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DESIGN OF A PERCUTANEOUS ARTICULAR FRACTURE REDUCTION SIMULATOR

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Background

The American Board of Orthopaedic Surgery has mandated dedicated skills training for first-year orthopedic surgical residents.[1] Most residency programs address this requirement with training exercises with cadavers and plastic foam bones. Some programs incorporate one or more simulators in their skills training, including several sophisticated virtual reality simulators and a variety of low-tech simulators. Simulators are helpful because they can provide repeatable educational experiences and quantitative performance assessment. Unfortunately, few simulators have been developed for orthopedic trauma skills training. Even fewer simulators have been developed and validated with more advanced students, such as residents in their 3rd or 4th year of training, and for more complex surgeries. In contrast to the completely virtual surgical simulation using haptic feedback devices and sophisticated renderings of soft tissue deformation, our group has chosen to use physical models, real surgical instruments and position tracking in conjunction with virtual reality.[2-4] The physical models provide experience with the surgical tools, and enable more realistic hand movements and haptic cue feedback.

The current work extends our previous efforts with 3D tracking for navigating guide wires/pins in treating fractures of the hip. In that prior work, we developed this capability first with electromagnetic trackers,[2,3] then with vision-based methods.[4] The new surgical task to be addressed is the percutaneous reduction of a distal tibial plafond fracture, a fracture of the articulating surface of the tibia with the talus. The surgical goal in this task is to reduce the displacement between fracture fragments so that the articulating surface is smooth and free of incongruity. For percutaneous reduction, surgeons manipulate fragments with a tenaculum, surgical wires or both, while using radiographic images from a operative fluoroscope to monitor the fragment positions. We simulate this task by using an electromagnetic tracking system to monitor the position of the manipulated fragments and rendering a simulated fluoroscope image when requested by the trainee (Figure 1).

Figure 1. Complete simulator showing a fragment being pinned percutaneously using a K-wire.

The simulator is intended to help train residents to percutaneously reduce fractures by manipulating fragments with a tenaculum under fluoroscopic guidance. The skill of aligning an irregularly shaped three-dimensional object while relying on planar images is both non-intuitive and challenging for residents to learn.

Methods

The simulator's synthetic tibial shaft, tibial fragments, and soft tissue envelope are based on a commercial tibial plafond fracture model (Sawbones, Vashon Island, WA). The positions of the synthetic bone fragments and the intact tibial shaft are monitored using an electromagnetic tracking system (Ascension Technology, 3D Guidance trakSTAR, Shelburne, VT), which includes an emitter and four tiny sensors. The tracking hardware is encased in a customized, plastic box and integrated mount for the ankle model (Figure 1).

A clamping mechanism connects the proximal end of the synthetic tibia to a ball-and-socket joint (Figure 2), which allows the surgeon to rotate and lift the foot within the working frame. A screw knob secures the desired position.

Figure 2. Rendering showing the bone model, tibia clamp and ball-and-socket joint (blue), locking knob (black), and the electromagnetic emitter (grey). The sensors are not shown.

The emitter (hidden under the simulator housing) produces an electromagnetic field. The tracking system can determine the 6-degree-of-freedom position of the individual sensors within this field. The sensors are precisely affixed to each of two model bone fragments and to the tibial shaft using a screw-in key and slot configuration (Figure 3). A soft tissue envelope is then placed around the bone model, hiding it from plain view, and the fragments are appropriately displaced to pre-determined locations so the surgeon can re-align them.

The electromagnetic sensors offer a large workspace, constituting a cube with sides of 20x28x30 cm from the center of the emitter. Within this workspace, the manufacturer claims that the sensor error is less than 1.4mm. The position accuracy diminishes as the sensors get farther from the electromagnetic source. This workspace comfortably accommodates the sensors affixed to the fragments and the tibial shaft while still allowing for the user to adjust the model during use.

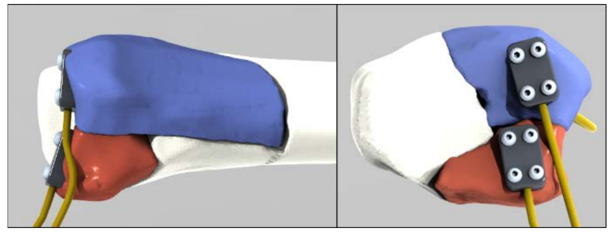

Figure 3. Fracture model with fragments (red and blue), sensor fixtures (black), and sensor leads (orange). The proximal end of the tibial shaft, with its sensor, are not shown.

Virtual fluoroscopic images are rendered based on the sensed positions of the physical fragments (Figure 4) to simulate the lateral and anteroposterior images typically collected during this operation.

