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Innovative Dynamic Minimally Invasive Training Environment (DynaMITE)

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Existing laparoscopic box trainers consist only of static tasks and do not adequately prepare surgeons to navigate the dynamic surgical environment. This paper describes an innovative design using controlled motorized target movements to enhance the training of dynamic motor skills. The prototype was tested using 15 subjects with different surgical experience levels. The task required accurate contact, using a laparoscopic tool, with targets moving in 5 different movement trajectories: (1) static, (2) horizontal, (3) vertical, (4) slow hourglass-shaped, and (5) fast hourglass-shaped. Expert surgeons were significantly faster than novices in the static, horizontal, and slow hourglass target conditions. Intermediate experienced subjects (PGY2s) were faster than novices in the horizontal target condition only. In the fast hourglass condition, experts were not faster than less experienced and novice subjects, but they were more accurate. There is the potential to train hand-eye coordination of even expert surgeons using this dynamic environment.

Keywords: dynamic tracking; laparoscopic skills trainer

Laparoscopic surgery is characterized by small incisions in the body through which a camera is inserted and surgical tools are manipulated. Laparoscopic surgery results in less trauma, reduced scarring, and shorter hospitalization time, making it a preferred procedure over open abdominal surgery.[1] However, laparoscopic surgery is susceptible to a great deal of error owing to sensory challenges that are not present under the conditions of conventional open surgery. A recent comparison of laparoscopic versus open hernia repair reported that 22 out of 469 (4.7%) laparoscopically treated patients were readmitted after surgery, compared with 10 out of 415 (2.4%) patients treated with open surgery.[2] Injury to the bile ducts during cholecystectomy occurs at a rate of 0.41%-1.1%,[3] compared with 0%-0.4% in open surgery,[4] which is 3 times higher than in open surgery.[5-7] Therefore, a conservative estimate of 500 000 annual laparoscopic surgeries means that there are 2000 bile duct injuries per year.[8] Other research suggests that injury rates have not improved with time or experience.[3] A recent study[9] suggests that the misidentification of biliary anatomy stems principally from misperception, not errors of skill, knowledge, or judgment.

One of the most prominent problems encountered when performing laparoscopy is the lack of depth perception in the laparoscopic environment.[10] During surgery, the bright light used to illuminate the body cavity creates a workspace with few shadows. This bright light, combined with the translation of the 3D work environment to a 2D image, creates a visual scene from which depth cues cannot be easily perceived.[11] The consequences of not being able to accurately judge an object's proximity from the camera include performance inefficiency and potential damage of surrounding tissue from misjudgment of distance.

A recent revolution in laparoscopic surgical training has demonstrated that surgical simulators can be used to improve the skill of laparoscopic surgeons prior to operating on a person.[12] However,

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existing physical simulators contain only static, or stationary, target objects. Although some of the tasks in these simulators require trainees to manipulate or pick up a needle or suture from different locations within the surgical environment (depending on where the needle or suture was dropped or placed), the target object is rarely in *active dynamic* motion during the acquisition phase. This may be a limitation of current simulators in that they do not provide an adequately challenging environment for the acquisition of advanced hand-eye coordination skills in laparoscopic surgery, such as manipulating *dynamically moving* tissues. Surgeons go to great lengths to immobilize target tissues during surgery because of the extreme difficulty of performing fine manual tasks on a moving target, and because of the lack of training in such maneuvers. The resulting disadvantages that the surgeon faces, and the consequences a patient can suffer as a result of inadequate training, suggest a need for a training environment that can provide exposure and experience with a wide range of task difficulty, including tracking dynamically moving targets. Since the surgeon is sometimes required to operate with rhythmic body motion in the patient (eg, beating heart or respiratory motion), a training program that develops advanced instrument positioning skills is highly desirable.

Past attempts at training surgeons to accurately gauge depth have called for the relocation and manipulation of objects at various distances in a static environment, as well as the cutting and suturing of static, or nonmoving, objects.[13] In these simulators, the trainee provides all of the motion; the target objects remain stationary even while they are being manipulated and moved around in the surgical environment. This method of training results in skills that are only moderately representative of those required in the dynamic environment of the human body. We propose a novel and innovative approach, using a mechanically controlled dynamic targeting system, to supplement the laparoscopic training environments with objects that can actively move in any selected direction relative to the camera. The training enhancement is expected to improve a surgeon's ability to efficiently control his or her tool motion, differentiate between an object in the foreground and background of the video image, and target specific objects while leaving the surrounding environment unharmed. In this paper, we present results from a study with a prototype system.

