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Application of a Mastery Learning, Error Management Training Curriculum to Improve Surgical Fasciotomy Performance

By

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Thesis submitted to the Faculty of the Health Professions Education Graduate Program, Uniformed Services University of the Health Sciences, in partial fulfillment of the requirements for the degree of Master's in Health Professions Education 2020

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DEDICATION

This thesis is dedicated to my wife, Jen. I would not have been able to complete this journey without your continued support. You have been by my side since medical school and your unwavering love has allowed me to get through even the most difficult times. I love you more than anything in the world. Thank you for always being there for me.

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ABSTRACT

Application of a Mastery Learning, Error Management Training Curriculum to Improve Surgical Fasciotomy Performance

Brenton R. Franklin, MD, 2020

Thesis directed by Steven Durning, MD, PhD, Director, Graduate Programs in Health Professions Education, Department of Medicine; Anthony Artino, PhD, Deputy Director, Graduate Programs in Health Professions Education, Department of Medicine; and E. Matthew Ritter, MD, Vice Chair of Education, Department of Surgery

Purpose: The purpose of this thesis is to evaluate a new curricular approach for the procedural training of a lower extremity fasciotomy. The proposed curriculum evaluates simulation-based mastery learning using error management training without dedicated procedural practice.

Methods: A mastery learning based error management training curriculum for lower extremity fasciotomy training was developed and tested with novice surgical residents. The effects of the curriculum on overall fasciotomy performance were assessed before and after training.

Results: All surgical residents had minimal fasciotomy experience prior to training and pre-testing showed overall poor performance. After completing the curriculum, learners

demonstrated significant improvement in fasciotomy performance evidenced by near perfect fasciotomy performance. The overall effect was very large and the total time commitment was less than 3 hours.

Conclusions: Implementation of an error management fasciotomy curriculum based on deliberate practice and mastery learning theory results in significant improvement in fasciotomy technique without reliance on repeated procedure performance nor clinical fasciotomy exposure. This curriculum is an option for surgical trainees lacking fasciotomy training during residency.

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ABBREVIATIONS

LEF – Lower Extremity Fasciotomy

CS - Compartment Syndrome

FIRE – Fasciotomy Improvement through Recognition of Errors

MCQ – Multiple-choice question

SBML – Simulation-based mastery learning

EMT – Error management training

WRNMMC – Walter Reed National Military Medical Center

PGY – Postgraduate year

CHAPTER 1: Introduction

Background

Compartment syndrome occurs due to increases in volume inside a fixed space, resulting in increased pressure. The increased pressure eventually inhibits blood flow resulting in ischemia of the enveloped tissue.[1,2] Although compartment syndrome can occur in the buttock, abdomen, and essentially all extremities, the lower extremity is most commonly affected.[1,3,4] Some of the common causes of compartment syndrome include long bone fractures, vascular injury, burns, hemorrhage and resuscitation.[1] After making the diagnosis, urgent decompressive lower extremity fasciotomy (LEF) is required. Delay in surgery prolongs ischemia time and has been shown to increase morbidity and mortality of trauma patients.[2-5] Regardless of timing, the accuracy and completeness of the LEF is imperative. The anterior compartment is the most vulnerable to compartment syndrome, and the most commonly missed; patients requiring revision of a fasciotomy also have increased morbidity and mortality.[1,4] In addition, limited fasciotomy of all 4 compartments has been associated with delayed compartment syndrome.[6]

The pathophysiology of compartment syndrome is well documented despite how challenging it can sometimes be to make the diagnosis, especially in an unconscious trauma patient.[2] Often, surgical teams are not afforded the time for serial examinations due to transport and a prophylactic LEF is required.[4] Combat scenarios and trauma patients injured in theater often present to forward surgical hospitals where damage control surgeries are performed and patients are expeditiously transferred to more capable facilities. After transfer to the new facility, deployed surgeons are responsible for evaluating the completeness of the fasciotomy. This system is used to bring medical assets closer to the point of injury in order to perform lifesaving damage control operations. However, it also creates a situation where the effects of inadequate or

improper fasciotomy are compounded. The longer a casualty goes without a needed, properly performed fasciotomy, the greater the likelihood of muscle necrosis, limb loss and death.[4]

Despite fasciotomies being a straightforward procedure used for the treatment and prophylaxis of compartment syndrome and the potentially devastating consequences with delayed or missed diagnosis, there is no consistent LEF training across surgical residencies and fellowships. Further, on average, the current graduating general surgery resident performs less than one LEF for trauma during their entire residency training.[7,8] This gap in needed education on compartment syndrome is amplified for newly graduating military surgeons who lack this necessary wartime skill and often deploy within weeks to months after graduation. These surgeons are frequently deployed to forward units where initial fasciotomy is needed and where inadequate training results in incomplete procedures. For example, I (BF) graduated general surgery residency having performed a total of three LEFs, one of which was during a cadaver training course. I (BF) then deployed three months after graduation to a location where I was the only general surgeon and was responsible for taking care of approximately 500 multinational forces with no immediate backup. There was no supplemental training prior to deployment and my comfort level with performing a LEF was quite weak.

Of fasciotomies performed in the deployed setting between 2005-2006, 17% required revision at the next echelon of care. The most common flaws were inadequate fascial incision length (63%) and failure to open a compartment altogether (41%) which were associated with increased rates of muscle excision, limb loss and death.[4] Moreover, studies have demonstrated that military surgeons do not have time to practice wartime surgical skills when not deployed and succumb to inevitable skill degradation.[9] There is not only a baseline need to teach surgeons how

to properly perform a LEF, but skill maintenance may also be needed for pre-deployment training of surgeons who are not facile with lower extremity fasciotomies.

Notably, the procedural deficiencies for LEF performance span all surgeons and are not insulated to new graduates. In a targeted needs assessment, we evaluated simulated fasciotomies performed on synthetic leg models that were part of a routine pre-deployment training course. These fasciotomies were performed by surgeons immediately before deployment and before any further fasciotomy training was undertaken. The results of this study mirrored those found in previous literature and highlighted the most common errors.[10] Additionally, Mackenzie et al found that only 4 of 10 experts were able to correctly perform a LEF and release all four compartments.[11] This is further evidence that current training and baseline knowledge is inadequate for the deploying surgeon. In today's graduate medical education context, there is no feasible way to increase the number of patients needing fasciotomies performed during residency training. Because of this, there is a considerable need for training to ensure surgeons have the necessary tools prior to deployment.

There have been multiple attempts to fix this need for additional fasciotomy education starting in 2007 with Kragh et al. who studied deployed surgeons before and after didactic fasciotomy training. This study showed that their training resulted in a decrease in mortality and revision fasciotomies.[12] Shackelford et al. developed a trauma-relevant surgical performance assessment that can be used to evaluate a surgeon's knowledge, procedural steps and technical skill.[13] Fasciotomy technical skill was tested and found to improve with a 1-day intensive training course. However, this course only briefly introduced fasciotomy techniques as a small part of a course more focused on vascular exposure. Furthermore, completion of this course only resulted in 33% accuracy for LEF performance immediately following training. Although their

efforts should be applauded, there is still a pressing need for effective and durable fasciotomy training.

