Effect of Short-Term Pretrial Practice on Surgical Proficiency in Simulated Environments: A Randomized Trial of the "Preoperative Warm-Up" Effect

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BACKGROUND: Surgery is a skill-driven discipline. While other high-stake professions with comparable cognitive and psychomotor skill requirements often use warm-up exercises for achieving better proficiency, the effects of such practice have not been investigated sufficiently in surgical tasks.

DESIGN: Subjects performed standardized exercises as a preoperative warm-up, after which the standardized exercises were repeated in a randomized order. In a variation to investigate the generalizability of preoperative warm-up, the experimental group was allowed to warm-up with the standardized exercises, after which a different task (electrocautery simulation) was performed. To investigate the effect of warm-up on fatigue, participants were involved in eight sessions (four before night call, four after night call), after which the tasks were repeated. Results were analyzed using ANOVA to plot differences between warm-up and followup condition.

RESULTS: All outcomes measures demonstrated statistically significant improvements after all of the post−warm-up exercises ($p < 0.01$), and were seen in all groups with differing experience levels. In addition, the simple warm-up exercises led to a significant increase in proficiency in followup electrocautery task for the experimental group when compared with the control group ($p < 0.0001$). There was also significant improvement in performance of the fatigued group to approximately baseline performance ($p < 0.05$), although they were not able to reach their optimal potential performance.

CONCLUSIONS: Preoperative warm-up for 15 to 20 minutes with simple surgical exercises leads to a substantial increase in surgical skills proficiency during followup tasks. (J Am Coll Surg 2009;208: 255–268. © 2009 by the American College of Surgeons)

The *Oxford English Dictionary* defines the term *warm-up* as "The act or process of 'warming up' for a contest, and so forth, by light exercise or practice."[1] More generically, warm-up is "The act or process of raising the temperature of an engine, electrical appliance, and so forth, to a level high enough for efficient working,"[1] which captures the concept of activating and preparing to a high level of efficiency before beginning an activity. In sports and sports-training literature, there are several published articles and books highlighting the importance of warm-up in improving performance and avoiding errors. The stretching handbook published by the Stretching Institute[2] says: "*Warming up before any physical activity does a number of beneficial things, but primarily its main purpose is to prepare the body and mind for more strenuous activity* . . ." it's important to start with the easiest and most gentle activity first, building on each part with more energetic activities, until the body is at a physical and mental peak. This is the state in which the body is most prepared for the physical activity to come.

Although the positive effect of warm-up on strenuous physical activity is wellknown, research has also shown positive effects of warm-up on cognitive skills[3] in physical sports. Research has also shown that subjects tend to perform better at cognitive exercises in followup tasks. The overall effect is seen as a *cognitive arousal* phenomenon that enables subjects to more fully concentrate their resources on the task at hand. As such, cognitive arousal has been shown to cause increased somatic and cortical activity[4] and can even aid in resisting sleep. The effect of short-term practice is not limited to sports or physical activity only. High-stake, high-performance professions with substantial

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psychomotor skills proficiency, such as dancers, musicians, sculptors, and painters, have, for centuries, used short-term practice or warm-up as a method of getting ready for the task at hand. A common thread among all activities that promote use of warm-up includes strenuous physical activity; strenuous mental activity with requirements of cognitive arousal; and ability to perform both within required coordination and task performance constraints.

Although warm-up has a documented positive effect on activities that involve these requirements, it is also known to be necessary to avoid deleterious consequences, such as injury to self and others in the environment and to trigger cognitive arousal that can substantially enhance performance ability.

Modern-day surgery certainly qualifies as a high-stakes, expertise-driven field.[5] The advent of minimally invasive surgery, although revolutionary for patients and the operating room, poses specific challenges for surgeons and residents. It requires surgeons to perform procedures with hard-to-manipulate tools that impose undesirable constraints on the movements of a surgeon. Although the advent of robotic surgery and more intuitive manipulators address some of these issues, modern-day surgery, and laparoscopic surgery in particular, still requires considerable cognitive and psychomotor proficiency. There is substantial research that has shown that surgery requires both strenuous mental and cognitive activity.[6] This raises an important question: if performing an operation involves strenuous physical and mental activity, then would a "preoperative warm-up" (or simply "warm-up" for the purposes of this article) activity that involves surgeons performing surgical exercises before the main task improve surgical performance in the main task at hand?

Some earlier work has been reported to address a few of these issues. Do and colleagues[7] used a laparoscopic "box trainer" simulator to study the effect of warm-up exercises on followup tasks. Participants performed a task involving grasping pill-like plastic elements from a petri dish and placing them into a bud vase. Time elapsed to complete the task and the number of pills successfully transferred to the bud vase were used as measures of performance. Overall laparoscopic performance was significantly improved for both residents (all years combined) and the medical student control group ($p < 0.0001$). Although the study showed encouraging results of warm-up being used before performing the main exercise, the study had certain limitations because, to a certain extent, it failed to distinguish between learning effect and warm-up effect. The increase in proficiency might have occurred because subjects were learning and adapting to the task. To isolate the effect of warm-up on surgical proficiency from the improvement in psychomotor activation and cognitive arousal, it is important to assimilate data across multiple trials with sufficient iterations to allow learning to occur to account for the "learning curve." Also, their study did not include sophisticated measures of surgical proficiency, such as hand-movement analysis and tool-movement analysis, which can quantify psychomotor proficiency in detail. In addition, tasks used in their experiment did not include a cognitive dimension, and therefore not allowing for the study of the effect of warm-up on cognitive arousal. Finally, as the study used the same exercise as warm-up and followup exercise, it does not sufficiently indicate that the increase in proficiency will carry over to other tasks, especially those with more clinical relevance.

This research embarks on defining a systematic methodology to study the effect of short-term pretrial practice on surgical proficiency. We use simulation tasks targeted to hone both psychomotor and cognitive skills to provide warm-up exercises that will enhance the performance of the main surgical procedures.

Several key questions need to be addressed to study the effect of warm-up on surgical proficiency and present a case for including preoperative warm-up as an advantageous activity for surgeons. We have developed a series of interrelated hypotheses that address the issue systematically. The flowchart in Figure 1 links the hypotheses with the key questions and variables they address. The first question that we address is whether warm-up does indeed affect the quality of performance in the followup tasks (the classic question of whether training translates to improved outcomes). Experiment 1 aims to establish the effect of warm-up exercises on followup tasks by looking at the global question (Hypothesis 5) and the main individual variables that can be the reason for the measured effect. These variables are experience of the operator, learning, fatigue, and the nature of followup tasks. They are studied through the following hypotheses.

Hypothesis 1: Warm-up is not dependent on the level of experience of a surgeon

This hypothesis aims to study if the experience level of a surgeon affects warm-up required. It is plausible that warm-up might only be required for less experienced surgeons or for procedures a surgeon is not familiar with. In sports, it has been established that warm-up is necessary regardless of the level of experience of a player. We aim to investigate the relation between experience and warm-up in surgery.