It was hypothesized that hand-eye coordination skills would be harder to execute in dynamic environments than in static environments, and that the faster and more unpredictable the movement of the target was, the more difficult it would be to track the target. It was further hypothesized that there would be an interaction between surgical experience and dynamic task difficulty such that the difference in performance degradation with difficulty would be smaller for experts than for novices.

To test these hypotheses, a prototype of a surgical training apparatus with dynamic targets was designed and fabricated. An experiment was then carried out in which subjects with differing amounts of laparoscopic experience were asked to perform a simple aim-and-point task in the new dynamic environment.

Methods

Subjects

Fifteen subjects (5 naïve subjects, 5 PGY2 surgical residents, and 5 surgical attendings) participated in the study. Subjects included both right-handed and ambidextrous people, ranging in age from 20 to 62. Six males and 9 females were tested.

Apparatus Design

A dynamic minimally invasive surgical training environment (DynaMITE) consisted of a 9" x 9" x 2" base, fitted with a target array (Figure 1), that had controlled motion in 2 directions. The dimensions of the base were chosen to fit the DynaMITE device within existing standard-sized laparoscopic simulators, such as the ProMIS (Haptica, Inc) or any other physical trainer box. The target array's overall dimensions were 2.75" x 2.75" x 1.375", with 5 vertical metal pegs, each surrounded by a light fixture. The movement of the target array in orthogonal directions, and its speed, were controlled by motors.

A control interface was developed to allow the motion of the target and the illumination of the lights to be controlled through a computer interface. This interface was used to control the following features of the apparatus: shape of target trajectory, speed of target motion, time limit for task completion, and order in which pegs should be touched.

Incorporated into the computer system was an automatic scoring mechanism, which detected

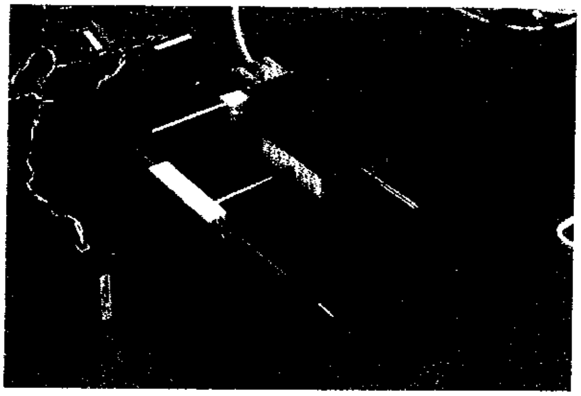

Figure 1. DynaMITE box, composed of a delrin base and dynamic target.

successful contact with illuminated pegs, undesired contact with nonilluminated pegs, time taken to successfully touch each peg, the frequency with which a subject exceeded the time limit before making contact with the target peg, and target location at time of contact with a peg.

Task and Experimental Design

Subjects were presented with a target array in 5 different movement and trajectory conditions: (1) static, (2) horizontal, (3) vertical, (4) slow hourglass-shaped, and (5) fast hourglass-shaped. They were required to use a laparoscopic tool to touch the top of one of the 5 metal pegs, according to which indicator light was turned on. When successful contact was made with the illuminated peg, a different peg was illuminated. This pattern continued until successful contacts were made with all 5 pegs, or until a specified allowable task time had elapsed. The order of the pegs to be touched was randomized. Subjects were presented with 1 trial of all 5 target conditions in order, beginning with static and ending with the fast hourglass condition. This series was repeated 3 times, for a total of 3 trials per subject in each target condition.

Dependent Measures

The dependent variables in the experiment were number of successful hits, number of misses (defined as inability to make contact with a peg in the specified time limit), number of errors (defined as contact with a nonilluminated peg), time to task completion, and spatial location of target at time of hit. Since the experiment was conducted with the DynaMITE apparatus fitted inside a ProMIS simulator, the additional dependent variables of tool path length and tool path smoothness were included in the data collection. Path length values represent the total length of the tool trajectory, measured in millimeters. Smoothness values indicate the degree of jerk in movements, where smaller values represent smoother tool motion.

Data Analysis

Data were analyzed using analysis of variance (ANOVA) and post-hoc Tukey tests.

