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Novel Positioning Feedback System as a Guidance in Bone Tumor Resection

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Abstract

Need: Bone resection using customized 3D-printed guides can improve accuracy, but the technique is still associated with clinically significant errors.
Technical solution: We developed an inexpensive optical feedback system (OFS) that compares intraoperative 2D camera images to the pre-operative plan, and accurately depicts the surgeon's guide placement prior to cutting, reducing the errors in resection.
Proof of concept: We simulated wide resections of a bone sarcoma on 24 cadaver femurs using 3 cutting guide types. Guide placement was measured using the OFS and compared to CT-scans showing the actual guide position. We carried out a second, controlled study on 20 sawbones, comparing the accuracy of the final bone cuts with and without the surgeon actively using the OFS to adjust the guide position before cutting.
Results: For cadavers, in 2 of 3 planes, the position of the jig recorded by the OFS closely matched its actual position, with an accuracy of .87° ± .65°(r = .94) and 1.2° ± 1.3°(r = .81) in the transverse and sagittal planes, respectively. In the second study, OFS increased accuracy of the final cut about the transverse and sagittal planes, respectively by 53.1% (P = .011)/54.7% (P = .04) and 33% (P = .051)/38% (P = .042) in terms of rotation and translation.
Next steps: Developing the OFS as a mobile application to reduce the processing time and improve accessibility in the operating room.
Conclusion: The OFS could accurately depict the guide placement on the bone and significantly improve the surgical accuracy of 3D printed jigs.

Keywords
surgical feedback technique, jig for bone surgery, resection, 3D printing, intra-operative guidance, computer vision

Need

In many orthopedic procedures, 3D-printed customized cutting guides significantly improve resection accuracy compared to traditional freehand techniques.[1,2] However, custom jig-assisted surgeries without external navigation still incur an error, on the order of 4 to 5 mm.[3,4] Even though the jigs are designed to fit in only 1 configuration on the bone surface, there is always some ambiguity on the surgeon's part as to where exactly to place the guide.[5] This can lead to clinically significant errors, with potentially disastrous consequences. Therefore, there remains a need to improve 3D-printed cutting guide's accuracy by minimizing human error.

Technical Solution

Intra-operative feedback guidance system. We designed an optical feedback system (OFS) (free of fluoroscopy or other bulky imaging equipment) that assists surgeons in accurate guide placement on the bone. The OFS, using image processing techniques (MATLAB), identified anatomical landmarks of the bone and optical markers on the 3D printed guide and plotted reference lines on the input image, along with the orientation error of the guide from its ideal position on the bone, providing the surgeon with appropriate feedback. The workflow of the algorithm is illustrated in Figure 1.

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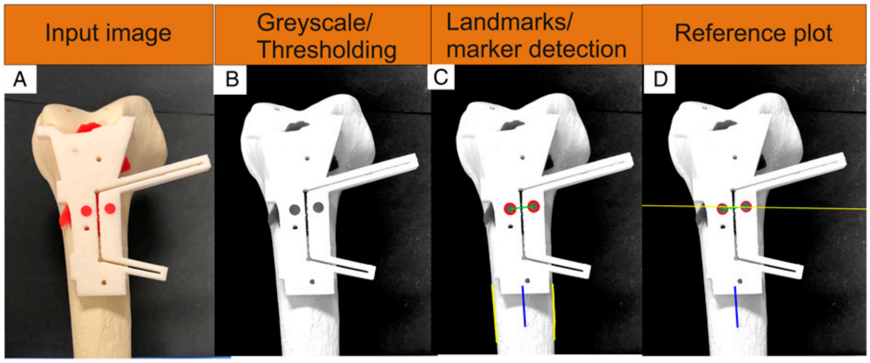


Figure 1. Workflow of the intraoperative optical feedback algorithm used to detect physical landmarks and optical markers to determine the positioning of the cutting guide. (a) RGB picture of the cutting guide placement, (b) RGB picture converted into greyscale image and undergoing histogram normalization and contrast thresholding of pixel intensities so that the optical markers look more pronounced (c) The resultant image goes through a boundary detection algorithm which detects high rates of change of pixel intensities and traces closed boundaries in the picture. The result is an image with boundaries of the optical markers and the bone's outline/boundary (anatomical markers). Using the selected landmarks, the algorithm plots the anatomical reference line (blue) and the guide reference line (green) joining the centers of the optical markers. (d) The guide reference line is compared with the pre-operative design's ideal reference line (yellow), and the surgeon is provided with feedback.

The detailed description of cutting guide design and determination of positioning error based on our mathematical model is explained in Supplemental Appendix A.