Hypothesis 2: Warm-up and its intensity do not vary with short-term practice

It could be hypothesized that warm-up is required only during training stages, and once a necessary level of learning has occurred for a particular task, there is no addi-

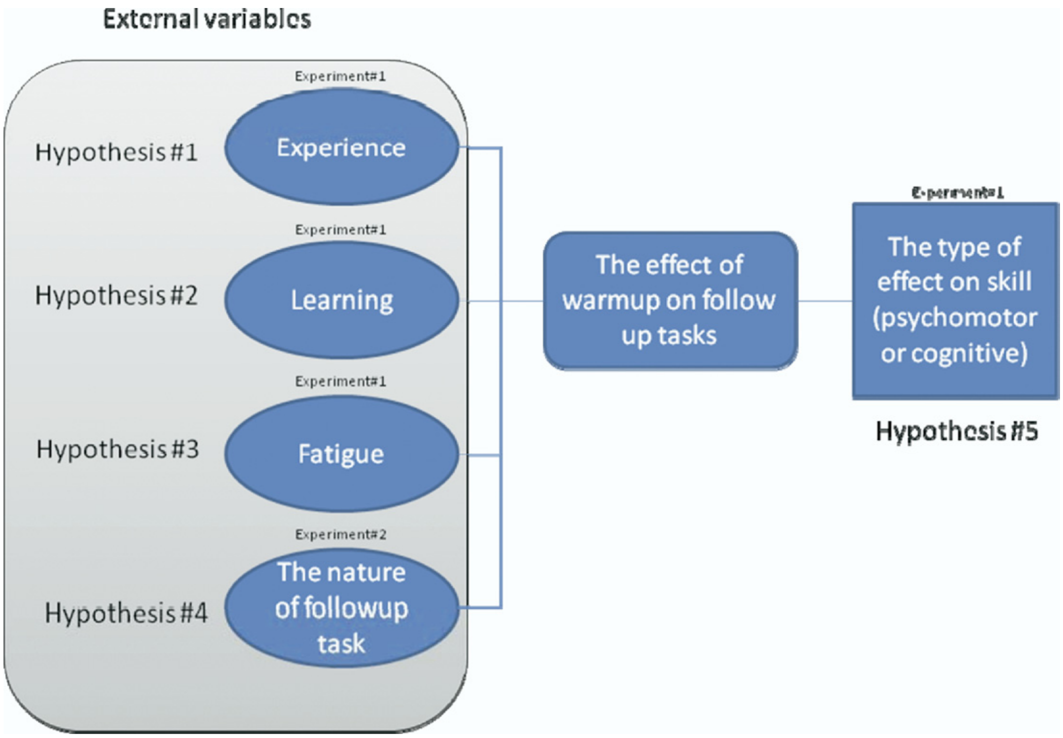

Figure 1. Conceptual framework of the experiments.

tional requirement for warm-up. In essence, warm-up is "learned" and does not provide benefit after an initial time frame. To test this hypothesis, experiments that track the performance of subjects during several sessions are required. It is a priori that no matter how experienced a surgeon might be, there is value added to performing a warm-up before every surgical procedure.

Hypothesis 3: Warm-up is effective in reducing errors resulting from fatigue

Research has shown that fatigue from night call and sleep deprivation can lead to decreased surgical proficiency.[8] Whether warm-up would help in alleviating some of the effects of fatigue is an intriguing question, with many pragmatic and positive implications.

Hypothesis 4: Effectiveness of warm-up is independent of the followup task to be performed

From a scientific point of view, this is an important investigation that will reveal whether effects produced by generic practice and exercises can carry over to more complex tasks; from a pragmatic standpoint, this study will reveal whether a single "standard" warm-up is sufficient or will multiple different types of warm-ups sessions need to be developed.

The final investigation lies in studying the nature of increase in proficiency.

Hypothesis 5: Warm-up affects both cognitive and psychomotor skills

The study aims to establish if the increase in proficiency is purely psychomotor, helping increase dexterity, or does it also affect cognitive abilities of the surgeon. This will be measured by including both attention and memory tasks, such as highlighting series of pegs for a few seconds, which requires the subject be attentive enough to locate each peg and then, after turning off the series, the subject must remember the order of placement of the rings (see Methods section).

METHODS

Earlier approval was obtained by the Institutional Review Board at Banner Good Samaritan Medical Center before conducting any experiment.

The present study focuses on a series of experiments designed to systematically explore the effect of warm-up. The experimental design extends the methodology proposed by Do and colleagues[7] by using exercises in warm-up condition and followup condition. Subjects across varying specialties and experience levels (including senior trauma surgeons) were involved in multiple sessions performing exercises. These sessions were held in both precall and postcall condition, allowing for study of warm-up in alleviating the effect of night call on both cognitive and psychomotor fatigue. In an additional experiment, different exercises

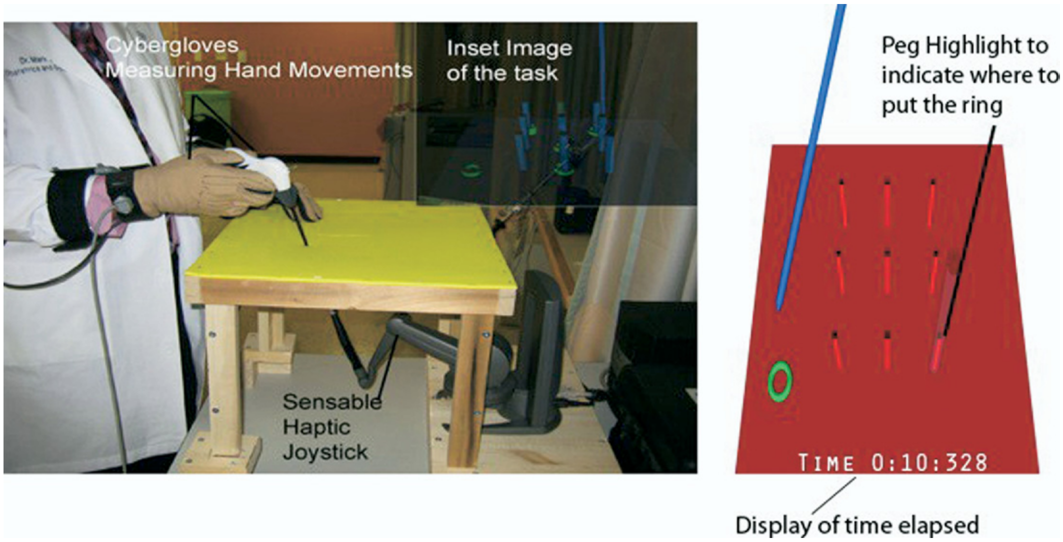

Figure 2. Ring-transfer task implemented using the Sensable Haptic joystick. Simulation requires the participant to pick the ring and then place it on the highlighted peg. Movement of the tool and hands are measured in the process. A subject using the system. It should be noted that the hand-movement data-capture gloves can be worn with any simulator and can potentially be used for evaluation in actual operations.

were used for warm-up and followup tasks. This allowed quantification of carry-over effect (generalization) of warm-up exercises. The study design and controls will be discussed in subsequent sections of this article.

A series of virtual simulations were developed that measured both psychomotor and cognitive skills in a controlled manner. A simulation was designed for the virtual ring transfer task that is a part of validated basic laparoscopic course offered by ProMIS Simulator and the American College of Surgeons Certified Fundamentals of Laparoscopic Surgery curriculum. In the virtual ring transfer task (see Fig. 2), residents were tasked with grasping a series of "virtual" rings and placing each on randomly highlighted pegs on a board. The simulation was implemented using the Sensable haptic joystick, which allows for generation of three degrees of force feedback in response to events in the virtual environment. OpenHL programming applied programming interface was used to design the simulation. The simulation allows for measurement of the tool tip in the virtual environment. Additionally, while performing the simulated tasks, subjects wore the Cyberglove and Polhemus Liberty Tracker that allowed for capture of hand movements (see Fig. 2). The basic task involved 10 rings. After the participant places a ring on a highlighted peg, another peg is randomly chosen for the participant to put the ring on. This is repeated until all 10 rings are correctly placed. This basic ring transfer task is a psychomotor task used and validated in many simulators to hone tool-manipulation skills. A cognitive error is marked for every time the participant attempts to place a ring on the wrong peg, signifying error in judgment by the subject. It should be noted that the simulation does not allow placement of a ring on the wrong peg, and the participant is required to continue selecting pegs to put the ring on until the correct peg is chosen.

