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Long bone fracture reduction using a fluoroscopy-based navigation system: A feasibility and accuracy study

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Abstract
Objective: Long bone fracture reduction during intramedullary nailing can result in a small but significant rate of angular and rotational malalignment, which can in turn lead to long-term morbidity. Current techniques for intraoperative reduction rely heavily on fluoroscopy, and their reproducibility can be limited. We suggest that fluoroscopy-based navigation may improve the precision of long bone fracture reduction and reduce radiation exposure.

Methods: A cadaveric tibia was stripped of soft tissues and fractured at its midline. The ends were then cemented to two mobile brackets within a fracture/deformity simulator. Optical trackers were drilled into each fragment. Radiographs were obtained including AP and lateral views of the proximal and distal ends of the bone as well as the fracture site. These radiographs were stored in the computer navigation system. Fracture reduction was performed using a fluoroscopy-based navigation system with virtual intraoperative planning software. The system used 4 sets of lines drawn by the surgeon on the fluoroscopic AP and lateral images. While navigating the reduction of the fracture these lines aligned together, providing graphic and numerical descriptions of the reduction. The lines included the anatomic axis of the bone, the matching of the fracture lines, the short segment anatomic axis (near the fracture site), and the AP mid-sagittal joint line (MSJL) of both the plateau and the plafond. Anatomic reduction was then performed and the computer assessment of the angulation and translation of the fragments was recorded. Each stage was repeated 25 times for each set of lines. For the control group the surface of the bone was tracked using an optical probe.

Results: The accuracy of the system varied according to the planning method. The most accurate technique was matching of the fracture lines, which yielded 2.68 ± 1.18 mm of translation and 2.5 ± 1.27° of angulation. The next most accurate method was using the short segment anatomic axis, followed by using the anatomic axis method. The control group was the most accurate (1.78 ± 0.67 mm translation, 1.58 ± 0.97° angulation). The AP MSJL yielded errors greater than 10°.

Conclusions: Fluoroscopy-based navigation is sufficiently accurate for long bone fracture reduction, potentially increasing angular and translational accuracy while reducing the amount of intraoperative fluoroscopy. Navigation may improve the outcome of treatment of a long bone fracture by better restoring the normal mechanical axis of the limb in a less-invasive closed manner.

Keywords: Long bone fracture reduction, fluoroscopy, navigation

Introduction
Long bone fracture reduction during surgery requires extensive use of fluoroscopy, especially during closed reduction for intramedullary nailing. Unsatisfactory postoperative limb alignment is not uncommon following these procedures [1], and malalignment of long bone fractures is often reported in all radiographic planes [2,3]. It has been shown repeatedly that even a small degree of mechanical axis malalignment can adversely
affect clinical results and may lead to osteoarthritic changes [4–6]. Conventional methods for verifying correct limb alignment during surgery are qualitative and may fail to detect small deviations from the normal mechanical axis; they may also require increased fluoroscopic radiation exposure [7,8]. These methods are insufficiently accurate to eliminate complications.

Computerized navigation in fracture surgery has the potential to improve the alignment of diaphyseal fractures while reducing the amount of intraoperative radiation exposure. Several studies have demonstrated the feasibility of using computerized navigation of limb alignment during fracture reduction. CT-based systems, CT matched with fluoroscopy, and kinematic systems used in imageless joint replacement have repeatedly proven accurate in the determination of mechanical limb axes [10,11]. However, these systems are cumbersome for fracture reduction because they require preoperative CT and/or an open approach for surface registration in an imageless system. Fluoroscopic navigation systems, on the other hand, do not require registration, and data acquisition is performed intraoperatively [12–14]. Therefore, the use of fluoroscopy-based navigation for fracture reduction is a logical choice. The purpose of this study was to test the accuracy of a prototype software for fluoroscopy-based navigated fracture reduction using different alignment strategies on a cadaveric model of a tibial fracture. The ultimate goal of the work is to direct the future development of a more advanced fluoroscopy-based fracture reduction technique with the simplest available workflow.