Simulated model and mannequin-based training has been shown to improve knowledge and technical skill of trauma related procedures.[14,15] Additionally, intensive surgical training courses have been found to improve self-confidence, knowledge and procedural skill.[13,16] These points can be utilized to create a LEF simulation training curriculum grounded in educational theory using commercially available fasciotomy leg models. The ideal curriculum would result in nearly perfect fasciotomy performance as anything less than perfect results in increased patient (warfighter) morbidity and mortality. Desired outcomes would also be durable due to the high deployment tempo and the length of deployments. Importance also needs to be placed on the ability to not only perform, but identify and propose corrective action for any and all incorrectly performed fasciotomies.

Instructional Design Guided by Educational Theory

A proficiency curriculum based on mastery learning principles has been found to have positive training outcomes and durability when compared to informal instruction or short intensive training courses like those listed above (i.e. boot camps, single day training courses).[17] Introduced almost 60 years ago, mastery learning is based on the principle that learners are able to attain a certain level of performance (mastery) given enough time and practice.[18] Prior to instructional design of a mastery learning curriculum, learning objectives are broken down into their component parts, also known as educational units. Education units are mapped sequentially and typically build on one another. A mastery standard for each educational unit is determined and set at what would constitute expert performance, or result in an "A" grade.[19] Repeated practice of each educational unit is required until the standard is met, and before advancing to the

next educational unit. The amount of time required to attain the mastery standard is variable and learner specific; however, given enough time and practice, all learners can achieve mastery. Mastery learning differs from traditional teaching/training which typically measures the amount a person learns over a set period of time, and is independent of desired outcome.

Mastery learning principles are grounded in deliberate practice theory which differs from regular practice for multiple reasons. Specifically, deliberate practice requires the learner to engage in purposeful effort focused on improvement of a well-defined task (educational unit)[20]. Performance outcomes need to be clear and objective so the participant can engage in goal directed practice. There should be immediate performance feedback to help the learner guide repeated iterations of deliberate practice until the mastery standard has been met.[20] In order to limit fatigue and maintain concentration, deliberate practice training sessions should be limited to less than one hour.[20]

When trainees engage in deliberate practice using mastery learning theory, outcomes are superior when compared to other methods of instruction.[17] Furthermore, simulation-based mastery learning (SBML) has been found to be more efficient and consistent than traditional in-hospital training for procedural skills.[21] Attaining proficiency (mastery) has also shown to decrease operative time in conjunction with decreased patient complications and morbidity.[22,23] SBML is ideal for teaching fasciotomies to deploying surgeons because of its durability and skill retention seen at 12 months after initial instruction.[24,25] This is favorable as most fasciotomy learners typically don't perform this procedure immediately after training.

A further benefit of simulation learning is the low-stakes environment of a simulation lab where mistakes and errors are never a direct threat to patients. The repetitive practice of individual education units employed in mastery learning allows learners to continually make

mistakes until the mastery standard has been met. Unfortunately, procedural tasks are typically taught (traditional or mastery learning approach) using an error avoidance methodology and traditional LEF training programs, whether clinical or simulated, have focused on error prevention/avoidance. This methodology "aims at erecting a barrier between the action and the error, that is, errors are eliminated before they occur."[26] The emphasis is placed on correct performance and avoids errors during training which prevents learners from interacting with potential pitfalls.

This contrasts with error management training (EMT) which focuses on, and even encourages, errors during training. EMT has a less structured learning environment that forces learners to interact with errors in order to find appropriate solutions and prevent the downstream consequence of the error. In EMT, "errors should not be avoided but explicitly incorporated in training; trainees should be given ample opportunities to make errors during training and to learn from them."[26] As mentioned, deployable surgeons need to not only know how to properly perform a LEF, but higher echelons of care are responsible for evaluating the completeness of fasciotomies which makes EMT an attractive option.

EMT was initially incorporated in software skills training but has also demonstrated encouraging results when applied in medical simulation training. It was shown to be non-inferior to traditional teaching methods for immediate recall and showed superior retention and adaptive task transfer at 30 days after instruction.[27] Adaptive task transfer involves applying a "learned skill to novel problems that required development of new solutions,"[28] and is particularly attractive for training surgeons in the deployed setting. The destructive nature of modern weaponry results in massively distorted and complex anatomy that requires skill

adaptation to ensure optimal results. This distortion can be compounded with attempting to evaluate and revise previously performed fasciotomies.

Curriculum Design

Merging SBML and EMT as the backbone of an educational curriculum for LEF training has the potential to exploit strengths from both instructional approaches. However, using mastery learning as part of a simulation LEF curriculum would involve repeated procedures on either cadaveric (difficult to procure) or simulated calf models (prohibitively expensive). Furthermore, this curricular approach does not guarantee errors are encountered by the learner which is important to error recognition and EMT. The question remains, how can both of these seemingly ideal instructional approaches be simultaneously incorporated into a LEF training curriculum?

The LEF is not a technically demanding skill and only requires use of a scalpel and scissors. Procedural deficiencies are usually due to improper fasciotomy knowledge and not a deficiency in technical skill. Therefore, designing a SBML curriculum for this particular non-complex psychomotor task may not be best suited for repeated psychomotor practice to technical proficiency, but rather sequential cognitive educational units focused on fasciotomy knowledge. This curriculum and training methodology would replace repeated LEF performance with repeated evaluation of correctly and incorrectly performed fasciotomies. The training would follow tenants of EMT where learners must be able to accurately recognize right versus wrong, as well as propose corrective action for procedural errors. Specifically, if learners are able to recognize all errors of a non-complex procedure and correctly propose corrective actions to a mastery standard, then they may be able to successfully perform the procedure without psychomotor training.

This curriculum is a novel approach to simulation procedural training that may have implications for training of other psychomotor tasks. Additionally, it can fill a needed void in graduate medical education due to the low volume of fasciotomy procedures being performed by graduating residents. Success of this curriculum may even curtail the need for residents to perform a single LEF as part of their training. The curriculum can also be applied to graduated surgeons with pending deployments, omitting the need for increased operative volume or cadaver-based education. The biggest and most important downstream effect of this curriculum is the potential for improved patient outcomes, namely decreasing morbidity and mortality in our injured service members.

The proposed thesis takes a unique approach to SBML that overcomes the aforementioned logistic and financial obstacles. Specifically, the study evaluates a SBML fasciotomy EMT curriculum applied to surgeons performing a lower leg fasciotomy. Our research question was to evaluate whether using cognitive exercises without repeated, or even isolated procedural practice, would result in improved surgical performance. Our hypothesis is that applying this mastery learning framework using a cognitive based EMT approach will translate into improved surgical fasciotomy performance when compared to pre-training ability.

CHAPTER 2: Piloting the FIRE: A Novel Error Management Training Simulation Curriculum for Fasciotomy Instruction

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Abstract

Background: Multiple studies have demonstrated poor performance of lower extremity fasciotomy (LEF), highlighted by missed and/or inadequately released compartments. Incorporating error management training into surgical simulation has been promoted as a way to gain deeper understanding of procedural errors and overall performance. The purpose of this study was to evaluate LEF performance using a Fasciotomy Improvement through Recognition of Errors (FIRE) simulation training curriculum to train novice surgical trainees.

Methods: A mastery learning based error management training curriculum was developed, and surgical residents were enrolled and pre-tested with a multiple-choice question (MCQ) written test, and a simulated fasciotomy using a lower leg model. Each trainee then watched a 15-minute narrated PowerPoint followed by two rounds of fasciotomy error recognition and management training exercises to a mastery standard. During each round, trainees performed hands-on assessment of unique fasciotomy leg models containing a variable number of procedural errors. They were required to identify and propose corrective action for all errors. Serial rounds of remediation were implemented until the mastery standard was attained on both error identification rounds. All trainees were post-tested with the same MCQ and another simulated fasciotomy.