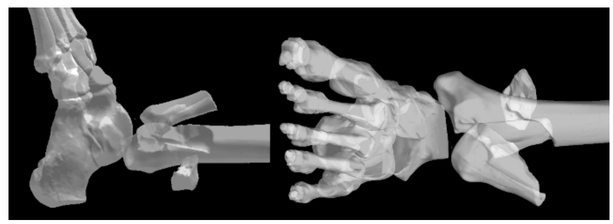

Figure 4. Virtual fluoroscopic images of exaggerated fracture with dislocated fragments in two common viewing angles.

Based on clinical guidelines for success in this surgery, the fragment positions must be tracked within 1mm. To quantify the fragment tracking precision, we constructed a fixture to move the sensors through a space slightly larger than the soft tissue envelope. The fixture consisted of a keyed cube, which holds three of the sensors, a reference board with four precisely located cube locators spaced 10cm apart, and a set of non-metallic clamps to position the plane. (Figure 5). Using the sensor readings, the reference board was carefully aligned to be parallel to one of the emitter's primary axes. The calibration cube, with the three sensors attached, was then moved between three or four indents of the reference board, spanning a region larger than the needed workspace. Relative measurements of the distance from the starting indent could then be compared against the known spacing of the indents.

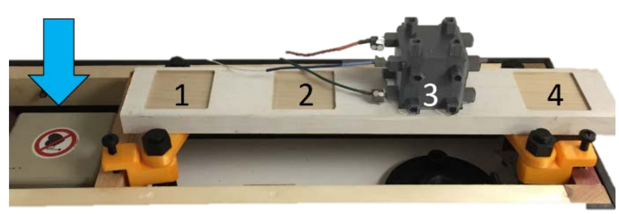

Figure 5. Reference board (white) aligned along axis with calibration cube (black) inserted in the 3rd indent. Numbers indicate 10cm spaced indents. Blue arrow shows emitter.

The sensor error was estimated for movements along each axis in nine trials, three repetitions along each of 3 axes. The first position on each trial, the position closest to the emitter (indent 1), was used as reference. Each subsequent indent location on the board was adjusted by subtracting the average position of the reference. The error of the three sensor reports and their standard deviation along the principal axes were reported for each trail, representing the relative bias and precision of sensor readings in the selected directions.

Results

Figure 6 presents the bias and precision of the relative sensor movements in the x and y directions within the workspace of the simulator. Error bars represent the standard deviation of the values from three repeated trials.

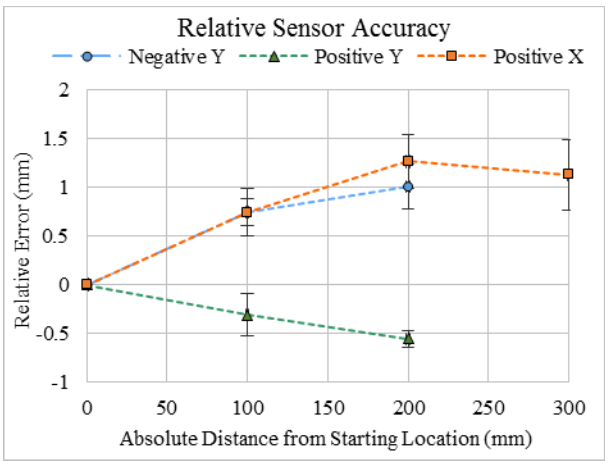

Figure 6. Sensor error with increasing distance from the starting location.

Discussion and Conclusion

The workspace for the sensors in the simulator is within 100mm of the trials reported above. The bias in this region is less than 1mm and the standard deviation is better than 0.25mm, performance sufficient for the alignment of articular fragments. This improves on our previous result of 3.7mm.[3] These results confirm the viability of the new simulator for creating a new, useful educational opportunity for surgical residents and introducing a technical platform that may support other high precision surgical simulations as well.

This work addresses limitations presented in the previous imagery-based simulator, where the objects to be tracked had to be visible and with a clean viewing path between the object and the camera[4]. The electromagnetic system is not hindered by line-of-sight requirements because the electromagnetic field can penetrate solid material. This simulator also improves upon the first electromagnetic system through the use of the key and slot system devised for placing the sensor on the object to be tracked, allowing the user to manipulate the whole model as well its fragments independently without losing their locations. The previous model relied on a fixed bone in a known location with a single tracker placed in the surgical drill to locate the k-wire. That system relied upon a complex calibration procedure to determine the bone and wire location[3].

This simulator will allow residents to practice percutaneous reduction using a repeatable model that can also be easily adapted to other fracture models using the novel key and slot sensor attachment. This work successfully increases the number of different surgeries that can be simulated using our physical model and virtual reality platform and addresses limitations in previous generations of surgical simulators that prevented them from being able to reproduce a fracture reduction surgery.

Acknowledgements

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