A Real-Time Local Flaps Surgical Simulator Based on Advances in Computational Algorithms for Finite Element Models

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Background: This article presents a real-time surgical simulator for teaching three- dimensional local flap concepts. Mass-spring based simulators are interactive, but they compromise accuracy and realism. Accurate finite element approaches have traditionally been too slow to permit development of a real-time simulator.

Methods: A new computational formulation of the finite element method has been applied to a simulated surgical environment. The surgical operators of retraction, incision, excision, and suturing are provided for three-dimensional operation on skin sheets and scalp flaps. A history mechanism records a user's surgical sequence. Numerical simulation was accomplished by a single small-form-factor computer attached to eight inexpensive Web-based terminals at a total cost of $2100. A local flaps workshop was held for the plastic surgery residents at the University of Wisconsin hospitals.

Results: Various flap designs of Z-plasty, rotation, rhomboid flaps, S-plasty, and related techniques were demonstrated in three dimensions. Angle and incision segment length alteration advantages were demonstrated (e.g., opening the angle of a Z-plasty in a three-dimensional web contracture). These principles were then combined in a scalp flap model demonstrating rotation flaps, dual S-plasty, and the Dufourmentel Mouly quad rhomboid flap procedure to demonstrate optimal distribution of secondary defect closure stresses.

Conclusions: A preliminary skin flap simulator has been demonstrated to be an effective teaching platform for the real-time elucidation of local flap principles. Future work will involve adaptation of the system to facial flaps, breast surgery, cleft lip, and other problems in plastic surgery as well as surgery in general. (*Plast. Reconstr. Surg.* 137: 445e, 2016.)

Computer-based simulation provides a highly effective training environment for complex tasks that are too expensive or too dangerous to practice in reality. Surgeons, like airline pilots, meet these specifications exactly. The current apprenticeship model should be augmented by simulation to develop high-level surgical thought. Despite the obvious benefits of such an approach, simulators of classic open surgery are largely absent from the surgical training landscape.

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Received for publication June 2, 2015; accepted August 13, 2015.

DOI: 10.1097/01.prs.0000475793.38984.7e

Disclosure: *Skin and scalp flap models were produced by Aaron Oliker with Dr. Cutting during his tenure as chief animator in Dr. Cutting's computer graphics laboratory at New York University Medical Center. Aaron Oliker is now a principal at Biodigital Systems, Inc. Biodigital Systems did not produce any of the software or models used in this article. None of the authors has a financial interest in any of the products, devices, or drugs mentioned in this article.*

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In their pioneering article on the subject, Pieper et al. were the first to describe the use of the finite element method to simulate local skin flaps.[1] In the finite element method, the simulated patient is represented by a large number of tiny interconnected solids (usually cubes or tetrahedra). As forces are applied by sutures or skin hooks, these tiny solids deform, which propagates response forces to their neighbors. After several passes, equilibrium between force and deformation can be computed, and the result of the surgeon's action on the overall patient can be displayed. Unfortunately, at the time that article was written, available computer processing power and memory were limited, as were the algorithmic approaches to realization of efficient finite element solutions. For these reasons, a real-time simulator for local flap concepts has not been previously demonstrated.

In previous work, our group simulated a breast reduction and various local flap procedures in a largely offline environment.[2,3] This allowed production of scientifically accurate video footage of simulated procedures. For the past several years, simulation that involves large deformations of elastic solids has been an exceptionally active research topic in the computational physics and graphics community. Recent advances in this area have permitted our group to revisit the local flaps problem to produce a realistic real-time surgical simulator.

