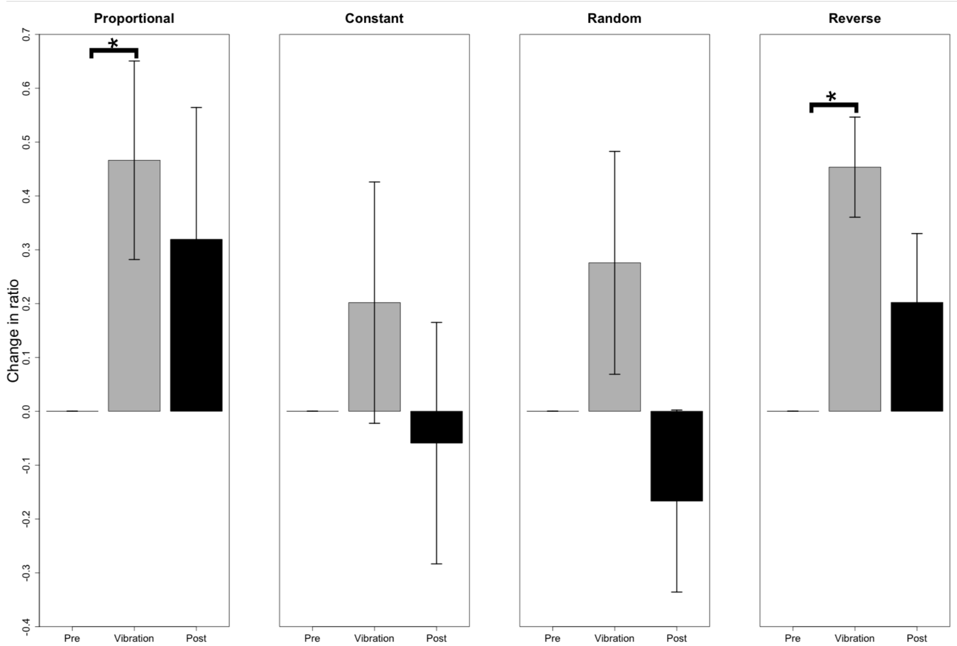

FIGURE 2.9: Muscle use in the feedforward phase. In patients, there was a significant increase ($P < 0.05$) in use of vibrated arm during both proportional and reverse vibration, similar to what was seen during the stabilization phase. This is seen by the increase in the ratio from block 2 to block 3, in which vibration was provided.

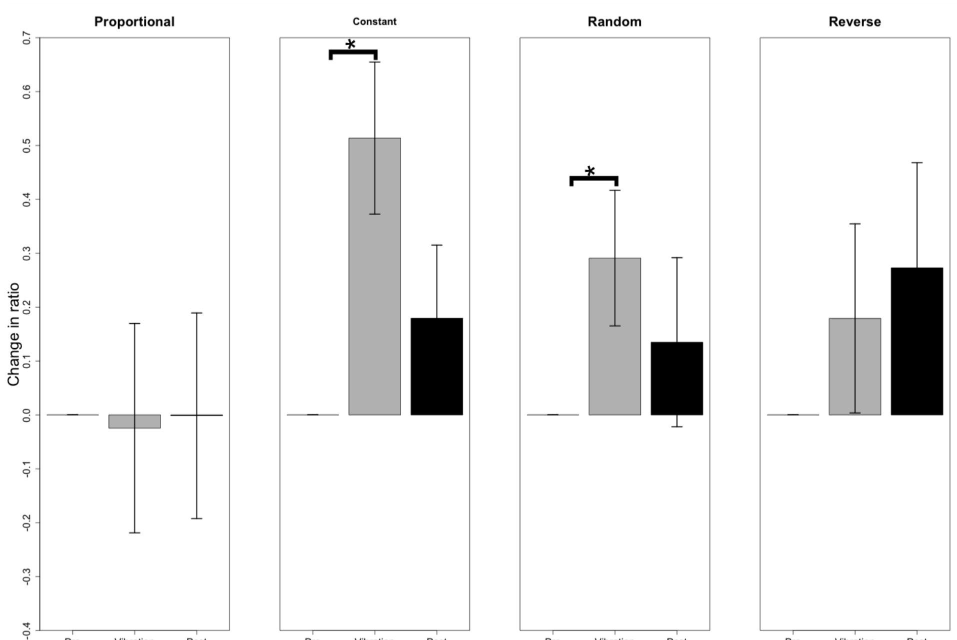

FIGURE 2.10: Control subjects showed significant increases in vibrated arm use during constant and random vibration. These effects did not persist post vibration, though.

2.2.3 Discussion

We have shown that in children with dystonia, scaled forms of vibratory feedback increased sensory awareness to task-relevant information, thus supporting our primary hypothesis. This increased sensory awareness was made apparent via changes in muscle use that were not accompanied by changes in overall performance. In a previous open-label clinical trial, we had found that long-term use of vibratory biofeedback (via a portable vibration unit) scaled to muscle activity improved specific motor skills in children with secondary dystonia (Bloom, Przekop, and Sanger, 2010). Our present results showed changes in muscle activity, but without significant changes in task performance for both groups of subjects. This may have been due to the nature of the task and the shorter period of time in which the stimulus was given. It must be noted, however, that control subjects performed better overall and had lower movement times to reach targets than did patients, as expected in speed-accuracy trade-off tasks involving healthy controls and children with dystonia (Lunardini et al., 2015b; Bertucco and Sanger, 2014; Lunardini et al., 2015a; Avanzino et al., 2014). Patients may have moved slower due to the inherent muscle activity that is not correlated to the task.

The type of vibration was key to causing an unconscious bias in muscle use. We saw that only muscle activity-related vibration was able to cause significant changes in the pattern of muscle use during the stabilization period in subjects with dystonia. Thus, it is possible that in the dystonic group, scaled vibration provided useful sensory information to the system, while non-scaled vibration resulted in habituation to the stimulus, with no significant changes occurring as a result. These effects were seen during the feedforward stage as well, signifying that some sort of anticipatory behavioral adjustments took place in the presence of scaled types of vibration, prior to when feedback started to play a role.

In control subjects, we saw a significant increase in muscle use only during constant vibration. This may have occurred because control subjects are already able to perform this task close to an energetically favorable manner, and providing them with scaled vibration is redundant to signals provided by the properly functioning sensory system. On the other hand, their behavior may have changed with non-scaled vibration since task-irrelevant information could have been distracting (thus bringing attention to the vibrated muscle) and induced a response involving more muscle activity. Only constant vibration caused significant changes in muscle activity after the feedforward stage, though, which was not as expected because we hypothesized random vibration would have also caused similar changes. Perhaps random vibration is more easily ignored in this type of task as compared to constant vibration. Further investigation should help understand this difference better.

We also showed that although there was always an energetically favorable solution for completing the task, scaled forms of vibration were able to bias away from this, and bring attention to the more dystonic limb (in subjects with dystonia). This is clinically relevant because we have shown that it is possible to selectively change muscle patterns in children with dystonia, thus potentially alleviating cramping and discomfort, and in the long-term, improving performance. The results are even more interesting since we did not give specific instructions to subjects to use one muscle more than the other, and they were thus able to change their actions subconsciously. It is possible that the mechanism of efficacy of vibration feedback is different in different disorders. This particular use of vibration could, however, be used for learning purposes when retraining muscle patterns in children with dystonia (Avanzino and Fiorio, 2014).