Results: All 14 residents had minimal experience with only 0.3 +/- 0.6 fasciotomies performed prior to instruction. There were 3 +/- 1.6 missed or inadequately released compartments on the pre-test. Residents examined 14 +/- 2.5 legs, including an additional 2 +/- 2.5 legs during

remediation to attain mastery. All residents demonstrated significant improvement following the FIRE curriculum for the MCQ (57% +/- 16% vs. 78% +/- 13%; p=0.01; Cohen's *d* = 1.4), fasciotomy score (10 +/- 7.1 vs. 28 +/- 1.9; p<0.001; Cohen's *d* = 3.6) and achieving a complete fasciotomy (14% +/- 36% vs. 93% +/- 27%; p<0.001; Cohen's *d* = 2.5). Only a single cumulative compartment was missed on post-testing.

Conclusion: Implementation of a mastery learning based error management training curriculum for fasciotomy simulation training results in significant improvement in fasciotomy technique without reliance on repeated procedure performance nor clinical fasciotomy exposure. This curriculum is an option for surgical trainees lacking fasciotomy training during residency.

Introduction

Compartment syndrome (CS) occurs due to increases in volume inside a fixed space, resulting in increased pressure that can result in ischemia of the enveloped tissue.[1,2] The lower extremity below the knee is most commonly the site of CS requiring intervention. After making the diagnosis of CS, urgent decompressive lower extremity fasciotomy (LEF) is required, and delays in surgery prolong ischemia time with resultant morbidity and mortality. [2-5] Regardless of timing, the accuracy and completeness of the LEF is imperative as patients requiring revision also have increased morbidity and mortality.[1,4] In addition, inadequate release of all four leg compartments has been associated with delayed compartment syndrome.[6]

Despite LEF being a relatively straightforward procedure, there is no consistent training for this procedure across surgical residencies and fellowships. Further, on average, the current graduating general surgery resident performs less than one LEF for trauma during their entire residency training.[7,8] This gap in needed education on CS and performance of LEF is further amplified for newly graduating military surgeons who lack this necessary wartime skill and often deploy within weeks to months after graduation.

Of fasciotomies performed in the deployed setting between 2005-2006, 17% required revision at the next echelon of care. The most common flaws were inadequate fascial incision length (63%) and failure to open a compartment altogether (41%) which were associated with increased rates of muscle excision, limb loss and death.[4] The procedural deficiencies for fasciotomy performance span all surgeons and are not insulated to new graduates.[10,11,29,30]

In a targeted needs assessment, we evaluated simulated fasciotomies performed on synthetic leg models that were part of a routine pre-deployment training course. LEFs were

performed by surgeons immediately before deployment and the results of this study mirrored those found in previous literature and highlighted the most common errors.[10] These errors included inadequate length and location of the skin incisions, inadequate length of fascial incisions, and failure to open a compartment altogether. Additionally, in civilian hospitals, 26% of fasciotomies performed following trauma missed at least one compartment, and 44% of fasciotomies for burns required revision after transfer to a higher echelon of care.[29,30] Most concerning, Mackenzie et al found that only 4 of 10 experts were able to correctly perform a LEF and release all four leg compartments.[11]

There is currently no feasible way to increase the number of fasciotomies performed during residency training. Simulation offers one potential solution, as model and mannequin-based simulation training has been shown to improve knowledge and technical skill of trauma related procedures.[31,32] Additionally, intensive surgical training courses have been shown to improve self-confidence, knowledge and procedural skill.[13,16] The ideal curriculum would result in nearly perfect fasciotomy performance. Thus, the purpose of our study was to create and test a simulation fasciotomy training program for surgical trainees that results in improved technical competency.

A curriculum based on mastery learning principles has previously been shown to have positive training outcomes and durability when compared to informal instruction or short intensive training courses.[17] Mastery learning principles are grounded in deliberate practice theory, which argues that expert performance is based upon the deliberate (effortful) practice with feedback of the component parts (educational units) of an activity to be mastered (e.g. fasciotomy).[20] When trainees engage in such deliberate practice using this methodology, outcomes were superior when compared to other means of instruction.[17] Furthermore,

simulation-based mastery learning (SBML) has been found to be more efficient and consistent than traditional in-hospital training for procedural skills.[14] SBML has also shown to decrease operative time in conjunction with decreased patient complications and morbidity.[15,23] SBML is ideal for teaching fasciotomies, particularly for deploying surgeons, because of its durability and skill retention seen at 12 months after initial instruction.[24,25]

The majority of curricula for SBML involve repetitive practice of educational units using an error avoidance methodology. This methodology "aims at erecting a barrier between the action and the error, that is, errors are eliminated before they occur."[26] This contrasts with error management training (EMT) which focuses on, and even encourages, errors during training which is consistent with deliberate practice theory. In EMT, "errors should not be avoided but explicitly incorporated in training; trainees should be given ample opportunities to make errors during training and to learn from them."[26] EMT was initially incorporated in software skills training but has also demonstrated encouraging results when applied in medical simulation training. It was shown to be non-inferior to traditional teaching methods for immediate recall and showed superior retention and adaptive task transfer at 30 days after instruction.[27,28] Surgeons, including military, need to not only know how to properly perform a fasciotomy, but higher echelons of care are responsible for evaluating the completeness of fasciotomies which makes EMT an even more attractive option.

Merging SBML and EMT as the backbone of an educational curriculum for LEF training has the potential to leverage strengths from both instructional approaches and is consistent with deliberate practice theory whereby a coach or mentor provides immediate feedback. However, using mastery learning as part of a simulation fasciotomy curriculum would involve repeated procedures on either cadaveric (difficult to procure) or simulated calf models (prohibitively

expensive). Furthermore, this curricular approach does not guarantee errors are encountered by the learner which is important to error recognition and EMT.

The LEF is not a highly demanding psychomotor skill and procedural deficiencies are usually due to inadequate procedural or anatomical knowledge. Therefore, designing a SBML curriculum for fasciotomy training may not be best suited for repeated psychomotor practice to technical proficiency. Rather, a SBML curriculum with sequential cognitive training exercises focused on fasciotomy procedural knowledge is more likely to be effective.

This curriculum and training methodology could replace repeated fasciotomy performance with the tenants of EMT where learners must be able to accurately recognize right versus wrong, as well as propose corrective action for procedural errors. Specifically, if learners are able to recognize all errors of a non-complex procedure and correctly propose corrective actions to a mastery standard, then they may be able to successfully perform the procedure without additional psychomotor training. Thus, the curriculum shifts focus away from repeated fasciotomy practice (psychomotor skill) and solely onto error identification (cognitive training).

This study evaluates a SBML Fasciotomy Improvement through Recognition of Errors (FIRE) curriculum applied to surgical trainees to determine if there is improvement in LEF performance. Our hypothesis was that applying this mastery learning framework using only EMT exercises, without reliance on additional procedural practice, will translate into improved surgical fasciotomy performance when compared to pre-training ability.

Methods

This study is a single-group, pre-post design that was approved by the Walter Reed National Military Medical Center (WRNMMC) Institutional Review Board, protocol number WRNMMC-2017-0104.

