Original Article

The effect of drill hole location on load bearing capacity of long bones

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ABSTRACT

We investigated how load bearing capacity (LBC) of long bone differs with a bicortical drill hole in a compressive/tensile location vs. a neutral location.

Group I had a hole drilled through 0°/180° ([compressive at 0°/maximum tensile at 180°]), Group II at 90°/270° ([neutral]), and Group III at 135°/315° ([tensile at 135°/compressive at 315°]). Maximum load at failure and stiffness was measured.

A significant ($p < 0.05$) decrease in LBC of all Group I and Group III bones was observed. Loss of strength for Group II was statistically insignificant ($p > 0.05$). Changes in stiffness for both tibias and fibulas was not statistically significant ($p > 0.05$).

1. Introduction

The drilling of bone is a common practice in orthopedic surgery and is often employed for the treatment of fractures due to physical trauma. Depending on the individual, the process of healing a fractured bone can take from several months to years, based on the bone and type of fracture.^{1–4} Excessive motion of the fractured bone components may cause delayed union or non-union.² Thus, to aid the fracture healing, the bones are often stabilized with intramedullary nails and plates secured with screws.² This technique involves a repositioning of the fractured bones to their normal alignment, at which point they are “screwed” and held together by metal plates secured to the surface of the bone.^{5,6} The nature, location, and size of the drill holes used to secure these plates depend on the nature of the fracture and the size of the bones.^{6–9} Although the necessity of surgical drill holes is recognized for its overall benefit in the healing process for patients, the impact these drill holes have on bone strength is a topic that has been the subject of numerous reports.

Multiple studies have confirmed a quantitative decrease in the strength of long-bone after drill hole placement. One study analyzing canine femurs reported up to a 55% decrease in the energy absorption capacity of the bone with the presence of 2.8-mm or 3.6-mm non-occupied drill holes.¹⁰ Another investigation found that a non-occupied transcortical hole drilled into a femur reduced torsional strength by 60%.¹¹ A mean decrease in failure load of 40.4% was reported by a notable study observing the impact of non-occupied surgical drill holes in fibulas.¹² Even bone biopsy holes, traditionally smaller than drill

holes used for internal fixation, can result in a significant reduction in femoral bone strength.¹³ Additionally, a hole of larger width will generally reduce strength to a greater degree than a smaller sized drill hole.¹³

These findings leave little doubt that the presence of drill holes has significant implications on the integrity of healing bone.

2. Objectives/Aims

For this study, we question if the specific placement of these drill holes can be chosen to minimize the loss in bone strength that is typically associated with the existence of these holes. In many cases of internal fixation, implant removal after an expected successful fracture healing has resulted in a false sense of security: patients often return to their previously routine daily activities only to suffer another fracture due to the weakened state of the bone, in part due to the presence of surgical drill holes.⁵ In a 2007 study, Saha showed that the location of unicortical drill holes in a Plexiglas® tube affected the load carrying capacity in a bending test.¹⁴ Results indicated that the strength of the tubes was most negatively impacted when drill holes were located in zones where the tensile stress was maximum. However, this finding had not been corroborated in authentic human long-bone. Thus, the objective of this study was to investigate how the quantitative loss in strength of a long bone with a drill hole in a compressive/tensile location compares to the loss in strength of an identical long bone with a hole in a neutral location. We hypothesized that bones with drill holes located at tensile locations would be weaker compared to bones with

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drill holes at neutral locations. The ultimate aim was to offer some clarity on how much strength (as defined by load bearing capacity) a bone can lose with just a single surgical drill hole and whether or not this can be mitigated by choosing an optimal drill hole location.