Proof of Concept

Feasibility of using still image feedback. We carried out a feasibility study on twelve pairs (left and right) (n = 24) of cadavers using three types of guides (four pairs each) (Supplemental Appendix A). The surgeon constrained the specimen femurs rigidly on a bench vice and positioned the cutting guide on the femur. A surgical drill was used to fix the cutting guide to the bone using three 3.5 mm Steinmann pins. Photographs of this setup are taken using an iPhone camera in three mutually perpendicular planes (sagittal, coronal, and transverse) (Figure 2(a)) to calculate the orientation using OFS. The surgeon then carried out the resection using a sagittal saw (Stryker, Kalamazoo, MI) equipped with a .89 mm saw blade.

We compared the guide's orientation calculated from the OFS to that obtained from post-operative CT-scan by running a Pearson's correlation study, with a significance level of .01. Bland-Altman analysis[6,7] was used to study the degree of agreement between the two measurements.

Effectiveness of using Instantaneous Feedback

We carried out a second controlled study using standard guides on twenty Sawbones® with modeling clay of random thickness on the patellar surface to simulate soft tissue on the bone. We carried out ten resections (5 right and left each), with and without using OFS to adjust the cutting guide's positioning. Multiple iterations of guide placement were done till all the rotational errors shown by the OFS were under 3°.

Post-operative CT-scans were compared with the pre-operative models to determine the cutting guide's positioning error. We carried out statistical T-tests to compare the rotational error incurred with and without the OFS. We also compared the translation error, to get an idea of placement with respect to all degrees of freedom.

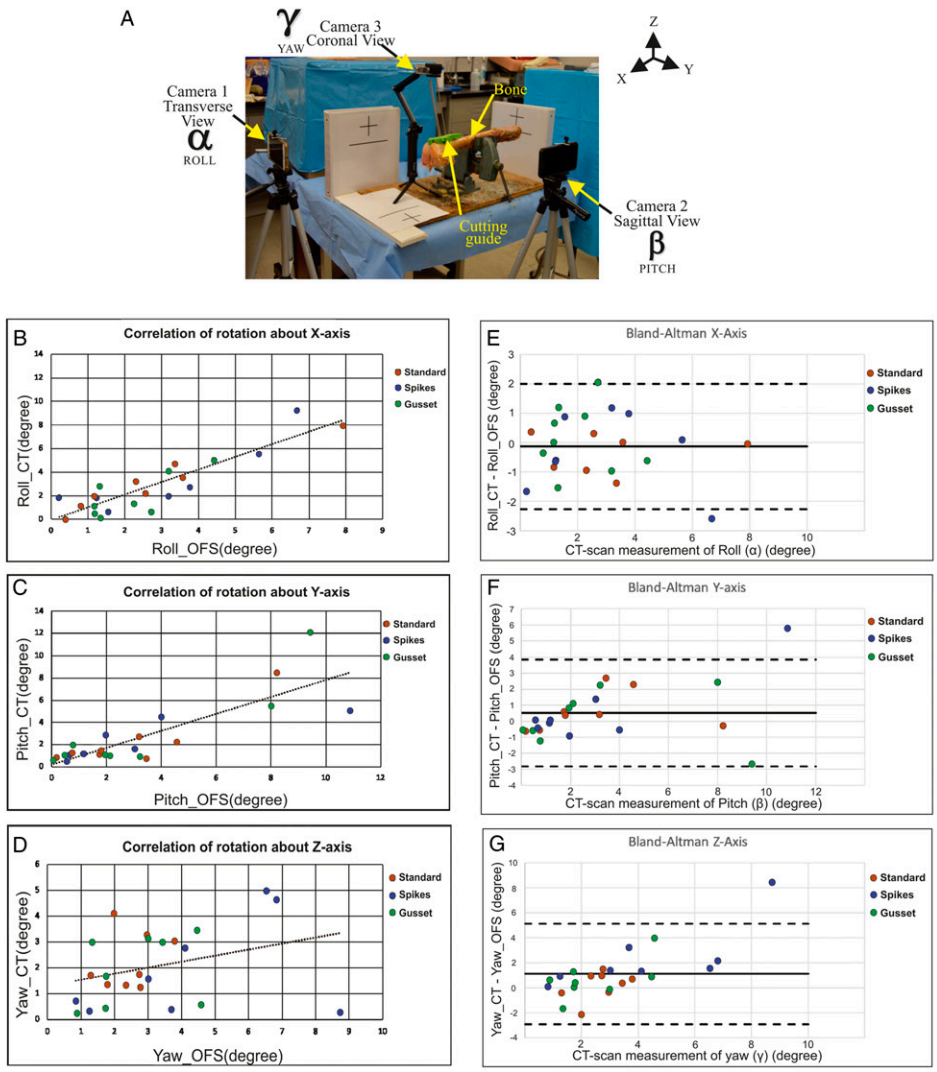
Results

In the cadaveric study, there was a significant correlation in the two orientation measurements in the transverse plane ($P<.01$ and $r=.94$) and sagittal plane ($P<.01$ and $r=.81$) for all jig types (Figures 2(b) and 2(c)). We were unable to get significant correlation results for rotation in the coronal plane. Data of the two planes are shown in Figures 2(h) and 2(i), respectively. These high levels of accuracy demonstrate huge potential for OFS to become a valuable tool in guide placement.