Subjects

A convenience sample of residents at WRNMMC was chosen for recruitment in the study. Subjects were identified and voluntarily enrolled to complete the FIRE curriculum after informed consent was obtained. Inclusion criteria were surgical residents or fellows at any level of training. Specialties included, but were not limited to, general, orthopedic, vascular, and OB/GYN. Individuals who have already completed a SBML and/or EMT fasciotomy curriculum (we are not aware of any such curriculum) were excluded from participation. Individuals who have completed other fasciotomy training courses were included with previous training data documented.

Equipment

Fasciotomy models containing a variable number of errors were chosen from the set of legs catalogued by our group as part of a needs assessment for the FIRE curriculum.[10] These legs were used for all rounds of error identification. Pre-testing and post-testing were performed on new and identical leg models. The standardized fasciotomy leg (Figure 1) costs about $750 and is commercially available (Operative Experience; North East, MD, USA). Required basic surgical supplies include a marking pen, scalpel, scissors and various retractors (Army-Navy, Weitlaner, etc.). These items were borrowed from our simulation center.

FIRE Curriculum

All enrolled subjects underwent the FIRE curriculum (Figure 2). After confirmation of eligibility, residents were voluntarily enrolled in the study and informed consent was obtained. Basic demographic information and fasciotomy experience were recorded. Initially, each resident was pre-tested with a 13-question multiple-choice question (MCQ) written test. This test was created specifically for this study and has not been previously used. The MCQ focused on basic knowledge of CS including its pathophysiology, diagnosis and surgical treatment. Each question was developed using information pulled from surgical textbooks in order to represent the general knowledge expected from a practicing surgeon. Once this pre-test was completed, residents were oriented to a new fasciotomy leg model and available surgical instruments for a simulated fasciotomy pre-test. They were then asked to perform a two-incision, four-compartment LEF. The test proctor was only available to assist with retraction when prompted. There was no time limit for either test.

Fasciotomies were scored using a previously developed rubric (Table 1) that evaluates comprehensive procedural performance with a maximum score of 30.[33] Each leg was also evaluated solely on the basis of the number of compartments released, including the adequacy of released compartments. A fasciotomy was considered "complete" if all 4 compartments were opened and adequately released (fascia opened ≥100% of the length of an appropriate skin incision), regardless of other scored metrics. These fasciotomy legs were catalogued for potential use in future iterations of error identification.

After pre-testing, each resident was required to watch a 15-minute narrated LEF PowerPoint prior to error identification. They were given unlimited access to the PowerPoint and

could view it as many times as desired throughout the curriculum. Residents could utilize other learning resources; however, no other fasciotomy materials were supplied.

Each resident then completed two rounds of error identification. During each round, residents engaged in hands-on assessment of six previously performed fasciotomy leg models with a variable number of errors, to include one leg without errors. Using the scoring rubric as the standard, residents were required to identify all errors and propose corrective action for each error. Findings that were considered errors included anything that would prevent a fasciotomy from being complete (see definition above). These metrics included skin incision length and location, fasciotomy length, and visualization of pertinent structures. These metrics were chosen as they represent majority of errors that lead to incorrect fasciotomy performance. Secondly, understanding the etiology of the error committed requires knowledge of correct fasciotomy technique.

The first round was "assisted," and learners could use either a member of the research study team or a fasciotomy checklist while assessing legs for errors. The second round was unassisted and required error identification without any resources. There was no time limit, and each round was complete when a list of errors and corrective action was proposed for all errors present. Round 1 error identification performed without a proctor, and all of round 2 required errors to be written down for later review by a research study team member.

For residents choosing to complete the round 1 (assisted) without a proctor, mastery was attained if all errors were identified. Unsatisfactory performance required remediation with three new fasciotomy models, again with one containing no errors. Round 1 with a proctor guaranteed all errors were identified and discussed, thus preventing a need for remediation. During round 2 (unassisted assessment), performance met the mastery standard when all errors were correctly

identified. Those residents who did not attain the mastery standard were remediated in identical fashion with three new fasciotomy models. Remediation with three additional models was continued until all errors were correctly identified. New and unique error-containing legs were used for all rounds of identification.

After completion of the curriculum, all residents were post-tested a minimum of one day later in an identical fashion as the pre-test with both an MCQ test (the same questions as the pre-test) and a new simulated fasciotomy. Both tests were scored with the same rubric as above (Table 1). After post-testing, study subjects were asked to complete a short survey based on fasciotomy confidence and performance ability.

All stages of the study were separated by at least one day. Specifically, pre-testing, narrated PowerPoint viewing, each error recognition or remediation round, and post-testing all occurred on separate, but not necessarily consecutive days. Participants could voluntarily withdraw from the study at any time.

Statistical Analysis

Normally distributed, continuous variables were compared between groups using paired Student's t-test. All p-values less than 0.05 were considered statistically significant. All values are reported as mean +/- standard deviation unless otherwise noted. Effect size was calculated using Cohen's *d*. Effect sizes of 0.1-0.3 were considered small, 0.4-0.6 medium, 0.7-1.0 large, and >1 very large. All statistical analysis was performed using SPSS V25 statistical software (SPSS Inc., Chicago, IL).

Results

A total of 14 surgical residents were enrolled (12 general surgery, 2 orthopedic surgery). There were 5 female and 9 male trainees. Residency training level ranged from PGY1 to PGY4 (2 PGY1, 3 PGY2, 6 PGY3, 3 PGY4). Only three participants had previously performed a LEF (0.3 +/- 0.6; range 0-2). Three residents noted having previous cadaveric fasciotomy training (2 PGY1, 1 PGY3), none of which used a SBML nor EMT curriculum. Only one resident subjectively felt at baseline that they could perform a LEF.

On fasciotomy pre-testing, there were 1.3 +/- 1.2 missed compartments, and only 2 residents correctly and completely released all four compartments. There were 3 +/- 1.6 cumulative missed or inadequately released compartments. The deep posterior followed by the anterior were the most commonly missed compartments at 8 and 6 times, respectively. The lateral was missed three times and superficial posterior compartment missed one time

During error identification, residents examined 14 +/- 2.5 legs (range 12-21) with 2 +/- 2.5 of those legs (range 0-9) examined during remediation. Eight of 14 residents (57%) required at least one round of remediation (0.7 +/- 0.8; range 0-3). The majority of participants (12 of 14; 86%) opted to have a research team member present during the assisted round of error identification. Two of 14 (14%) residents who performed round 1 without assistance required a single iteration of remediation after round 1.

There were statistically significant increases seen when comparing pre- and post-test scores across nearly all measures (Table 2 and Figure 3). Notably, there were significant differences in MCQ scores (57% +/- 16% vs. 78% +/- 13%; p=0.01; Cohen's d = 1.4). More notably, there were significant differences in fasciotomy scores (10 +/- 7.1 vs. 28 +/- 1.9;

p<0.001; Cohen's *d* = 3.6), missed compartments (1.3 +/- 1.2 vs. 0.07 +/- 0.3; p=0.003; Cohen's *d* = 1.4), cumulative missed or inadequately released compartments (3 +/- 1.6 vs. 0.07 +/- 0.3; p<0.001; Cohen's *d* = 2.6), and achieving a complete fasciotomy (14% +/- 36% vs. 93% +/- 27%; p<0.001; Cohen's *d* = 2.5). As noted, the effect sizes of the learning intervention (Cohen's *d*) were considered very large.

There was no difference in time to complete the fasciotomy between pre-testing and post-testing (720s +/- 268s vs. 613s +/- 138s; p=0.23). Cumulatively, there was only a single compartment missed (deep posterior) on post-test, and there were no incompletely released compartments.