METHODS

A local flaps workshop was held for the residents and fellows of the University of Wisconsin Division of Plastic Surgery on October 3, 2014. Hardware for the workshop consisted of a single central processing unit (Intel Core i7-4770R, Santa Clara, Calif.), 8-gigabyte random-access memory server (Gigabyte BRIX Pro, New Taipei City, Taiwan; cost, approximately $900), which served eight intranet client workstations (Google Chrome boxes, Mountain View, Calif.; cost, approximately $150 each). Using modern Web technologies, each client presented an independently controllable three-dimensional view of the simulation, which ran within a generic Web browser (Google Chrome). Workshop participants included nine residents, four clinical and research fellows and, five plastic surgery faculty members. Custom surgical software was implemented to allow a user to make incisions, perform excisions, retract using skin hooks, and suture wound edges together. These instructions were conveyed into a custom physics engine running on the server to perform the simulations. All software used in this simulator is currently academic and noncommercial and is produced under the aegis of a grant from the National Science Foundation to the University of Wisconsin. A surgical history mechanism was provided to allow recording and playback of complete procedures that were performed by a resident or faculty member. Models of flat and three-dimensionally deformed skin sheets, produced at New York University, were used to demonstrate basic local flap concepts. A full scalp flap model was created to demonstrate more sophisticated uses of multiple and sequential flaps. In the scalp flap model, flaps were allowed to collide with the underlying skull and temporalis muscles. Surgical procedures simulated were: (1) several variations of Z-plasty on flat sheets and three-dimensional webs; (2) rhomboid flap and the related S-plasty on flat sheets; (3) progressively longer rotation flaps on the scalp; (4) dual S-plasty on the scalp; and (5) the Dufourmentel-Mouly quad rhomboid flap on the scalp. All simulation rates approached real-time (two to three frames per second, with approximately 2700 physics nodes). Participant responses to the experience were recorded in prose for use in future modifications of the simulator.

RESULTS

A large number of local flap principles were demonstrated at the symposium. Representative examples included the following: variants of the Z-plasty procedure in a flat model, altering angles and lengths (see Fig. 1 and **Video, Supplemental Digital Content 1**, available in the "Related Videos" section of the full-text article on PRSJournal.com or, for Ovid users, at ***http://links.lww.com/PRS/B601***). Z-plasty on a three-dimensional web, demonstrates advantages of opening angle to nearly 90 degrees with recreation of the web space (Fig. 2). In three dimensions, the distal ends of the Z incision are already close together. In this case, opening the Z-plasty flap angle beyond 60 degrees simply deepens the web space, without the twisting that occurs in the planar case. Rhomboid (Fig. 3) and S-plasty flap closure of secondary defects with strategies for minimizing secondary skin stresses were demonstrated. Rotation flap (Fig. 4), dual S-plasty (Fig. 5 and **Video, Supplemental Digital Content 2**, ***http://links.lww.com/PRS/B600***), and the Dufourmentel-Mouly quad rhomboid[4] (Fig. 6) were

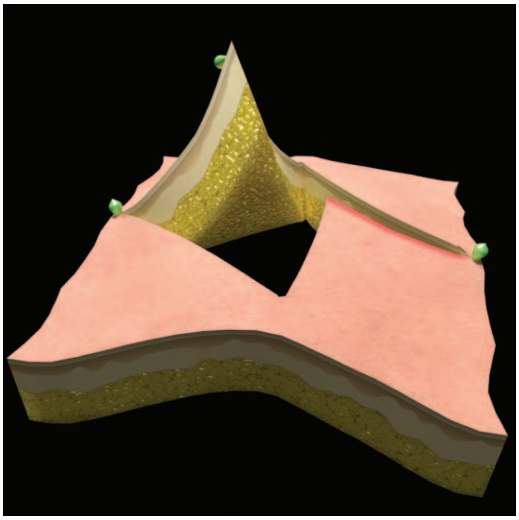


Fig. 1. Planar Z-plasty after elongation of initial contracture and transposition of flaps.

demonstrated on a scalp flap model. **Videos, Supplemental Digital Content 1 and 2**, demonstrate use of the simulator to perform Z-plasty (***http://links.lww.com/PRS/B601***) and scalp dual S-plasty (***http://links.lww.com/PRS/B600***).

Feedback from the symposium participants suggested several future improvements: (1) graphics should be used to show where secondary closure stresses in the skin are highest; (2) surgical action recording is a useful mechanism for repeating demonstrations, but it could also be used in board examinations to demonstrate competence; and (3) additional indicator graphics, such as instructor grease pencils and anatomical details such as blood vessels, could be included to help guide users where to make incisions.

DISCUSSION

The need to develop simulators to augment surgical training has become increasingly apparent.[5,6] Flight simulators are arguably more important in the training of a commercial pilot than additional hours in the cockpit. Simulators make it possible to routinely practice and develop automatic responses to difficult situations such as loss of an engine or landing gear, which hopefully will never happen in that pilot's commercial experience. The same paradigm holds true for a surgeon. If a surgical procedure is poorly designed, it is better to experience the consequences in a simulator than with a real patient. Often the burden of surgical training is borne by the economically disadvantaged in our society. In the apprenticeship model currently in place, the novice surgeon usually gets his or her personal experience primarily in a large public hospital. With the recent government-mandated reduction in training time and work hours, simulators may better prepare the beginning surgeon for his or her apprenticeship experience. Real plasticized models are an alternative to computer simulation, but for open surgery, they must be disposable with each use. If the anatomic model is a complex one, such as that to simulate local flaps of the face, the cost of real plasticized models is prohibitive.

