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Skill learning from kinesthetic feedback

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ABSTRACT

Background: It is important for a surgeon to perform surgical tasks under appropriate guidance from visual and kinesthetic feedback. However, our knowledge on kinesthetic (muscle) memory and its role in learning motor skills remains elementary.
Objectives: To discover the effect of exclusive kinesthetic training on kinesthetic memory in both performance and learning.
Methods: In Phase 1, a total of twenty participants duplicated five 2 dimensional movements of increasing complexity via passive kinesthetic guidance, without visual or auditory stimuli. Five participants were asked to repeat the task in the Phase 2 over a period of three weeks, for a total of nine sessions.
Results: Subjects accurately recalled movement direction using kinesthetic memory, but recalling movement length was less precise. Over the nine training sessions, error occurrence dropped after the sixth session.
Conclusions: Muscle memory constructs the foundation for kinesthetic training. Knowledge gained helps surgeons learn skills from kinesthetic information in the condition where visual feedback is limited.

1. Introduction

Hand dexterity requires a high level of integration between motion execution and sensory perception. In surgery, skillful performance is constantly regulated by movement schema saved to memory and instantly adjusted via sensory feedback loops, mainly via visual and kinesthetic pathways.[1] Ernst and Banks demonstrated how humans learn skillful movement through vision and kinesthetic feedback loops either separately or by integrating visual and kinesthetic feedback loops over time. Individuals benefit most from visual feedback, but learning can be enhanced further when simultaneous feedback from visual and kinesthetic sensory systems is combined.[2]

Guided Kinesthetic training allows a trainee to attempt to reproduce the movement patterns of an expert.[3] Similarly, kinesthetic memory obtained through guided kinesthetic training helps a trainee to actively learn complex 3D motor skills such as surgical maneuvers by directly performing a movement.[4] For instance, a cholecystectomy procedure is a complex task that can be broken down into smaller simpler surgical tasks, maneuvers and gestures to be more easily remembered in the OR and when offering focused feedback to trainees.[5] During kinesthetic training, kinesthetic memory allows one to memorize and recall which of one's movements and body part positions are necessary to perform a task. Continuous practice of a motion makes it more automatic, thus creating “muscle memory.”[6] Moreover, this guided kinesthetic training offers the novice direct information on the position of body parts, improving kinesthetic memory by decreasing the number of errors while completing a task.[7] In this manner, surgical trainees may increase confidence and task performance by tapping into their muscle memory in situations where visual feedback is limited during training.[8]

The purpose of this study is twofold. First, we examined the natural ability of human operators to store movement information in their muscle memory through the kinesthetic feedback loop. Second, we intend to investigate the effectiveness of learning a motor skill purely through kinesthetic feedback. Specifically in Phase 1, we asked a group of participants to perceive movement through a master-slave delivery system through kinesthetic feedback. When the complexity of the task increased with incrementing number of movement steps, we analyzed the accuracy of kinesthetic memory, i.e. the participants' ability to duplicate the

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movement. In a following Phase 2 of the study, participants were required to perform the same task over 9 trials. We explored the learning process of the participants in performing the movement acquired purely from kinesthetic feedback. We hypothesized that: a) increasing complexity of a movement pattern will challenge the human capacity to store in the kinesthetic memory (i.e., accuracy recall will significantly drop to a certain degree when movement complexity increases); b) repeated practice will facilitate skill learning as human operators will develop strategies to optimize memory information storage with practice.

2. Methods

2.1. Environment and participants

The controlled laboratory study was performed in the Surgical Simulation Research Lab at the University of Alberta. A total of twenty volunteer university students (45% female; 95% right-handed. Age range: 18–39 years old, median age = 26 years) participated in the experiment in the first phase. Among them, five participants entered the second phase to complete the nine training sessions over a period of three weeks. The University of Alberta Health Ethics Review Board approved the study's protocol. Information and objectives were explained to the participants prior to obtaining their consent.

