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“Can You Feel It”: An Early Experience with Simulated Vibration to Recreate Glenoid Reaming

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Background: When developing educational simulators, meaningful haptic feedback is important. To our knowledge, no shoulder arthroplasty surgical simulator exists. This study focuses on simulating vibration haptics of glenoid reaming for shoulder arthroplasty using a novel glenoid reaming simulator.

Methods: We validated a novel custom simulator constructed using a vibration transducer transmitting simulated reaming vibrations to a powered nonwearing reamer tip through a 3D-printed glenoid. Validation and system fidelity were evaluated by 9 fellowship-trained shoulder surgeon experts performing a series of simulated reamings. We then completed the validation process through a questionnaire focused on experts' experience with the simulator.

Results: Experts correctly identified 52% ± 8% of surface profiles and 69% ± 21% of cartilage layers. Experts identified the vibration interface between simulated cartilage and subchondral bone (77% ± 23% of the time), indicating high fidelity for the system. An interclass correlation coefficient for experts' reaming to the subchondral plate was 0.682 (confidence interval 0.262-0.908). On a general questionnaire, the perceived utility of the simulator as a teaching tool was highly ranked (4/5), and experts scored “ease of instrument manipulation” (4.19/5) and “realism of the simulator” (4.11/5) the highest. The mean global evaluation score was 6.8/10 (range 5-10).

Conclusions: We examined a simulated glenoid reamer and feasibility of haptic vibrational feedback for training. Experts validated simulated vibration feedback for glenoid simulation reaming, and the results suggested that this may be a useful additional training adjuvant.

Level of Evidence: Level II, prospective study.

Introduction

Surgical training evolves at a remarkable rate. The increasing technical demands of surgical subspecialties necessitate constant advancement in our training paradigm. Training programs rapidly invest in novel avenues developing the complex psychomotor skills necessary for technical proficiency among

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trainees before entering the operating room[1-4]. Training simulators recently gained intense attention within medical education fields. The Royal College of Surgeons of Canada, American College of Surgeons, and several surgical societies across North America established simulation guidelines and programs developing simulation as a fundamental teaching tool facilitating the mastery of complex psychomotor skills. Many surgical specialties developed simulations and regularly use surgical trainers[5-12]. Orthopaedic surgery lends itself to using these tools, but to date, only a limited number of simulators are actively deployed[13-15]. Currently, most orthopaedic virtual reality simulation trainers focus on knee and shoulder arthroscopy (ArthroSim, Arthro-S, and Arthro-Mentor) and more recently on lower extremity arthroplasty (Ortho-Sim and Sim-K), spine surgery (TraumaVision), and trauma (TraumaVision)[13,15,17-19]. To our knowledge, vibration feedback is not included as part of surgical simulation.

When preparing the glenoid for total shoulder arthroplasty, appropriate removal of the articular surface is of paramount importance. Removing glenoid cartilage and exposing but preserving the supportive subchondral bone layer help provide a strong support foundation for the glenoid arthroplasty implant. This “glenoid reaming” step helps ensure the longevity of the total shoulder arthroplasty and is therefore of fundamental importance. Glenoid reaming can be a technically challenging part of shoulder arthroplasty and is fraught with potential complications related to poor intraoperative reaming techniques[20-25]. To simulate the “real environment” and kinesthetic forces associated with the removal of cartilage surface during reaming, accurate haptic feedback is required to recreate the experience for the user. “Vibration” provides a novel and uninvestigated haptic tool which may allow generation of a palpable simulated force mimicking the experience during glenoid reaming.

The purpose of this study was to propose, examine, and validate a recently developed novel glenoid reaming simulator (GRS) using vibration as main training haptic feedback. Two content validation tests were completed: (1) identification of an isolated surface profile and (2) simulation of a standard glenoid ream while using the GRS. A questionnaire was used to evaluate the potential utility and ease of use of the system. We believe that this innovative study will facilitate the development of a comprehensive and realistic shoulder arthroplasty simulation for use by orthopaedic trainees at all levels.

