EPiC Series in Health Sciences
Volume 1, 2017, Pages 333–339
CAOS 2017. 17th Annual Meeting of the International Society for Computer Assisted Orthopaedic Surgery

Feasibility of Using Optical Sensing to Measure Bore Depth in Surgical Bone Drilling

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Abstract

The depth gauge is used in many osteosynthesis surgeries to measure drilled bore depth for screw selection, and has significant limitations. Its use has been shown to contribute to placement of incorrectly sized screws, which can lead to adverse outcomes in patients.

We have developed an automatic depth gauge prototype which mounts on an existing surgical drill and makes use of an optical sensor. This builds off previous work in our lab which showed that drilled bore depth could be computed from continuous measurement of drill displacement relative to the bone. We tested our device in animal models and compared it with digital calipers as a gold standard. In a simple porcine model the prototype showed potentially superior performance (mean error 2.05mm, SD 0.67mm) compared with the conventional depth gauge (mean error 0.83 mm, SD 1.55 mm). However, this could not be reproduced in a more realistic porcine model.An automated depth gauge mounted on a conventional surgical drill shows potential as a replacement for the existing depth gauge, but the design needs to be refined for use in an operating room setting.

1 Introduction

Fractures of the human skeleton are common and frequently treated with operative fracture reduction and placement of mechanical hardware (osteosynthesis) to facilitate healing and allow early mobilization. The most common osteosynthesis method involves placing plates and screws into the fracture segments to stabilize them in appropriate alignment. The screws chosen must be of an appropriate length – too short and there is a risk of a weak fixation construct (“Oxford Textbook of Trauma and Orthopaedics - Oxford Medicine” 2017); too long and there is risk of damage to tissue structures adjacent to the bone (Caruso, Vitali, and del Prete 2015; Maschke et al. 2007).

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K. Radermacher and F. Rodriguez Y Baena (eds.), CAOS 2017 (EPiC Series in Health Sciences, vol. 1), pp. 333–339

The current method for measuring bore depth in bicortical bone osteosynthesis involves using a depth gauge, which is a thin wire instrument with a hook on one end and measurement gradations along its length. This instrument is placed through the drilled bore, hooked on the far cortex, and gently retracted. The depth of the bore is measured from the gradations marked on the instrument. Focus sessions and individual interviews with surgeons who use this instrument have identified that it is 'frustrating, time consuming, and inaccurate to use.' Using the current instrument results in placing screws that are too long 9% of the time in certain operations (Ozer and Toker 2011). Screws that are too long can lead to complications such as tendon rupture(Schnur and Chang 2000; Caruso, Vitali, and del Prete 2015). A number of technologies have been developed recently to address this and related problems (eg, McGinley Orthopedics 'intellisense', Smart Medical Devices, Surgionix) but all involve modifying the surgical drill, which makes them incompatible with the large stock of existing drills. Our overall goal, then, is to develop a device that is retrofittable to existing surgical drills and that can automatically provide an accurate measurement of the bore depth.

Prior work in our lab demonstrated that a displacement sensor attached to the surgical drill could accurately compute the bore depth in an animal model based on the depth vs time trajectory when compared with digital calipers (mean error 0.5mm, standard deviation 0.5mm)(Cavers et al. 2016). Briefly, there is a point of rapid drill acceleration after the breech of each cortex that allows us to identify the time at which the drill bit has exited the bone. The change in displacement between the initial and exit positions corresponds to the bore depth. While last year's study showed that the approach was feasible, its use of a linear sliding mechanism would complicate its translation to the operating room. In this study, therefore, we examine whether it is feasible to use an optical sensor to make these measurements instead, which we believe would be a more practical approach.

2 Materials and Methods

We first further characterized the use case scenario for our proposed bore depth measurement device for use in osteosynthesis surgery. We interviewed practicing surgeons in orthopedic and plastic surgery and reviewed surgical texts for procedures where a drilled bore needs to be measured. We then obtained information from the Vancouver General Hospital (VGH) business office on the number of such cases performed per year. VGH is a quaternary referral and academic centre, and is the second largest acute care hospital in Canada. We then identified the most frequently used surgical drills to determine the most appropriate devices to design for.