This basic validated laparoscopic exercise was modified to include cognitive variations, such as attention, visiospatial tracking, and intermodal transfer. Eight variations of the game were designed and are described in detail in Kahol and colleagues[9]. These newly developed simulations were validated through controlled experiments that showed that the developed exercises can suitably replicate the realistic work environment of surgeons, offering exercises that require both psychomotor and cognitive dimensions. Table 1 summarizes the exercises and cognitive modality they address. For detailed definitions on the cognitive modality please see Kahol and colleagues.[9]

Objective proficiency evaluation measures

This section on methodology defines the hand-movement data-capture system and variables, and the tool-movement capture system and variables. For measuring laparoscopic proficiency, we used a combination of hand movement and tool movement. Tool movement measured as movement of the tool tip in virtual environment is a validated measure for surgical proficiency.[10] Kahol and colleagues[11] introduced hand movement measured through Cyberglove and the Polhemus Liberty Tracker as an effective measure of surgical proficiency. Both tool movement and hand movement are representative of economy of motion, overall smoothness in execution, and their construct validity has been established. Tool acceleration was calculated for the

Table 1. Exercises and the Primary Cognitive and Psychomotor Faculty Engaged

	Exercises						
Cognitive and psychomotor faculty	**Sensorimotor coordination**	**Two-dimensional tracking**	**Three-dimensional tracking**	**Orientation**	**Preparatory attention**	**Working memory**	**Visiohaptic transfer**
Sensorimotor coordination	X	X	X	X	X	X	X
Working memory		X	X	X		X	
Movement planning		X	X	X			X
Preparatory attention		X	X	X	X	X	X
Intermodal transfer				X			X

entire duration of a task and normalized in a range of 0 through 1. Smoothness of tool movement as predicted through this measure is 1 when overall acceleration is close to 0. This is generally the case in well-executed motion with controlled accelerations. On the other hand, jerky motions show higher normalized acceleration and lower smoothness. The smoothness of tool movement was calculated using the following formulas:

$$\text{Tool-movement smoothness} = 1 - \text{normalized (tool acceleration)} \quad (1)$$

$$\text{Hand-movement smoothness} = 1 - \text{normalized (wrist acceleration)} \quad (2)$$

The data-capture setup shown in Figure 2 depicts the wireless Cyberglove glove and the Polhemus Liberty tracker. The wrist acceleration is calculated through tracking of the sensor placed on the wrist. With regard to tool-movement smoothness, jerky hand motions lead to less smoothness, while controlled movements lead to increased smoothness. For every simulation exercise, time required to complete a task is recorded; cognitive errors are recorded as the number of times the ring is placed on the wrong peg. These four objective measures are also supplemented with gesture-level proficiency measure. Task decomposition has emerged as a validated method to measure surgical proficiency.[11] In this approach, hand movement or tool movement is decomposed into smaller gestures (such as in, out, grasping and rotation). Each individual gesture is analyzed and, based on its similarity to the optimal occurrence of a gesture as determined by setting a benchmark criteria from an expert group's performance of that gesture, is given a proficiency rating. For this article, hand movement was used for task decomposition. The algorithm for this purpose was described by Kahol and colleagues[11] and was shown to correlate highly with subjective proficiency ratings obtained by surgeon teachers. The scoring method used is a standard Likert scale between 0 and 10 for an entire exercise. Zero implies least proficiency in accomplishing the task and 10 implies highest proficiency. This measure is estimated through combination of time elapsed and kinematic analysis of hand motion. These five measures (gesture-level proficiency, hand-movement smoothness, tool-movement smoothness, time elapsed, and cognitive errors) provide a broad framework for global assessment of proficiency.

Experimental design

Two experiments were performed. The first experiment consisted of eight sessions and the second experiment consisted of a single session of data capture. Experiment 1 was designed to evaluate the overall effect of warm-up on surgical proficiency and its relation to experience level, short-term practice, fatigue level, and cognitive and psychomotor skills. In Experiment 1, every subject acted as their own control, wherein their performance was measured during warm-up and then during followup trials. Experiment 2 was designed to test if warm-up conducted in basic skills was able to effect performance in a complex surgical task. A control group of subjects who performed a complex task without warming up was compared with an experimental group of subjects who warmed up with simple laparoscopic exercises before performing a complex task.

Experiment 1: Subjects

Forty-six surgeons participated in the study. Fourteen PGY1 OB/GYN and general surgery residents, 10 PGY2 OB/GYN and general surgery residents, 11 PGY3 OB/GYN and general surgery residents, and 10 attending trauma surgeons were involved in the experiments. Nineteen women and 27 men comprised the subject pool, with 21 subjects of OB/GYN specialty and 25 subjects of general surgery specialty.

Experiment 1: Design

Each participant was involved in eight sessions during 4 weeks. Four of these sessions were held precall before the residents performed their night call and the remaining four sessions were held postcall. In each session, three exercises were performed after filling in the fatigue questionnaire. These three exercises were randomly chosen from the eight variations of the ring transfer exercises described here previously. Each exercise was repeated two times. The first iteration was marked as warm-up trial and the second iteration was marked as the followup exercises. This experiment permitted an in-subject design wherein every subject was their own control. During each session the subject wore Cyberglove and the Polhemus Liberty tracker on their dominant hand. In the first session, the glove was calibrated to a participant's hand and the calibration was stored. For every session performed by a participant, the calibrated glove was used to accurately record hand movements and wrist movements. Each session lasted approximately 15 to 20 minutes. Exercises in the precall condition and the postcall condition were not matched. This was done to control for learning effect that could have been produced for a particular exercise. During the course of eight sessions, each subject performed six iterations of eight exercises as described by Kahol and colleagues.[9] Three of these iterations were for warm-up and the remaining three iterations were marked as followup condition.

Data captured in the eight sessions on hand movement, tool movement, time elapsed, and errors were processed as per methodology defined in the Objective Proficiency Evaluation Measures section to calculate the five objective proficiency measures for each exercise iteration. Statistical analysis was performed to compare performance of surgeons during warm-up and followup exercises. ANOVA was used to study the difference between warm-up and followup conditions.

In the first level of analysis, all trials performed during warm-up were grouped together and compared with all trials during followup. This analysis provided statistical data to study the global differences between followup and warm-up conditions to investigate questions of whether warm-up improves performance of a subsequent task.

In the second level of analysis, data were grouped according to experience level of the surgeons (PGY1, PGY2, PGY3, and senior surgeons) and the groups' warm-up and followup exercise iterations were compared using ANOVA. This analysis allowed study of Hypothesis 1 regarding differences of the effect of warm-up on surgical proficiency of surgeons who had different levels of experience.

In the third type of analysis, exercise iterations were grouped according to sessions in which they were performed. Overall change in proficiency measures in followup condition and warm-up condition was plotted as a curve across the iterations of exercises and sessions. This graph helped provide insight into Hypothesis 2, about whether the need for warm-up alters with short-term learning of surgical skills and exercises in eight sessions.

The fourth type of analysis grouped precall warm-up and followup sessions and compared them to postcall warm-up and followup sessions. This comparison allowed for studying Hypothesis 3, whether warm-up has a positive effect on surgical proficiency during postcall fatigue state, thus improving performance of fatigued surgeons. In previous studies, we have performed detailed analysis on fatigue and its effect on profi-