In this experiment, we were unable to account for subject expectation after the first visit because we followed the same block design. However, expectations within trial were dealt with since the bar targets were presented in a pseudorandom order. Persistent effects are also not significant in this study, mostly because the vibration was only applied during one block i.e. approximately 8 minutes. A longer period of vibration could have caused a strong effect similar to what was seen during the vibration block, and multiple days of vibratory feedback could potentially cause long-term changes.

2.3 Implications of vibratory feedback

In conclusion, it was shown that scaled vibratory feedback can be used to bring selective attention to a specifc muscle in a one-dimensional task. This is a clear portrayal of how vibratory feedback may be helpful in answering the credit assignment problem.

Chapter 3

Visualization as a mode of communication to bring focus to non-visual sensations.

3.1 Relevance of visualization

Visualization, or mental imagery, has been widely used in the field of psychology, rehabilitation, and coaching. Coaches believe in the importance of this powerful tool for training their athleted. The term “mental imagery” is described in diverse ways in the literature, with no clear consensus on its defining characteristics (Driskell, Copper, and Moran, 1994). Some researchers use “mental imagery” to refer to situations where subjects are asked to envision themselves completing a sequence. For example, a rower could be asked to take a few minutes before the start of a race to mentally review the steps involved in completing the race, to imagine what the air would feel like, what it would feel like to reach the finish line, and what it would take to win the race (*Rowing faster* 2011). Others use “mental imagery” to practice specific skills to improve performance. In other words, if the task is to learn to abduct the thumb to a given angle, one can use mental imagery to practice this skill without actually physically executing it (Liu, Song, and Zhang, 2014). Still others utilize imagery to improve upon the style and expression of the task e.g. asking someone to move like a swan.

3.1.1 Mechanistic explanation

For my research purposes, I have defined visualization as techniques that communicate non-visual sensations, which can be proprioceptive, tactile, or emotional. As mentioned in Chapter 1, visualization techniques can be used to substitute (1) the task, (2) the body, and (3) the emotional context. These techniques are allowing one to evoke movement sensations that access stored associated motor patterns/sensations in order to complete the motor task. Refer to Figure 1.6 for the model describing its effects.

Learning to master such techniques, especially in developmental movement stages may prove to be a highly relevant psychological skill (Simonsmeier and Buecker, 2017).

3.2 Using visualization techniques to create task-equivalent kinematics and dynamics

In this work, we designed myocontrol experiments that created task-equivalent kinematics and dynamics to solve the credit-assignment problem by bringing selective attention to specific movement sensations. We predict that this type of task equivalence changes muscle patterns, which is especially useful in children with movement disorders since this provides the ability to manipulate their muscle activity using a non-invasive sensory technique. With continued practice, we predict such techniques can also improve overall motor performance.

3.2.1 Hypothesis

In order to test our predictions, we designed and completed two tasks. Task 1 was designed to understand how muscle patterns were affected when task equivalent-kinematics was used on a 1D kinematic task. We presented subjects with a coupled physical system meant to elicit sensations involved in manipulating the real coupled system of muscles used in completing the task.

Task 2 was designed to understand how creating a task-equivalent dynamics using a 1D kinematic task can change muscle patterns. Here, we presented subjects with a visualization of a "go-signal" that was meant to create a sensation of explosive energy in the form of a spring being released. We also created an alternate version of this task in order to test for the importance of the type of "go-signal" for creating said sensations since we predicted that the nature of the visualization should have an effect on a subject's perceptions, and eventual performance.

Both of these tasks represented the concepts of "substituting the task" and "substituting the body" as discussed in Chapter 1, and are expected to be helpful bringing selective attention to movement sensations. The results from these experiments would help inform further studies of interventions to retrain muscle patterns in children with movement disorders.

3.2.2 Materials and Methods

Subjects

The experiment was conducted on 4 children (age 17.3 ± 3.3 years) with secondary dystonia and 5 healthy controls (age 17.0 ± 5.1 years) in accordance with the Declaration of Helsinki. The University of Southern California Institutional Review Board approved the study protocol (UP-12-00457). All children and their parents gave informed written assent/consent for participation. Authorization for analysis, storage, and publication of protected health information was obtained from parents according to the Health Information Portability and Accountability Act (HIPAA).

Experimental setting

We used surface EMG electrodes (DE-2.1 electrodes with Bagnoli-8 amplifier, Delsys Incorporated, Boston, MA, USA) with 20-450 Hz band-pass filter and 1000x amplification on the brachioradialis and/or first dorsal interosseous (FDI) muscle bellies of the more dystonic arm (in patients) and the non dominant arm (in controls). The EMG signals were sampled at 1KHz using an ADC (Power 1401, Cambridge Electronic Design Limited, Cambridge, UK) that was controlled by custom data acquisition software. The EMG signals from each muscle were processed online in the following manner: a high-pass Butterworth filter (fourth order, 1 Hz cutoff) followed by a Bayesian filter 38, and then a low-pass Butterworth filter (second order, 5 Hz cutoff). A round 2-inch gel ground electrode (PainRX Store, Fountain Valley, CA, USA) was placed on the backside of the palm of the opposite hand. We obtained the maximum voluntary contraction (MVC) at the beginning of each experiment set by asking subjects to flex each of the muscles recorded maximally during a period of 16 s. Their tested arm was resting on the armrest, with the wrist strapped onto the armrest to ensure isometric contraction. Throughout the experiment, subjects were seated in front of a computer screen, which presented them with tasks that were controlled by muscle activity levels of the brach and/or FDI.

Task 1

We designed a two-muscle, unilateral myocontrol task where activation of the brachioradialis and FDI muscles resulted in the horizontal motion of a red box on the computer screen. The experiment had three blocks (ABA design), with a visualization of the coupled physical system shown during block 2 (Figure 3.1) only. Blocks 1 and 3 were pre-intervention and post-intervention blocks, respectively, where subjects only saw a red box and a blue target on the computer screen. Each block consisted of 20 trials lasting 16 s each. The first 5 trials of each block were meant for practice only; hence, they were not included in the data analysis. The goal of the task was to move the red box into a blue vertical target as quickly as possible, and then keep the box in there until the target moved back to its original location. There was only one target presented, and subjects had to reach it quickly, but this was not a Fitts' paradigm since we did not present different targets to the subjects.

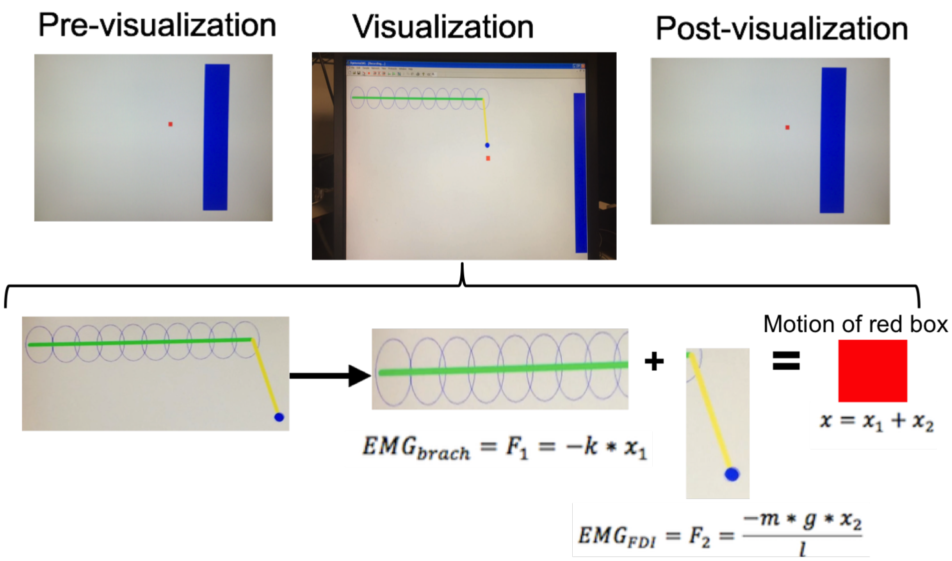

FIGURE 3.1: The three blocks of task 1 are shown here using screenshots of the task at play. As can be seen from the visualization block, the coupled physical system is comprised of a spring and a pendulum that represent the activity of the brachioradialis and FDI, respectively. The sub tasking allows subjects to understand how each of the muscles contributes to the motion of the red box.