2.2. Apparatus

A master-slave delivery system was used to transfer movement between two persons (Fig. 1). In this study, the participants' vision was blocked, and could only feel the movement from the slave-end by placing their hand in the style. The trainer for all of the trials was one of the researchers (DP) and was the only person who performed the movement at the master-end. By following the shallow groove engraved on the wooden plate, the experimenter ensured that the same movement pattern was delivered consistently over the trials. In this study, five movement patterns were chosen randomly with increasing movement complexity (Fig. 2). Each pattern was comprised of movements with three lengths (short: 5 cm, medium: 10 cm, and long: 15 cm) and different movement directions (N, S, E, W, NE, NW, SE, SW). Participants had a chance to inspect the experiment apparatus and were informed with basic

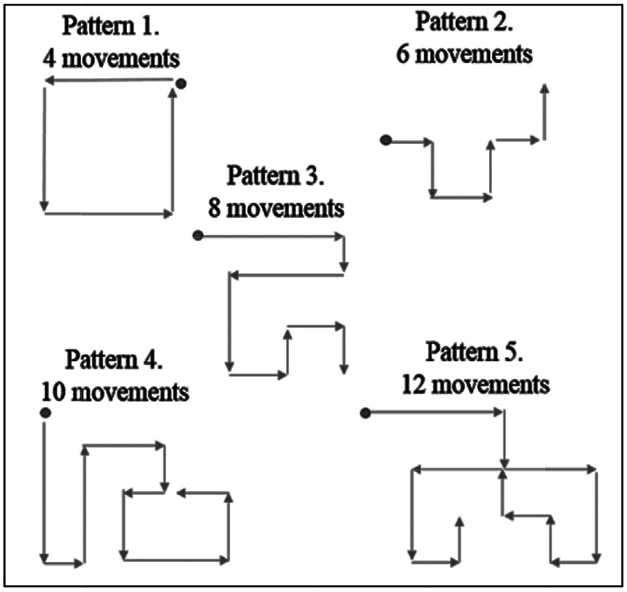

Fig. 2. The five movement patterns used for this experiment. The arrows show the direction of the movement (lines), while the red dot indicates the starting point of the pattern.

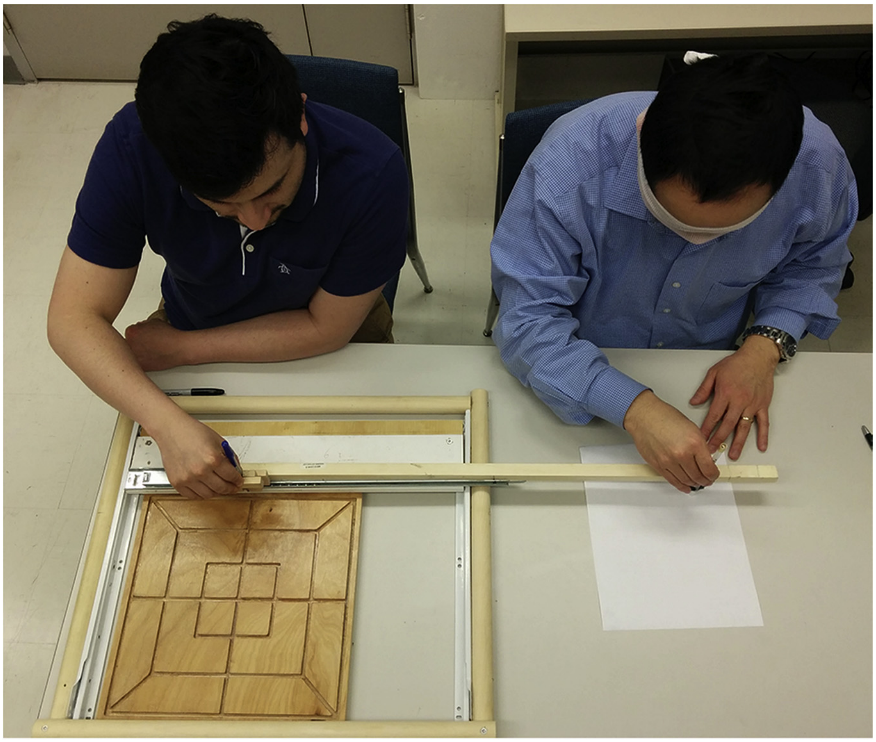

Fig. 1. Kinesthetic guidance device allows feedback translate between the master and trainee. Note that trainee's vision is blocked. The participants experienced the movement of the trainer by grasping the guide.

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features of the board before entering the study.

2.3. Task and procedure

On the first day of the study, each participant perceived the movement of the five pre-determined patterns via kinesthetic feedback. The order in which the patterns were presented was counterbalanced among subjects. At the end of each movement, the participants duplicated the movement on a piece of plain paper with a pen. The accuracy of the participant's kinesthetic memory was assessed by comparing the outcome recorded on the paper (illustration) to the trainer's patterns. In this way, each movement of the pattern is represented on the paper in the form of a line.

