Development of a Sensorized Distal Radius Fracture Model for Teaching Casting via Simulated Fluoroscopy

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Background: Proper fracture reduction and casting is vital to overall recovery, but medical students and orthopaedic residents do not receive objective, real-time feedback when learning the casting process. This, consequently, slows and reduces the effectiveness of training. The development of a distal radius fracture training model is described in this paper. This teaching tool allows users to train to properly reduce distal radius fractures using a graphical user interface (GUI) to highlight important reduction metrics, such as force magnitude and localization, and bone realignment via simulated fluoroscopy.

Methods: A prototype for fracture reduction training and evaluation was developed using a modified Sawbones® distal radius fracture model. The model was retrofitted with a force-sensing linear potentiometer and inertial measurement units that allow for a readout of reduction quality to the user via a GUI. Tests were developed to ensure the force-sensing linear potentiometer could detect a range of 1-70 N, the angular sensors are accurate to ± 2°, and the GUI properly mimics fluoroscopy.

Results: The force-sensing linear potentiometer successfully detected forces within the 1-70 N range, and its ADC output correlates directly with force ($R^2 > 0.95$). Position sensing was also shown to be reliable, with the output ADC value correlating inversely with position ($R^2 > 0.99$). It was further demonstrated that during the reduction process, position of force application may remain similar, however there could be significant variation in its magnitude. Both of these results should be explored further. The simulated fluoroscopy angles are consistent to ± 2° and were also deemed accurate when compared with actual fracture angle under fluoroscopy over the range of output IMU angles.

Conclusions: We developed and validated a sensorized distal radius fracture model for teaching and evaluating casting via simulated fluoroscopy.

Clinical Significance: Non-surgical reduction of distal radius fractures have greater than a 23.5% rate of malunion upon final recovery[1]. Training simulators that include real-time objective feedback of performance could improve the proficiency of trainees, reducing malunion rates.

The epidemiology of distal radius fractures has been well-documented. Distal radius fracture (DRF) reduction is one of the most common procedures handled by orthopaedic surgeons. This is due do the high frequency of DRFs, with one-sixth of adult and one-third of pediatric fractures treated in emergency departments occurring on the distal radius[1,2]. Traditionally, a physician's reduction technique is acquired through trial-and-error and observation of senior practitioners performing actual castings. Flaws in training correlate to poor outcomes in the clinical environment.

Malunion is considered any misalignment in the fully healed bone that leaves the patient with a recordable loss of functionality on the arm. Malunion results from improper bone realignment and if severe necessitates additional hospital visits. Findings indicate a 23.5% malunion rate associated with non-surgical DRF reduction[3]. While the angle of misalignment is highly variable, misalignments greater than 10 to 15 degrees tend to be where malunion symptoms occur[4]. Development of a simulator that can reliably teach surgical residents how to reduce and cast a DRF, with less than 10 degrees of misalignment, could greatly improve overall outcomes of patients who seek treatment of a DRF.

Currently, there are several life-like DRF models on the market[5,6,7]. Orthopaedic residents train using simulators largely obtained from Sawbones® and treat these models as if they were real fractures. A three-point molding technique is the most widely taught technique for aligning and reducing a fragmented radius before casting[8]. If accessible, fluoroscopy can be used to evaluate reduction alignment after casting is complete[6]. While the Sawbones® model has been well-received by the orthopaedic community in terms of its validity[5,9], current evaluation of the training procedure is subjective[10], often coming from a resident's senior practitioner. This leads to inconsistencies in training, and therefore inconsistencies in casting capabilities, which likely contributes to the high rate of malunion. Thus, there is growing interest for objective testing of casting competency[11,12].

For any orthopaedic simulation model, lifelikeness and function of fracture replication are important in establishing effective training techniques and easing the transition from simulation casting to casting in a clinical setting. Accordingly, it is crucial for the data the model collects to be accurate. Residents will make corrections to their technique in response to simulator feedback, so inaccurate data could engender flaws with casting techniques, which would increase the frequency of malunion in the clinical setting rather than decrease it.

Study and analysis of successful learning techniques has shown that a key factor in mastering tasks requiring concurrent use of psychomotor and cognitive skills is an accurate calibration of understanding via immediate feedback[13]. A person's calibration of understanding is defined as the accuracy of their self-performance judgement compared to his or her actual performance. Recent studies have found empirical evidence that improved calibration of understanding correlates to improved achievement in the given field of education[14]. We seek to create a simulator that will replicate the anatomical feel of DRF reduction and casting, while giving accurate real-time feedback to help students accurately calibrate their understanding of the procedure.