Methods

Materials and equipment

A cadaveric tibia with a normal anatomic axis was stripped of surrounding soft tissues. A straight line was marked on the crest with permanent ink. The bone was fractured obliquely in the mid diaphyseal area using an oscillating saw. A mechanical fracture simulator was used to hold and manipulate the fracture [15] (Figure 1). The fracture simulator consists of two brackets connected to a plastic frame, allowing simulated fracture deformity in multiple planes including rotation, vertical and horizontal translation, and angulation. The articular surfaces of the tibia were cemented using Bondo® acrylic cement with a clay spacer around the joint to facilitate radiographic imaging. Two dynamic reference frames were inserted into the two main fragments using 3-mm threaded wires. The StealthStation TRIA FluoroNav system (Medtronic SNT, Louisville, CO) with prototype fracture reduction software was used as the fluoroscopic image guidance platform. The software was developed as a prototype to examine the options for intraoperative fracture reduction using fluoroscopy. Essentially, the software provides a coordinate system for tracked fluoroscopic images of two fracture fragments. User-defined lines depicted on both radiographic projections (coronal and sagittal) were used to determine the spatial position of each fragment. The lines originally recommended by the manufacturer were the anatomical axes of the bone fragments, but the software permits selection of any line around either of the fracture fragments, enabling flexibility in the segmentation and planning of the correct fracture alignment.
Image acquisition

Several sets of fluoroscopic images necessary for the procedure were acquired (each at separate time points): Anteroposterior (AP) and lateral images of the proximal (plateau) and distal (plafond) tibia; AP and lateral images of each fracture fragment at the fracture line; and an AP and lateral image of each fragment in the diaphyseal region. There were a total of 6–12 images for each set; in some cases two fields of interest could be located within the same view. The marked line on the tibial crest served for C-arm calibration during image acquisition, and thus standardized AP and lateral images were acquired each time.

Segmentation and planning

The software allows the surgeon to create a line on the AP and lateral projections of each fragment. This line represents an axis in 3D space for each fragment and is graphically represented as a cylinder. The axis for each fragment is established by connecting two points on one projection (i.e., AP) of the fragment and then localizing those same points to the appropriate position on the second (i.e., lateral) projection. When the fracture is reduced, the cylinders depicted by the navigation system on the computer screen, representing the fracture axes, should align on the AP and lateral views.

Four different fracture fragment axes were constructed and used for fracture reduction navigation. These were as follows: (i) Standard method: the anatomic axis of the entire bone fragment (Figure 2); (ii) Short Segment method: the anatomic axis of a short bone segment adjacent to the fracture site (Figure 3); (iii) Fracture Line method: an axis connecting the most proximal and distal points of the fracture line in each fragment (Figure 4); and (iv) AP Joint Line method: a mid-sagittal axis parallel to the tibial plateau for the proximal fragment and a mid-sagittal axis parallel to the tibial plafond on the distal fragment (Figure 5). As a control group, a navigated pointer was used to touch the known fracture end and the inked line on the crest for registration (Figure 6).

All the segmentations and navigated reductions were performed by a single surgeon (Y.A.W.), who was experienced in the use of similar software systems.

Navigation

The fracture was reduced anatomically based on the inked landmarks and stabilized manually using a bone clamp (Figure 7) while being tracked with the
navigation system. The navigation system displayed the alignment of the fracture graphically, based on the selected lines, and also numerically by displaying the translation and angulation (in mm and degrees, respectively) of the fragments with respect to one another (Figure 8). For each method, 25 new segmentations and reductions were carried out and the values recorded. The control group was sampled 10 times (using the pointer without the images).

Figure 3. Using the Short Segment method. The use of a similar line to the anatomical axis only in the vicinity of the fractures allows for fewer fluoroscopic images (not including the knee and ankle) and also theoretically improves alignment in a non-straight bone such as the femur. The anatomical axis was depicted from the fracture ends towards the joint using a length of approximately 5 cm in all views. [Color version available online.]

Figure 4. Aligning the fracture “spikes” by using imaginary lines connecting the base and apex of each fragment allows reduction based on fracture morphology rather than on the remote axis of the bone. Each “spike” was marked on the AP and lateral views. [Color version available online.]