Video 1. Supplemental Digital Content 1 demonstrates complete simulation of a 60-degree Z-plasty on a flat skin sheet with a contracted skin scar in the middle. The Z-plasty is cut, the contracture is elongated, and the flaps essentially "transpose themselves." Tack sutures are placed and the wound is closed. This video is available in the "Related Videos" section of the full-text article on PRSJournal.com or for Ovid users, at ***http://links.lww.com/PRS/B601***.

The simulated surgical environment presented

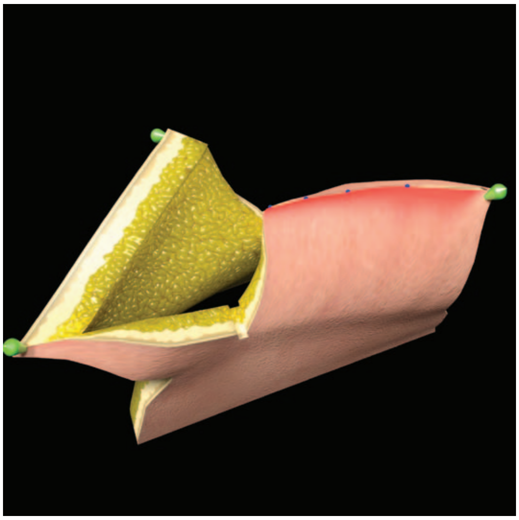


Fig. 2. Three-dimensional Z-plasty of web contracture using angles of approximately 85 degrees. Note that in contrast to the 60-degree planar case, where the perpendicular shortens, in three dimensions, the web space desirably deepens, and the contracture can be additionally lengthened by opening the Z-plasty angle.

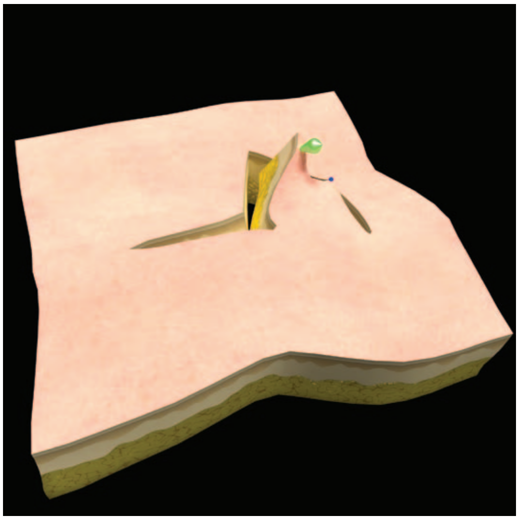


Fig. 3. Rhomboid flap closure on an initially square skin sheet. Note how proper flap design distributes closure stresses in two perpendicular directions.

here is a bare minimum. All retraction is done with a spring-like "skin hook." A skin hook is attached to the tissue with a mathematically modeled spring. If the user pulls the skin hook beyond the stretch limit of the skin, the "spring" simply stretches, and the skin moves no further toward the hook. Similarly, wound closure is affected with a simple

Fig. 4. A rotation flap had been initially too short to close a large wedge defect in the scalp. Extension of the incision lengthens the flap, allowing closure of the defect.

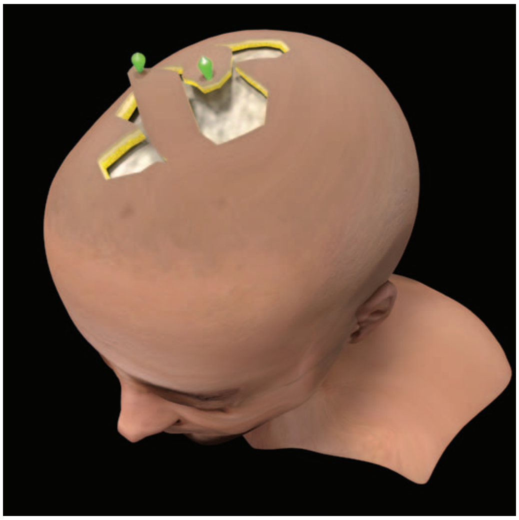


Fig. 5. Dual S-plasty closure of a large ovoid scalp defect. The "curvy" S-plasty wastes less tissue than its angular rhomboid counterpart. Careful flap design allows closure stress to be distributed into four parallel coronal lines and one sagittal line.