Results

Static Task

In the static condition, there was a statistically significant difference in time to task completion ($P <$ .001), number of misses ($P = .04$), path length ($P =$ .04), and path smoothness among the different subject groups ($P = .016$) (Table 1). A post-hoc Tukey test showed that the experts were significantly faster than the novices, but not faster than the PGY2s. Experts also had significantly better smoothness results than both PGY2 and novice groups.

Horizontal Task

There was a statistically significant difference in time to task completion ($P < .001$), path length ($P = .002$), and path smoothness ($P < .001$) among the 3 subject groups (Table 2). A post-hoc Tukey test showed that PGY2s were better than novices in time, path length, and smoothness, but not in number of misses; experts were better than novices in the smoothness, path length, and time measures.

Vertical Task

There was a statistically significant difference in time to task completion ($P < .001$), number of misses ($P = .04$), and tool smoothness ($P = .005$) among the 3 subject groups (Table 3). A post-hoc Tukey test

Table 1. Summary of Results for Static Target Condition

	Task Completion Time (sec ± SD)	Total Misses	Total Errors	Path Length (mm ± SD)	Smoothness (s^3/m ± SD)
Novice	5.71 ± 3.55[*]	3	4	3668.67 ± 1580	253.9 ± 113.7[*]
PGY2	3.90 ± 2.2	0	4	2583.33 ± 1013	189.6 ± 53.8[†]
Expert	2.83 ± 1.98[*]	0	0	2712 ± 1146	176.6 ± 54.5[*†]
P value	.001	.04	NS	.04	.016

SD, standard deviation; NS, not significant.

[*†] Indicate significantly different means between groups as determined by a post-hoc Tukey test. *P* values indicate significance levels determined by an ANOVA test.

Table 2. Summary of Results for Horizontal Target Trajectory Condition

	Task Completion Time (sec ± SD)	Total Misses	Total Errors	Path Length (mm ± SD)	Smoothness (s^3/m ± SD)
Novice	5.56 ± 3.37[†]	4	8	3466.67 ± 925.7[*]	246.13 ± 71.9[†]
PGY2	3.40 ± 1.81[*]	0	10	2227.33 ± 994.8[*†]	146.9 ± 44.1[*]
Expert	2.54 ± 1.81[*†]	0	3	2477.33 ± 1004[†]	135.65 ± 29.2[*†]
P value	.001	NS	NS	.002	.001

SD, standard deviation; NS, not significant.

[*†] Indicate significantly different means between groups as determined by a post-hoc Tukey test. *P* values indicate significance levels determined by an ANOVA test.

Table 3. Summary of Data for Vertical Target Trajectory Condition

	Task Completion Time (sec ± SD)	Total Misses	Total Errors	Path Length (mm ± SD)	Smoothness (s^3/m ± SD)
Novice	4.84 ± 3.13	1	4	3464.67 ± 1676	219.4 ± 71.18[*]
PGY2	3.29 ± 2.56	0	5	2537.33 ± 1693	150.7 ± 64.92[†]
Expert	2.90 ± 2.1	0	12	2554.67 ± 1676	150.9 ± 46.87[*†]
P value	.001	.04	NS	NS	.005

SD, standard deviation; NS, not significant.

[*†] Indicate significantly different means between groups as determined by a post-hoc Tukey test. *P* values indicate significance levels determined by an ANOVA test.

showed that experts and PGY2s were better than novices in tool smoothness only.

Slow Hourglass Task

There was a statistically significant difference in time to task completion ($P < .001$), number of misses ($P = .005$), path length ($P = .03$), and tool smoothness ($P < .001$) among the 3 subject groups (Table 4). A post-hoc Tukey test showed that experts were faster and smoother in movement, with significantly fewer misses than novices, whereas PGY2s used a shorter path length and were smoother in movement with significantly fewer misses than novices.

Fast Hourglass Task

There was a statistically significant difference in time to task completion ($P = .001$) and number of misses ($P = .006$) among the 3 subject groups (Table 5). Post-hoc Tukey tests showed that experts had significantly fewer misses than novices.