After identifying the most common surgical drills, we designed and constructed a prototype optical sensor device that mounted first on a home improvement drill, then on a drill from one of the top two orthopedic surgical drill manufacturers in North America (Conmed/Linvatec MPower2). The prototype consisted of a laser triangulation sensor (KEYENCE IL-300, repeatability 20 µm, 900Hz sampling frequency) mounted on the superior aspect of the drill parallel to the drilling axis and an Arduino DUE microprocessor connected to Matlab (MATHWORKS) running on a MacBook Pro personal computer. Time and position relative to the surface directly in front of the laser sensor were measured, and velocity and acceleration were estimated from the position signal following application of a second order Butterworth filter with a cutoff frequency of 10 Hz. Bore depth measured by the optical sensor was computed by taking the difference in displacement between the initial position and the position just prior to breech of the second cortex, as indicated by a spike in the acceleration signal at that time point.

Three animal models were used to test the optical sensor. In Model 1, chicken thighs were purchased from a grocery store. An axial incision was used to expose the femur, and the specimens were placed on a surgical table. The optical sensor was affixed to a DeWalt home improvement drill, and the displacement was measured from the table surface. A series of 21 holes were drilled transversely through the bone with the optical sensor measuring displacement, and digital calipers were used to provide a ground truth depth value.

In Model 2, a pig femur was used, as it is a closer approximation of human bone. This was obtained from a local butcher with all soft tissue removed. The optical sensor was affixed to a surgical drill, and the displacement was measured relative to the surface of the tibia. Again, a series of 9 transverse holes were drilled. The conventional depth gauge was also used by a surgery resident to measure the drilled bore depth, and digital calipers were used to provide a ground truth depth value.

In Model 3, a full pig leg was used, as a close approximation of a surgical exposure on the human appendicular skeleton. The femur and tibia were exposed surgically by the primary author, a surgery resident. Drilling and measurement was the same as in Model 2, with the exception that the displacement measurements for the optical sensor were taken from the soft tissue in the adjacent surgical exposure. We drilled 25 transverse holes in this experiment.

All experiments were conducted at the Biomedical Engineering Laboratory in the Centre for Hip Health and Mobility, part of the University of British Columbia.

3 Results

Surgical services using the depth gauge for measuring drilled bore in bone at VGH were Orthopedic Trauma, Oral Maxillofacial Surgery, and Plastic Surgery. A total of 1087 of these surgeries were performed at VGH in the 2015/2016 fiscal year, with the distribution by service displayed in Figure 1. Orthopedic trauma made up most of the cases. We also learned that 68% of medium size surgical drills in North America are sold by Stryker, and the second largest vendor is Conmed/Linvatec at 16% (private communication with Stryker representative).

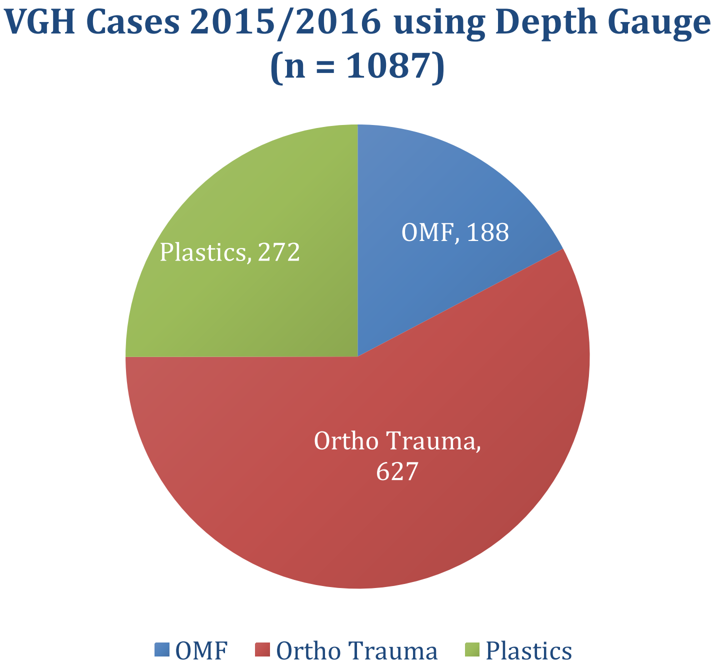

Figure 1: Distribution of cases using the depth gauge among surgical services

The measurement errors of the optical sensor in the chicken bone scenario are shown in Figure 2.