3. Methods

Sixty-eight human embalmed cadaveric long-bones were obtained from the SUNY Downstate Gross Anatomy Lab (450 Clarkson Avenue, Brooklyn, NY 11203). With two exceptions, four bones were collected from each of the 18 available donor bodies: two tibias, and two fibulas. The ages of the bodies ranged from 59 to 100 years old with equal distribution of sex (9 male and 9 female). One body had amputated a leg prior to death, and another had significant surgical alteration to one leg that warranted exclusion from the study. Thus, only 2 bones were sourced from each of these two bodies and were used for initial testing of our equipment. Tibias and fibulas were chosen for inclusion due to availability and relative ease of access, in addition to their propensity for fracture in severe lower extremity trauma.

The bones from each donor body were kept together in individualized labeled plastic bags and stored in a refrigeration unit when not being tested/analyzed. The fibulas were disarticulated from their respective tibias and each bone was manually cleaned to remove excess tendon, ligament, and muscle tissue. Each bone was subsequently radiographed to spot any abnormalities not readily apparent to the naked eye. Length, diameter, and cortical thickness of each bone was measured by using a scale and a micrometer. Additionally, each fibula was cut in half in order to maximize the amount of bone material available for experimentation. Time constraints ultimately prevented the testing of distal fibula samples, but each proximal sample was tested.

Our methodology allowed us to test how differing the placement of an identical drill hole in two bones might impact their strength (defined as load bearing capacity). It was decided that for each experimental bone sample, the control bone counterpart would come from the contralateral limb of the same body, as this would eliminate any biological variables (i.e. age, sex, etc.) that may impact bone density, strength, or flexibility. The presence of such variables would inevitably impact results if the paired control and experimental bone were from different donors. Additionally, designating the left or right bone as either control or experimental was randomized via computer algorithm for each body.

One drill hole was drilled into each experimental bone, with the controls being unaltered in any way. For the tibias, the hole was drilled in the exact center of the bone using a 4.1-mm drill bit attached to an electric drill press. Fibulas were drilled 1/4 of the length from the proximal articulation (i.e. 1/2 the length of a fibula cut in half) using a 3.2-mm drill bit. Our drill holes were bicortical, meaning the drill bit travelled entirely through the bone and pierced both cortical layers with a defined entrance and exit point. Our rationale for employing a bicortical drill technique was to mimic established surgical procedures: standard internal fixation methods typically use bicortical drill holes. Additionally, prior research has shown that the mean thrust force applied by the average surgeon when using a drill bit of these sizes is roughly 110 N.¹⁵ Therefore, since our drill allows force to be measured when drilling, we applied this same force when drilling our bones.

The holes were drilled in the same plane on each bone, with their location differing only by their placement along the circumference of that plane. The exact midline posterior tibia/fibula was designated as 0°. We divided the bone samples into three groups to test, each differing by their placement of the drill hole along the circumference. There was a total of 20 bones in each group: 10 control and 10 experimental (5 tibia and 5 fibula each). Group I had a hole drilled through 0°/180° (compressive at 0°/maximum tensile stress at 180°), Group II at 90°/270° (neutral), and Group III at 135°/315° (medium tensile stress at 135°/compressive at 315°) [Table 1 and Figs. 1 and 2]. Ages/sex of donor bones were evenly distributed amongst the groups. A statistical

Table 1

Summary of Groups. Each group contained 20 bones, 10 control (5 fibula + 5 tibia) and 10 experimental (5 fibula + 5 tibia). The control bones were unaltered and the experimental bones were drilled according to the group in which they were placed.

Group Number (N = 20)	Control (N = 10; 5 fibula and 5 tibia)	Experimental (N = 10; 5 fibula and 5 tibia)
Group I	Unaltered	Drill Hole at 0°/180° [Max compressive/tensile force]
Group II	Unaltered	Drill Hole at 90°/270° [Neutral]
Group III	Unaltered	Drill Hole at 135°/315° [Medium compressive/tensile force]

power analysis was performed to determine the necessary amount of bones to maintain the validity of our study: with an alpha of 0.05 and power of 0.80, the projected sample size needed per group was 15. Thus, our sample size of 20 per group was more than sufficient for our objectives.