Experience

Two factor ANOVA tests did not reveal any significant interactions between experience and path type. However, 1-way ANOVA tests, examining the effect of path shape on performance within each experience

Table 4. Summary of Data for Slow Hourglass Target Trajectory Condition

	Task Completion Time (sec ± SD)	Total Misses	Total Errors	Path Length (mm ± SD)	Smoothness (s^3/m ± SD)
Novice	5.52 ± 3.97*	6*	8	3657.78 ± 1470*	226.47 ± 66.5*
PGY2	3.45 ± 2.5	0†	9	2404 ± 1004*	155.3 ± 45.55†
Expert	2.69 ± 1.81*	0*†	2	2808 ± 1444	137.29 ± 46.8*†
P value	.001	.005	NS	.03	.001

SD, standard deviation; NS, not significant.

*†Indicate significantly different means between groups as determined by a post-hoc Tukey test. *P* values indicate significance levels determined by an ANOVA test.

Table 5. Summary of Data for Fast Hourglass Target Trajectory Condition

	Task Completion Time (sec ± SD)	Total Misses	Total Errors	Path Length (mm ± SD)	Smoothness (s^3/m ± SD)
Novice	6.45 ± 4.29	10*	4	4244.73 ± 2137.9	248.1 ± 95
PGY2	4.93 ± 4.13	4	14	3514.67 ± 1537	218.9 ± 71.5
Expert	4.26 ± 2.5	0*	6	3473.33 ± 980	193.3 ± 52.1
P value	.001	.006	NS	NS	NS

SD, standard deviation; NS, not significant.

*Indicates significantly different means between groups as determined by a post-hoc Tukey test. *P* values indicate significance levels determined by an ANOVA test.

group, showed that path shape had a significant main effect on time and smoothness values for PGY2s and experts, but not for novices.

A post-hoc Tukey test revealed a significant difference in time values between the slow and fast hourglass cases for the expert group. There was also a significant difference in smoothness values between the fast hourglass condition and all other path shapes, including the static condition. However, the horizontal, vertical, and slow hourglass were not different from one another in the smoothness measure. For PGY2s, there was a significant difference in smoothness values when the horizontal, vertical, and slow hourglass conditions were compared with the fast hourglass conditions.

Discussion

It was originally hypothesized that hand-eye coordination skills would be harder to control in a dynamic environment than a static one. Our results partially support this hypothesis. Experts had significantly better smoothness values in the static task than in any of the moving conditions. However, post-hoc Tukey tests revealed no significant performance differences in time to completion when static targets were compared with slowly moving targets. Since the static task was always performed first, the users may have gained familiarity with the testing environment during the static test that proved useful to improving scores on the later dynamic tests. It is also possible that the slow speed chosen for this experiment was in fact too slow, and too similar to a static test.

Also hypothesized was that a faster and more complex path would prove to be harder. This hypothesis is only partially supported by the data, as the novice group did not show this effect. This observation may be explained by the fact that the novices had no experience at all and therefore found all surgical tasks equally challenging. Experts, on the other hand, were well practiced in the static and slower tasks. They showed performance deterioration only with the fast and unpredictable target movements.

The third hypothesis stated that the range of data would decrease as the subjects were more experienced. In fact, the novices performed equally slowly for all of the conditions (Figure 2) but made progressively more misses in the vertical, slow hourglass, and fast hourglass conditions, with the highest number of misses in the fast hourglass condition. This finding suggests a speed-accuracy tradeoff,