spring "suture." If tissue elasticity does not permit the desired spring movement, the suture does not close the tissue together, and a gap remains. Incision can be performed only with a perpendicular, one skin layer, "scalpel." Excision is done only on an isolated "skin island." Most surgeons will complain that these operators are far too limited and that they underimplement a typical surgical environment. In this preliminary simulator, they were chosen for ease of computer program realization. It should also be noted that this minimal operator set was sufficient to perform every surgical maneuver

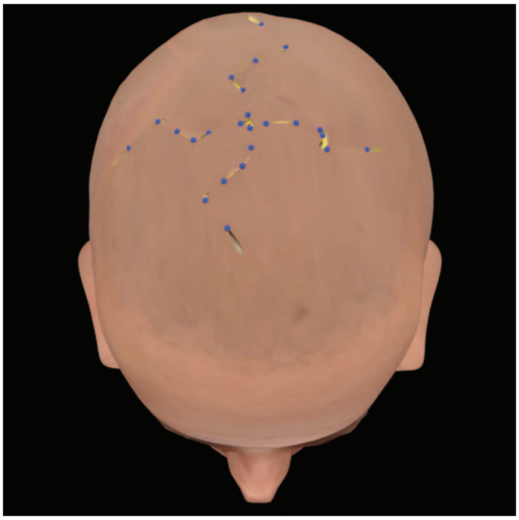


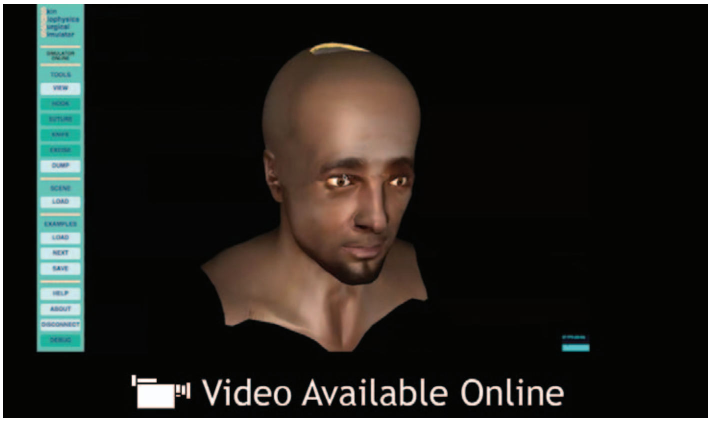
Fig. 6. The Dufourmentel-Mouly quad rhomboid flap closure of a square scalp defect produces nearly circular secondary closure stress.

required in the workshop. Fortunately, the type of simulator required to teach high-level surgical thought is a cognitive one, and it does not require near instantaneous psychomotor feedback.[7] Tactile feedback, required to teach manual surgical skills,[8,9] is not a part of this environment.

A surgical history mechanism has been created and found to be extremely useful. As a series of surgical steps is executed on a model, they can be recorded and played back if desired. This allows complex surgical demonstrations by an expert surgeon to be composed and recorded. In previous work with three-dimensional animation, the complex surgical sequences of Ralph Millard, John Mulliken, Sam Noordhoff, and others were stylized for posterity.[10–12] These animation sequences have been recently converted for three-dimensional "video game" playback, mixing in live surgery sequences and commentary.[13,14] Although these materials are the next steps beyond a two-dimensional text, prospective recording of scientifically accurate surgical processes is not possible with these playback simulators. The surgical history mechanism presented in this article points to the future in this regard.

Feedback from workshop participants was open form in this preliminary study. In the future, careful Web-based analytics of participant experience will become part of the simulation environment. Previous experience with such analytics in a three-dimensional animation playback simulator has been found to be extremely helpful in assessing student skill acquisition.[14]

The simulator presented in this article is prospective, allowing users to perform their own surgical procedures on an untouched surgical model. This is necessary for evaluation of resident trainees, design of patient specific surgical procedures, and possibly for development of new surgical designs for old problems such as cleft lip repair and breast reduction. With a prospective simulator, plastic surgery board examination could go much deeper. Seldom are Moh's defects of the face formulaic in their solution.[15,16] The practicing



Video 2. Supplemental Digital Content 2 demonstrates dual S-plasty closure of a circular scalp defect. S-plasty is best defined as a "curvy" version of a rhomboid flap that eliminates the need to remove 4 normal "corners" to produce a rhomboid. The dual S design divides the secondary closure stress in half, distributing each half to one of the flap donor areas. The dual S design results in a yin-yang closure pattern. This video is available in the "Related Videos" section of the full-text article on PRS-Journal.com or for Ovid users, at ***http://links.lww.com/PRS/B600***.