Drilled bones and their control counterparts were mechanically tested via a four-point bending test using a mechanical testing machine (Instron Model 1011[®]), as shown in Fig. 3. The four-point bend test was selected so that the central portion of the beam was subjected to a uniform bending moment. The bones were attached to a holding apparatus that ensured they maintained the same position when force was applied during each test. Tibias were tested with a beam span of 255-mm and an upper jig span of 50-mm. Measurements for the fibulas were accordingly adjusted to 100-mm and 20-mm respectively. Crosshead speed was maintained at 10-mm/min for all tests. All bones were placed with their anterior face down such that the force from the bend test apparatus was applied at 0° (i.e. the midline of the posterior surface.) Software recorded displacement and load bearing capacity in real time. All results were compiled into SPSS for final analysis. Statistical tests used were the two-sample *t*-test and ANOVA.

4. Results

Our experiment generated analyzable data that showed a statistically significant ($P < 0.05$) decrease in strength of all tibias and fibulas with a hole drilled at 0°/180° and 135°/315° compared to their respective control group (Tables 2A, 2B, 3A and 3B). Differences in strength between the control and drilled tibias and fibulas in the 90°/270° group was statistically insignificant ($P > 0.05$). For the 0°/180° group (where one hole was located at the maximum tensile stress region) and 135°/315° group (where one hole was located at a medium tensile stress region), tibias experienced average decreases in strength of 43.4% ($\pm 6.5\%$) and 35.3% ($\pm 25.7\%$) respectively [Formula: $100 - (\text{avg. experimental LBC} / \text{avg. control LBC} * 100)$]. The failure load for the fibulas for these same respective groups showed a decrease of 34.6% ($\pm 11.5\%$) and 27.9% ($\pm 5.1\%$) in the load carrying capacity. ANOVA statistical analysis performed on all tibia and fibula data in each group indicated that the differences observed in the decrease in strength between drill holes placed at 0°/180°, 90°/270°, and 135°/315° was also statistically significant ($P < 0.05$). In addition to load bearing capacity, the stiffness for each sample was calculated by taking the maximum force prior to fracture (i.e. force at load bearing capacity) and dividing it by the displacement produced by such force. The results showed no statistical significance ($P > 0.05$) in the difference in stiffness between control bones and their experimental counterparts, indicating that the drill holes had no appreciable impact on overall stiffness of our samples.

Finally, when taking into consideration bone length, diameter, and cortical thickness of each of our samples, there was no significant finding that suggested any one of these parameters effected the relative loss in bone strength due to the drill hole. Though cortical thickness may have an impact on overall bone strength, having a thicker cortical layer did not prevent the drill hole from weakening the bone to the

Fig. 1. (A) Posterior view of tibia and cross section view of tibia. The black line marks the exact center of the tibia. Along this plane, a drill hole was placed at either 0°, 90°, and 135°, with 0° being the exact center of the posterior surface. (B) In the cross section view, holes were drilled along one of the dotted lines depending on the group being tested.

same relative degree compared to other experimental bones with differing cortical thickness (regardless of group).

5. Discussion/Conclusion

Ultimately, the data supports our hypothesis: bones drilled with holes at 0°/180° experienced the maximum loss in load bearing capacity, as these holes were located at the maximum tensile and compressive zones. This was followed by the 135°/315 group, which represented more moderate compressive and tensile zones and thus experienced a more moderate decrease in load bearing capacity. Holes at 90°/270°, representing neutral zones, retained the largest amount of load bearing capacity. Regarding stiffness, our results indicating no significant difference between experimental and control bones did not challenge our initial expectations: while the presence of a drill hole did impact the maximum load bearing capacity (depending on the group), it did not change the displacement of the bone at any given force. Thus, even though an experimental bone from the 0°/180° group may have failed at a lower force compared to its control counterpart, its displacement was also comparatively smaller, reflecting the lower maximum force. This explains why there was no statistically significant difference in stiffness between experimental bones and control bones.

