Veterinary Record Open

Can a surgeon drill accurately at a specified angle?

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To cite: Brioschi V, Cook J, Arthurs GI. Can a surgeon drill accurately at a specified angle?. *Vet Rec Open* 2016;**3**: e000172. doi:10.1136/ vetreco-2016-000172

▸ Prepublication history for this paper is available online. To view these files please visit the journal online (http://dx.doi.org/10.1136/ vetreco-2016-000172).

Received 19 February 2016
Revised 26 April 2016
Accepted 4 May 2016

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ABSTRACT

Objectives: To investigate whether a surgeon can drill accurately a specified angle and whether surgeon experience, task repetition, drill bit size and perceived difficulty influence drilling angle accuracy.

Methods: The sample population consisted of final-year students (n=25), non-specialist veterinarians (n=22) and board-certified orthopaedic surgeons (n=8).

Each participant drilled a hole twice in a horizontal oak plank at 30°, 45°, 60°, 80°, 85° and 90° angles with either a 2.5 or a 3.5 mm drill bit. Participants then rated the perceived difficulty to drill each angle. The true angle of each hole was measured using a digital goniometer.

Results: Greater drilling accuracy was achieved at angles closer to 90°. An error of ≤±4° was achieved by 84.5 per cent of participants drilling a 90° angle compared with approximately 20 per cent of participants drilling a 30–45° angle. There was no effect of surgeon experience, task repetition or drill bit size on the mean error for intended versus achieved angle. Increased perception of difficulty was associated with the more acute angles and decreased accuracy, but not experience level.

Clinical significance: This study shows that surgeon ability to drill accurately (within ±4° error) is limited, particularly at angles ≤60°. In situations where drill angle is critical, use of computer-assisted navigation or custom-made drill guides may be preferable.

INTRODUCTION

Orthopaedic surgeons and neurosurgeons perform bone drilling to place implants on a daily basis. In many instances, for example in diaphyseal fracture repair, the precision of screw, external skeletal fixator (ESF) pin or K-wire positioning is not critical. However, in some cases, accuracy of screw or pin position, direction and depth is critically important because of adjacent structures such as joints, spinal cord, cauda equina or major blood vessels. Compromise of these structures by implant penetration could have serious consequences such as the development of degenerative joint disease, fatal bleeding from vessel penetration or irreversible paralysis from nerve/spinal cord damage. Specific examples in small animal surgery include placement of a sacroiliac screw or a humeral transcondylar screw and placement of screws or ESF pins in vertebral bodies for stabilisation of spinal fractures or luxations.

A number of studies have been published investigating and describing the optimal drilling angle for implant placement in various osseous structures in order to achieve internal fixation safely and effectively (Watine and others 2006, Shales and others 2009, Barnes and others 2014).

Barnes and others (2014) described the optimum drilling position and trajectory for placement of a transcondylar screw in the canine elbow as parallel to a line drawn between the medial and lateral epicondyle (epicondylar reference line) in the transverse plane and 2° from the same line in the frontal plane.

Shales and others (2009) determined that sacroiliac lag screws for surgical treatment of sacroiliac luxation in cats should have a dorsoventral angulation of 90° from the articular surface of the sacrum. The same study found that an error of only 4° would result in ventral exit of the screw from the sacral body in 58 per cent of cases and a 2° error would result in ventral exit in 35 per cent of cases. In dogs, a drill angle of 100° ±4° to the articular surface of the sacrum would avoid vertebral canal penetration in 91 per cent of sacra and a slight shift to 97±4° avoids vertebral canal penetration but risks ventral screw exit in 30 per cent of sacra (Shales and Langley-Hobbs 2005).

For the surgical stabilisation of vertebral fractures and luxations, the ideal starting position and drilling angle (from vertical) for safe implant placement into the vertebral bodies has also been described using CT imaging and mapping of the spinal column anatomy: C_2: (cervical vertebral body 2) 45–60°; C_3: 33–45°; C_4: 30–45°; C_5: 30–35°; C_6: 30–40°; C_7: 45–55°; T_{10}: 20–25°; T_{11}: 25–35°; T_{12}: 25–35°; T_{13}: 40–45°; and L_1–L_6: 55–65° (Watine and others 2006, Hettlich and others 2010).

Although these studies have very precisely defined the optimal drilling position and angle for screw placement in bones, can a surgeon actually drill with the required accuracy? The consequences of inaccurate drilling due to drilling error include suboptimal bone purchase leading to reduced construct rigidity and increased chance of premature screw loosening or damage to the surrounding structures including nerves, spinal cord or vessels (DeCamp and Braden 1985, Shales and others 2010).