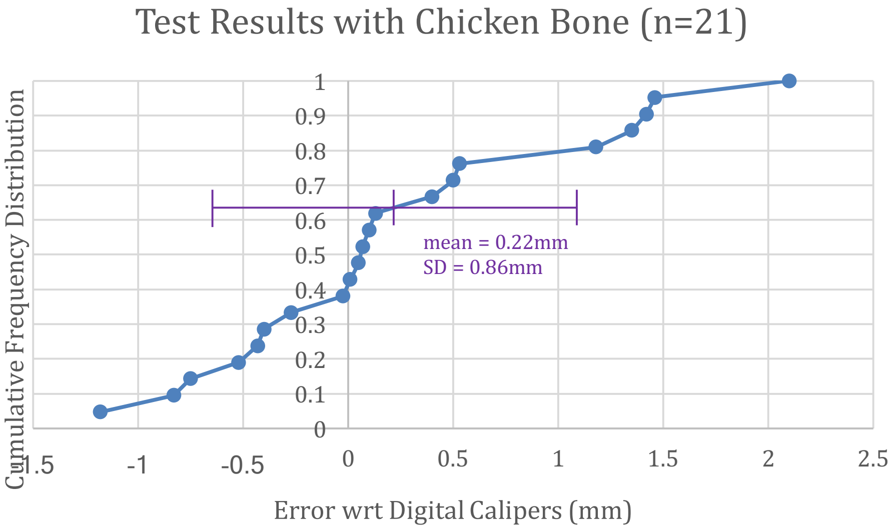

Figure 2: Model 1 (Chicken Bone) Results

The measurement errors of the optical sensor and the depth gauge in the pig femur scenario are shown in Figure 3. The mean error of the optical sensor was both greater than that of the depth gauge ($p<0.05$, t-test) and greater than what we found with the chicken bones. However, the variability of the reading from the optical sensor was lower than that of the depth gauge ($p<0.05$, F-test).

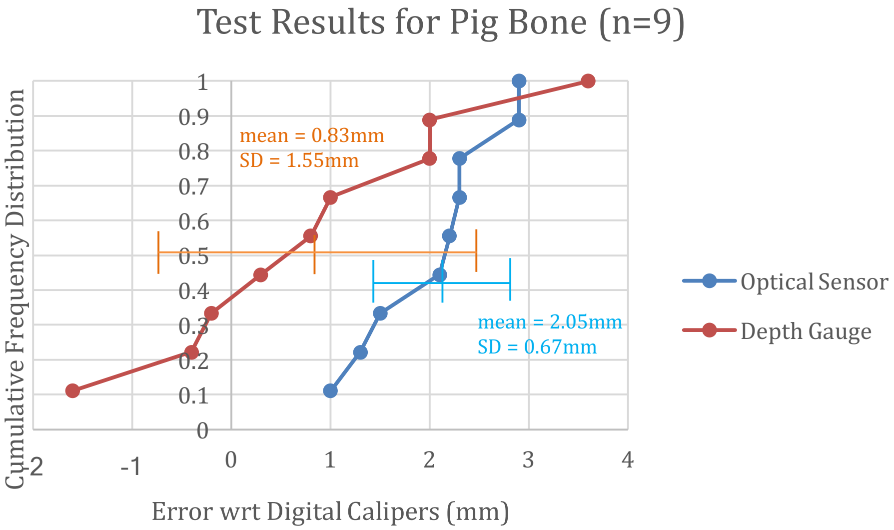

Figure 3: Model 2 (Pig Bone) results

The measurement errors of the optical sensor and depth gauge in the pig leg scenario are shown in Figure 4. The mean error of the optical sensor was slightly greater in this scenario than in the stripped pig femur scenario, but the variability was considerably higher (and similar to that of the depth gauge, which likewise was more variable than with the stripped pig femur). Mean error of the optical sensor was greater than that of the depth gauge (statistically significant, $p<0.05$, t-test). The difference in the standard deviations of the two methods was not statistically significant ($p>0.05$, F-test).