Materials and Methods

The GRS

Our Institutional Research and Ethics Board approved this prospective study. This is part of a multistudy larger project. The GRS already demonstrated an ability to recreate vibrational data previously recorded during reaming[26]. The GRS uses a vibration transducer, which transmits simulated reaming vibrations through a 3D-printed glenoid. The system uses a functional (i.e., “real world”) powered reamer fitted with a 3D-printed, nonwearing reamer tip (Fig. 1). The system is calibrated to generate distinct vibrational “profiles” for cartilage, subchondral bone, and cancellous bone based on experimentally recorded vibrations. The vibration output from the simulator matches nearly perfectly with recorded “real-world” vibrational profiles (measured as a peak-to-peak and total vibration energy). The GRS is a low-cost tool using 3D-printed components allowing patient-specific simulation and improved realism.

Nine local experts, all fellowship-trained shoulder surgeons, were recruited to validate our custom-built GRS. The experts were initially given 3 minutes of “open time” to manipulate, familiarize, and interact with the system freely. During this time, the system looped through a simulated “reaming profile” composed of all sequential profile layers of the glenoid surface (cartilage, subchondral bone, and cancellous bone) to mimic real reaming experience. Subsequently, the experts performed 2 separate tests, evaluating the simulator's content validity. The first test assessed the experts' ability to correctly identify a specific tissue layer based solely on the associated vibration profile generated while the experts were reaming (see below). In the second test, the experts were asked to simulate a standard glenoid ream while relying solely on vibration feedback provided by the GRS (see below). Noise-canceling over-ear headphones (Bose QC25 Bose Corporation 2017) were used to isolate any additional acoustic feedback from the vibration transducer not dampened by the simulator housing. Interrater reliability was also evaluated.

Testing Station 1—Isolated Surface Profile Identification

The first station simulated 20 isolated samples of randomly selected surface “profiles” (cartilage, subchondral bone, and cancellous bone). The simulator generated each profile as the experts interacted with the system. Experts were given as much time as required to familiarize themselves with the sample and were asked to report which “profile” they thought was simulated, based on vibration feedback alone. Each expert's accuracy was recorded.

Testing Station 2—Simulated Standard Glenoid Ream

The second station required experts to interact with 10 simulated reaming samples with varying depths of simulated cartilage, subchondral bone, and cancellous bone profiles (based on force integral data). Each profile was scaled on an established force integral which factored the amount of reaming required based on applied force at the interface. The force applied and the time to detection of entering the subchondral plate were previously recorded. Based on experimentally derived values, a force integral was generated per profile layer, allowing the simulator to respond to the applied force and amount of time a user interacts with the system. This allows the system to transition between profile layers (cartilage to subchondral then cancellous) as the user applies force to the system, and the force integral value for each layer is reached. In this manner, the system automatically calculates reamed depth from the user's applied force over time: less force during reaming equates to more time to complete reaming.