In the visualization block (block 2), subjects were shown (on the computer screen) a spring-pendulum system whose motion was directly correlated to the muscle activation levels through equations of motion for a spring and a pendulum:

$$EMG_{brach} = F_1 = -k * x_1 \tag{3.1}$$

$$EMG_{FDI} = F_2 = \frac{-m * g * x_2}{l} \tag{3.2}$$

The overall motion of the red box was defined by the following equation:

$$x = x_1 + x_2 \tag{3.3}$$

Therefore, we essentially used a "sub tasking" method (similar to what coaches do) that allowed subjects to link individual muscle activity to sub parts of the task, instead of simply just showing the overall motion. The expectation here was that showing sub parts of the task would help subjects better understand how each muscle contributes to overall task success.

Task 2

For this task, we designed a one-muscle myocontrol task where activation of the brachioradialis muscle controlled the horizontal motion of a red sphere on the screen. In this task, there was a discrepancy in timing between the presentation of a blue vertical target and movement initiation i.e. the sphere wasn't able to move until 5 s after the target appears. Therefore, subjects would usually have a high level of muscle activity pre-target presentation, and this may not be efficient in the long-run. We wanted to study how providing task-equivalence dynamics would reduce brachioradialis pre-activation levels. This experiment also consisted of three blocks (ABA design), with a visualization of a block breaking apart to allow the red sphere to move presented in block 2 only (as shown on Figure 3.2). In blocks 1 and 3, subjects were only shown the red sphere and the blue target. Each block consisted of 20 trials, and each of the first 5 trials were for practice purposes only. Subjects were instructed to "shoot" the red sphere into the blue target 5 s after it appeared on the screen. The motion of sphere was defined by the equation of motion of a spring:

$$EMG = F = -k * x \tag{3.4}$$

We designed a control experiment for task 2, which was completed by the control subjects only. The goal of this experiment was to show that the nature of the visualization provided was important in affecting one's adoption of the sensations that would result in changed muscle patterns. We believed that it was the sensation of "block-and-release" in task 2 that enabled movement sensations to be elicited because of the dynamics involved, and therefore, a simple color change indicating movement initiation should not have the same effect. Therefore, during the visualization block of the control condition, subjects were shown a blue box on the top left of the screen that would change to cyan when it was time for the sphere to move.

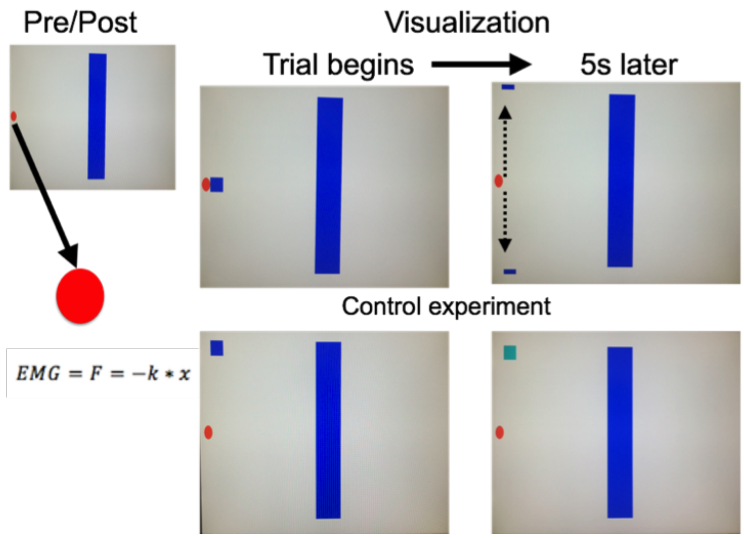

FIGURE 3.2: The block design for task 2 is shown here. The top panel for the visualization block shows how the box blocking the red sphere separates 5 s after the trial start to signify movement initiation. The bottom panel shows the control case where the blue box changes color to cyan to signify movement initiation.

Data Analysis

Data were analyzed using Matlab® R2015b software (Mathworks® Inc., Natick, MA, USA). All EMG signals were normalized to their corresponding MVC values. In order to assess changes in muscle use with visualization during task 1, we calculated the ratio (R_{EMG}) of brachioradialis EMG to FDI EMG for each block. The change in this ratio ($Ratio_{change}$), with respect to the first block (baseline), indicated how muscle use changed over time. A positive change in ratio meant that subjects tended to use the brachioradialis muscle more during that specific block, and vice versa.

$$R_{EMG} = \frac{EMG_{brach}}{EMG_{FDI}} \tag{3.5}$$

$$Ratio_{change} = \frac{R_{Block\ x} - R_{Block\ 1}}{R_{Block\ x} + R_{Block\ 1}} \tag{3.6}$$

We also measured the movement time, defined here as the time it took to reach the target (from the time of target presentation) and stay for at least 200 ms. For task 2, we measured change in brachioradialis pre activation levels (during the 5 s period before the sphere was able to move into the target) with respect to block 1. Decrease in EMG signified lower levels of muscle activity during the pre activation period. The movement time we measured for task 2 was how long it took subjects to move into the target from the end of the 5 s period onwards.

We used RStudio® version 0.98.977 (RStudio Inc.®, Boston, MA, USA) for statistical analysis. We used a linear mixed effects model (R-package lme4, version 1.1-7) to determine interactions and effects of two factors (subject type and block) on the dependent variables. For the analysis of movement time, the variables block (3 levels), and subject type (2 levels) were set up as fixed effects, while the intercepts for subjects were random effects. This is the model for movement time for both tasks:

$$Movement\ Time \sim Subject\ type + Block + (1|Subject) \tag{3.7}$$

In order to analyze effects of block and subject type on the brach:FDI ratio for task 1, we created the following model:

$$Rato \sim Subject\ type + Block + (1|Subject) \tag{3.8}$$

To analyze how the brachioradialis EMG changed throughout the experiment in task 2, we created the following model:

$$EMG_{brach} \sim Subject\ type + Block + (1|Subject) \tag{3.9}$$

After creating these models, we tested the significance of each of the fixed effects on the dependent variable by comparing the model (full) against reduced models (null) in which one of the fixed effects was removed each time. The rest of this statistical analysis was done in the same manner as in the analysis section of Chapter 2.

3.2.3 Results

Task 1

Visualization resulted in increased use of the brachioradialis muscle in all patients, and increased use of the FDI muscle in most control subjects. These changes were mostly visible in the visualization block, as seen in Figure 3.3. While controls took significantly ($P < 0.05$) less time to reach the target than patients in the visualization block, there were no significant changes within each group (Figure 3.4). Statistical analysis showed that both subject type and block did not have significant effects on movement time. Thus, there was no significant interaction between the two factors either.