There is remarkably little information, evidence or research regarding the ability of a surgeon to achieve the recommended safe drilling angles in either the veterinary or human orthopaedic literature. A recent detailed review on human orthopaedic bone drilling cited no studies investigating drilling accuracy but simply concluded that the accuracy of drilling depends on the surgeon's manual skills and that automated drilling systems may be developed to minimise human error (Pandey and Panda 2013).

The ability of veterinary surgeons to drill at a specific angle was crudely evaluated as a small part of a study that assessed the safe corridor for screw placement in the canine sacrum (Shales and Langley-Hobbs 2005). Eleven qualified veterinary surgeons were asked to drill holes free hand 'by eye' at 97° from the horizontal. The authors estimated that the acceptable margin of aiming error when placing sacroiliac screws in dogs was ±4° and found that 82 per cent of participants achieved drilling angles within this margin of error.

Another recent study assessed the ability of 14 qualified veterinary surgeons to drill holes free hand at 90° from the horizontal (Sparrow and others 2015). They identified a systematic error in all individuals and found that left-handed individuals had a mean aiming bias of 2.3° (range 0–7.7°) to the left and right-handed individuals had a mean aiming bias of 1.5° (range 0.3–3.1°) to the right.

Thus although the ability of qualified veterinary surgeons to drill at 90° and 97° from the horizontal has been investigated, there is otherwise very limited information in terms of the range of drilling angles required on a daily basis and individual's ability to drill clinically relevant angles.

The aim of this study was to investigate how accurately a specified drill angle could be achieved, whether surgical experience had an influence on drilling accuracy and whether the perceived level of difficulty varied with the angle. The null hypotheses were that

1. drill bit size would not influence the ability to drill accurately;
2. all angles could be drilled with equal accuracy;
3. drilling angle accuracy was not related to surgical experience (i.e. board-certified orthopaedic surgeons would not perform better than non-specialist veterinary surgeons or students);
4. perceived difficulty of drilling would be equal for all drilling angles and would be unrelated to the error attained and to the experience level.

Having established this, the margin of drilling accuracy/error generated by this data set was analysed and presented as a percentage of participants that could drill within a certain error margin. The error margins were compared with previous publications on safe corridors.

MATERIALS AND METHODS

Rectangular sections of oak wood were used as a drilling substrate, which were presented flat on a table top and held securely using a table-top clamp (Dremel Project Table, commercially available). A standard 18 V cordless power drill was used (DC100KA-GB, DeWalt, Slough, UK). Participants were randomly assigned using the toss of a coin either a 2.5 or a 3.5 mm drill bit ('Drill bits, Stainless steel 316 implant quality, Short life', Veterinary Instrumentation, Sheffield, UK). Each drill bit was replaced after it was used 10 times. An appropriately sized drill guide was provided to aid freehand drilling during the assessment, as may be used during routine surgery ('3.5 mm Combination drill, tap and insert sleeve', Veterinary Instrumentation, Sheffield, UK).

Each participant was asked to drill a series of holes in a section of wood at the specified angles of 30°, 45°, 60°, 80°, 85° and 90° from the surface of the wooden plank (0° being horizontal and 90° being vertical) in a plane parallel to the long axis of the wooden panel. No time constraint was imposed. No instruction was given, or constraints imposed, as to how participants could or should aim. Each angle was attempted and recorded twice (i.e. the same angle was drilled twice before moving onto the following angle in the sequence), with each individual drilling a total of 12 holes. Participants were requested to drill all 12 holes, with the option to attempt the sequence in ascending or descending order of angles, and stating clearly which angle they were attempting at the time of drilling. They were asked to drill to a sufficient depth such that an identically sized drill bit could be placed securely in the hole produced. After completion of the drilling task, participants were asked to rate the perceived difficulty of drilling each angle on a scale of 1–10, with a score of 1 being most easy and 10 being most difficult. In order to eliminate any possible learning component, accuracy of drilling was not measured and no feedback was given until the drilling task had been completed in full. The angle of each hole drilled was then measured to an accuracy of 0.1° by replacing the drill bit in each hole and using a digital angle measurer (GemRed Digital Angle Rule, 200 mm, GemRed, Guangxi, China) to measure between the drill bit and the surface of the wood. Results were recorded on a prepared anonymous individual record sheet. In order to gauge the effect of experience level on ability to accurately drill at a specified angle, participants were divided into three experience groups. Group 1 (students) consisted of final-year veterinary students, representing individuals with good understanding of the task, but no previous experience of orthopaedic surgery. Group 2 (non-specialist veterinary surgeons) consisted of qualified veterinary surgeons including interns, anaesthesia and internal medicine residents, representing veterinary surgeons with a range of interests and exposure to relevant surgical techniques, equivalent to that expected in a cross section of general practitioners. Group 3 (orthopaedic specialists) consisted of board-certified small animal veterinary orthopaedic surgeons, representing veterinary surgeons with a high level of experience in the relevant surgical field.