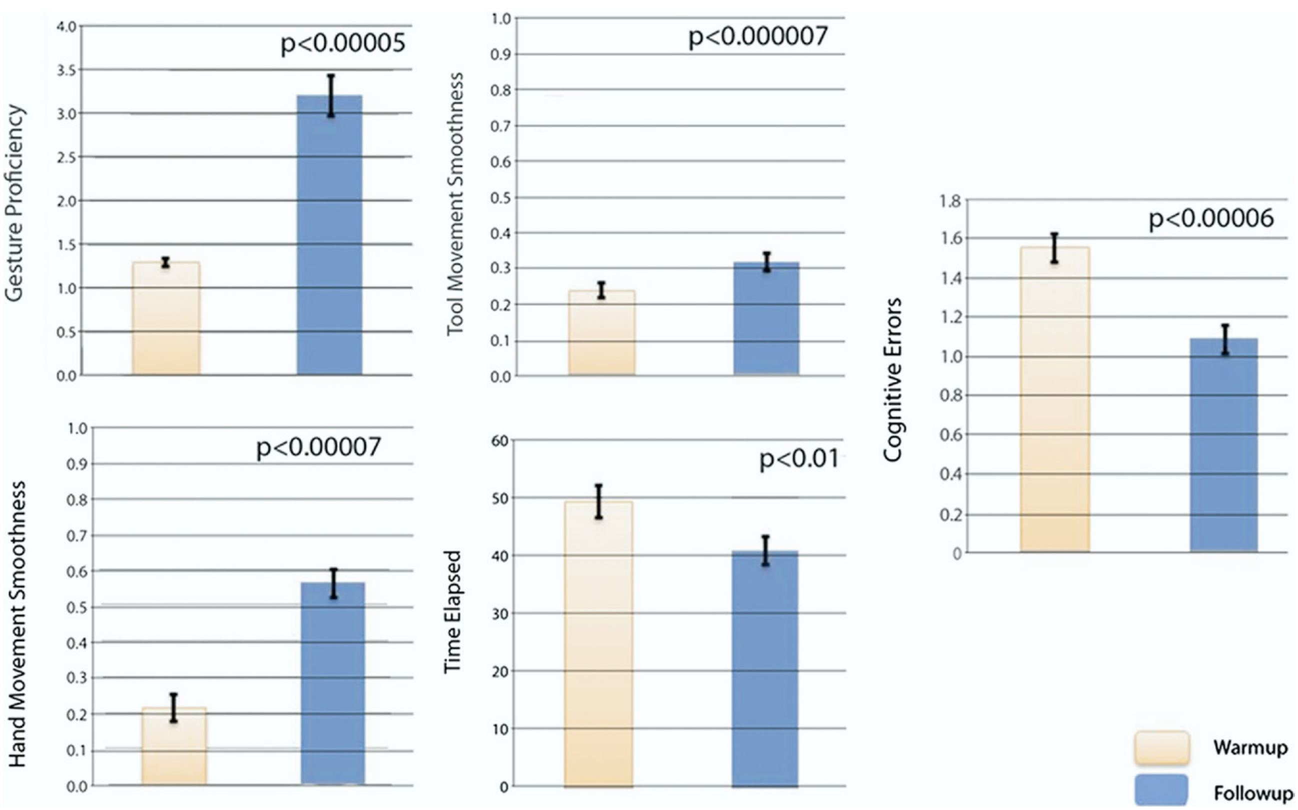

Figure 3. ANOVA plots comparing proficiency in warm-up and followup condition.

ciency.[9] Overall methodology is detailed in Kahol and colleagues,[9] but a few key points about the methodology and result need to be elucidated. Exercises in the precall and postcall session were not matched and postcall session exercises were chosen from the pool of exercises not used in precall session. Overall, results showed that a surgeon's cognitive skills and psychomotor skills were negatively affected by fatigue. Cognitive skills were more substantially affected. Results from the fatigue experiments showed a very high correlation between reported levels of fatigue in the questionnaire and actual performance.

In the fifth type of analysis, warm-up and followup iterations of sensorimotor coordination exercise were compared with warm-up and followup iterations of all the other types of exercises grouped together. Table 1 shows that all exercises, except sensorimotor coordination exercise, had a substantial cognitive component. This analysis was performed for Hypothesis 4 to reveal if warm-up had a considerable effect on psychomotor skills and cognitive skills and to compare the performance differential.

Experiment 2: Subjects

Eight PGY2 and four PGY3 residents (six OB/GYN residents and six general surgery residents) participated in the second experiment designed to study effect of warm-up on surgical proficiency in complex surgical procedures. Participants were taken from the same pool as in Experiment 1, but this experiment was performed after completion of Experiment 1. Both groups had equal exposure to and education of the ring-transfer exercises before they began Experiment 2.

Experiment 2: Design

Residents were divided into two groups of six residents each. The control group performed only the surgical electrical diathermy task on the ProMIS simulator (with no preliminary warm-up exercises). The surgical diathermy task mimics electrosurgery skills required of excision of the gall bladder during laparoscopic cholecystectomy. The task (which has been validated) requires the surgeon to perform incision, removal of the cyst using diathermy, and suturing. Complete details of the operation are available from Bass and colleagues.[13] Traditionally, the operation is performed during earlier stages of the residency program and requires medium skill level. The experimental group performed the simulated surgical diathermy task after performing warm-up exercises. Three warm-up exercises were randomly chosen from the eight exercises defined in Table 1 and by Kahol and colleagues.[9] Each exercise was repeated twice by the experimental group. The surgeons wore Cyberglove and Ascension Tracker while performing the diathermy simulation. The tool movement was available from ProMIS simulator but no direct cognitive errors could be recorded in the ProMIS simulator as it does not allow for any such recording. This analysis was performed for Hypothesis 5 to determine whether warm-up improves performance independent of the

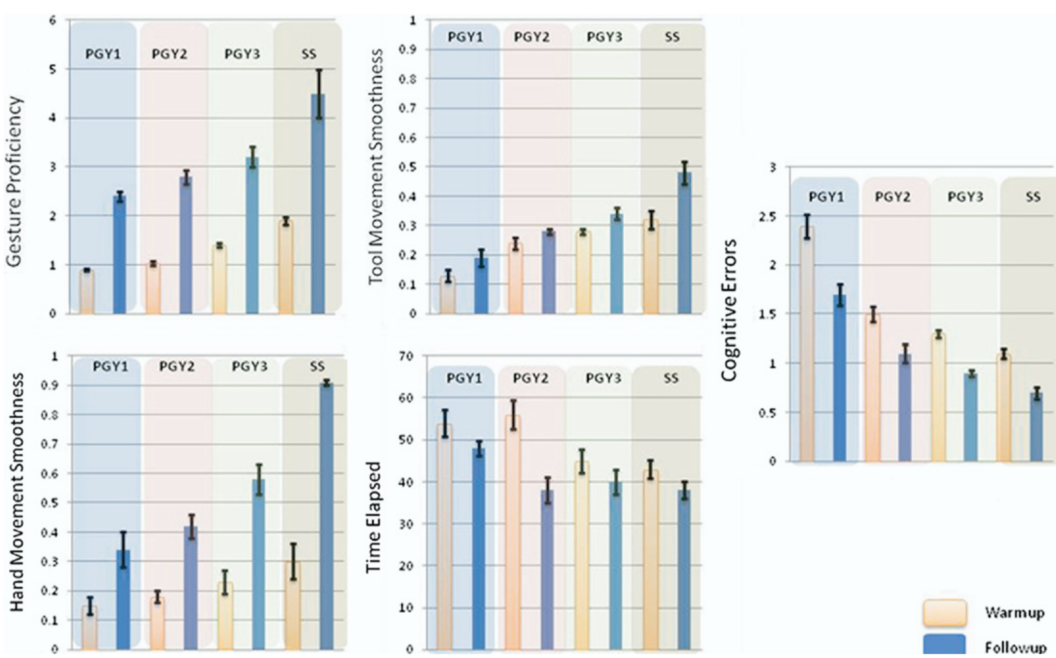

Figure 4. ANOVA plots comparing proficiency in warm-up condition and followup condition data grouped according to experience level. SS, senior surgeon.

type of followup task (or procedure). The performance of the control group and experimental group was compared on the diathermy simulation task using ANOVA.

RESULTS

Figure 3 shows the plot for comparison of the objective proficiency measures evaluated in the experiment in warm-up and followup condition. Each of the measures showed a statistically significant difference between warm-up and followup conditions ($p < 0.005$). The time required for completion of tasks and number of cognitive errors decreased and gesture-level proficiency, hand-movement smoothness, and tool-movement smoothness increased considerably. Overall reduction in errors was 33%.

Hypothesis 1: Warm-up is not dependent on level of surgeon experience

Figure 4 shows plots of the five objective proficiency measures, grouped according to level of experience of the participants.