In this paper, we describe the development of a sensorized distal radius fracture model for teaching casting via simulated fluoroscopy. We detail the assembly of the sensorized prototype and subsequent validation of sensor accuracy. We present our usability testing results and feedback from experienced orthopaedic surgeons at UW Hospital. We hypothesize this model will improve proficiency of students in DRF reduction without adding additional time to the training of this procedure.

Materials and Methods

Development of Interactive Distal Radius Fracture Model

An existing distal radius fracture model, manufactured by Sawbones®, was modified to provide additional user feedback. This prototype is capable of accurately collecting data from user reduction. Data was collected through use of two types of sensors: a 7.6 cm x 1.0 cm force-sensing linear potentiometer (FSLP) from Interlink Electronics® and a BNO055 inertial measurement unit (IMU) from Adafruit®. Sensor readings were interpreted by a microcontroller and presented to the user in the form of real-time simulated fluoroscopy (Figure 1).

Figure 1. GUI displaying live updates to reflect the changes to the modified arm via a dynamic force indicator (green bar, right image) and a simulated fluoroscopy feed (left image).

The implanted FSLP provides accurate, quantitative, real-time measurement of a practitioner's applied force and its corresponding location. This measurement is particularly important for two reasons: first it allows for a standard to be set regarding optimal force application to reduce these model arms, second, once a standard has been set it provides a metric that medical professionals can use to grade a student's three-point molding technique. The location of the FSLP is also important as it needs to be able to capture data from a range of practitioners who may have varying, but also valid, casting techniques. The FSLP is implanted distally to the fracture site on the dorsal side of the Sawbones® DRF model. The positioning of the FSLP is in accordance with feedback from medical practitioners who interacted with the previously prototyped model at the 2017 International Orthopaedic and Pediatric Symposium (IPOS). The function of the FSLP is to capture amount, and location, of force applied by the practitioner to reduce the fracture at a given site along the FSLP, and detect between 1-70 N.

The IMU model used is a BNO055; it consists of an accelerometer, gyroscope, and magnetometer. This model was selected because it provides reliable measurements of acceleration, orientation, and nearby magnetic fields. When combined all of these measurements allowed for euler angles to be derived from a quaternion expression. A quaternion is a mathematical representation of an object's orientation in 3D space. For this application, each BNO055 has a unique quaternion as it moves in free space. The two quaternions output by the BNO055s can be mathematically manipulated to give functional angle differences between the two sensors. One sensor was placed on the distal fragment of the radius, near the fracture site on the model, and the other was placed more proximally on the radius to act as a reference for the distal sensor. The distal sensor deflects with the natural motion of the hand as it undergoes reduction, and the proximal sensor remains fixed. The quaternions can then be converted to angles as the IMUs move allowing for a quantitative measure of the bone alignment during reduction; ideally after reduction, the angle between the two sensors is zero, indicating perfect reduction (see Figure 2). This measurement could prove useful in determining reduction quality by a medical student, or a practitioner assessing the ability of a student.

Figure 2. Internal placement of the FSLP and two BNO055 IMU 9-DOF Absolute Orientation IMU Fusion Breakout Boards. IMU sensors can provide angle data between the two sensors can be used to determine reduction quality. The sensors accurately report the angle, with a deviation slightly under ± 2°.

The GUI (Figure 1) intuitively displays the information output from the FSLP and the IMUs. The focal point of the GUI is the simulated fluoroscopy component on the left. The image displayed in this component is correlated to an angle reading from the IMUs. Thus, as the IMUs detect the angle changes of the fractured wrist, the image updates dynamically and fluidly to display what the fracture would look like, at that angle, under live fluoroscopy. The GUI can also be easily modified to numerically display the angle the IMUs output if this is deemed valuable. The secondary component of the GUI is the display of the magnitude and location of force applied at the fracture site. The image displayed is a dorsal fluoroscopy image of the fracture model with the embedded sensors displayed. As force is applied to the fracture site, the location of the applied force is highlighted, and the color of the highlight changes depending on the magnitude of the force. For instance, if excessive force is being applied to an area the highlight will be red, and if the force is within the proper range it will turn green. The aim for this GUI is to simulate fluoroscopy and dynamically display reduction quality metrics.

Functional Testing Methods

In order to validate the functionality of the device, testing was completed in multiple phases. Calibration of the FSLP involved creating a correlation curve of applied force, via an MTS machine, versus ADC output. Four force trials were conducted by adding force in increments of 5 N from 0-70 N. Figure 3a is a photo of the MTS testing setup.