Comparing our results to the 2007 study using Plexiglas® tubes in place of human bone, our results corroborate what was found: drill holes located in zones where tensile stress was maximum resulted in the largest decrease in load bearing capacity. Our results also augment the results of prior studies in this realm of orthopedic research. Though we cannot comment on the impact of drill holes of varying size, we can say that the specific location of any one drill hole will have an impact on overall bone strength relative to an alternative location, validating

what was implied as a potential for future study in a report published in the Journal of Bone and Joint Surgery.¹³

Given the irregular shape and density of bone however, we expected there to be unforeseen problems that might confound our data. Although most bones in groups I, II, and III experienced catastrophic failure in the central region between the jig span of the loading actuator where the drill holes were located (Fig. 4), some failed at either far distal or proximal locations outside this zone (Fig. 5). These bones most likely had substantial inherent weaknesses that were unforeseen and invalidated their results, since a failure outside the jig span provides no indication on the effect of a drill hole. Such outliers represented only a minority of the bones (3 tibias and 4 fibulas) and they, plus their respective contralateral counterpart, were excluded from the final analysis.

The major limitation of our study is its confinement to the lower limb. Although the number of tibias/fibulas we had available per group was more than sufficient as per our statistical power analysis, it would have been ideal to test other long bones as well (e.g. humerus, radius/ulna, etc.). However, sixty-eight tibias/fibulas was the maximum we could obtain given the time frame and donor body availability. Other limitations include only being able to test embalmed specimens as opposed to fresh human bone, and a relatively elderly population of donor bodies instead of a mix of young and old. Elderly bones, in conjunction with the embalming process, likely resulted in weaker bones than would be observed with younger fresh human specimen. In addition, there are many more variables that can be considered in future studies. For example, our conditions for loading weight onto each bone was static across all specimens. Future studies may want to investigate how varying the load rate beyond 10-mm/min impacts results. Effect of drill holes on torsion, axial compression, or cantilever bending are also areas

Fig. 2. (A) Posterior view and cross section view of fibula. The solid black line marks the exact center of the tibia, where it was cut in half. The dash line marks the quarter length of the fibula, where holes were drilled. Along this plane, drill holes were placed at either 0°, 90°, and 135°, with 0° being the exact center of the posterior surface. The distal half of the fibula was stored in case further analysis was needed. (B) In the cross section view, a hole was drilled along one of the dotted lines depending on the group being tested.

Fig. 3. Schematic of the four-point bend test set-up. Specimen = Tibia or fibula. Beam span/jig span was adjusted for tibia or fibula specimens.

Table 2A
Results of Tibia Load Bearing Capacity Data. The average percent difference between control and experimental samples is also shown. ANOVA p-value reports a significant difference in load bearing capacity between each group.

	Control Load Mean ± SD (N)	Experimental Load Mean ± SD (N)	Average Percent Difference ± SD	P-Value
Group I	5825 ± 1541	3226 ± 542	56.6% ± 6.5%	0.00046
Group II	3839 ± 1673	3975 ± 1879	95.6% ± 8.5%	0.38684
Group III	3920 ± 1847	2808 ± 2278	64.7% ± 25.7%	0.03553

ANOVA p-Value: 0.017.

Table 2B

Results of Tibia Stiffness Data. The average percent difference between control and experimental samples is also shown. ANOVA p-value does not report a significant difference in stiffness between each group.

	Control Bone Average Stiffness $\pm$ SD (N/M)	Experimental Bone Average Stiffness $\pm$ SD (N/M)	Average Percent Difference $\pm$ SD	P-Value
Group I	543,044.1 $\pm$ 185,173.9	538,430.1 $\pm$ 134,928.1	103.2% $\pm$ 19.8%	0.383
Group II	306,728.9 $\pm$ 164,162.7	346,618.1 $\pm$ 184,446.0	114.6% $\pm$ 15.1%	0.075
Group III	361,085.1 $\pm$ 187,387.1	428,530.6 $\pm$ 227,483.8	121.0% $\pm$ 22.1%	0.077

ANOVA p-value = 0.724453.