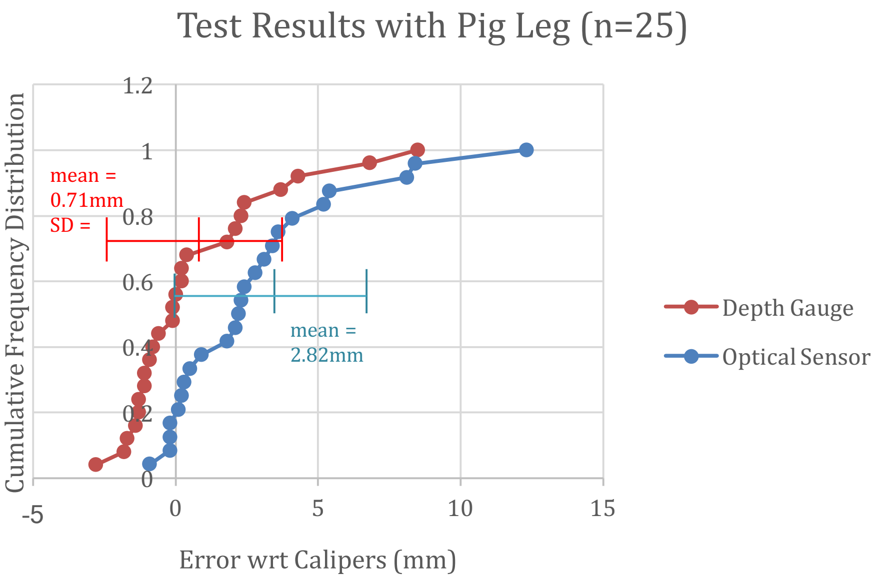

Figure 4: Model 3 (Pig Leg) results

4 Discussion

Preliminary research into the use case scenario demonstrated that a novel depth sensor compatible with the Stryker or Conmed surgical drill line could potentially be useful in a large number of surgical cases. An optical sensor mounted on a surgical drill would remove the additional step of measuring the drilled bore, and could address surgeon's complaints around the usability of the existing depth gauge. Optical sensors have previously been shown to be successful in measuring drilled bore in bone using a fixed drilling apparatus, with a mean error of 0.15mm and a standard deviation of 0.07mm (Quest, Gayer, and Hering 2012). Using an optical sensor, rather than a linear potentiometer as in our previous work, would limit the intrusion of the device into the surgical field. It would also facilitate creating a single design that is compatible with multiple drills and simplify issues related to design for sterilization.

The results of the chicken bone experiment demonstrated similar performance of our optical sensor prototype and our previous linear potentiometer-based device (Cavers et al. 2016), which produced a mean error of 0.5 mm and a standard deviation of 0.5 mm using similar specimens.

The data from the stripped pig femur showed that the optical sensor is more repeatable than the depth gauge in this more realistic bone model. While there was a consistent positive bias to the measurements, this could be easily compensated for in the device algorithm (subtract mean error from computed measurement). We hypothesize that the positive bias is due to unanticipated plastic deformation of the bone or adjacent periosteum just prior to breech of the second cortex. This could lead to the drill acceleration being 'delayed' slightly beyond the actual breech point of the second cortex. It may be possible to correct this in practice by applying a bias correction, so we place more importance on the variability results, which favour the optical sensor.

Challenges with applying the optical sensor to a more complicated scenario emerged in the pig leg model. The mean error of the optical sensor was similar to that found in the stripped pig femur, which suggests a consistent phenomenon. However, there was a significant increase in the standard deviation. We hypothesize that this increased variability was primarily due to changes in the relative position of the drill hole and the point where the laser beam hit the tissue during drilling. We believe that most of this variability could be eliminated by incorporating a drill guide into this process and directing the laser beam at a point on the drill guide as this would remain relatively invariant with changes in the drill orientation during drilling. We had originally tested the drill in a stand-alone condition as this mode is occasionally used in some procedures, particularly in plastic surgery. Nonetheless, based on discussions with our collaborating surgeons, we believe that most surgeons would have no concerns about using the device in combination with a drill guide, so we plan to repeat our tests shortly with a guide. Previous work by Quest et al (Quest, Gayer, and Hering 2012) showed significantly better performance than our prototypes, using a more constrained measurement system – the drill and sensor is fixed relative to the bone. By changing our design to direct the beam onto a machined drill guide surface and measuring movement between pieces of instrumentation we are moving closer to their design.

5 Conclusion

Our work demonstrates that an optical sensor mounted to a surgical drill can accurately measure the drilled bore in bicortical bone under controlled conditions, and that there could be a significant need for such a device. Further work is required to ensure consistent performance under more realistic operating room conditions.

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