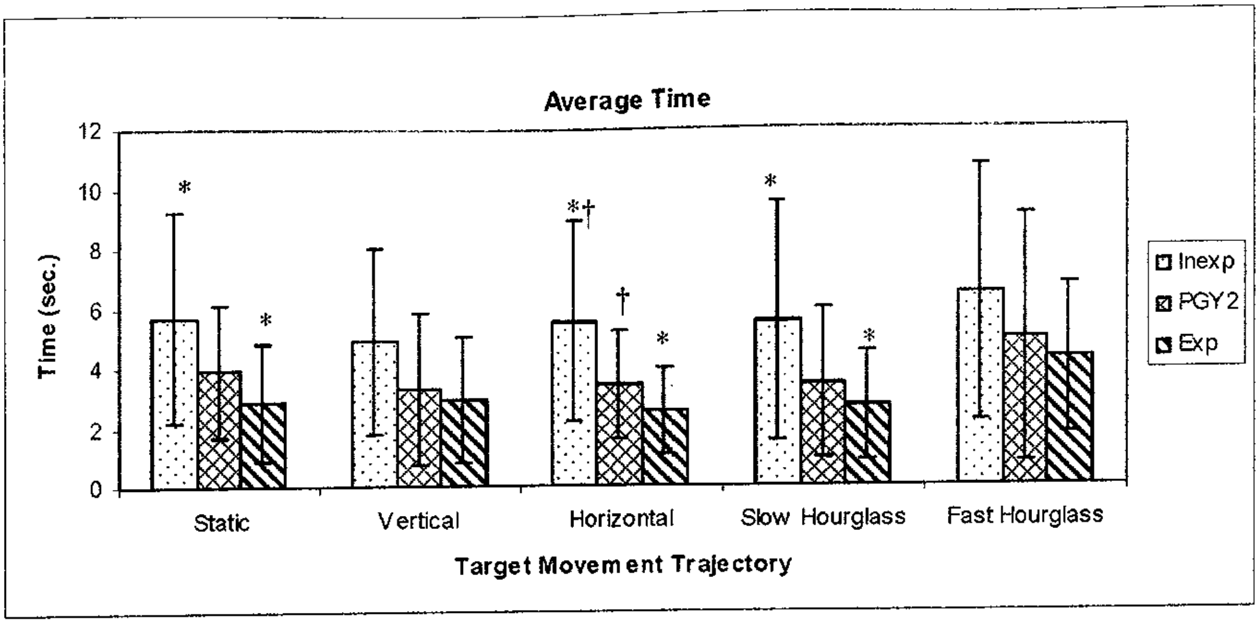

Figure 2. Average time to task completion across experience levels.
*†Indicate significantly different means between two groups as determined by a post-hoc Tukey test.

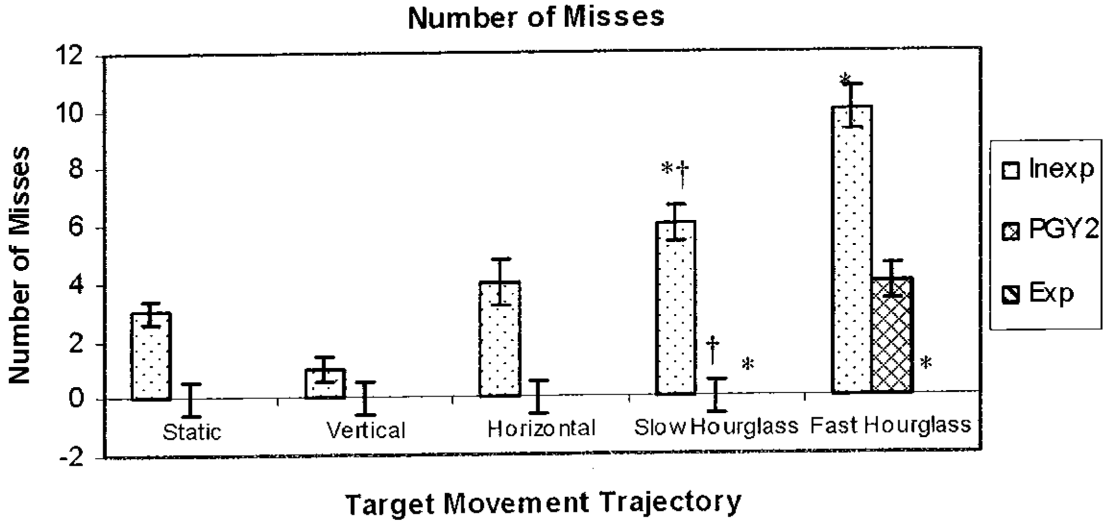

Figure 3. Total misses across experience levels.
*†Indicate significantly different means between two groups as determined by a post-hoc Tukey test.

sacrificing accuracy for speed. The experienced surgeons, on the other hand, were slower in the fast hourglass condition, but made no misses, sacrificing speed for accuracy (Figure 3). This result can be attributed partly to the surgeons' previous experience in surgery and on previous models of static training simulators, which gave them additional familiarity with the task unavailable to the novices.