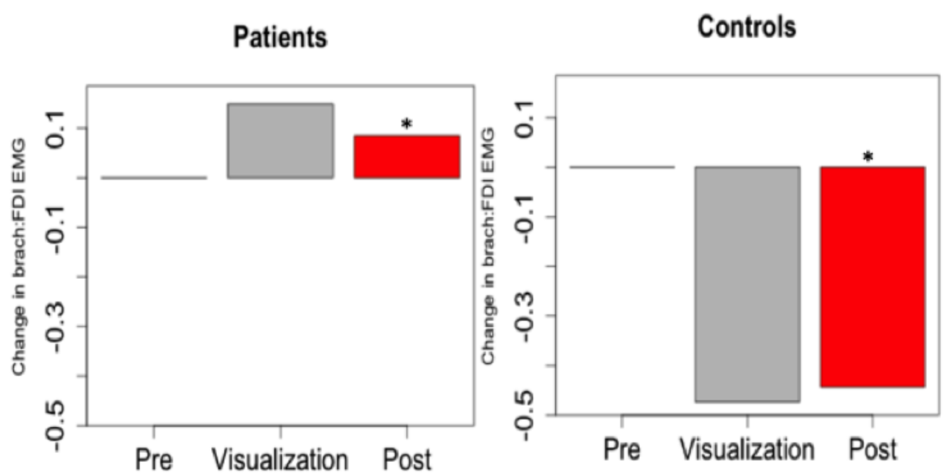

FIGURE 3.3: Patients used the brachioradialis muscle more during and after visualization, while control subjects used the FDI muscle more.

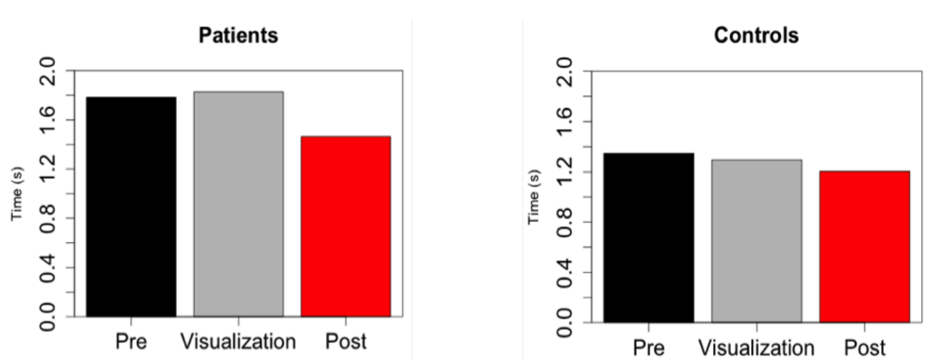

FIGURE 3.4: There were no significant changes in time to reach target for either group of subjects.

Task 2

There was a slight and persistent reduction in brachioradialis muscle activity during the period before the "go-signal" appears in both groups, and this reduction is not seen with the control case of the task (Figure 3.5). Linear modeling results showed that both block (AIC_{full}=908.37; AIC_{null}=912.43; $P<0.05$) and subject type (AIC_{full}=908.37; AIC_{null}=912.68; $P < 0.05$) were significant regressors on movement time. In addition, the interaction between subject type and block was considered significant (AIC_{full}=899.45; AIC_{null}=908.37; $P < 0.01$).

There was a significant ($P < 0.05$) decrease in movement time post visualization. Overall, control subjects performed the task significantly ($P < 0.05$) faster than subjects with dystonia. Analysis of the change in brachioradialis activity showed that block (AIC_{full}=-1691.4; AIC_{null}=-1661.8; $P < 0.001$) was a significant regressor on the model, while subject type was not. Here, there was a significant ($P < 0.0001$) decrease in EMG between blocks 1 & 2 and blocks 1 & 3.

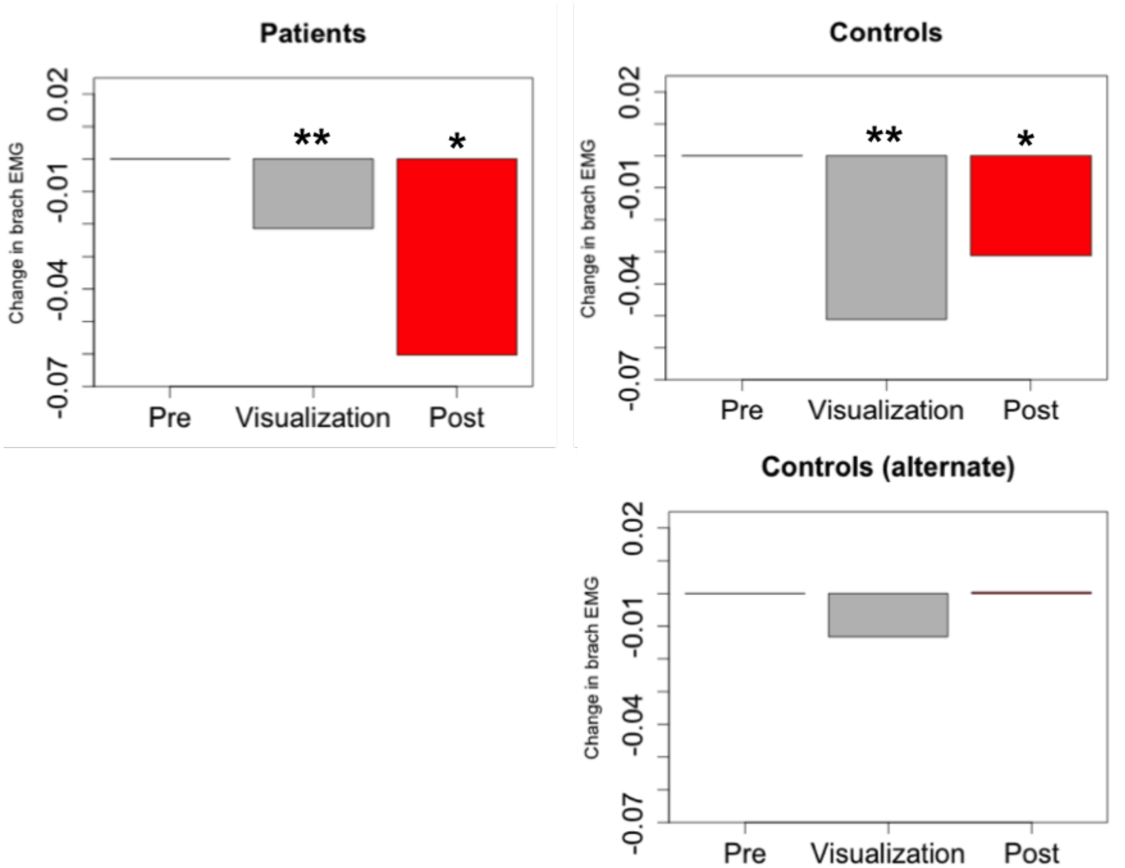

FIGURE 3.5: The top panel shows the results of task 2, where use of the brachioradialis muscle reduces during the period in which subjects wait for the movement to initiate. The bottom right graph shows the results for the control case where it can be seen that there is almost no change in activity of the muscle post visualization, in control subjects.

3.2.4 Discussion

We showed, through task 1, that providing a visualization of a coupled physical system of the two muscles involved helped subjects change their muscle patterns. Subjects with dystonia were able to increase the use of their brachioradialis muscle, while control subjects increased the use of their FDI muscle. What is interesting here is not that there is a difference in the type of muscle activated by each group, but that we were able to change muscle patterns in the first place. With regards to overall performance, subjects did not have any significant change, and this may be because the task was not difficult to complete anyway, and that with a small amount of practice, improvements can occur and plateau easily. The difficult presented in this task was in the ability to modulate muscle activity in order to prevent muscle fatigue and maintain consistency in movements. And we believe the task-equivalent dynamics was able to create sensations of motion in the spring-pendulum system, thus making it easier to modulate activity.