The linear potentiometer in the FSLP changes resistance as force is applied along its length. A voltage is applied to this component and the ADC output varies with force location. A calibration curve was created to relate the ADC output to location of force in units of centimeters. Next, to investigate how force influenced the sensor's positional reading, three tiers of force (i.e., 200, 400, and 600 ADC force units) were applied in 0.635 cm increments from one end of the sensor to the other. Figure 3b is a close-up photo of positional markers on the FSLP.

Figure 3. (a) Layers of foam and silicone from another Sawbones® model were placed over the FSLP to simulate forces experienced after implantation. (b) The white dots act as positional markers to reference while testing force location.

Calibration of the IMUs involved correlating the angle output by the model, to the angle of a fluoroscopy image, as measured by a ImageJ. An equation was derived relating the two and then used to adjust the IMUs' angle output to match the simulated fluoroscopy image. Testing was performed to validate that the displayed simulated fluoroscopy angle matched the true angle of the fracture in the model. This was done by capturing the actual fluoroscopy image of the model and the simulated fluoroscopy image simultaneously at a designated IMU angle (Figure 4). These angles were measured using ImageJ. Four trials were completed for specific IMU angles across the uncalibrated range of the IMU (approximately -45° to 45°) in increments of 5 degrees. The average and standard deviation for each tested IMU angle were calculated separately for the actual fluoroscopy images and the simulated fluoroscopy images. Both datasets were graphed (Figure 8) to determine how closely the simulated fluoroscopy angles match the actual fluoroscopy angles for a given IMU reading.

Figure 4. Side by side comparison of the fracture model under fluoroscopy (left) and simulated fluoroscopy image (center) at a given IMU output angle.

Usability Testing & Feedback

The product evaluation testing is aimed to create benchmark values for determining casting competency. Participating physicians are provided two rolls of webril, two rolls of fiberglass casting material, and a water basin. Initially, participants will be asked to complete a reduction without viewing the GUI. Once the arm is considered reduced and the position is marked, the participant will be instructed to repeat the reduction using the GUI. The two reductions are then graded against the "perfect" reduction to assess casting competency. A brief questionnaire (see Supplementary Material) is administered to gather usability data.

Results

FSLP Force and Position Validation and Test

The tests conducted were all in an attempt to validate the sensing system used to describe reduction quality. The device needed to be properly calibrated and proven reliable before medical professionals could be expected to trust and rely on be what is being shown on the GUI. The first set of tests were designed to properly calibrate the FSLP so it could properly display force (in Newtons) and position of force (in cm). The FSLP was positioned on the dorsal hand hand, beginning just off the fracture and extending distally for another 7 cm. From these results, calibration curves describing force and position behavior for the sensor each had accurate trend lines fit to them ($R^2 > 0.95$) (see Figure 5).

Figure 5. (a) Graph depicts correlation of magnitude of force applied to FSLP and the corresponding ADC value output by the FSLP. (b) Graph depicts correlation of position of force applied on the FSLP and the corresponding ADC value output by the FSLP. Note that this ADC output is distinct from the ADC output corresponding to the magnitude of applied force.

An expert orthopaedic physician from hospital also reduced the sensorized model, and the force magnitude and position were collected during their trial. The output of the sensor is in ADC, which is a dimensionless unit, but it can be transformed into an applicable value (e.g., N or cm) with the calibration curves generated in Figure 5. However, for comparison, the two readings were kept in ADC (Figure 6). The ADC force readings varied widely between each procedure, while the ADC positions readings did not vary significantly. This indicated that the position of force application remained similar during the reduction procedures, but the force applied did not.

Figure 6. Graph of the average applied force and location during three casting trials in ADC. There is a significant difference in force applied between all three casting procedures. The localization of the force application remained similar between procedures.

IMU Angle Calibration and Angle Validation

IMU angle calibration and validation tests were conducted to ensure that IMU output angle and the corresponding simulated fluoroscopy image were in sync with each other and with the fracture angle in the model itself. Figure 7 shows that although the IMU angle output isn't the same as the simulated fluoroscopy angle, there is a strong linear relationship between the two ($R^2 > 0.98$). Therefore, the linear equation relating the two can be used to calibrate the IMU output angle so that it matches the angle displayed by the simulated fluoroscopy.

Figure 7. Graph depicts correlation between BN055 angle output and actual measured fluoroscopy angle.