Plots show that before warm-up, statistically significant correlation did not appear between the groups. In the followup condition, each of the groups show a statistically significant difference ($p < 0.001$). Consistent with results of overall analysis, the time required for completion of tasks and number of cognitive errors decreased, although gesture-level proficiency, hand-movement smoothness, and tool-movement smoothness increased considerably. The percentage reduction in errors was calculated for each of the groups. PGY1, PGY2, PGY3, and resident surgeons showed 31%, 30%, 44%, and 29% reduction in errors. These reductions show that each subject group showed consistent and substantial improvement supporting the hypothesis that warm-up is needed for subjects at different levels of expertise.

Hypothesis 2: Warm-up and its intensity do not vary with short-term practice

Figure 5 shows improvement in objective proficiency in three sessions of the exercises. Data were grouped in terms of each session of the exercise performance and the improvement in proficiency was calculated for each session. Figure 5 shows that improvement in proficiency introduced because warm-up is shown in all three sessions consistently and does not increase or decrease with short-term learning. Only gesture proficiency showed a statistically significant difference ($p < 0.005$) between the three sets of exercise performance, but there was not a continuous improvement (eg, learning curve), but rather simply differences in amount of improvement from one set to the next.

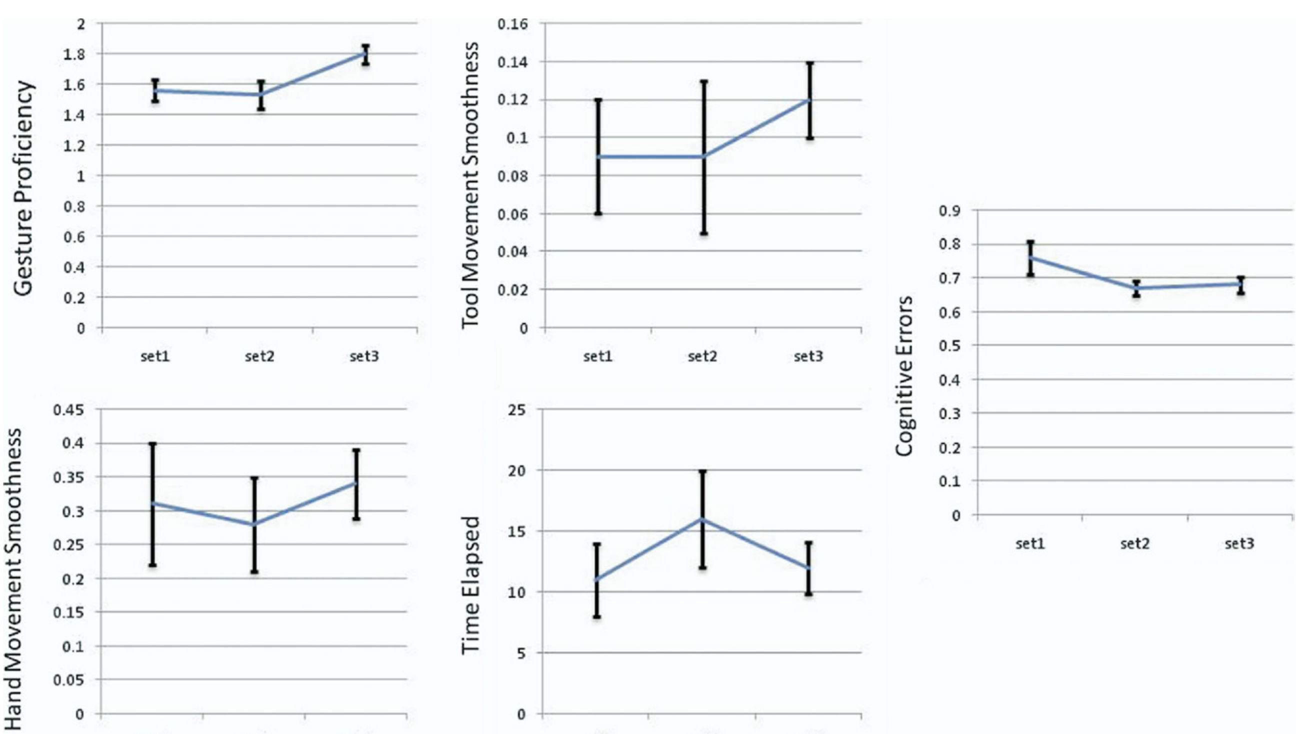

Figure 5. ANOVA plots comparing change in proficiency in three iterations of exercises.

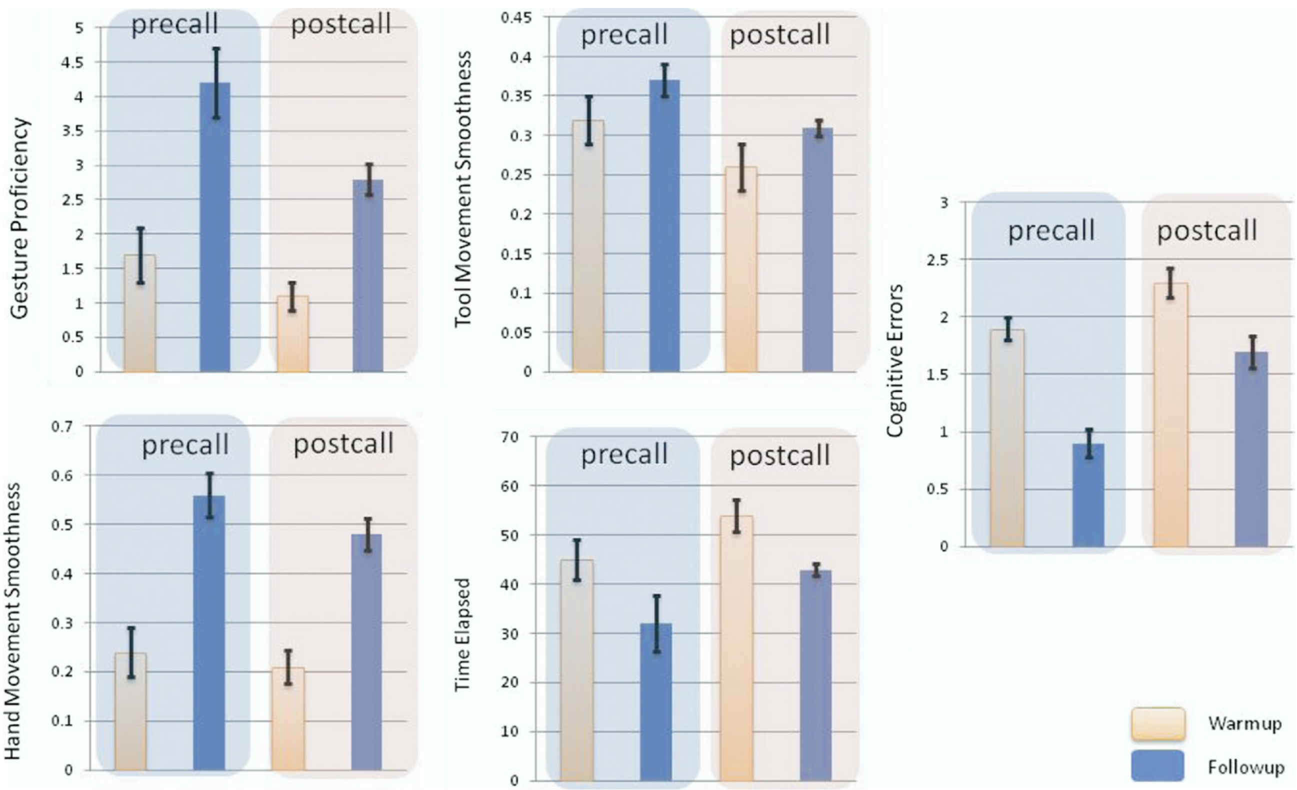

Figure 6. ANOVA plots comparing proficiency in warm-up and followup condition. Data were grouped into precall and postcall condition.