Results from task 2 showed that muscle activity could be modulated when eliciting task-equivalent dynamics to a 1D kinematic task, and that this modulation of activity is dependent on the nature of the visualization provided. It is important in the design and implementation of visualization techniques that we pay much attention to the kind of image that we help form; it needs to actually result in a non-visual percept, and cannot simply be a visual indicator. We were able to use this simple visualization to reduce pre activation levels of the brachioradialis, and thus it could prove useful in bringing selective attention to muscles that need to be better controlled in those with movement disorders, such as dystonia.

3.2.5 Implications of visualization

Visualization allows subjects to retrain muscle patterns by communicating a non-visual percept in a task-equivalent system. This can be achieved with little to no guidance on what to do. Thus, this powerful tool can be used in the retraining of complex muscle patterns in both healthy subjects and those with movement disorders.

Chapter 4

Vibratory feedback and visualization to bring focus to control variables in a three-dimensional myocontrol task

4.1 A 3D myocontrol study

Most of the work done up to this point was focused on understanding the effects of the two sensory interventions (vibratory feedback and visualizations) in one-dimensional moyocontrol tasks. The exception to this is the ongoing vibratory feedback studies on the Figure-8 and spoon tasks described in Chapter 2. In order to understand the effects of visualization on a real-world like environment, it was important to design a three-dimensional task. Therefore, the credit-assignment problem was studied using a desktop robot. Additionally, this paradigm was used to study multi-muscle vibratory feedback since all our studies up to this point have focused solely on single-muscle feedback.

4.1.1 Introduction

While the implementation of a 3D task to study effects of these interventions is a novelty, there are long-term benefits of this study for those with movement disorders. For example, with the design of myocontrolled exoskeletons (an ongoing project in the Sanger lab), one would require efficient control of a set of muscles in order to make smooth movements. This type of control is not easily understood nor is it easily learned, since the mapping of muscles to task space is unclear; hence, the credit-assigment problem arises once again. The lack of congruence between muscle activation and robot movement results in a great difficulty of adapting these systems for everyday use. The perceptual basis of control reflects how complex movements may be performed with simple visual feedback (Mechsner et al., 2001), and we study this concept in terms of how attention is modulated to achieve this purpose.

With regards to visualization techniques, we believe that a complex muscle-to-task mapping can be simplified because task equivalence allows one to adopt non-visual perceptions. Therefore, lack of congruence in mapping is solved by allowing one to think and feel the sensations that would allow the task to be made congruent by paying attention to selective parts of the task/body, without actually thinking about it this way. In this work, the effects of visualization were studied in terms of their ability to change overall muscle patterns, as well as overall task performance. The types of visualization techniques used could be any of the 3 mentioned in Chapter 1 or any other type deemed most useful. This study was designed in order to incorporate all 3 categories i.e. substituting the task, the body, and the emotional context.

With regards to the use of vibratory feedback, we have been studying the effects of vibration applied to only one muscle at a time. We have seen significant effects of single-muscle vibration, and wanted to study how multi-muscle feedback could change performance in a task where there is a credit-assignment problem. There is now less selective attention to a specific muscle since more than one muscle is being vibrated. This results in more attention being brought to the entire limb as a whole, instead of a specific muscle. We therefore predicted that such an intervention would result in worsening in performance, and no changes to muscle patterns.

This pilot study was conducted on healthy subjects, with the hope that the results would help in the design of an experiment targeted towards children with movement disorders for whom such sensory interventions would be deemed helpful.

4.1.2 Materials and Methods

Subjects

We recruited 14 healthy undergraduate and masters students (5 males, 9 females; aged 22.57 years ± 2.62 years) at the University of Southern California (USC). The Institutional Review Board at USC approved the study protocol (UP-12-00457). All gave informed written consent for participation. Authorization for analysis, storage, and publication of protected health information was obtained from the students according to the Health Information Portability and Accountability Act (HIPAA). This study was performed in accordance with the Declaration of Helsinki.

Experimental setting

The experiment was conducted so that one of the two sensory interventions (visualization or vibratory feedback) would be tested on the first day, and the other on the second day. We used a Phantom Omni dektop robot (Sensable Technologies Inc.) whose arm movement (the x,y,z coordinates) was controlled by the activation of three muscles. We placed surface EMG electrodes (DE-2.1 electrodes with Bagnoli-8 amplifier, Delsys Incorporated, Boston, MA, USA) on the muscle bellies of the flexor carpi ulnaris (FCU), brachioradials, and posterior deltoid of the non-dominant arm. A round 2-inch gel ground electrode (PainRX Store, Fountain Valley, CA, USA) was placed on the dorsal side of the dominant hand's palm. Maximum voluntary contraction (MVC) values were recorded from all three muscles over a period of 60 s at the beginning of the experiment, and the EMG trace during this period was broken into segments of equal length, with the signal in each bin averaged to obtain a value. The maximum value of all the bins was determined to be the MVC.

We created the task interface through two programs that communicated via UDP protocol (Visual Studio 6.0, Microsoft, Redmond, WA, USA). The first program was designed to receive EMG signals from the three muscles, and to scale those values to corresponding values in the robot's coordinate space. These position values were sent via UDP to a program on a different computer where the robot's current position was read in, and a calculation of the force needed to be exerted to move the robot to the new position was made. As a result, force values were sent to control the 3D motion of the robot arm.

The activation of these three muscles was supposed to signal movement in the x,y,z directions, respectively, because it would have been fairly intuitive to expect that mapping (x direction is left/right, y direction is up/down, and z direction is in/out). However, instead of providing such a congruent mapping, we intentionally shuffled the mapping so that it would be less intuitive e.g. movement in the x direction would be represented by activation of the brachioradialis, movement in the y direction by the posterior deltoid, and movement in the z direction by the FCU. These permutations would not be making the task entirely impossible to complete, but they would be expected to make it less straightforward to learn.

Task

For both days of the experiment, subjects were asked to sit on a chair in front of the robot, with their non-dominant arm strapped to the armrest at the wrist and at the elbow in order to ensure isometric contraction (Figure 4.1). The experiment was conducted in an ABCD design for the visualization protocol, and an ABA (or ABAC) design for the vibratory feedback protocol. Of the 14 subjects, 10 completed the visualization protocol, 12 completed the vibratory feedback protocol, and some of the subjects only did one of the protocols. We used a Fitts' (Fitts 1954) paradigm with four square targets of varying distances (4 or 6 inches) and widths (1 or 2 inches) from the start point of the robot arm (represented by a blue rectangular region of the same height as the target). Subjects were instructed to move the robot arm up and to the right, into the blue target. They were asked to do this as many times as possible (and as fast as possible each time) in a 60 s period, and were asked to return to the blue origin box at the end of each "target hit".

In this experiment, one was technically able to understand the muscle mapping after a certain amount of practice. However, this was not enough since the movement was due to the combination of all three muscles, and it was this combination that was difficult to learn without sensory interventions.