The average time commitment required for each resident to complete the study, including pre- and post-test, ranged between 2-3 hours. The time to complete the entire study was 113 +/- 78 days (range 8-194).

The post training survey response rate was 100%. All respondents had more confidence and 13 of 14 (93%) felt they could perform an unsupervised LEF in the operating room (p<0.001). Thirteen of the 14 respondents (93%) felt they could teach someone how to perform a fasciotomy and all 14 would recommend this curriculum to their peers.

Discussion

The LEF is a straightforward procedure that is often performed incorrectly resulting in increased morbidity and mortality. Limited clinical exposure during graduate medical education results in surgeons who often lack the knowledge and technical skill required to correctly perform this operation. This study aimed to create a simulation fasciotomy training curriculum (FIRE) for surgical residents as a viable substitute for the paucity of fasciotomy procedural volume to determine if such cognitive training would improve subsequent LEF performance. The FIRE curriculum drew from two established learning methodologies, mastery learning and error recognition/management, both of which are consistent with deliberate practice theory. Unique to the FIRE curriculum was the fact that it did not rely on repeated, or even isolated procedural practice. This was chosen due to the relative simplicity of a fasciotomy coupled with the untenable cost of repetitive psychomotor training.

Residents of all training levels were included to span the breadth of baseline fasciotomy knowledge and exposure. Despite this, the average number of fasciotomies performed in the clinical setting was still less than one, with 11 residents having never performed a LEF. Baseline pre-testing testing also showed that 3 of the 4 compartments were either missed or inadequately released, and only two residents could perform a complete LEF. Notably, only one of the three residents with previous fasciotomy training could perform a complete LEF. After completing the FIRE curriculum, we saw not just a statistically discernible, but clinically significant improvement in LEF performance with very large Cohen's *d*'s which is unusual for educational studies. Thirteen of 14 residents performed a complete LEF with only a single compartment missed after training which is superior to all previous fasciotomy training courses.[11-13,16]

The total time required for the FIRE curriculum was short with all residents needing no more than three hours for completion. During this time, they had exposure to, and evaluated an average of 14 fasciotomies. This is an exponential increase in the typical fasciotomy experience of a trainee during residency. The minimal time commitment also likely overshadows what would be required to perform that same number of fasciotomies in a clinical setting. The FIRE curriculum also utilizes artificial leg models and omits the need for cadavers which are often difficult to procure for majority of institutions. These leg models are customizable and can be used for many iterations of training courses.

It is also worth noting the significant difference in both fasciotomy and MCQ test scores following implementation of the FIRE curriculum. All effect sizes were considered very large. With minimal resources and time commitment, we believe that the FIRE curriculum is a practical simulation training solution with immediate outstanding results that has the potential to supplant strict reliance on clinical fasciotomy exposure.

There have been many studies incorporating SBML, but much fewer evaluating EMT for medical or surgical simulation. In an early study, error identification was found to improve when trainees spent more time assessing their results during simulation training for total knee arthroplasty.[34] This group noted that specifically focusing on errors during training does not affect technical outcomes and improves the learner's ability to identify obvious errors. In a separate study, medical student knot tying ability improved only after watching videos of both incorrect and correct technique.[35] Although there was statistical improvement in ability, the overall knot tying proficiency of each medical student was not described. Incorporating EMT into central venous catheter placement resulted in similar outcomes showing no detriment in

immediate outcomes, but overall improved skill retention as well as adaptive transfer to new skills at 30 days.[27]

Over the last decade, there has been a slow, but gradual push to further incorporate EMT into simulation. DaRosa and Pugh believed that it was imperative to utilize this methodology in surgical training.[36] They stated that focus should shift away from error avoidance and recommended that error-directed curricula be integrated into the simulation arena. This was followed by Gardner et al who believed that simulation training is optimized when errors are encouraged.[37] All previous studies have noted that simulation using EMT creates a safe learning environment where leaners can create a deeper understanding of the task at hand, as well as build a strategy for the emotional management of errors.

The FIRE curriculum pulled from previous studies and was designed to focus solely on error recognition. There was no time dedicated to skill practice, and we hypothesized that if trainees could recognize right versus wrong by identifying errors, this would result in the ability to correctly perform a fasciotomy. We also chose to use a mastery learning model to ensure trainees were held to the highest standard, and could accurately and consistently identify all errors in each fasciotomy model. Our study shows that repetitive error recognition without reliance on specific skill practice can result in improved procedural performance.

The impetus for this curriculum was based on the high incidence of incorrect or incomplete fasciotomies performed by deploying surgeons. Our study shows that minimal time and resources are required to successfully train novice surgeons correct fasciotomy technique. Because of the curriculum's success on surgical trainees, it is reasonable to anticipate FIRE would be successful for surgeons at any stage of their career. Using EMT may also be the optimal approach for fasciotomy instruction because of the potential for adaptive transfer. The

ability to transfer a newly learned skill to new problems is paramount for trauma patients requiring fasciotomy. The destructive nature of modern weaponry results in massively distorted and complex anatomy that requires skill adaptation to ensure a correctly performed fasciotomy. This distortion can be compounded when attempting to evaluate and revise previously performed fasciotomies for patients transferred to higher levels of care.

The FIRE curriculum was also chosen due to significant cost savings when compared to a typical SBML approach. Assuming the same number of legs were required per trainee, a mastery learning curriculum would have required 198 fasciotomy leg models. With each leg priced at $750, this would equate to a curriculum costing $148,500. The most legs evaluated by any one learner in the FIRE curriculum was 21 which equates to a savings of $132,750.

This approach is not meant to supplant hands-on skills practice and surgical training. However, its principles should be considered and employed when appropriate. Many surgical trainees graduate without a thorough understanding of common errors or complications encountered during many surgical procedures. Furthermore, residents often don't fully understand when or how to manage these complications. Simulation based EMT has the potential to increase this important fund of knowledge in a low-stakes environment. The ability for residents to interact with errors in this setting takes away any personalization that may be associated with real-life clinical errors, or the potential stigma and shame when presenting at a morbidity and mortality conference.

This is the first study that incorporates an EMT and SBML curriculum to a procedural task without the use of hands-on practice. The study shows that a surgical procedure can be correctly performed once trainees have demonstrated the ability to differentiate between correct and incorrect surgical performance. Although this approach is not generalizable to all surgical

procedures, it may be feasible for those that only require basic surgical skills. Using EMT with deliberate practice as a theoretical foundation could also be used for training outside of the medical field where errors have the potential for similarly dire outcomes (i.e. architecture, construction, electrical engineering, etc.)

There are several limitations to this study, most notably the convenience sample used to assess the feasibility and positive effects of this novel curriculum. However, it should be noted that even with the small number of subjects, we found statistically significant (and very large) learning effects after implementation of the FIRE curriculum. Another limitation was that our scoring rubric did not take into account all errors. The rubric was meant to be comprehensive but not exhaustive. Notable errors not accounted for included, but are not limited to, injury to the neurovascular bundle in the deep compartment, peroneal nerve injury, and exact orientation/location of skin incisions. In addition, the fasciotomy leg models used are not perfect replicas of exact human anatomy. This particular leg model was chosen as it is the most realistic model that is currently commercially available.

Finally, although majority of residents believed they could perform a LEF in the clinical setting, our study does not directly measure true surgical ability. The leg model used is only one of few commercially available for simulation training and may not perfectly reflect human anatomy and tissue handling. Future studies could examine this curriculum applied to a larger number of residents, including retention testing at 3-6 months. Retention testing can also incorporate testing on both the same fasciotomy leg model as well as fresh cadaver legs to better simulate a real-life clinical scenario.