Five participants, selected at random, were called back to repeat the performance for a total of nine trials. All nine practice trials were arranged over a period of three weeks, three times per week. During the entire phase of the experiment, participant did not receive any visual feedback or auditory instruction on their performance.

2.4. Measures

Time of task completion is a typical performance measure. Since we recorded the time that every participant took to reproduce every pattern, we could analyze the time relationship with the number of lines in each pattern. Performance measurement can be complemented by analyzing the number of performance errors for each participant in each movement pattern.

Movement duplication accuracy was assessed by recording the number of errors in direction and length recall for each of the lines in the illustrations. Each movement pattern could be comprised of movement in eight directions (N, S, E, W, NE, NW, SE, SW) and three different line lengths (short: 5 cm, medium: 10 cm, and long: 15 cm). Errors could occur when attempting to duplicate the movement's direction and length.

Since the patterns were hand-crafted, they were scanned, digitized, and then analyzed in MATLAB (Mathworks, Palo Alto, CA.). To determine the accuracy in duplicating movement direction, the angle of each line stroke was compared to the master pattern. If the angle fell within a 30° range to the master direction, a correct match was recorded.

It was challenging for us to attempt to measure the length accuracy of the lines drawn. Although participants had knowledge that each line could only be one of three measurements (short: 5 cm, medium: 10 cm, and long: 15 cm), when duplicating the pattern on a piece of paper, they did not make an effort to draw the lines with any extra length. However, we noticed that the participants all tried to make the lines as close to the three different lengths as possible. To detect the accuracy in length duplication, we created a special algorithm by using the longest line recorded on the each pattern as the trial-specific ruler. Specifically, the length of the longest line in each duplicated pattern was detected and measured. The short line should be proportionally equal to one third of the longest line while the middle line should be equal to two thirds. If the line drawn fell within ±25% range of the calculated line length, an accurate match was recorded; otherwise, a mismatch error in the line length was recorded. As an example, in duplicating a movement in Pattern 3 (which includes one long line of 15 cm, five short lines of 5 cm, and two middle lines of 10 cm), a subject made a longest line of 12 cm. When the subject made a short line that fell within ±25% range of 4 cm (i.e., 3–5 cm) we recorded an accurate match; outside this range, an error was recorded.

For each trial, the overall error of duplicating the movement from the master pattern was calculated by adding the movement errors in direction and length.

2.5. Data analysis

Task times and accuracy variables in duplicating the movement through kinesthetic feedback were compared over 5 different movement patterns using a one-way between-subject ANOVA (SPSS 22.0, Chicago, IL). A 5 (movement pattern) x 9 (training session) between-subject ANOVA was employed to examine the learning process of training purely from kinesthetic feedback. Mean and Standard Deviation (SD) are presented. $p < 0.05$ was considered statistically significant in this study. Post-hoc analysis was also completed (*Bonferroni*) when needed.

3. Results

3.1. Phase 1: accuracy on task performance

Descriptive statistics: When asked to duplicate a pattern with four movements, the twenty subjects did not make any mistakes. All the participants (100%) accurately recalled the movement pattern from their kinesthetic memory. However, recall accuracy decreased as the movement complexity increased (pattern 2 with 6 movements: 90%; pattern 3 with 8 movements: 70%; pattern 4 with 10 movements: 80%; pattern 5 with 12 movements: 60%).

As the complexity of the movement patterns incremented, the duplication errors increased significantly ($p_{\text{direction}} = 0.038$; $p_{\text{line length}} < 0.001$; $p_{\text{sum errors}} < 0.001$). As displayed in Fig. 3, errors constantly increased until duplicating pattern 3 with eight movements, then showed a reduction in pattern 4, followed by an increase in pattern 5 with twelve movements.

3.2. Phase 2: skill acquisition from kinesthetic feedback

A 5 × 9 between subjects ANOVA was conducted to determine whether or not the sum of errors in both direction and length decreased over the collective of the nine sessions. Results showed that as guided kinesthetic training continues, the sum of errors decreased ($p < 0.0001$). The error drop varied to different degrees among the five movement patterns ($p < 0.0001$) compared over the nine sessions. As shown in Fig. 4, training Pattern 5 with the highest level of complexity, errors decreased from 74% to 7% from the first to the last sessions. In contrast, training Pattern 1, errors dropped from 35% to 0%.