Hypothesis 3: Warm-up is considerably effective in reducing errors resulting from fatigue

Figure 6 shows plots of objective proficiency measures in warm-up and followup conditions with data being grouped into precall and postcall. Data shows that warm-up does positively affect proficiency during postcall condition characterized by fatigue and sleep deprivation[12] to a point where the warm-up returns performance in a fatigued subject to the same level as a precall subject who has not warmed up. Proficiency obtained in the postcall fatigue followup condition is less than the proficiency measures obtained in the precall followup group. These results indicate that warm-up does help in countering some of the effects of fatigue and sleep deprivation by returning performance in the fatigued subject to the equivalent of a nonfatigue baseline (with no warm-up). It appears that fatigue prevents enhancing beyond baseline performance of a fresh (precall) subject. This interesting phenomenon deserves additional, more deliberate investigations than these preliminary trials. It is important to emphasize that even in a fatigued subject, every single parameter improved (hand-motion smoothness improved 198%, tool motion improved 23.8%, gesture proficiency improved 103%, time decreased by 32%, and errors decreased 34%), demonstrating that substantial performance improvement can be achieved even in a fatigued individual, and that the improvement can return performance to approximately that of the baseline performance of a rested individual who has not warmed-up.

Hypothesis 4: Effectiveness of warm-up is independent of the followup task to be performed

Figure 7 shows the objective proficiency measures (except cognitive errors) for the two groups involved in Experiment 2. The control group that did not warm-up before performing the diathermy task on the ProMIS simulator achieved inferior proficiency scores when compared with the experimental group. The experimental group that warmed up with the exercises designed for this experiment showed statistically significant better performance ($p < 0.01$) except for time elapsed where $p < 0.08$ was noted). This demonstrates, at least preliminarily, that simple warm-up tasks can be generalized for more than one type of procedure, but this trial is quite limited and needs much more exploration.

Hypothesis 5: Warm-up affects both cognitive and psychomotor skills

Figures 8 and 9 show, respectively, the plots of objective proficiency measures (means) in warm-up and followup

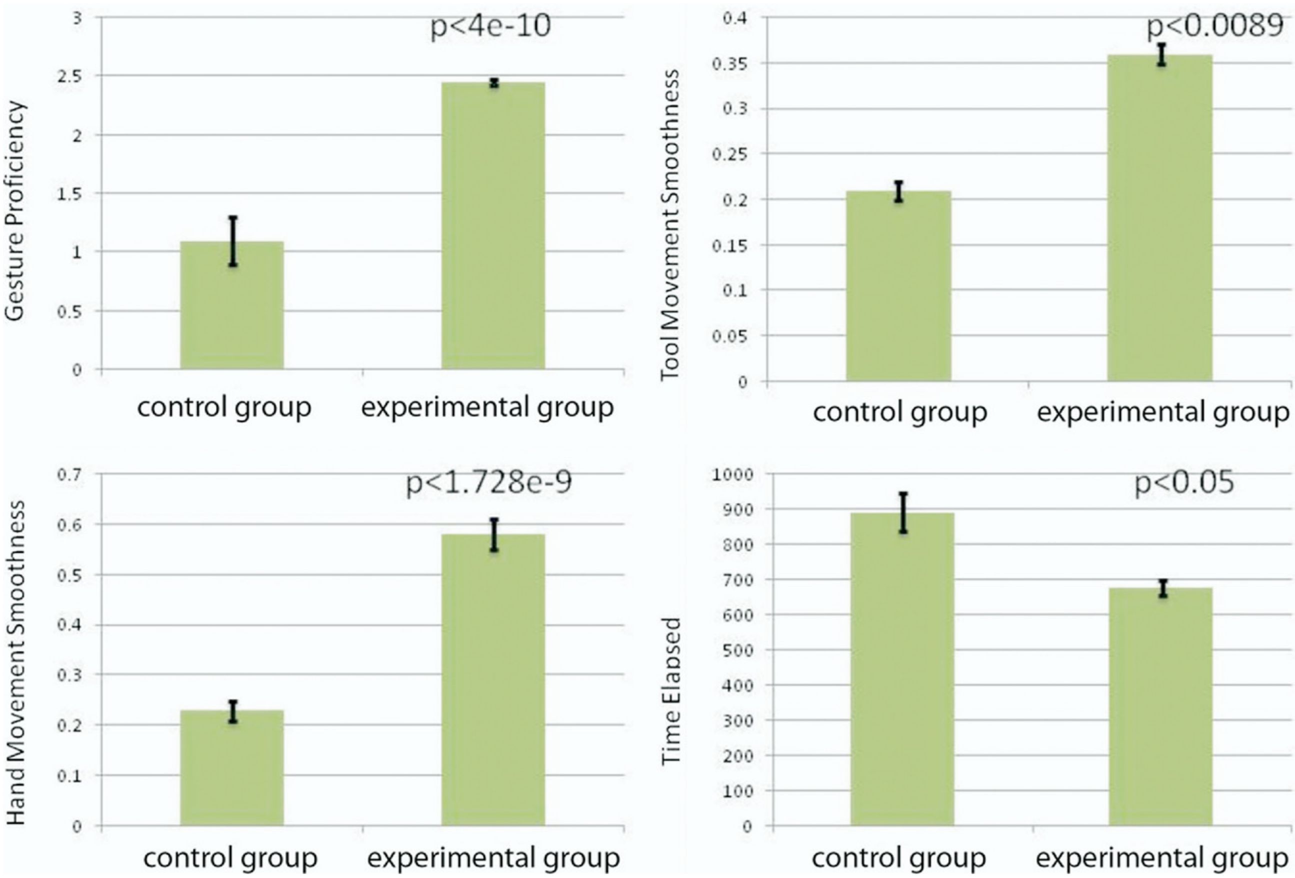

Figure 7. ANOVA plot comparing performance of control group and experimental group (warmed-up) on diathermy task on ProMIS simulator.

conditions for the sensorimotor coordination (psychomotor skills) exercise and the cognitive exercises (grouped together), although Figure 10 shows t-statistic measure for gesture proficiency and cognitive error for each exercise separately. The t-statistic value represents the change in objective proficiency in the warm-up and followup condition and shows how warm-up affects skills associated with each of the exercises separately. The highest value was noted for orientation exercise, although the lowest values were noted for the memory exercises with four pegs to remember and put the ring on. These results support the hypothesis that warm-up does lead to improvement in both types of skills.

DISCUSSION

Results of this study provide substantive evidence that short-term practice (warm-up) for 15 minutes with exercises designed to target both psychomotor and cognitive skills that are involved in surgical procedures can greatly enhance skill proficiencies during a followup procedure. Gesture-level proficiency, movement smoothness, and tool-movement smoothness are favorably enhanced with simple practice. Errors are substantially reduced, which is arguably the most important positive effect of warm-up exercises. Time required to complete a task, which is one important indicator of efficiency, is also reduced substantially.

Participants of varying experience levels all can benefit from warm-up. It is important to note that before warm-up, there was no statistically significant difference ($p < 0.69$) among the different levels of experience (although there was a tendency for the more senior levels to have a slightly higher, though not statistically significant ($p < 0.04$), baseline performance capability in the hand- and tool-movement tasks). After warm-up exercises, there are substantial differences within each of the expertise levels between warm-up and followup tasks, with approximately equal improvement for all levels of expertise. Because the improvement is so strong among all levels (25% to 40% reduction in error), it is fair to conclude that warm-up provides a quantifiable performance improvement for subsequent tasks regardless of experience level or expertise. What cannot be concluded is whether improved task performance will transfer to improvement in the operation