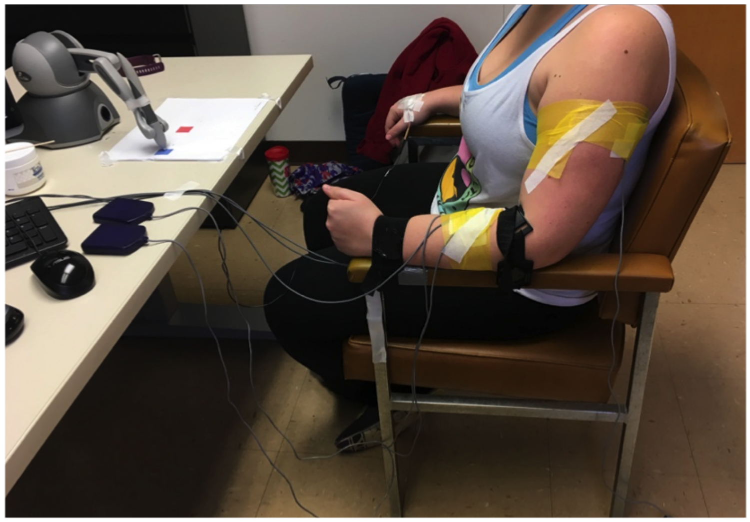

FIGURE 4.1: The experimental setup for both the visualization and vibratory feedback protocols. Subjects were seated in front of the robot, with their tested arm strapped onto the arm rest in order to ensure isometric contraction. Subjects were instructed to activate their muscles accordingly to move the robot arm into each of the 4 red targets presented to them, and to get as many hits into the target as possible within 60 s.

Visualization protocol

The block design was ABCD, where the visualization techniques were presented in the second and fourth block. Blocks 1 and 2 involved a non-intuitive mapping of muscles to task space, which we did not describe to the subjects, and in which they were given 60 s per target to explore and decide on the best way to reach it. In block 2, we asked subjects to imagine themselves holding tightly to a coffee mug filled to the brim with very hot coffee, and to move this mug across the table. We asked subjects to take a few minutes to internalize this image, and to understand the emotions and sensations felt when doing this task. We also gave subjects one practice trial on a target before continuing with the experiments. The idea here was to evoke an emotional sensation (extreme caution) along with a proprioceptive sensation (pattern of activation of the muscles involved in holding a mug tightly) because this would be most helpful in achieving task success. Unknowingly, visualizing this scenario would allow subjects to activate the necessary muscles to lift and move the robot to the right. In this block (and in block 4), subjects were presented with each target twice in order to maximize practice (in the analysis, we averaged the values in the two trials). Block 3 involved a different muscle mapping from blocks 1 and 2.

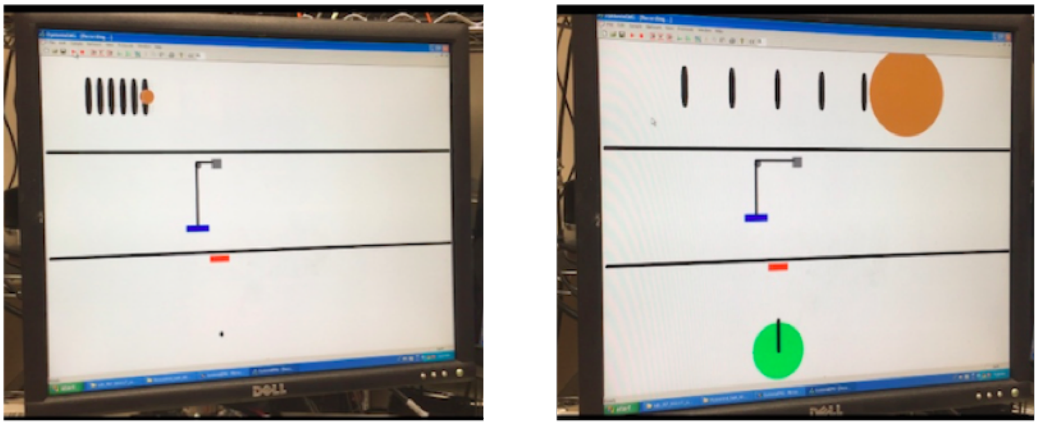

FIGURE 4.2: The coupled physical systems representing how activation of each muscle moves the robot arm. The left image shows the three systems when the subjects are fairly relaxed, and the image on the right shows what happens to the systems when each of the three muscles is activated. The FCU is represented by a spring that is extended during activation, resulting in an orange circle growing bigger, to signify the in/out movement of the robot arm. The brachioradialis is represented by a pulley system in which a blue box attached to the bottom moves up with activation, resulting in the horizontal motion of a grey box attached to the other end (this makes the robot arm move to the right). The posterior deltoid is represented by a small green circle that grows bigger upon activation, resulting in a line moving up to signify the up/down movement of the robot arm.

In block 4, we provided another type of visualization to help subjects understand how to tackle the complexity of the task. This was an extension of the coupled physical systems used during the one-dimensional visualization experiments from Chapter 3. The reason these systems were used was because they were deemed intuitive mapping of muscle activity to robot task space.

We told subjects that each of their muscles was represented as a coupled physical system, which we would show on the screen for them to first understand and explore, and then use as needed during the task (Figure 4.2). We represented the FCU as a horizontal spring that stretches with increased activation, and causes an orange circle to grow proportionately bigger (this emphasizes how the robot moves in/out when the FCU is activated). The brachioradialis was represented as a coupled pulley system, where activation causes a box attached to a pulley to move up, which then causes a box attached to the other side of the pulley to move to the right, representing the robot left/right motion. The posterior deltoid was represented by a green circle that grows bigger with increased activation, and causes a line to go up (and this is how the robot moved: up/down direction). These systems were explained very carefully, and subjects were asked to try and imagine each of their muscles as these corresponding systems in order to help them improve performance.

Vibratory feedback protocol

We ran an ABA block design for this protocol. In blocks 1 and 3, there was no intervention. We used the same shuffled muscle mapping for blocks 1 to 3 as was used in the visualization protocol's first 2 blocks. In block 2, we provided vibratory feedback to each of the 3 muscles using a portable vibrating unit (designed and developed by Dr. Terence Sanger; patent number: US 8,311,623 B2) whose sensor was placed next to the electrode on each muscle belly. The sensor of each device picked up muscle activity and vibrated that muscle proportionally to its activity i.e. higher muscle activity corresponded to higher levels of vibration, and vice versa. We expected vibratory feedback to bring selective attention to each of the 3 muscles, and thus help subjects modulate muscle activity accordingly. For example, we expected vibratory feedback to increase deltoid activity since it was difficult to activate in the configuration subjects were in. We also expected both brachioradialis and FCU activity to reduce since subjects have a better understanding of how each muscle behaved, and therefore didn't have to co-contract to make the robot move.

In block 2, each target was presented twice. The expectation is that subjects could also perform better because of this increased attention to task-relevant information. Here, we are using the concept of sub tasking and task substitution to break a complex motor task (moving a robot arm) into individual parts through a vibratory stimulus. Block 3 was set up to study after-effects of vibratory feedback, and therefore, we did not provide vibratory feedback during that block.

Data Analysis

Data were analyzed using Matlab® R2016a software (Mathworks® Inc., Natick, MA, USA). We counted the number of hits per target in each block as an indicator for performance. We also calculated the time to reach the target for each of those hits. These times were averaged to give the movement time for each target. We analyzed performance by measuring overall movement time aggregated over all targets. A decrease in overall movement time signified improvement in performance.

In order to assess how muscle activity was modulated, we measured muscle effort by determining the average strength in each muscle, as well as the average total strength in all three muscles. Muscle strength was defined as the square of the root mean square value of the raw EMG signal.

Statistical analysis was performed using RStudio® version 0.98.977 (RStudio Inc.®, Boston, MA, USA). We used a linear mixed effects model (R-package lme4, version 1.1-7) to determine interactions and effects of four factors (ID, block, subject type, intervention) on outcome measures i.e. movement time, number of hits, muscle power. We created linear mixed effects models using maximum likelihood (R-package lme4, version 1.1-7) to analyze effects on a dependent variable. We conducted post-hoc analyses using pairwise Tukey's tests on the linear model with the lowest Akaike value (refer to Chapter 3 for details on the statistical analyses employed).