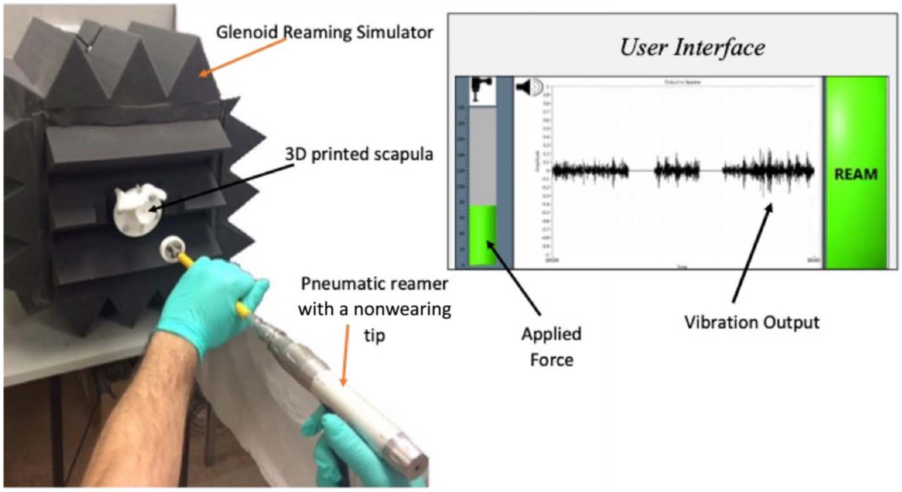

Fig. 1-A

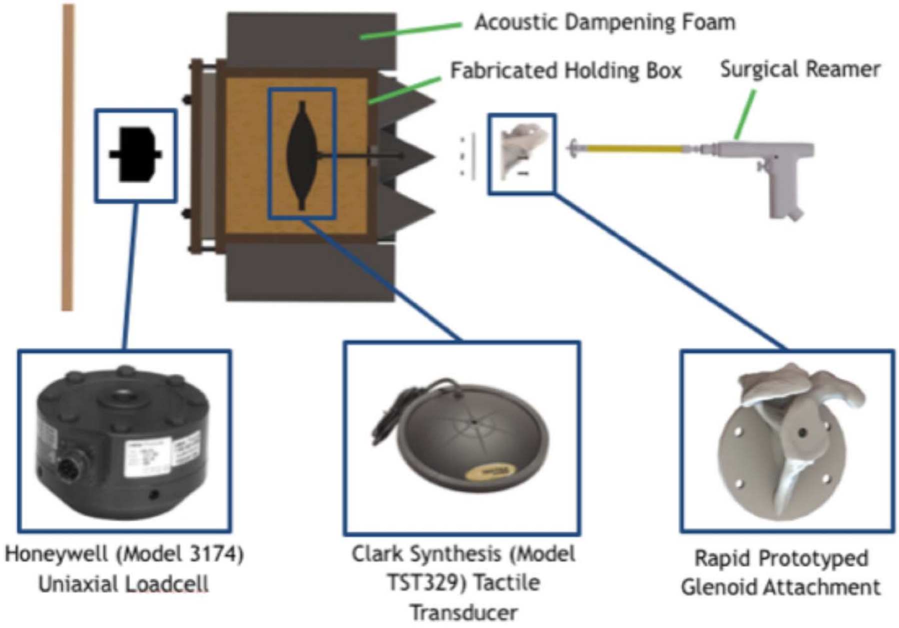

Fig. 1-B

Fig. 1 Simulated reaming trials were performed using the glenoid reaming simulator (GRS) and a clinical grade pneumatic reamer fitted with a custom-built nonwearing tip. A tactile transducer was used to produce vibration profiles to the user through a 3D-printed scapula. A computer readout was provided to the users while they performed the simulated ream. **Fig. 1-A** Overall look of the simulator and (**Fig. 1-B**) detailed view of the simulator.

Conversely, if increased force is applied, the simulator generates a corresponding shorter sample.

The experts were asked to simulate a standard glenoid ream using their preferred technique, down to the subchondral bone. Experts were asked to verbally identify and stop reaming when they detected a change from cartilage to the subchondral plate. The accuracy of the experts' detection of profile transition was compared with the actual vibration output profile. In addition, the total force integral applied by each expert was recorded and compared with the simulated value required to reach the subchondral layer. A successful ream was characterized if the physician completed their simulated ream by finishing in the first third of the subchondral plate. Furthermore, the force applied by the experts to the glenoid/reamer interface was recorded and compared between users. After completion of the testing session, experts repeated the protocol 1 month later to evaluate the reproducibility and fidelity of the results. The design implementation of the testing protocols was generated based on previous simulator validation studies in the literature aiming to provide consistency[4,27].

General GRS Questionnaire

After concluding the second testing station, the experts completed a short survey to critique their experience with the GRS. The questionnaire evaluated subjective ease of use and potential utility of the device as a trainer for novice surgeons.

A 9-question Likert scale general questionnaire was created based on previous similar questionnaires from the literature[16,28-31]. This questionnaire was reviewed by the authors to ensure clarity and minimize bias.

Statistical Analysis

All statistical analysis was performed using SPSS (Ver. 18.01, SPSS). The Fleiss kappa coefficient was used to assess reliability between experts based on their evaluation of random profile samples. An interclass correlation coefficient (ICC) was performed to evaluate interrater reliability of the experts' accuracy. Test and retest evaluation was performed using the dependent *t* test. Statistical significance was set at $p < 0.05$. Descriptive statistical analysis was performed on survey results.

Results

Nine experts completed the simulator evaluation protocol and questionnaire. The experts reported an average of 295 lifetime glenoids reamed (range 25-1,000+).

Testing Station 1—Isolated Surface Profile Identification

Overall, experts correctly identified 52% ± 8% of the randomly selected surface profiles. The cartilage profile was correctly identified 69% ± 21% of the time. Subchondral and cancellous surface profiles were correctly identified 54% ± 13% and 34% ± 17% of the time, respectively. The Fleiss kappa value of 0.19 (standard error = 0.02) suggests that experts had low levels of agreement when predicting the random samples.