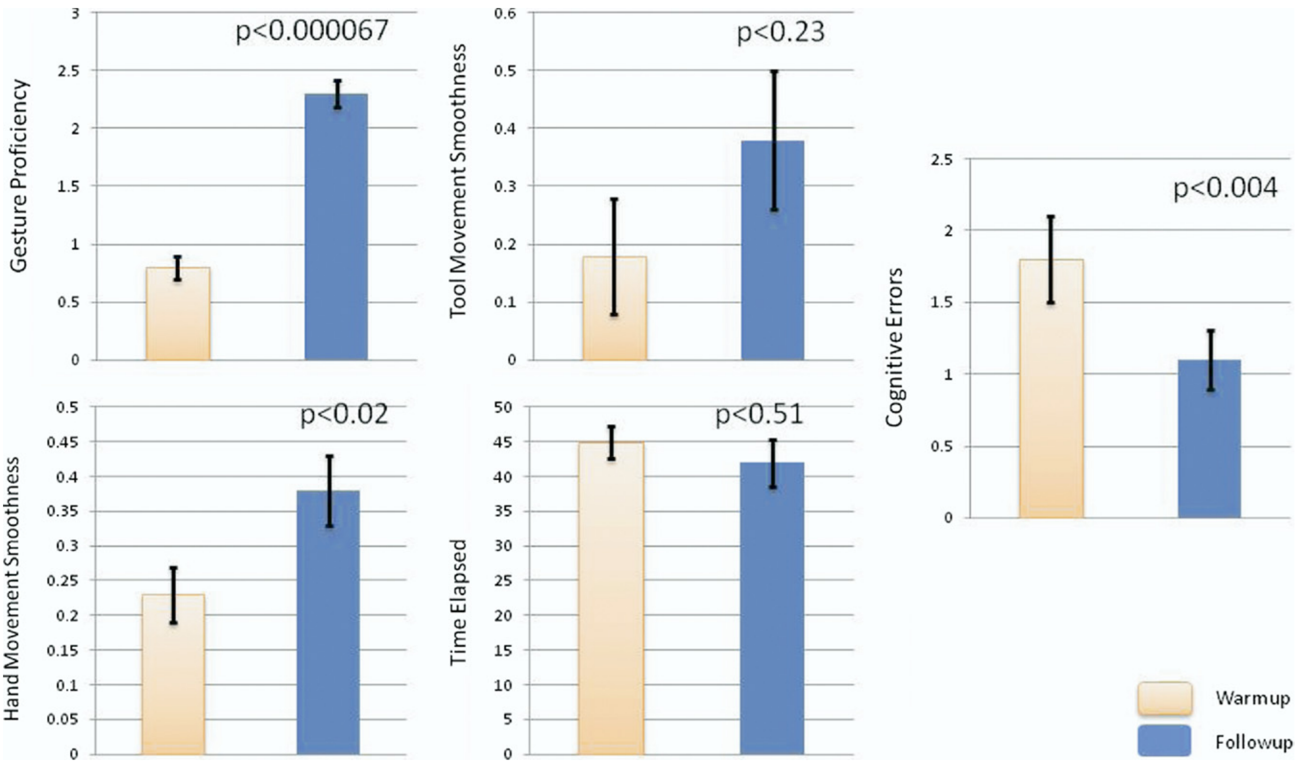

Figure 8. ANOVA plots comparing proficiency in warm-up condition and followup condition for sensorimotor coordination exercise.

room (virtual reality to operating room) and, more important, whether improvement in the operating room will result in improved overall clinical outcomes. These are many more longterm studies that must be pursued.

Another possible explanation for the favorable effect of warm-up exercises on followup exercises could be "short-term familiarization effect." The key element in clarifying such an explanation requires that warm-up exercises and followup exercises are exactly the same. When the same task is performed before and after warm-up, the results unequivocally demonstrate improvement. Results also show that the group that warmed-up with simple exercises before a complete procedure performed considerably better than the control group that directly performed the task. Because improvement was demonstrated in both the same followup task and a different followup task, the improvement is not a result of familiarization or the learning curve. In a similar fashion, the results demonstrate that the immediate onset (first trial) of improvement from the warm-up exercises implies that this rapid improvement in skill cannot be attributed to familiarization effect or learning effect.

Analysis of data collected during precall and postcall condition indicated that warm-up can improve proficiency in the fatigued individual, and can bring their performance to a level equivalent to their baseline nonfatigued condition. Warm-up cannot take a fatigued person and improve their performance to their potential best performance (ie, followup performance after warm-up in a nonfatigue state).

In trying to understand the reasons for improved performance, analysis of the portfolio of tests demonstrates that warm-up exercises enhance performance not only through basic psychomotor skills (sensorimotor coordination), but also by intensifying cognitive faculties. Previous research suggests that four concurrent tasks might be close to the limit of working memory,[14] beyond which skill deteriorates; this was also suggested by the studies mentioned in this article that demonstrated a decrease in performance when the subject was required to remember four (rather than three) sequential pegs. Improvement caused in proficiency might only be a result of improvements in psychomotor skill (sensorimotor coordination) and some cognitive skills, but not a result of expanding or enhancing the available working memory.

Additional analysis indicates that warm-up exercises can allow for surgeons to achieve cognitive arousal coupled with exercises invoking motor circuits in the brain and warming-up of hand and shoulder muscles to achieve sensorimotor coordination. This is based on improvements shown in all types of exercises, including the ones with substantial cognitive components. This hypothesis is consistent with findings in the sports domain[15] as related to warm-up. Such effects last until a followup task is

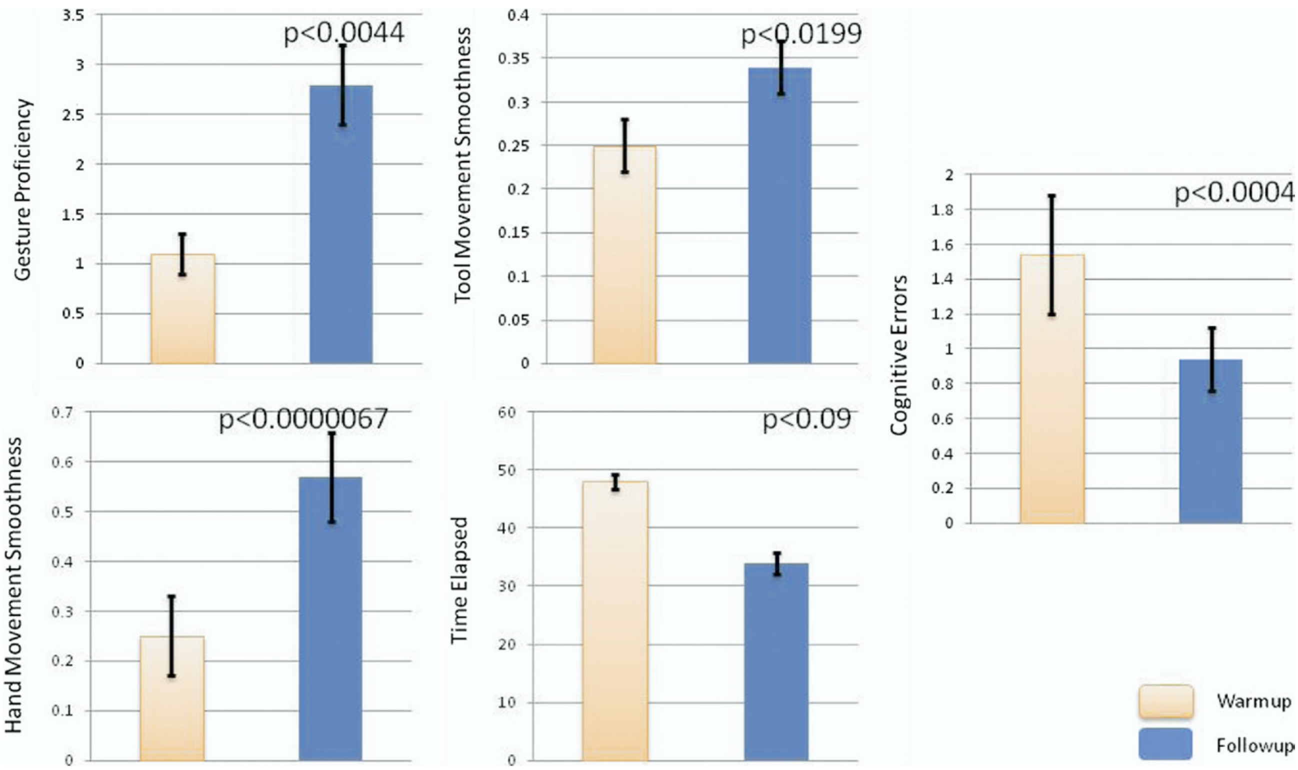

Figure 9. ANOVA plots comparing proficiency in warm-up condition and followup condition for cognitive exercises grouped together.

completed. Warm-up decrement has been shown to occur in sports domain when a period of rest is introduced between exercises and the task. Future studies will investigate whether such effects are also a factor in laparoscopic surgery, or whether waiting for a prolonged time after warm-up negates the benefit of warm-up.