4.1.3 Results

Visualization protocol

Ten subjects completed this protocol. We found the overall number of hits increased post both visualization cases; however, this increase was not statistically significant in either one. With regards to movement time, we found a decrease in average movement time (from 17.03 s $\pm$ 3.49 s to 13.24 s $\pm$ 3.60 s) across targets from block 1 to block 2 i.e. time to reach the targets was reduced post visualization of coffee mug scenario. However, we did not see similar results after the presentation of the physcial systems since there was a slight increase (from 14.21

s ±4.79 s to 15.69 s ± 4.83 s) in movement time after the muscle mappings were swapped. Figure 4.3 below shows these results.

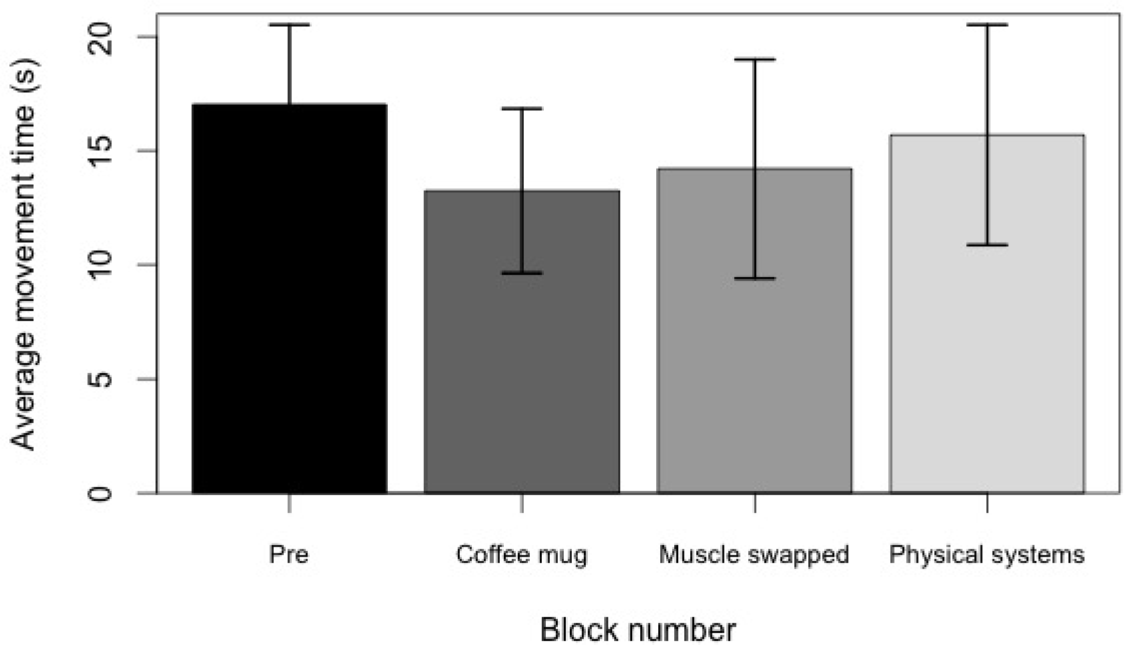

FIGURE 4.3: Using a simple visualization of holding and moving a coffee mug filled to the brim with hot coffee evokes sensations that allow to reach targets faster. While the results are not statistically significant, the trend is promising.

To analyze muscle strength, both total and individual, we used the following model:

$$Muscle\ strength \sim Target + Block + (1|Subject) \tag{4.1}$$

We found target to be a significant (P < 0.05) regressor on total muscle strength i.e. increase in total muscle strength as the targets get more difficult, with the exception of target 2, which caused the highest amount of signal strength (and was very similar to that for target 4). This may be because targets 2 and 4 were the furthest from the origin, and although the index of difficulty was less for target 2, it may have been more difficult to modulate activity for this target. The block factor was not statistically significant at the 0.05 confidence level (P =

0.087), but it was significant at the 0.1 level. We noticed a slight decrease (from 0.2455 mV ± 0.0573 mV to 0.2160 mV ± 0.0552 mV) in overall muscle effort after the coffee mug scenario was brought up, and a slight increase (from 0.2414 mV ± 0.0573 mV to 0.2758 mV ± 0.0552 mV) after the coupled physical systems were introduced. There was no significant interaction between block and target on muscle strength.

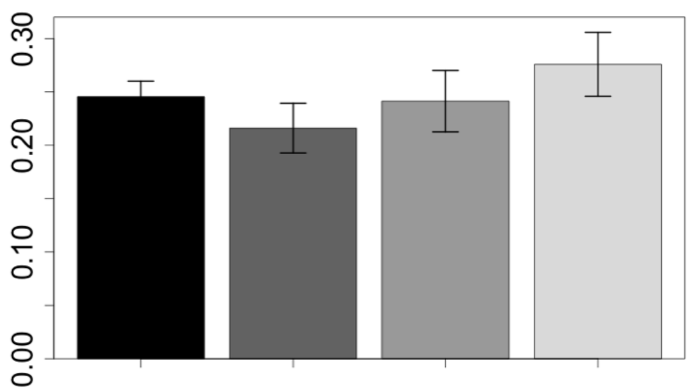

FIGURE 4.4: Muscle power reduced post "coffee-mug" visualization only; however, these changes were not statistically significant.

We then looked at individual muscle strength changes, and found statistical significance in the changes to the posterior deltoid muscle, and not to the FCU and brachioradialis muscles. The block factor was a significant regressor on the posterior deltoid's strength i.e. there was a significant ($P < 0.05$) decrease (from 0.0563 mV ± 0.0105 mV to 0.0283 mV ± 0.0095 mV) in effort following the coffee mug scenario. The change after the coupled physical systems was presented (from 0.0239 mV ± 0.0105 mV to 0.0334 mV ± 0.0095) was not significant ($P = 0.6073$), however. FCU effort increased (from 0.118 mV ± 0.0375 mV to 0.13 mV ± 0.0358 mV) during the second visualization intervention of coupled physical systems, and decreased (from 0.0994 mV ± 0.0375 mV to 0.0927 mV ± 0.0358 mV) slightly during the first intervention (the coffee mug); however, these were not significant changes. We performed similar analyses for the brachioradialis muscle effort changes, and found it increased after each of the visualization interventions.

Vibratory feedback protocol

We conducted our analysis on 9 of the 12 subjects who completed this protocol because three of the subjects were either not able to complete the task due to time constraints or because the vibratory feedback was not strong enough for the subjects to feel the effects on their skin.

Movement time actually increased with the application of vibratory feedback (from 10.39 s ± 2.39 s to 14.36 s ± 4.20 s), and reduced (to 10.46 s ± 2.90 s) once the vibratory feedback was removed (Figure 4.5). Because of large amounts of variance in these results, we found no statistical significance here. Additionally, most subjects did not like the application of vibratory feedback, and believed that it actually made them perform worse.