Although the error data do not show clear trends according to subject experience or dynamic task conditions, the number of errors made was lower in the static condition than in any of the dynamic conditions

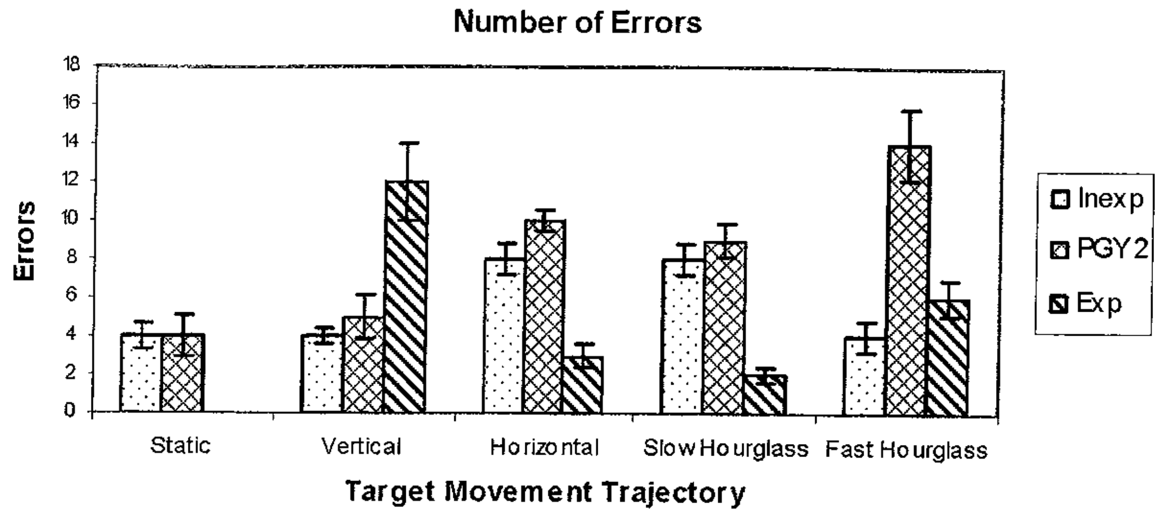

Figure 4. Total errors across experience levels.

for both experts and PGY2s (Figure 4). Notable for the expert group is the large number of errors in the vertical movement condition, compared with other conditions, and compared with the other 2 groups of subjects. One possible explanation for this anomaly is that this group may have had difficulty making precise contact with the pegs in a condition where they were relying purely on their depth perception for guidance, without any visual cues in the horizontal direction. This explanation indicates that even experienced surgeons find it difficult to maneuver laparoscopic tools to specific locations in a dynamic environment, without making errors. This lack of precision could lead to unintended contact between the surgical tools and delicate surrounding tissues, potentially resulting in injuries. Given the short movement time (Figure 2), it is also possible that this represented a speed-accuracy trade-off in the surgeons' performance.

In general, the dynaMITE seems to be able to challenge even expert surgeons, suggesting that there is potential for it to supplement the current training repertoire of motor skills. Practice in dynamic environments can help to improve efficiency of tool motion in environments that are unpredictable and difficult to navigate. In addition, practice in making contact with specific targets inside a dynamic environment can only help to develop precise tool motion, leading to reduced errors and decreased damage of surrounding tissue.

There were several limitations in this study. According to feedback from the subjects, it was difficult to determine whether or not the surgical tool engaged in successful contact with the pegs in the target array. The high number of errors may have been caused by this ambiguity and the lack of feedback from the system.

Also, the testing conditions were always in the same order, starting with the static condition. By repeating the same paths 3 times, the subjects may have been able to anticipate the motion of the target. There was likely a learning effect in the data.

A final limitation, revealed by the preliminary data, is that the device failed to statistically discriminate between expert and intermediate subjects in many task conditions. It should be noted, however, that this study tested subjects on only a portion of the task options available with the DynaMITE apparatus. Future work will use more of the device functionalities to identify the conditions under which expert subjects are able to surpass intermediate subjects in performance. It is possible that different combinations of speed and target path will reveal additional information about the capabilities of these 2 subject groups, allowing more effective testing conditions to be chosen.

Additional future work will include randomizing the test order to prevent any learning effect and anticipation of the targets' motion. A randomized path will be introduced, so that the subject cannot anticipate the target's position and simply wait for it to reach a convenient location. The speeds will be increased to allow for a greater differential between the slow test and the static test without changing the difference between the fast test and slow test. In addition, the targets will be refined to allow the subjects adequate feedback about successful contact with the pegs.

The ultimate goal of this device is to aid in the training of efficient and controlled tool motion, differentiation between objects in the foreground and background of an image, and targeting of specific objects. We expect that practice on the DynaMITE device will help surgeons to improve these skills by learning to minimize task completion time, minimize or eliminate contact errors, and master tasks in which targets occasionally shift positions in the task space during surgical manipulation. Further studies will be conducted to validate this expectation.

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