Figure 8 was from data obtained after calibration, and shows that both the simulated fluoroscopy angle (blue line) and the actual fluoroscopy angle (orange line), as functions of IMU output angle, are highly linear (R^2 > 0.96 and R^2 > 0.99, respectively). They also have similar slopes (0.8994 and 0.8222) and similar initial angles (33.48° and 34.501° with respect to IMU output angle). Standard deviations are also low for all data, largely within ± 2°. Plotted together, this graph illustrates how closely the GUI display matches the true angle of the bone fragment as it undergoes reduction.

Figure 8. Graph depicts similarity between measured GUI angle and actual angle of model at various (uncalibrated) IMU oupt angles.

Discussion

The development of a sensorized distal radius fracture model for teaching casting via simulated fluoroscopy is a novel design idea with few competitors. The only commercial product available for training medical students is the Sawbones® distal radius casting trainer. There have been several private academic models created for simulated treatment of distal radius fractures as well. These commercial and academic models contain a fractured radius, which trainees attempt to reduce by feel; however, users do not receive any real-time objective feedback.

Our design is a modified Sawbones® distal radius trainer. We have incorporated a number of sensors that capture and provide quantitative, real-time feedback to the trainee about their reduction quality, in hopes of improving their casting proficiency. Feedback was incorporated in this design design via the use of simulated fluoroscopy in conjunction with a force sensor and IMUs to capture relevant data such as force applied and bone realignment. During use, a custom GUI displays a responsive X-ray video to simulate the reduction of a fracture under live fluoroscopy. A dynamic force indicator shows whether a participant is applying proper force to an acceptable location, as determined by expert physician data. Upon completion of casting, force and angle data pertaining to bone realignment can be graphed as a function of time to show the user how their technique varied throughout the procedure. Analysis of the collected casting data provides objective measurement of trainee competency.

We were able to validate the accuracy of the objective feedback, though further usability testing is needed to determine whether or not trainee proficiency can be improved by this device. The force output of the FSLP was calibrated by correlating the force applied by an MTS

Criterion™ electromechanical test systems to the ADC output read during the application of force. The FSLP was secured under a section of the Sawbones® model (see Figure 3a) to replicate placement in the final prototype. Then tests were performed across a range of force values from 0 to 70 N by increments of 5 N, and the data was used to create the graph in Figure 5a. The validation of the angle accuracy was accomplished by comparing the angle shown on the GUI to an image captured simultaneously using a fluoroscope. From the results, it can be concluded that the system used to track internal changes in bone alignment via angle measurements is reliable, and the GUI used to simulate fluoroscopy is an accurate replacement for actual fluoroscopy. This effectively eliminates the need to use fluoroscopy to evaluate wrist flexion/extension reduction quality.

We acknowledge there are limitations to our training model, functional testing and usability testing methods. Our sensor placement has been expanded from previous prototypes, but it is still limited to a small set of three-point molding techniques. This simulator has a limited life in use for each individual, as users could only do a limited number of trials before they become familiarized with the model. In addition our usability testing is currently limited to a small, relatively homogeneous, sample taken from a single event (IPOS 2017). Further usability testing in various locations with users of different skill levels would result in a much more robust assessment of the usability of our training model. The actual improvement to clinical results cannot be evaluated until the simulator is broadly used by healthcare systems and residency programs.

This device offers improvement to the current training system by providing an effective means of teaching novices, declaring objective competency of casting, and contributing data on appropriate reduction angles and casting forces required for satisfactory treatment of distal radius fractures. If commercialized, this design would reduce costs for both patients and practitioners, and increase overall quality of healthcare. Our device ultimately aims to lower the prevalence of improper reductions and increase procedure efficiency.

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Supplementary Material

Usability Questionnaire

Prior to Simulator Use

1. Level of education & training? (circle one)

Resident   Fellowship training

2. Years in Practice ________________

3. Number of distal radius fractures treated? (circle one)

None   1-10   11-20   21-30   31+

4. Right or left handed? (circle one)   Right   Left

After Simulator Use

1 = Strongly Disagree   2 = Disagree   3 = Neutral
4 = Agree   5 = Strongly Agree

5. The model accurately simulated distal radius fracture reduction

1   2   3   4   5

6. The fluoroscopy simulation was responsive

1   2   3   4   5

7. The fluoroscopy simulation provided valuable feedback

1   2   3   4   5

8. Would you consider using this model in resident education?   Yes   No

Design Improvements and Additional Comments:

Notes

Cast Index ____________   Width _____________   Depth ______________