Figure 5. The Joint Line method depicted the center of the tibial plateau and the center of the ankle (a point on a perfect lateral view and a transverse line on the AP view). Theoretically, in an anatomically reduced tibia, the angle between these two lines should be zero. [Color version available online.]
Statistical analysis

A two-tailed $t$-test and non-parametric Mann Whitney U test were used to determine statistical significance, using SPSS/PC software. A $p$-value $<0.05$ was considered statistically significant.

Results

The translational errors displayed on the computer screen after anatomic reduction of the fracture using the different planning methods, as well as the results for the control group, are presented in Table I. The lowest translational error was found with the Fracture Line method: A statistically significant diminution in error was found when this method was compared with the Standard method. There was a strong tendency towards a lower translational error with the Short Segment method when compared to the Standard method, but this difference did not reach statistical significance. The errors that occurred in the control group were significantly smaller than those for the other methods.

For angulation errors (Table II), the average errors did not differ significantly among the study groups, although the Fracture Line method had a strong tendency towards a lower angulation error when compared to the Standard method. Again, the error in the control group was significantly smaller when compared to those for the other groups.

Discussion

Restoration of the anatomic and mechanical limb axis in fracture reduction and fixation is crucial for maintaining normal function and avoiding future complications. Based on the available software, we found the accuracy of the system to be in the range of 3 mm of translation and less than 2° of angulation. This is acceptable for most diaphyseal fractures. A larger error was obtained with all three methods when compared to directly touching the marked bone ends with a tracked pointer. Part of this error can be attributed to the error in the depiction of the points on the images before performing the reduction. The further the axes depicted are from the actual fracture site, the greater the chance of error, especially in non-straight bones like the femur. It is logical to assume that creation of a short segment axis adjacent to the fracture or the creation of axes using identifiable points that “key together” from each fracture fragment may yield more accurate results than simply drawing a long line from the joint to the fracture.

The work presented in this study enables a better understanding of matching fragments using fluoroscopy-based navigation. Although a CT-based model such as the one developed by Joskowicz and colleagues [11] can offer greater accuracy by providing a true 3D picture of each fragment, obtaining a preoperative CT scan of the femur, transferring the data and performing intraoperative registration creates an operative time burden that is unacceptable to most trauma surgeons performing this type of surgery on an acute or semi-acute basis. Given the very low penetration rate of navigation systems in the orthopaedic trauma community in the United States [12], our goal was to simplify the workflow in order to create a more “user-friendly” environment. Therefore, the potential advantage of a navigation system should not ultimately be offset by the complexity of its operation and handling.

Surprisingly, when trying to reduce the fracture by aligning the joint line AP axis, the resultant numbers given by the computer were inaccurate. On the coronal view, the horizontal line of the tibial plateau should be within 1–3° medial to the parallel and within 5° in the sagittal plane when considering...
the posterior slopes of the ankle and knee joints. It should be also noted that true AP and lateral images of the joint line were acquired using the tibial crest as a reference. The reason for this discrepancy is unclear, but it may be due to several causes: (i) the image quality of the joint areas was compromised due to the use of the cement for binding the bone to the simulator, and therefore a user error in accurately depicting the joint line might have contributed to the mismatch observed; (ii) the distance from the fracture site to the joint line was approximately 17 cm, which might have

Figure 7. An anatomical open reduction using a Verbruge bone clamp was achieved. The reported values from the computer screen (angulation and translation) were recorded after obtaining the reduction.

Figure 8. A screenshot representing an image of the reduced fracture, in this instance using the Short Segment method. The colored cylinders represent the current position in space of the fracture fragments, while the numbers at lower right indicate the angulation and translation between the lines defined previously. [Color version available online.]
increased error based on tracking of the fracture site; and (iii) there might be a software problem associated with this method of segmentation and planning.

Although the other planning methods used for fracture reduction in this study performed within reasonable accuracy limits, we cannot recommend using this software for aligning joints (e.g., in cases of deformity correction) until this problem is resolved. This error was reported to the manufacturer (Medtronic SNT) and a new software module is in the final stages of development which will allow matching between anatomic landmarks around joints to allow for rotational control of both femoral and tibial fracture fragments.