Conclusion

Application of the FIRE curriculum with a group of novice surgical trainees resulted in demonstrable improvement in lower extremity fasciotomy procedural performance. Omitting hands-on practice and relying solely on cognitive exercises focused on error recognition represents a novel approach to the training of procedural tasks in surgery.

Figure 1. Fasciotomy leg model

Medial view

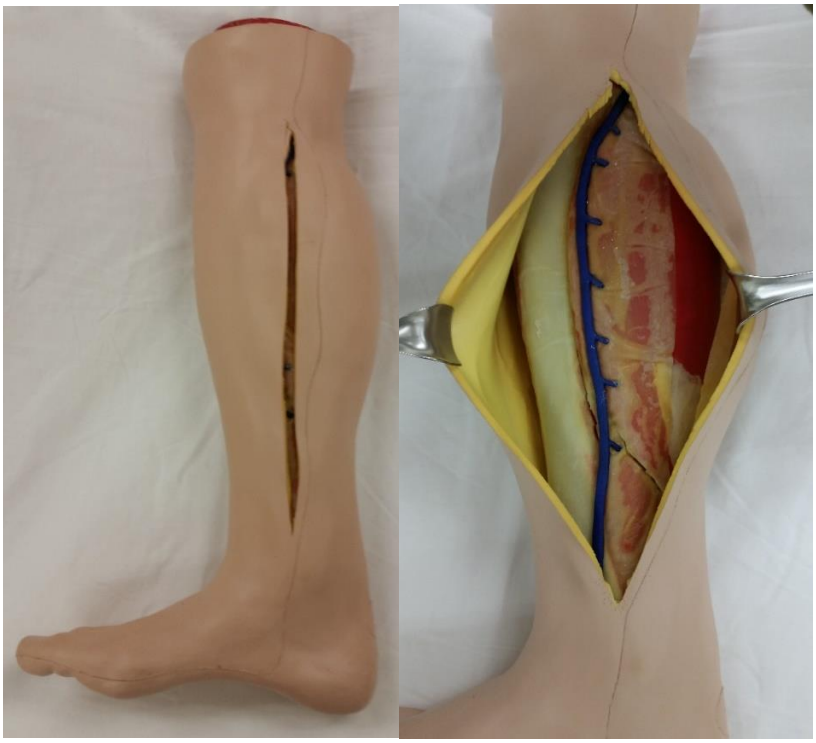

Figure 2. FIRE curriculum flowsheet

MCQ = multiple-choice question test, EMT – error management training

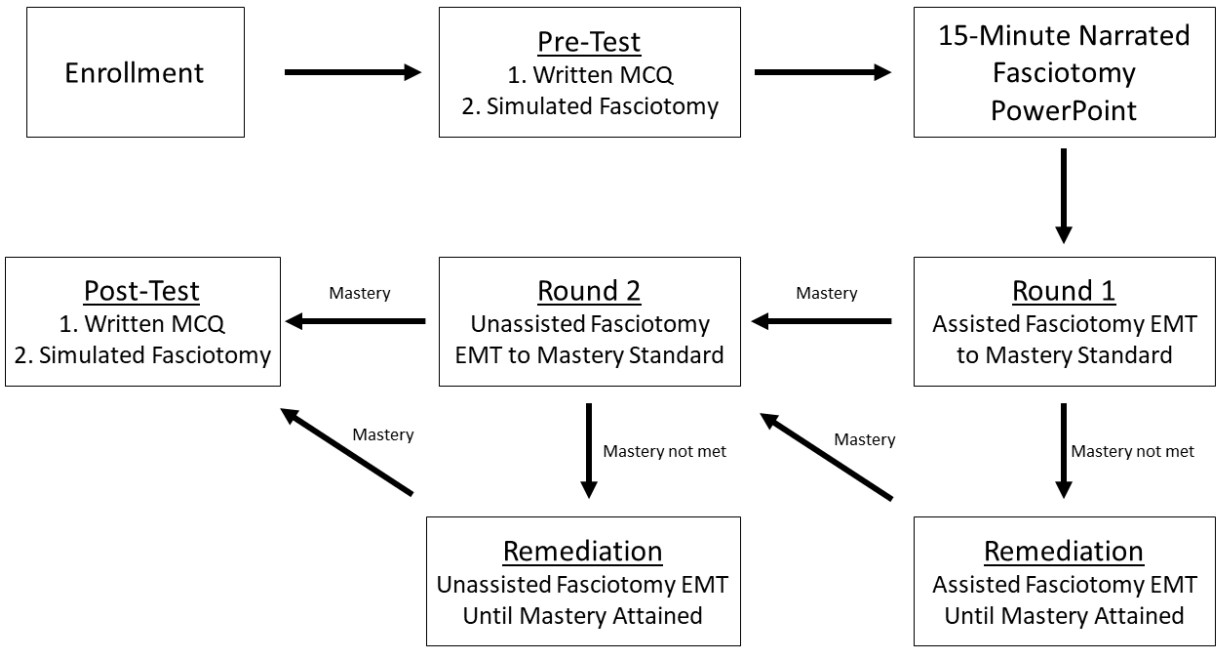

Figure 3. Pre/post-test comparison of outcomes following FIRE curriculum

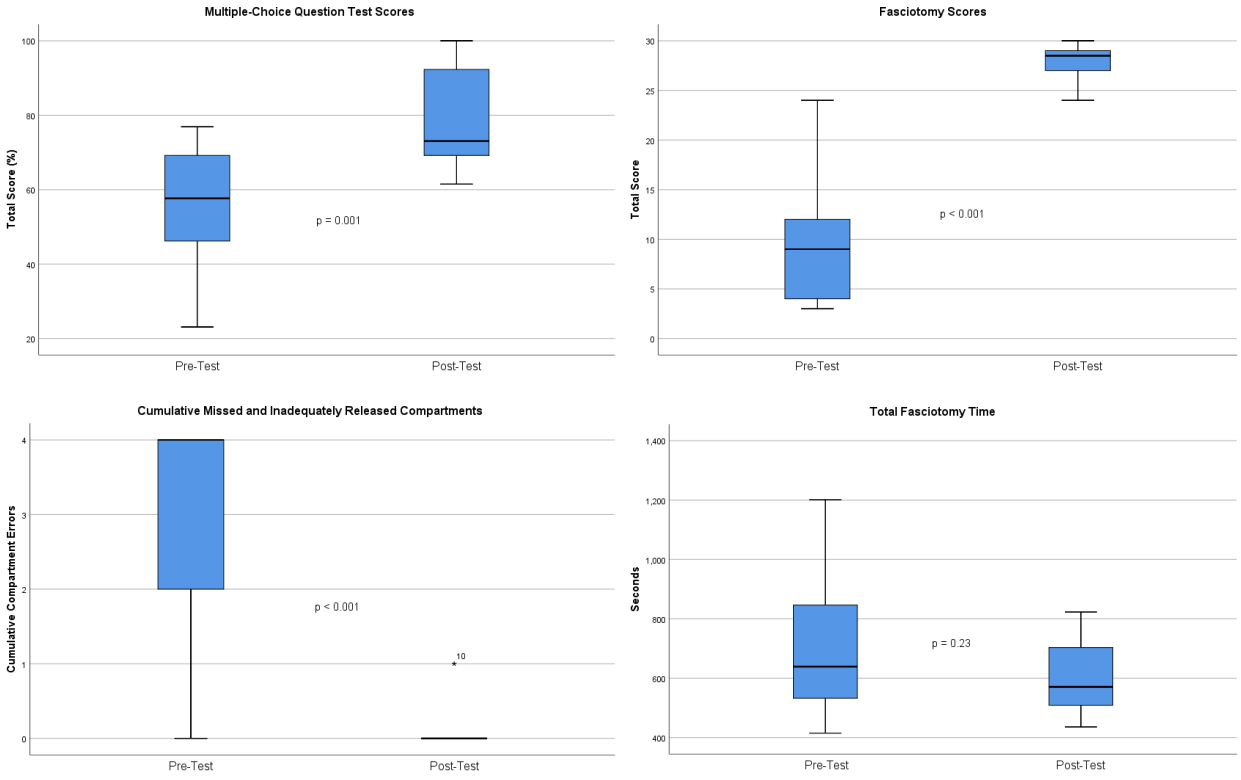

Table 1. Simulated fasciotomy scoring rubric

Each item worth one point (total 30 points). *Opens fascia ≥ 100% of the length of an appropriate skin incision

Lateral Skin Incision Marking

- Marks head of fibula proximally
- Marks lateral malleolus
- Marks the course of the fibula
- Marks incision one finger in front of the fibula (1.5 - 2.5 cm)
- Marks upper end of incision two fingers (3.0 - 5.0 cm) below the knee
- Marks lower end of incision two fingers (3.0 - 5.0 cm) above the lateral malleolus

Medial Skin Incision Marking

- Marks medial aspect of tibial plateau
- Marks medial malleolus
- Marks length of medial edge of tibia
- Marks incision line one thumb behind tibia
- Marks upper end of incision two fingers (3.0 - 5.0 cm) below tibial plateau
- Marks lower end of incision two fingers (3.0 - 5.0 cm) above the medial malleolus

Lateral Skin Incision

- Makes incision one finger in front of the fibula (1.5 - 2.5 cm)
- Upper end of incision is two fingers (3.0 - 5.0 cm) inferior to fibular head
- Lower end of incision is two fingers (3.0 - 5.0 cm) above the lateral malleolus

Lateral Fasciotomy

- Verbalizes/Identifies the correct location of the septum
- Makes transverse portion of H-shaped incision first across the septum
- Underruns fascia with closed scissors prior to opening
- Opens fascia with partially closed scissor tips
- Points tips of scissors away from the septum

Opens fascia completely* in anterior compartment

Opens fascia completely* in lateral compartment

Medial Skin Incision

Makes incision one thumb behind tibia (2.0 - 3.0 cm),

Upper end of the incision is two fingers (3.0 - 5.0 cm) inferior to tibial plateau

Lower end of incision is two fingers (3.0 - 5.0 cm) above the medial malleolus

Medial Fasciotomy

Verbally identifies and does not injure greater saphenous vein

Opens fascia completely* over the superficial compartment

Takes down the soleus bridge from the tibia to expose the deep posterior compartment

Opens the fascia completely* over the deep posterior compartment

Posterior tibial neurovascular bundle visible in the deep compartment

Table 2. Pre- and post-test metrics following FIRE curriculum

*All 4 compartments opened and adequately released (fascia opened ≥100% of the length of an appropriate skin incision). All values listed as mean +/- standard deviation. MCQ = Multiple-choice question

	Pre-test	**Post-test**	**p-value**
MCQ test score	57% (16)	78% (13)	0.001
Fasciotomy score (30 total points)	10 (7.1)	28 (1.9)	<0.001
Compartments missed	1.3 (1.2)	0.07 (0.3)	0.003
Missed or inadequately released compartments	3 (1.6)	0.07 (0.3)	<0.001
Complete* fasciotomy	14% (36)	93% (27)	<0.001
Fasciotomy time (seconds)	720 (268)	613 (138)	0.23

CHAPTER 3: Discussion

The lower extremity fasciotomy is a straightforward procedure that is often performed incorrectly resulting in increased morbidity and mortality. Limited clinical exposure during graduate medical education results in surgeons who lack the knowledge and technical skill required to correctly perform this operation. This thesis evaluated an EMT fasciotomy curriculum (FIRE) with novice surgical trainees at various levels of training. Residents of all training levels were included to span the breadth of baseline fasciotomy knowledge and exposure. Despite this, the average number of fasciotomies performed in the clinical setting was still less than one, with 11 residents having never performed a fasciotomy. Baseline pre-testing testing also showed that 3 of the 4 compartments were either missed or inadequately released, and only two residents could perform a complete fasciotomy. Notably, only one of the three residents with previous fasciotomy training could perform a complete LEF.