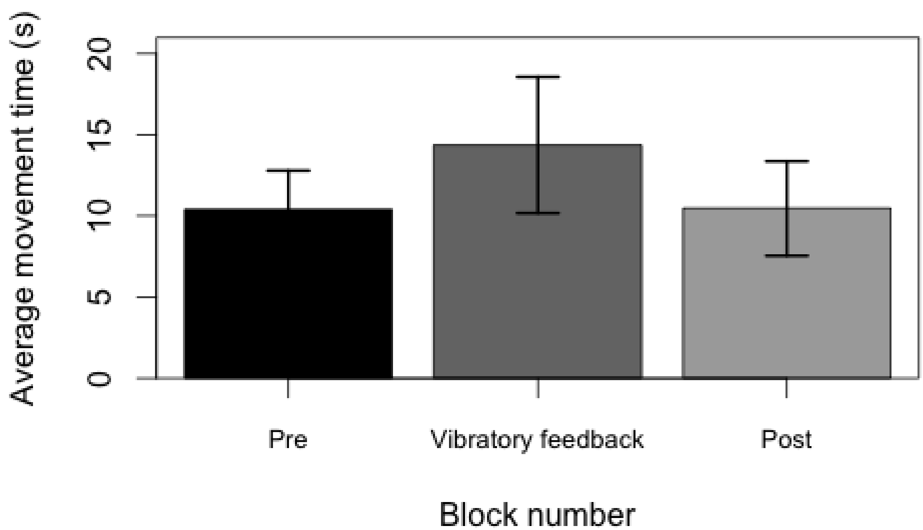

FIGURE 4.5: Vibratory feedback results in lower performance as shown by increased movement times across targets.

We conducted the same type of analysis on the muscle effort as was conducted for the visualization protocol.

We found target to be a significant ($P < 0.05$) regressor on total muscle strength, and we saw similar results from the visualization protocol with respect to target 2. Block was not a significant regressor on total muscle effort, although we saw a slight increase in effort across blocks (from 0.2254 mV ± 0.0392 mV in Block 1 to 0.2363 mV ± 0.0392 mV in Block 2). There was no significant interaction between block and target on muscle strength.

The posterior deltoid's signal strength changed significantly (P = 0.05) during the vibration block where we saw an increase from 0.0122 mV ± 0.0045 mV to 0.0185 mV ± 0.0042 mV. Its signal strength was not affected significantly by target size. There was no significant effect of block on the brachioradialis muscle strength. While there was a slight decrease in muscle strength (from 0.1307 mV ± 0.0238 mV to 0.1225 mV ± 0.023 mV) during vibratory feedback, there was an increase post vibration (to 0.1369 mV ± 0.0238 mV). The FCU effort results were also not statistically significant, with an increase (from 0.0826 mV to ± 0.0282 mV) in muscle effort during the vibration block, followed by a decrease (to 0.0823 mV ± 0.0282 mV) in muscle effort.

4.1.4 Discussion

The results from the visualization protocol showed an increase in performance with the coffee mug imagery because of the evoked movement sensations. We also saw a slight decrease in overall muscle activity after the coffee mug scenario, with the posterior deltoid muscle significantly reducing its activity. The results were as predicted because we believed this specific type of visualization helped subjects substitute the task, body, and the emotional context in order to perceive the movement sensations necessary to succeed. The lack of congruence provided by the task was easily solved using this simple visualization. However, the same was not true when we provided the other type of visualization (the set of coupled physical systems). This may be because while the visualizations were helpful individually, the use of all three visualizations at the same time was providing too much sensory stimuli, and not allowing one to focus attention on a specific area. Statistical significance may not have been seen in these results because of the variability in imagery capabilities across subjects (Kosslyn et al., 1984; Egan and Grimes-Farrow, 1982). Since subjects had the freedom to perceive as they wished based on the instructions that were given, there would be variability in their approaches, and hence, in their performance.

Results from the vibratory feedback study supported our hypothesis that multi-muscle feedback would not be as useful as single-muscle feedback. Subjects did not generally seem to like vibratory feedback, and mentioned they were able to complete the task better without it. Vibratory feedback resulted in increased overall muscle activity across blocks. The posterior deltoid specifically had a significant increase in activity during vibration, contrary to what happened in the visualization protocol. Based on the experimental design, reduced activity in the deltoid muscle would have helped with performance, and subjects were unable to do get that kind of control with vibratory feedback. These results suported our general theory that providing attention to multiple muscles all at once is not very helpful. Muscle activity is already known (to a certain level) through proprioception, and feedback would only be helpful if it were providing maximum attention to specific parts of the task/body that required augmented sensory information. Therefore, vibratory feedback in this experiment may have been more helpful if it were provided in a graded manner. For example. during the stage of the task that required activation of the FCU and brachioradialis, perhaps vibratory feedback of only the deltoid may have helped with better control.

These results, along with our previous studies, are promising since they provide support for our hypothesis that it is possible to improve performance and change muscle patterns by bringing selective attention to the task/body. We have been able to implement the visualization protocol on a three-dimensional myocontrol task to provide a solution for the credit-assignment problem posed by incongruent mapping of robot to task space. The results also showed that when providing these interventions, it is very important that they be designed to promote selectivity, and not simply be adding more sensory information to the system.

4.1.5 Conclusion

This work is an important step in understanding how simple sensory intervention techniques can be utilized carefully to aid with changing muscle patterns and improving performance on a motor task that may be encountered fairly frequently in the real-world. Focused visualization evokes associated movement sensations that activate relevant muscle patterns in order to complete a movement successfully, and scaled vibratory feedback helps by modulating activity of individual muscles to change overall performance (Figures 1.6 and 1.7).

Chapter 5

Conclusions and Future work

In this work, I have endeavored to show how simple non invasive sensory methods can be used to provide a solution to a question in motor Neuroscience: the credit-assignment problem. With movement, it is fairly difficult to identify the actions and choices that resulted in the error signal without bringing selective focus to a certain area of the body. The role of attention on performance has been studied, and I ventured to look at sensory modulators of attention. I studied the roles of visualization and vibratory feedback on modulating attention by understanding how they affected performance by changing muscle patterns and creating movement sensations.

Each of these sensory methods was expected to create task equivalence and augment sensory information to the system. This would in turn help bring selective focus to task-relevant components of a motor skill, thus improving performance. This work has shown how these methods are used to provide a means for not just "what" a movement should be like, but "how" to make that movement.

Scaled vibratory feedback was shown to increase muscle use while non scaled feedback did not have a significant effect on changes to muscle use in dystonia (Refer to 2). This may be of use in clinical rehabilitation programs when trying to increase/decrease muscle use to train specific motor skills. Additionally, these findings have provided support for a possible solution to the credit-assignment problem, whereby selective focus aids in better understanding the error signal, and therefore, aid with motor learning (refer to Figure 1.6).

Similarly, it was shown that visualization has the ability to create task equivalence to bring selective attention to parts of the task, body, and/or context. This is also another solution to the credit-assignment problem since a new plant/sensor system is used to predict the error signal (refer to Figure 1.7), which then helps change muscle patterns almost immediately. Visualization is a powerful tool because it has the ability to create non visual sensations that could be tactile, proprioceptive, and/or emotional, resulting in changes in motor performance. This set of studies is an initial foray into understanding how visualization is used to answer a problem in motor Neuroscience, and further research in this field could have major implications on models of motor learning and motor control.

Long-term motor learning studies conducted using each of these sensory methods would help look at retention effects that were not studied in my work. At a neural level, it would be beneficial to study the effects of these interventions on strengthening cortical associations in order to understand how they may be of use in the presence of brain damage. There is also the potential to study how these interventions can work together, similar to the "cocktail of strategies" coaches adopt to train their athletes. Such work would be helpful in implementing these interventions in learning paradigms for children with movement disorders, and for the implementation of motor learning using exoskeletons.

Since this work was inspired by concepts from the coaching world, I hope I have shown that there is a lot more to gain by looking at how real-world skills are taught and learned by experts such as coaches. We can aim to look at these strategies to inform the design of future experiments to answer questions in motor Neuroscience.

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