There have been several reports of navigated fracture reduction, primarily using either CT-based or CT/fluoroscopy matched systems [15]. These are problematic in the trauma setting since they involve the use of preoperative CT and intraoperative registration, which are time-consuming and can also lead to inaccuracies. A recent study used navigated high tibial osteotomy software to compare limb alignment measurements performed with conventional fluoroscopy to those performed with a navigated fluoroscopy-based system [16]. The accuracy results were similar to those in our study. However, the authors used imaging software to measure the reduction, while we had direct control of reduction by achieving anatomic reduction and then providing the error reported by the computer. This was achievable with the use of the fracture simulator device, thus avoiding the possible error associated with an indirect measuring device such as a CT scan. Also, in a fracture case, a previous “non-fractured” limb alignment (as used in osteotomy modules) is not available for comparison with the pathological situation. Future systems may, however, incorporate a “well limb” alignment measuring tool that will allow such a comparison in the case of a unilateral fracture.

The reduction in fluoroscopic radiation exposure is another major advantage of navigated fracture reduction. During intramedullary nailing, the hands of the surgeon are exposed to high radiation doses often exceeding the annual permitted dose [17,18]. During this study, the fracture was reduced and clamped without using the fluoroscope. Providing the accuracy is maintained in the clinical setting, this would enable a significant reduction in radiation exposure during the phase of the procedure that typically requires prolonged fluoroscope use. This has been shown previously to be the case in distal locking of intramedullary nails [19].

Accuracy values achieved using the software were better than those obtained using conventional fluoroscopy. Most studies define malalignment of a long bone fracture as a deformation measuring >5° [2,20]. In two recent studies, the resulting angular malalignment rates of tibial and femoral nailing were 5–13% and 9%, respectively [2,20]. This can be theoretically avoided by monitoring for correct alignment intraoperatively.

A limitation of the model is the total dependence on manual segmentation using either method. Even a few pixels of deviation or fracture edge can result in significant inaccuracies. Further developments including fully automated segmentation are required to overcome this limitation.

This software is still only a prototype and rotational alignment remains problematic, although it is indirectly solved with the use of the Fracture Line method. In oblique fractures, the fracture lines key together or match only with correct rotation. However, in the case of a transverse or comminuted fracture, this method does not provide an option for correcting rotational malalignment, which is a major concern in intramedullary nailing of long bone fractures [1,2]. In its current state, the system can provide the surgeon with a solution for monitoring adequate reduction of a long bone fracture in order to pass an intramedullary guide without using fluoroscopy. However, to achieve perfect reduction supervised by data concerning the limb’s mechanical axis, as well as the periaxial rotation, further improvement is required. Such an improvement is currently under development and will be

### Table I. Translational errors using different reduction methods as displayed for the anatomically reduced fracture

<table>
<thead>
<tr>
<th>Method</th>
<th>N</th>
<th>Translational error (°)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard</td>
<td>25</td>
<td>4.11 ± 2.34</td>
<td></td>
</tr>
<tr>
<td>Fracture Line</td>
<td>25</td>
<td>2.68 ± 1.18</td>
<td>0.005*</td>
</tr>
<tr>
<td>Short Segment</td>
<td>25</td>
<td>3.12 ± 2.24</td>
<td>0.07*</td>
</tr>
<tr>
<td>Control</td>
<td>10</td>
<td>1.78 ± 0.67</td>
<td>&lt; 0.01†</td>
</tr>
</tbody>
</table>

*Compared to standard method.
†Compared to all other groups.

### Table II. Angulation errors using different reduction methods as displayed for the anatomically reduced fracture

<table>
<thead>
<tr>
<th>Method</th>
<th>N</th>
<th>Angular error (°)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard</td>
<td>25</td>
<td>2.89 ± 1.71</td>
<td></td>
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<tr>
<td>Fracture Line</td>
<td>25</td>
<td>2.5 ± 1.27</td>
<td>0.07*</td>
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<tr>
<td>Short Segment</td>
<td>25</td>
<td>2.24 ± 1.75</td>
<td>0.18*</td>
</tr>
<tr>
<td>AP Joint Line</td>
<td>25</td>
<td>15.12 ± 4.59</td>
<td>0.001†</td>
</tr>
</tbody>
</table>

*Compared to standard method.
†Compared to all other groups.
available soon (Medtronic SNT, personal communication).

References