After completing the FIRE curriculum, we saw not just a statistically discernible improvement, but also a clinically significant improvement in LEF performance with very large effect sizes (Cohen's d) – effects that are unusual for educational studies. Residents also scored higher on the written multiple-choice question test which aimed to evaluate their basic knowledge of compartment syndrome including its pathophysiology, diagnosis and surgical treatment. There was also a very large increase in total fasciotomy scores which was used as a measure of their comprehensive procedural performance. Additionally, 13 of 14 residents performed a complete fasciotomy with only a single compartment missed after training which is superior to all previous fasciotomy training courses.[11-13,16] There were no inadequately released compartments on post-testing. These near perfect results highlight the potential impact and

effectiveness of the curriculum when applied to surgical trainees with minimal fasciotomy experience.

Although residents required an average of almost 4 months to fully complete the curriculum, the total time required for the FIRE curriculum was short with all residents needing no more than three hours for completion. During this time, they had exposure to, and evaluated an average of 14 fasciotomies. This is an exponential increase in the typical fasciotomy experience of a trainee during residency. The minimal time commitment also likely overshadows what would be required to perform that same number of fasciotomies in a clinical setting.

The curriculum was evaluated using surgical residents early in their training to determine if fasciotomy performance would improve independent of previous experience. Post-testing outcomes were near perfect and showed relatively little variance indicating that surgical residents can attain outstanding results after completion of the FIRE curriculum, even early in training. The successes of the curriculum may also suggest that this training could, or should be incorporated earlier during residency. Early mastery of this procedure allows for residents to correctly execute an uncommon procedure with greater confidence and technique which may result in improved patient outcomes.

Early implementation of the FIRE curriculum may also help with emotional growth of the resident. Simulation based EMT creates a safe learning environment where leaners can create a deeper understanding of the task at hand, as well as build a strategy for the emotional management of errors. Many surgical trainees graduate without a thorough understanding of common errors or complications encountered during many surgical procedures. Furthermore, residents often don’t fully understand when or how to manage these complications. Simulation based EMT has the potential to increase this important fund of knowledge in a low-stakes

environment. The ability for residents to interact with errors during simulation takes away any personalization that may be associated with real-life clinical errors, or the potential stigma and shame when presenting at a morbidity and mortality conference.

Theoretical Implications

This thesis aimed to create a simulation fasciotomy training curriculum (FIRE) for surgical residents as a viable substitute for the paucity of fasciotomy procedural volume to determine if such cognitive training would improve subsequent LEF performance. The FIRE curriculum drew from two established learning methodologies, mastery learning and error recognition/management, both of which are consistent with deliberate practice theory. Unique to the FIRE curriculum was the fact that it did not rely on repeated, or even isolated procedural practice. This is the first study that incorporates an EMT and SBML curriculum to a procedural task without the use of hands-on practice. This was chosen due to the relative simplicity of a fasciotomy coupled with the untenable cost of repetitive psychomotor training.