From a very pragmatic standpoint, it is encouraging to note that improvement in performance with warm-up is independent of the type of task that follows (Experiments 1 and 2). Should additional research confirm these preliminary results, it will be possible to develop a few, simple preoperative warm-up exercises that will be sufficient for whatever procedure will follow.

Although the focus of the study has been the effect (both cognitive and psychomotor) of a preoperative warm-up caused by physical stimulation (ie, performance of a specific task), there is a possible confound in the study—the psychological anticipation to perform a surgical procedure. This confounding factor might be that surgeons do not require such preoperative warm-up when conducting actual operations because the environment and expectation lead to required cognitive arousal, tuning of sensorimotor coordination, and preparatory attention. Additional studies need to be designed to address the issue of psychological anticipation in a real clinical environment.

The basic nature of these laboratory-based experiments will need confirmation and validation by other independent sources, and determination of whether laboratory results will transfer to the clinical domain. Future work in this domain would include conducting experiments on the effect of pretrial warm-up before actual operation. The current study also did not explore the effect of different types of exercises on proficiency in followup tasks. This issue will be explored through controlled experiments.

There are a few fundamental precepts that have emerged. First and foremost, the results confirm the a priori impression and observations of other high-risk professions that performing a preoperative warm-up exercise before a surgical procedure can improve operative performance—in terms of more efficient motion, reduced operative time (procedure efficiency), and reduced errors (patient safety).

Second, improvement appears to occur from both psychomotor and cognitive skill enhancement, although overall working memory does not seem to be increased. This improvement is completely independent of expertise of the surgeon, and the improvement will occur before every operative procedure—there is no learning curve after which warm-up is not helpful.

Third, preoperative warm-up can improve performance

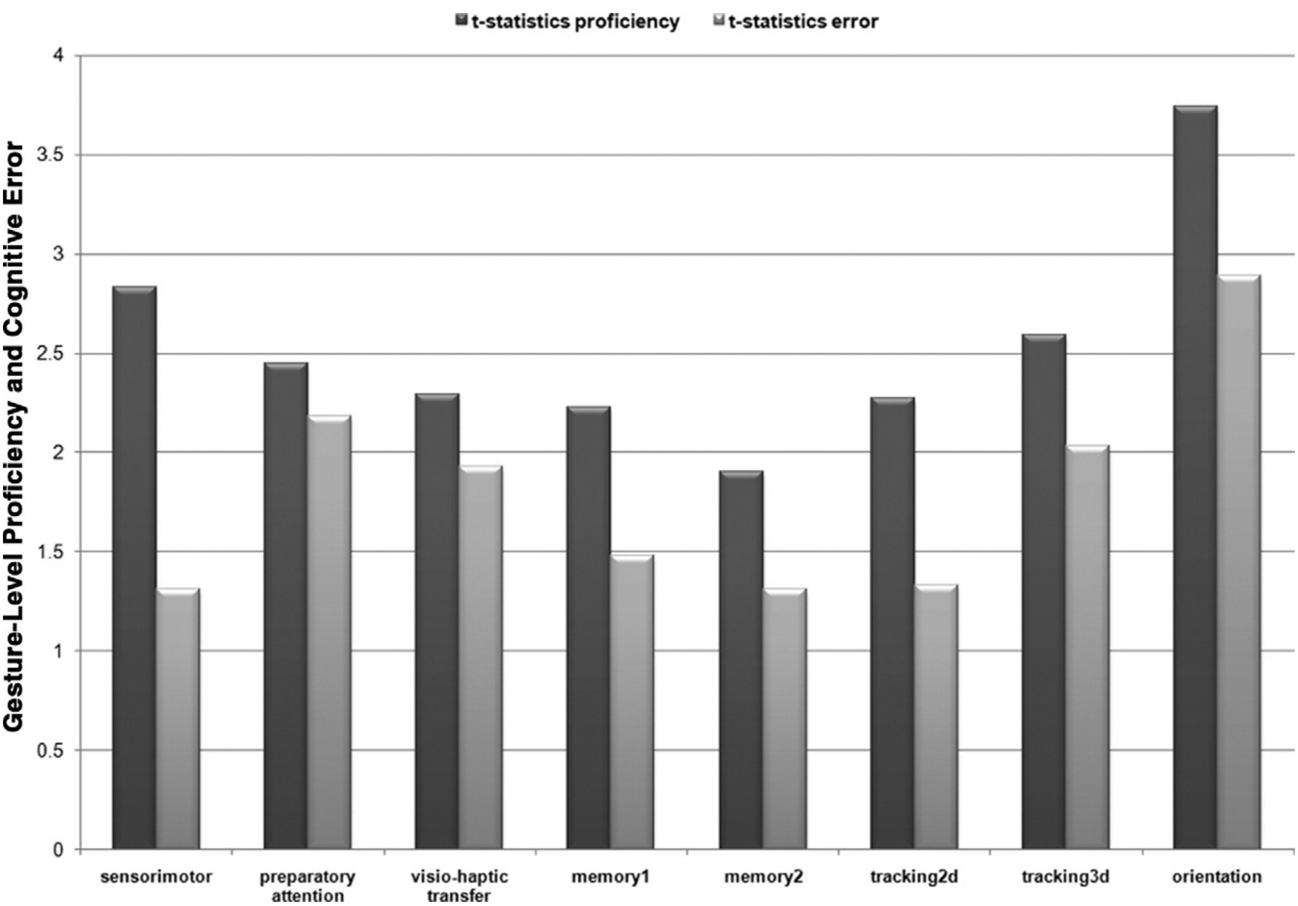

Figure 10. Comparison of t-statistic value for each exercise for gesture-level proficiency and cognitive error.

in a fatigued surgeon, although the performance improvement will only be to the surgeon's baseline level and not to their optimal potential level. This finding will require additional validation and investigation into other areas, such as a longer warm-up period and quantifying the amount of fatigue . . . period and quantifying . . . fatigue.

There are substantial policy implications from these results. The most important one is—if additional independent validation studies confirm these findings—whether there should be a required preoperative warm-up period before every surgical procedure (in the name of efficiency and patient safety). Will there be a specific, quantifiable level of proficiency the surgeon should obtain (on a simulator) before beginning a surgical procedure? Will it be required that the surgeon documents that the preoperative warm-up was complete before starting the procedure (thereby documenting that the surgeon was at their optimal performance)? Will it be necessary to require that operating suites have readily available access to preoperative warm-up stations? If a surgeon does not warm-up and an adverse event occurs, will the surgeon be liable? These are but a few of the possible implications, all of which need to be thoroughly investigated and discussed before any knee-jerk regulations are put into place.

Once again, health care is beginning to confront a "common sense" practice that is routine in many other high-stakes professions. Results of this study are intended to begin to form the scientific foundation for a new approach to surgical practice: the preoperative warm-up. Just as the "see one, do one, teach one" tradition of surgical education is yielding to quantitative training and assessment of technical skills and criterion-based benchmarks to demonstrate proficiency, so too can preoperative warm-up become a new standard for improving operative performance and patient safety.

Author Contributions

Study conception and design: Kahol, Satava, Smith, Ferrara
Acquisition of data: Kahol, Satava, Smith, Ferrara
Analysis and interpretation of data: Kahol, Satava, Smith, Ferrara
Drafting of manuscript: Kahol, Satava, Smith, Ferrara

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