The recorded data were tabulated and used to calculate the accuracy of drilling achieved. Drilling angle error (degrees) was determined for each hole drilled by calculating the difference of the angle attained from the angle intended. Whether the angle attained was higher or lower than the angle intended was not taken into account in the data analysis. Drilling accuracy was compared with the error margins documented in previous studies to determine what percentage of the participants in this study were able to drill within the margin of error. The effect of drill bit size (2.5 mm/3.5 mm) and experience level (groups 1–3) on accuracy achieved were also investigated. The reported perceived difficulty was correlated with actual accuracy.

Statistical analysis was performed using commercially available Microsoft Office Excel 2002 and IBM SPSS Statistics V.19 software. A Kolmogorov-Smirnov test was used to assess data for normal distribution. Following this, a Wilcoxon signed-rank test was used to compare continuous variables of accuracy attained on the first and second drilling attempts, and a Mann-Whitney U test was used to compare the accuracy attained using the different-sized drill bits. Kruskal-Wallis testing was used to compare the accuracy attained between the experience groups, the categorical variable of perceived difficulty between experience groups and the perceived difficulty between specified angles.

RESULTS

A total of 55 participants completed the drilling task, of which 25 were final-year veterinary students (group 1), 22 were qualified veterinary surgeons with no specific interest in orthopaedics (group 2) and 8 were board-certified veterinary orthopaedic surgeons (group 3). A total of 660 holes were drilled, 110 at each of the six specified angles.

Drilling angle error (degrees) was determined for each hole drilled. A Kolmogorov-Smirnov test ($P \leq 0.001$) found that error attained across all angles did not have a normal distribution, so non-parametric testing was used. A Wilcoxon signed-rank test was performed to compare the accuracy attained on the first and second drilling attempt; this revealed no statistically significant difference ($Z=-1.012$, $P=0.311$) between the two attempts; thus, thereafter, mean error calculated from the two attempts at each angle was used for statistical analysis, creating one overall mean error value from each participant (we refer to this value as 'error attained' for each participant in the text that follows). Figure 1 shows the error attained for each experience-level group at each specified drilling angle.

Effect of drill bit size on drilling accuracy

In total,27 participants were assigned a 2.5 mm drill bit and 28 were assigned a 3.5 mm drill bit (Table 1).

Median error was 4.65° (2.5 mm drill bit) and 4.1° (3.5 mm drill bit). Mann-Whitney U testing found no significant statistical difference in error attained between participants using a 2.5 mm drill bit (median 4.65, n=27) and a 3.5 mm drill bit (median 4.10, n=28), $U=13178$, $z=-0.496$, $P=0.62$. As there was no significant effect of drill bit size, the data set was subsequently analysed regardless of drill bit size.

How accurately a specified drilling angle can be achieved

This was assessed by calculating the percentage of participants able to drill at each specified angle within the following error margins: ±2°, ±4° and ±5°, and this was subsequently subdivided according to experience. This information is shown in Table 2.

A higher percentage of participants drilled within the error margin when the error margin was greater, that is, when less accuracy was required. The percentage of participants drilling within the error margin increased with angles approaching 90°; in other words, greater accuracy was achieved at angles closer to the perpendicular.

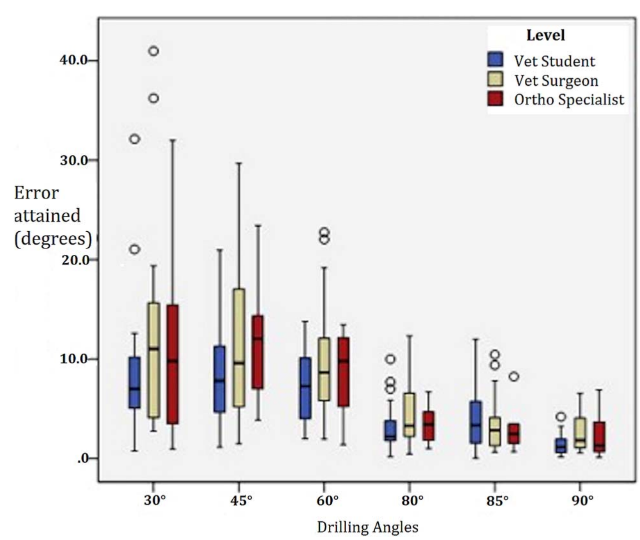

FIG 1: Box plot illustrating the error attained for each experience-level group at each specified drilling angle. The ends of the whiskers represent the lowest datum still within 1.5 IQR of the lower quartile, and the highest datum still within 1.5 IQR of the upper quartile. Any data not included between the whiskers was considered an outlier (represented with a dot). Outliers were the result of a participant drilling incorrectly at both attempts of the same angle; however, each outlying value relates to a separate participant (i.e. it was not the same individual drilling consistently at an incorrect angle)