We also found that the learning curves for each pattern display

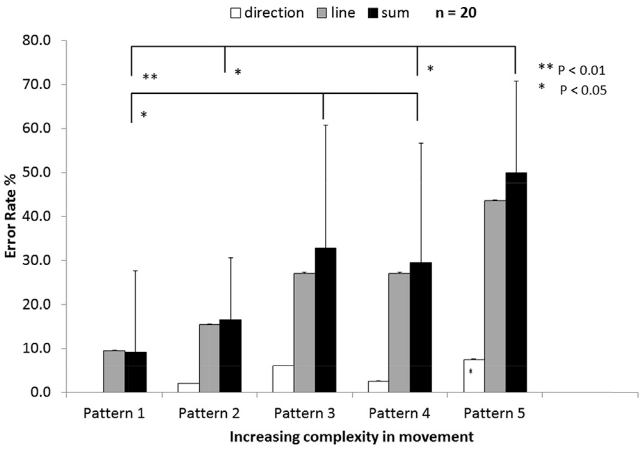

Fig. 3. Duplication accuracy for the first training session.

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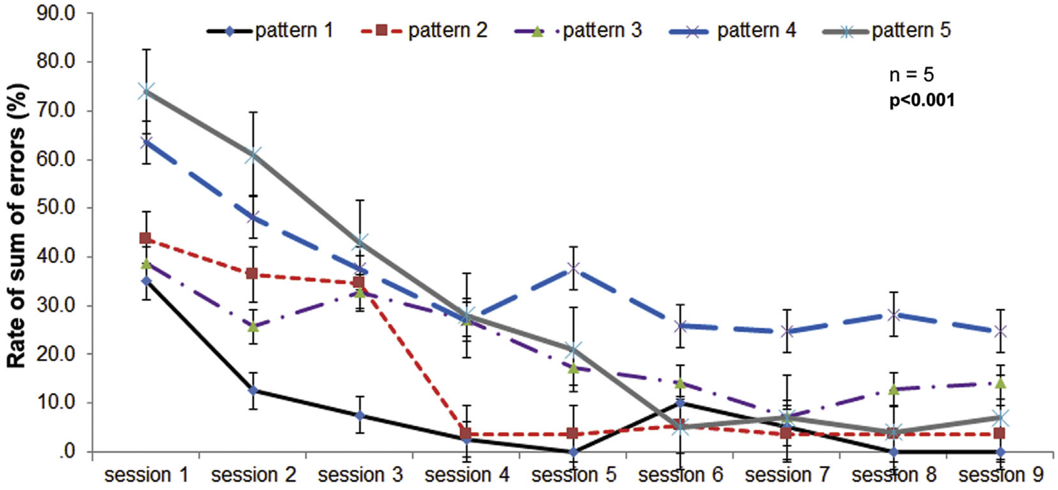

Fig. 4. Rate of sum of errors for each pattern over the nine training sessions.

different turning points which became significant in the later sessions of kinesthetic training for complex patterns. Specifically, when completing training Pattern 1, subjects achieved a significant error reduction in Session 2; but when training Pattern 3, the significant error reduction occurred in Session 4. For all patterns, the error reduction reached its lowest level in Session 6.

4. Discussion

The purpose of this study was to determine the effect of guided kinesthetic training on muscle memory and the building of foundations for skill acquisition. As surgeons are a group of performers that truly depend on kinesthetic feedback, knowledge gained from this project will provide direct benefits to surgical skills training in situations where visual feedback is not reliable or hand gestures are difficult to communicate. An example is teaching knot tying for a structure deep within in the abdominal cavity. Separating knot tying into smaller segments, where kinesthetic feedback on each step can guide the trainee has proven to be more effective for teaching novices these skills than the typical self-directed learning.[9]

Essentially, our research hypothesis was supported by our results. Results showed that a subject can receive significant information exclusively via kinesthetic feedback and improve the performance of a task. As shown in Fig. 3, muscle memory (represented by the movement direction and length) reached a saturation point around 8 movements. After the 8 movements, accuracy for duplicating the movements learned from the kinesthetic feedback loop drops significantly. We were surprised to see that Pattern 4, comprised of 10 movements, did not follow the expected learning style of the other patterns. In Pattern 4, the error rate dropped slightly. After checking the movement patterns, we noticed that the last 5 movements of Pattern 4 formed a square. This square in Pattern 4 made it easy to memorize the movements in groups (*chunks*) into a sub-unit. By using this chunking strategy, performers may feel it is easier to replicate more complex patterns, like Pattern 4, with less mental effort than patterns with less movements such as Pattern 3. These findings on the nature of muscle memory can be translated for teaching difficult motor skill tasks, such as those found in surgical training. Adding kinesthetic guidance to a surgical training task as groups of chunks can expedite muscle memory and skill acquisition.