surgeon is frequently required to invent his or her own patient-specific design. The need for patient-specific surgical simulation is amplified in military injuries.[7,17] There is nothing more difficult than developing a new solution to an old surgical problem[18–20] when a previous time-honored, but less than satisfactory, solution exists. Inevitably, the first patient to receive the new procedure must be operated on. If the new design is flawed in an unforeseen way, the patient is harmed, a potential lawsuit may follow, and the surgeon must carry the guilt for his or her failure. Successful development of prospective simulators will ease the process of creation of innovative surgical procedures.

At the heart of a prospective surgical simulator program is its physics library. Schendel and Montgomery were the first to describe a mass-spring-based cleft lip simulator. This pioneering effort does simulate tissue movement, but it has found its greatest success in testing accuracy of incision design.[22–25] Previous work by two of the authors (Cutting and Oliker) has demonstrated that a mass-spring network allows real-time simulation, but it does not produce realistic results.[21] A triangle of springs will never accurately simulate a triangle of elastic material. As the top point is pushed down to the middle of the base of the triangle, a solid elastic triangle will exert progressively increasing force to resist the movement. In a triangle of springs, the resisting force will initially increase then slowly drop to zero as the base of the triangle is approached. Further compression will cause the triangle to invert forcefully. Shape matching[26] is an alternative to finite element, offering real-time performance, but it still cannot provide scientifically accurate results.[27] The finite element method corrects for the deficiencies of these approaches.[28] It mathematically models its elements as interconnected elastic solids. In their pioneering work on local flaps Pieper, Laub, and Rosen were the first to simulate skin flaps using the finite element method.[1] Unfortunately, classical finite element implementations have not permitted real-time surgical simulation.[29–32]

Real-time scientifically accurate simulation of elastoplastic material is an intensely active area of research in computational physics at the present time. Advances in mathematical formulation such as sensible handling of inverted elements[33] and virtual node usage in a regular lattice[26,27,34] have allowed our group to perform realistic offline simulations of skin flaps and breast reduction.[2,3] Previous efforts in simulating surgical cuts in a model altered the shape of the elements, which produced numerical instability that the virtual node paradigm does not.[31,35] Summaries of these issues can be found in the technical literature.[36,37] This article presents our preliminary work using this physics implementation[34,38–40] to provide a real-time surgical simulation experience.

In the future, this work will be extended to patient-specific models. In this preliminary article, we limited ourselves to generic patient models, which is fine for teaching general concepts of skin flap management to the novice surgeon; however, a natural extension will be to provide this tool to the practicing surgeon to allow surgical design to be simulated for real patients.[41] This will require maximally accurate viscoplastic[42–44] as well as elastic parameters to be represented in the model. The automobile industry has been collecting human tissue data for crash testing.[45] Unfortunately, these are high-strain rate data. Strain rate is the time period over which the biological tissue is physically stressed. Strain rates for surgical procedures should be from 20 minutes to a number of hours. In this time frame, plasticity can be nearly neglected. If we allow consideration of tissue expanders, strain rate must be extended to a number of weeks.[46] Here, tissue plasticity is of paramount importance and is the entire point of tissue expansion. Human tissue can be regarded as "superplastic" in physics terms because new material is generated by the body to accommodate long-term stresses.[47] Accurate measurement of the mechanical properties of tissue should become an active area of research in surgical circles.

From the discussion in the previous paragraph, it can be seen that patient-specific, scientifically accurate prediction of surgical results will require significantly more computation time than is presented here. We propose that the surgeon develop his or her plan in a roughly accurate simulator and then submit the plan to a more numerically intense solver for final processing. In this way, the surgeon who works with the simulator will not be frustrated by slow response time. At the conclusion of his or her work, the plan will be checked for accuracy at high physics fidelity, which may take several seconds to a minute to compute.

CONCLUSIONS

A skin flap simulator based on a new approach to the finite element method was demonstrated at a workshop in a major university plastic surgery training program. This preliminary experience suggested that the simulator can be an effective vehicle for teaching local flap principles. Future work will involve adaptation of the system to facial flaps, breast surgery, cleft lip, and other problems in plastic surgery, as well as surgery in general.

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ACKNOWLEDGMENT

This work was supported by a grant from the National Science Foundation (IIS-1407282).

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