Testing Station 2—Simulated Standard Glenoid Ream

During the simulated ream, experts correctly detected cartilage-subchondral surface transition 77% ± 23% of the time. Test-retest force integral values were not significantly different between all 10 trials ($p > 0.05$). This suggests good reliability of experts during repeated detection of the subchondral layer through multiple trials, even after an interval period. An ICC of 0.682 (confidence interval 0.262-0.908) suggests modest reliability in the applied force integral between experts during detection of the subchondral layer. The mean force applied to the glenoid/reamer interface was 75.4 ± 29 N to the glenoid interface. Of the 90 simulated reams, 29 “over-reaming” events occurred, meaning that reaming was performed through the subchondral layer into the cancellous profile. Three of the 9 experts were responsible for most of these events (23 of 29, 79.3%). One expert, with the least self-reported experience (25 lifetime reams), was responsible for 9 of these events alone (31%).

General GRS Questionnaire

The subjective expert input demonstrated an overall mean global system evaluation of 6.81 of 10 (range 5-10). The highest scores were given to simulator appearance, interface, and its perceived utility as a teaching tool (Table I).

Comments provided by the experts were positive. Several experts recommended the addition of visual feedback cues highlighting the importance of this sensory modality. In addition, 2 comments reported the need to add torque mechanisms to the reamer to provide the realistic “kick” inherent during normal reaming. One expert mentioned the need for additional exposure to the simulator to familiarize oneself with the various simulated vibrations.

Discussion

Currently, we are not aware of any shoulder arthroplasty surgical simulators. This study examined and validated a simulated GRS for shoulder arthroplasty. Our results demonstrate that this early prototype provides satisfactory validity based on objective and subjective expert input.

Objectively, our results suggest that the current simulator reliably reproduces the interface between cartilage and subchondral layers, using only vibration as a haptic feedback. Our experts were accurately able to detect this interface 77% ± 23% of the time. This reliability was further demonstrated when

TABLE I Global System Evaluation Mean Scores for Subjective Expert Input Attained Through a Likert-Scale Questionnaire, as Rated by 9 Fellowship-Trained Shoulder Surgeons

Questions (Scale 1-5: Not At All/Extremely Disagree–Extremely Closely or Agree)	Mean	Range
Adapting to the simulator was…?	3.5	3-5
How closely did the experience meet your expectations…?	3.6	3-5
Realism of the haptic “vibration”…?	3.5	3-5
Manipulating the instruments/tools was…?	4.2	2-5
The visual appearance of the glenoid model provides sufficient realism for the training of basic reaming…?	3.9	2-5
The physical appearance of the glenoid model provides sufficient realism for the training of basic reaming…?	3.9	3-5
The reamer/glenoid interface provides sufficient realism for the training of basic reaming…?	4.1	3-5
Overall realism of the experience…?	3.6	3-5
Usefulness of this type of force feedback in glenoid reaming simulator…?	3.9	3-5
Utility of this type of simulator in training surgeons/residents (tool manipulation, feel, and force application during reaming)…?	4	3-5
Mean overall score	4.09	

test/retest evaluation was completed using a calculation of the force integral each expert applied while reaming to the subchondral layer during different trials. Values were not statistically different between sessions ($p < 0.05$), suggesting that the simulator consistently provides similar conditions and the user reproducibly interprets the feedback despite multiple attempts. Subjectively, the survey results suggest that most experts felt the simulator adequately reproduced the reaming environment and was useful as a potential teaching tool.

Although experts could discern the glenoid layers (they were reaming approximately 50% of the time the random sample), their ability to detect transitions between layers was substantially more sensitive. This may be related to the use of multiple feedback mechanisms to assess their level of reaming. Auditory, visual, and tactile clues are of paramount importance during surgery, and this study forced experts to rely solely on tactile sense in the form of vibration. The expert surgeons were more accurate in detecting *transitions* between tissue layers (≈75%) rather than *isolated* tissue layers (≈50%), suggesting that the experts may rely on relative differences in vibration profiles more than isolated vibration profiles.