In the Sawbones study, the use of OFS resulted in a significant reduction in mean error in the transverse plane (53%), and sagittal plane (33%) as shown in Figure 3(a). Additionally, significant reduction in translational error was observed in longitudinal (54.7%) and frontal (38%) axes. The translation error was not significant about the sagittal axis. With the use of OFS, we were successful in achieving rotational error below 3° for almost all cases, using two iterations or less.

Next Steps

In this study, we utilized three jig designs for specific bone cuts on the distal femur alone. Other jig types for different bone cuts may show different results. Secondly, as



H Mean difference in the rotation error

	Transverse plane	Sagittal plane
Standard guide	0.53 ($p<0.01$)	0.99 ($p<0.01$)
Guide with spike	1.08 ($p<0.01$)	1.14 ($p<0.01$)
Guide with gusset	0.99 ($p<0.01$)	1.46 ($p<0.01$)
Average	0.87	1.2

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Bland Altman analysis between OFS and post-op CT-scan

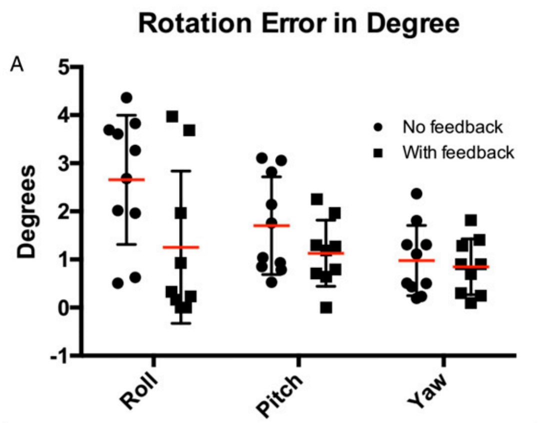
Plane	Bias	accuracy<1°	accuracy<3°
Transverse plane	0.13°	70.9%	100%
Sagittal plane	0.52°	62.3%	95.8%
Coronal plane	1.12°	58.3%	87.5%

Figure 2. (A). Setup for the experimental study done to calculate the feasibility of using OFS as a real-time application to determine the positioning of the cutting guide. Correlation of orientation of the cutting guide, calculated using CT scans and Image processing in roll(B), pitch(C), and yaw(D) is expressed for standard guide, guide with spikes, and guide with an added gusset. All values are in degrees; Bland-Altman plots to show the degree of agreement between the CT scan measurement and OFS measurement of roll(E), pitch(F), and yaw(G); (H)The mean difference in the rotation error calculated using the post-operative CT-scan and the optical feedback system; (I)Bland Altman analysis showing agreeability between the orientation measured by OFS and post-operative CT-scan. All values are in degrees.

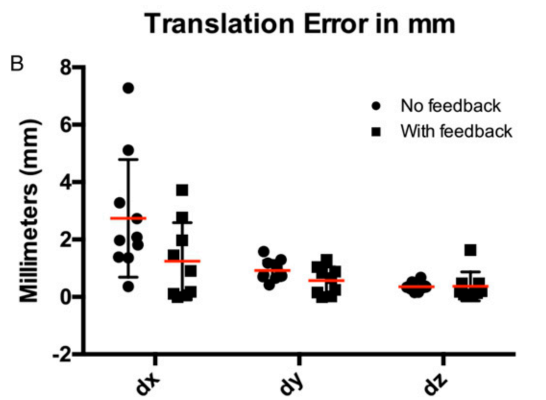
surgeons have varying experience in using jigs, we designed a practice module for surgeons to practive using OFS before surgery. Future studies are necessary.

Next, this technology would still need modifications through testing to extend the use of cadavers and sawbones to simulate live surgeries in the operating room environment with full dissection and bleeding before clinical applications.

Finally, we are working on incorporating into a mobile application, distortion removal and perspective correction



Rotation error	Without OFS	With OFS	p values
Transverse plane(roll)	2.66°	1.25°	<0.01
Sagittal plane(pitch)	1.70°	1.13°	<0.05



Translation error	Without OFS	With OFS	p values
Longitudinal axis(dx)	2.74mm	1.24mm	<0.05
Frontal axis(dy)	0.92mm	0.57mm	<0.05

Figure 3. (A) Rotational and (B)Translation error in positioning of the cutting guide observed in X, Y, and Z direction for sawbone resections with feedback to resections carried out without feedback. Error bars represent the standard deviation.

using image processing tools to overcome the need of capturing perpendicular perspectives and make it easier to use in the OR.[8]

Conclusion

The optical feedback system is a feasible tool to correct the customized guide's positioning and improve the accuracy of bone cuts.

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Author Contributions

Study concept and design: Fazel Khan, Imin Kao, Vamiq M. Mustahsan, Carlos G. Helguero.
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Declaration of conflicting interests

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Supplemental Material

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