Table 3A

Results of Fibula Load Bearing Capacity Data. The average percent difference between control and experimental samples is also shown. ANOVA p-value reports a significant difference in load bearing capacity between each group.

	Control Load Mean $\pm$ SD (N)	Experimental Load Mean $\pm$ SD (N)	Average Percent Difference $\pm$ SD	P-Value
Group I	1238 $\pm$ 650	1017 $\pm$ 433	65.4% $\pm$ 11.5%	0.02690
Group II	496 $\pm$ 338	487 $\pm$ 225	90.19% $\pm$ 16.9%	0.33309
Group III	810 $\pm$ 469	547 $\pm$ 313	72.1% $\pm$ 5.1%	0.00086

ANOVA p-Value: 0.049.

Table 3B

Results of Fibula Stiffness Data. The average percent difference between control and experimental samples is also shown. ANOVA p-value does not report a significant difference in stiffness between each group.

	Control Bone Average Stiffness $\pm$ SD (N/M)	Experimental Bone Average Stiffness $\pm$ SD (N/M)	Average Percent Difference $\pm$ SD	P-Value
Group I	345,747.5 $\pm$ 165,773.7	405,411.0 $\pm$ 304,548.1	127.7% $\pm$ 72.7%	0.251
Group II	110,162.2 $\pm$ 65,068.9	143,655.7 $\pm$ 108,152.2	119.7% $\pm$ 27.5%	0.171
Group III	158,300.2 $\pm$ 81,983.8	173,713.2 $\pm$ 108,403.1	109.9% $\pm$ 43.3%	0.400

ANOVA p-Value: 0.758.

Fig. 4. Example of tibia specimen that failed directly at the drill hole site. This represented the majority of outcomes.

of interest that were not addressed in this study. Furthermore, varying the size of the drill holes and testing other locations, such as ones closer to the epiphysis, may yield further useful results.

Our findings have clinical significance regarding guiding the placement of screws and plates in patients with long bone fractures. Although there are many factors involved in determining the placement

of internal fixation plates (e.g. the degree of comminution, the presence of soft tissue injury, the presence of blood vessels and nerves, etc.), the results of our study may be able to offer a contribution. Given that most holes left behind by internal fixation techniques usually heal in approximately 8 months, if they ever heal at all, the loss in bone strength during this time is significant enough to potentially put the patient at

Fig. 5. Example of tibia specimen that failed outside the experimental zone (i.e. the jig span). Here, there was an inherent weakness in the bone towards the distal end. Note that the area in between the jig span is still intact.

risk for further injury. Based on our results, we can conclude that drill holes placed at the neutral zone where the compression/tension stresses are minimum can most likely minimize the loss of bone strength associated with the existence of a drill hole. This information can aid orthopedic surgeons in determining where to drill holes to both minimize the inherent loss in load carrying capacity while maintaining adequate stability for fracture treatment. Our findings can also be beneficial for patients, who should be counseled on residual bone weakness due to drill holes after the removal of plates/screws. Ideally, patients should not return to full activity until the drill holes are fully healed due to risk of further possible fracture.

Authors contribution

Christopher James Yiachos: designed project, gathered materials, performed methodology, recorded/analyzed data, wrote manuscript.

Subrata Saha: Provided lab space and assistance when needed.

Conflicts of interest and source of funding

All authors declare they have no conflict of interest. No benefits in any form have been received or will be received from a commercial party related directly or indirectly to the subject of this article. This article does not contain any studies with human participants or animals performed by any of the authors.

Competing interests

None of the authors had, or currently have, competing interests in regard to this paper.

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