Findings gained from the first-day performance data are congruent with those found in previous studies regarding short term memory for kinesthetic enactment.[10] When abundant kinesthetic information is received in a short time, kinesthetic memory behaves in a similar manner to the declarative working memory.[11] The chunking behavior observed in Pattern 4 is consistent with what is observed in working memory. In other words, human subjects tend to combine individual information into a sub-unit, each content up to 8 bits (movements) of information. An illustration of this is when learning long numbers, such as phone numbers. Human performers have no difficulty in learning the first seven digits of the number, but when longer numbers such as the area code are added, the memory accuracy will drop significantly. To deal with this phenomenon, a merging strategy of grouping numbers into sets of 3 guarantees increased success in recalling the numbers afterwards. Furthermore, the high accuracy in the length recall score suggests a strong ability to remember the first movements performed (primacy effect), but difficulty remembering the most recent movement performed, akin to the findings of Allen et al. on enactment and working memory.[11]

This is the first time that we have examined kinesthetic skill learning purely from the kinesthetic feedback loop. Our investigation on kinesthetic skills learning yielded encouraging results (Fig. 4). Human performers can reduce errors in duplicating movements, indicating that kinesthetic memory can be optimized through kinesthetic training alone. This adaptation process builds the foundation of skill learning. Kinesthetic guidance has been widely employed in motor training for several years in other arenas such as stroke rehabilitation and tennis coaching.[7] Guidance has the benefit of offering restriction of movement error that may be used during early acquisition of skills. If applied during kinesthetic skill acquisition stages, kinesthetic guidance has been associated with decreased performance errors and thus greater learning.[1] Although numerous studies have looked into the effect of kinesthetic guidance in kinesthetic training, none have explored the behavior on kinesthetic memory.[7,12] In psychological theory, there are three types of memory storage: sensory memory, working memory, and long-term memory.[10,11] While sensory memory is instantaneous and working memory only stores a limited number of items for up to a minute—long-term memory preserves an extensive amount of information that can last a lifetime.[10,11]

The progress that computing technology has made to recreate kinesthetic feedback via robotic haptic interfaces has intensified research into the kinesthetic learning effect by recording and playing back motion. Examples of these robotic interfaces are robotic surgical systems and military drones.[4,13] A haptic interface

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employs sensors that transmit an electrical signal to a computer where the signal is translated to perform an action. These interfaces are capable of replicating force and tactile feedback, offering ample sensory information, making kinesthetic training with haptic interfaces a useful method for skill training.[4] By employing kinesthetic training via these robotic interfaces in surgery it is possible to record an expert surgeon's movement and play them back. Moreover, surgical programs could project training expectations based on pattern complexity and training schedule, as well as create maneuver evaluations for surgical trainees.

There are several limitations to our study. For one, it is limited only to a 2D scenario and we are not able to determine the effect of the depth component in kinesthetic memory. We surmise it would be more difficult to recall lengths rather than direction as seen in the work of Lee et al.[10] Another limitation is the small number of subject for the retention part of the experiment. The small number of subjects could have restricted a richer understanding of length characteristics of the kinesthetic memory. Future work in this field should employ more complex surgical tasks to assess the generalizability of kinesthetic guidance. Also, it is necessary to determine the effect of kinesthetic guidance on surgical trainee's depending upon their experience during the various years of training to develop a learning curve.

5. Conclusions

We discovered that kinesthetic information obtained from passive kinesthetic guidance can be stored in the kinesthetic memory span. Our results suggest a chunking effect in the kinesthetic memory for both direction and length recall that can be used for movement duplication. Finally, after repeated kinesthetic training, human performers can optimize their kinesthetic memory. This can provide the basis of learning kinesthetic skills, like those used in surgery, through a kinesthetic feedback loop.

Disclosure

This research had no financial support nor has any commercial interest in any product or concept discussed in this article.

Author contributions

DP and BZ contributed to concept and design. Data collection, analysis by DP and PS. Interpretation was carried by DP and BZ. Manuscript preparation and critical comments on manuscript were given by DP, RV, and BZ.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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Ethical approval

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed consent

Informed consent was obtained from all individual participants included in the study.

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