Our study showed that a surgical procedure can be correctly performed once trainees have demonstrated the ability to differentiate between correct and incorrect surgical performance. Although this approach is not generalizable to all surgical procedures, it may be feasible for others that only require basic surgical skills. Using EMT with deliberate practice as a theoretical foundation could also be used for training outside of the medical field where errors have the potential for similarly dire outcomes (i.e. architecture, construction, electrical engineering, etc.). Each of these fields is based upon scientific principles that require near perfect execution to prevent complications. A curriculum that allows learners to interact with errors may result in a deeper understanding of their respective field, and potentially improved execution of procedural tasks.

The FIRE curriculum yielded excellent results; however, could these outcomes also be achieved when applying similar EMT principles to more advanced surgical procedures? It is likely impossible to create hands-on simulation for all procedures due to limitations of technology, money, or both. The FIRE study showed that hands-on cognitive exercises alone resulted in improved overall procedural performance. This may indicate that a surgical procedure involves not just psychomotor skill/ability, but has heavy reliance on the cognitive domain. It also questions whether hands-on practice could be replaced with a different method of EMT cognitive exercises. For example, instead of evaluating error-ridden fasciotomy models, residents could watch and score videos of correct and incorrect fasciotomy performance. If they are able to identify errors similar to the FIRE curriculum, it is reasonable to think that their fasciotomy performance would also improve. If this is true, video-based EMT could potentially be harnessed for the training of other basic, or even complex procedures.

A large number of minimally invasive procedures are recorded, and within these recordings are likely numerous examples of errors and mistakes that will result in complications and/or suboptimal outcomes. These recordings could be used to create an EMT curriculum similar to the FIRE curriculum where trainees must be able to correctly identify correct versus incorrect technique. The downstream effect of this approach could again result in improved procedural performance as long as baseline fundamental skills are present (i.e. laparoscopic skill, suturing, cutting, etc.). No different than professional athletes watching film to improve future performance, surgeons may also benefit from similar exercises.

EMT also results in improved adaptive transfer which allows trainees to apply prior knowledge and formulate solutions to unique problems. It is impossible to know exactly how much adaptive transfer is gained with any one curriculum. Because of the similarities of certain

procedures, it is feasible to think that an EMT curriculum for any one procedure will result in some degree of improvement in similar types of cases. For example, EMT focused on a laparoscopic appendectomy might result in improved performance of a right hemicolectomy due to the related anatomy and potential complications.

The FIRE curriculum held trainees to a mastery standard, and all errors required identification prior to advancing through, and completing the curriculum. Prior studies have demonstrated robust durability and retention using mastery learning theory;[22,23] however, the FIRE curriculum used cognitive EMT exercises (educational units) in place of repeated psychomotor practice. It is unknown whether a lack of psychomotor practice will affect long-term retention. This simulation study also used fasciotomy leg models in place of cadaver specimens or clinical practice, and successful fasciotomy performance on human anatomy is unknown.

Military Relevance

The impetus for this curriculum was based on the high incidence of incorrect or incomplete fasciotomies performed by deploying surgeons. Our study shows that minimal time and resources are required to successfully train novice surgeons correct fasciotomy technique. Because of the curriculum's success on surgical trainees, it is reasonable to anticipate FIRE would be successful for surgeons at any stage of their career. Current recommended pre-deployment training involves cadaver-based training courses (ASSET, ASSET+, ATOM, Emergency War Surgery, etc.) whose aim is to broadly prepare surgeons to care for our injured servicemembers. The lower extremity fasciotomy is a core procedure in many of the courses listed above; however, post-testing reveals marginal performance.[16] The FIRE curriculum is an option for pre-deployment training that has demonstrated superior outcomes compared with all

previous training courses and does not involve cadaver procurement.[11-13,16] Minimal time is involved and the curriculum can be done anywhere with a small number of fasciotomy leg models resulting in cost-savings.

Using EMT may also be the optimal approach for fasciotomy instruction of deploying surgeons because of the potential for adaptive transfer. The ability to transfer a newly learned skill to new problems is paramount for trauma patients requiring fasciotomy. The destructive nature of modern weaponry results in massively distorted and complex anatomy that requires skill adaptation to ensure a correctly performed fasciotomy. This distortion can be compounded when attempting to evaluate and revise previously performed fasciotomies for patients transferred to higher levels of care.

The current battlefield spans the globe and surgeons are not always available for immediate care of wounded warriors. Joint Trauma System efforts are focusing on prolonged field care, often with a combat medic as the most highly trained medical personnel. Casualty evacuations can be delayed in excess of 24 hours and far-forward fasciotomies are potentially needed to preserve life and limb. The FIRE curriculum was implemented with extremely novice surgical trainees and resulted in near perfect fasciotomy performance. It is not unreasonable to believe that combat medics could have similar outcomes after completing the FIRE curriculum, assuming they have basic skill using a scalpel and scissors. As we continue to expand around the globe, our combat medics will need to trained in order to be facile with these basic interventions in order to preserve life and limb.

Limitations

There are several limitations to this thesis. The convenience sample used to assess the feasibility and positive effects of this novel curriculum was small. However, it should be noted that even with the small number of subjects, we found statistically significant (and very large) learning effects after implementation of the FIRE curriculum. Another limitation was that our scoring rubric did not take into account all errors. The rubric was meant to be comprehensive but not exhaustive. Notable errors not accounted for included, but are not limited to, injury to the neurovascular bundle in the deep compartment, peroneal nerve injury, and exact orientation/location of skin incisions. In addition, the fasciotomy leg models used are not perfect replicas of exact human anatomy. This particular leg model was chosen as it is the most realistic model that is currently commercially available. Furthermore, although majority of residents believed they could perform a LEF in the clinical setting, our study does not directly measure true surgical ability. The leg model used is only one of few commercially available for simulation training and may not perfectly reflect human anatomy and tissue handling. Finally, and arguably most notable, the FIRE curriculum wasn't compared to a control or alternate curriculum. Despite the significant improvement in LEF performance, it is unknown if a different intervention may result in better outcomes.

Future Research

This thesis evaluated the FIRE curriculum with a convenience sample of surgical residents. Moving forward, we plan to examine this curriculum applied to a larger number of trainees. As mentioned above, there may be a need for combat medics and far-forward medical personnel to perform a LEF. The FIRE curriculum will be evaluated with these very novice learners to see if similar success is achieved. Additionally, future studies will incorporate

retention testing to evaluate the durability of LEF performance over time. We will perform retention testing using the same fasciotomy leg model as well as fresh cadaver legs to determine if there is crossover to human anatomy.

As suggested above, EMT using cognitive exercises may not require hands-on evaluation, and using video recordings of correct and incorrect performance could supplant the requirement of leg models and in-person practice altogether. If outcomes of the FIRE curriculum continue to remain positive and possess durability over time, we plan to create an EMT study with video-based cognitive exercises in place of hands-on evaluation.

Conclusion

Overall, we found that application of the FIRE curriculum with a group of novice surgical trainees resulted in demonstrable improvement in lower extremity fasciotomy procedural performance. Omitting hands-on practice and relying solely on cognitive exercises focused on error recognition represents a novel approach to the training of procedural tasks in surgery. This approach is not meant to supplant hands-on skills practice and surgical training. However, its principles which are grounded in deliberate practice theory should be considered and employed when appropriate. Future studies could consider analogous curricula for the training of procedural tasks.

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