A striking finding was that nearly a third of the "over-reaming" events were produced by a single expert who self-reported as being the least experienced. This finding allows us to hypothesize that the simulator may assist in determining trainees's skill level based on the amount and frequency of "over-reaming" events. This will be investigated in future studies.

Our current prototype has several limitations. Our system focused solely on the recreation of vibrational qualities of glenoid reaming. Surgical glenoid reaming is a complex process, requiring an interplay of human senses, including visual, auditory, and tactile feedback. Previous studies looking at vibration alone as a teaching tool suggest that it is an important supplement, rather than as a stand-alone teaching haptic[32]. By isolating vibrational feedback, we have removed many of the "normal" mechanisms that provide the surgeon important information during the reaming process. This was clearly articulated by many experts involved in this study in the questionnaire's comments section. Although this focus on vibration alone can potentially introduce error and variation in the reaming process, it does isolate the haptic quality in question. Isolating this specific haptic has allowed us to study its importance alone before attempting to combine various additional feedback mechanisms. The effect of this lack of additional types of feedback (auditory, visual, etc.) is most evident when analyzing the results of the 20 random samples provided to the experts. A low Fleiss kappa score (0.18) and overall accuracy of detection (51%) among experts suggest that haptic vibrational feedback alone is only 1 modality used during glenoid reaming. Our results suggest that vibration alone is either not specific enough or experts do not rely on this haptic quality to determine their current reaming position. Experts could detect the transitions between layers, which suggests that vibrational input may be a useful feedback mechanism. Feedback in the form of visual interaction, reamer handset torque, and multiaxial force interaction is potential additional form of feedback. Further validation will be required to evaluate the importance, or lack thereof, of each modality during the simulation process. Future iterations of the GRS may include additional feedback mechanisms; however, this was not the purpose of this study or design.

An additional limitation of this study is the small number of experts involved. Although 9 experts are a small sample to validate a system, this study is a proof of concept and early validation project. Importantly, the present system needed to be examined and evaluated by experts in their field so that modifications and adjustments could be made to improve on the prototype. Despite a small number of participants and the limitations of the present system described above, the interclass correlational coefficient (0.68) for the system suggested moderate reliability for detecting the subchondral layer during reaming.

The measurement of applied loading force at the glenoid surface in this study was uniaxial, which limits the potential multiaxial input that would broaden the utility of this system as a teaching tool. The native glenoid anatomy can present unique challenges for the surgeon, particularly in advanced degenerative or inflammatory conditions with severely deformed bones. These conditions can require the application of a directed force along a specific vector relative to the glenoid surface to correctly perform the reaming process. An incorrect application or misunderstanding of these anatomic issues can significantly affect the outcome of the reaming process. Measurement of the direction of applied force could enhance the ability of the simulator to detect correct and incorrect reaming inputs. This would potentiate the training effect such a simulator could provide.

Finally, we appreciate that other aspects of glenoid preparation are important to successful technical placement. However, the purpose of this simulator was focused on the process of reaming and the isolated learning effect of such a simulator. We did not focus on pin placement, but this will be an important focus of future iterations of the device as we build increasing fidelity and realism.

Future development will explore the effect of using the simulator as a performance enhancing/teaching device. An effective teaching tool should allow users to improve simulated and real-life performance after use. We hope to demonstrate that using the simulator alone and under a guided teaching environment will help develop and refine/improve surgical skills and tool familiarity among users. Ultimately, we hope a smooth transition of applied skills can occur from the simulator to cadaveric training and into real procedures.

To our knowledge, no previous study explored or validated the importance of haptic feedback during shoulder arthroplasty. This is the first study to propose and examine a simulated glenoid reamer, and the feasibility of haptic vibration feedback for training. Experts validated the haptic vibration for glenoid simulation, and the results suggest that simulated reaming vibration may be a useful training tool. The use of a functional reamer provided additional realism. The use of 3D-printed simulated glenoids and reamer tips provides a cost-effective method to simulate patient-specific cases from computerized tomography scans and/or specific reamer types. We believe that the production of our GRS using vibration feedback provides the first important step to allow us to support the importance of this feedback mechanism in teaching and, more broadly, generate a more realistic, functional, and effective simulation tool. We ultimately hope that with the aid of appropriate and well-defined surgical simulations, the prevention of technical mistakes is possible and patient outcomes can be optimized. ■

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