TABLE 1: Distribution of drill bit sizes across participant groups

Drill bit size	Experience level	N
2.5 mm drill bit	Students (group 1)	12
	Non-specialist veterinary surgeons (group 2)	12
	Orthopaedic specialists (group 3)	3
3.5 mm drill bit	Students (group 1)	13
	Non-specialist veterinary surgeons (group 2)	10
	Orthopaedic specialists (group 3)	5

Figure 2 shows a graphic representation of this trend when drilling error margin achieved by participants was set at ≤±4°.

The relationship between error attained and specified angle (regardless of experience level) was investigated using Spearman's rank-order correlation test: this confirmed a strong, negative correlation between the two variables (r=−0.59, n=330, P≤0.001).

Effect of experience on drilling accuracy

To assess the effect of experience on drilling accuracy, the data were initially analysed regardless of specified drilling angle. Veterinary students (group 1) achieved a median error of 3.95 compared with 4.98 for non-specialist veterinary surgeons (group 2) and 4.30 for orthopaedic specialists (group 3). A Kruskal-Wallis test showed that there was no statistically significant difference between the three experience-level groups in error attained regardless of intended angle (χ^2 with 2 degrees of freedom (n=330)=4.59, P=0.10), meaning that the experience level of the participants had no significant effect on the drilling accuracy that they achieved.

Error attained was also assessed separately between specified angles, and a Kruskal-Wallis test confirmed again that there was no statistically significant difference in mean error for each angle between the three experience groups; χ^2 and P values are shown in Table 3 (2 degrees of freedom, n=55).

Perceived difficulty: effect of drilling angle, error attained and experience

Participants rated the perceived difficulty of drilling each angle on a scale of 1–10 (1, most easy, to 10, most difficult).

Participants' perceived difficulty for each drill angle was tested using a Kolmogorov-Smirnov test (P≤0.001), which found that the data were not normally distributed.

The relationship between perceived difficulty and error attained was initially investigated regardless of experience level using Spearman's rho correlation. There was found to be a medium positive correlation (according to Cohen's guidelines (1988)) between the two variables (rho=0.31, n=330, P≤0.001): increased perceived difficulty was associated with a greater drilling error attained.

The data were subsequently analysed with respect to experience: veterinary students reported a median score of 5 for perceived difficulty compared with 4 for non-specialist veterinary surgeons and 4 for specialist orthopaedic surgeons. Kruskal-Wallis testing revealed no statistically significant difference (χ^2 with 2 degrees of freedom (n=330)=5.34, P=0.07) in perceived difficulty between the three experience-level groups regardless of drilling angle.

Finally, the relationship between angle specified and perceived difficulty was investigated. The perceived difficulty score progressively reduced with angles approaching 90° (30° median=7; 45°, 60°, 80° median=5; 85° median=4; 90° median=1). Kruskal-Wallis testing revealed a statistically significant difference in perceived difficulty across the range of specified angles (χ^2 with 5 degrees of freedom (n=330)=139.0, P≤0.001).

In summary, participants found increasingly acute angles more difficult to drill and they perceived as more difficult angles where they attained greater drilling

TABLE 2: Percentage of participants within groups achieving error margins

Error margin	Experience level	30°	45°	60°	80°	85°	90°
% ≤ ±2°	All participants	11.8	8.2	10.0	40.0	38.2	60.0
	All veterinary surgeons	10.0	6.7	10.0	31.7	41.7	55.0
	Students	14.0	10.0	10.0	50.0	34.0	66.0
	Non-specialist vets	9.1	9.1	9.1	27.3	40.9	52.3
	Orthopaedic specialists	12.5	0.0	12.5	43.8	43.8	56.3
% ≤ ±4°	All participants	24.5	21.8	23.6	63.6	68.2	84.5
	All veterinary surgeons	23.3	18.3	21.7	55.0	71.7	76.7
	Students	26.0	26.0	26.0	74.0	64.0	94.0
	Non-specialist vets	20.5	20.5	18.2	54.5	68.2	75.0
	Orthopaedic specialists	37.5	12.5	31.3	56.3	81.3	81.3
% ≤ ±5°	All participants	33.6	29.1	29.1	71.8	75.5	90.0
	All veterinary surgeons	33.3	23.3	23.3	66.7	80.0	83.3
	Students	34.0	36.0	36.0	78.0	70.0	98.0
	Non-specialist vets	31.8	25.0	20.5	63.6	79.5	84.1
	Orthopaedic specialists	37.5	18.8	31.3	75.0	81.3	87.5

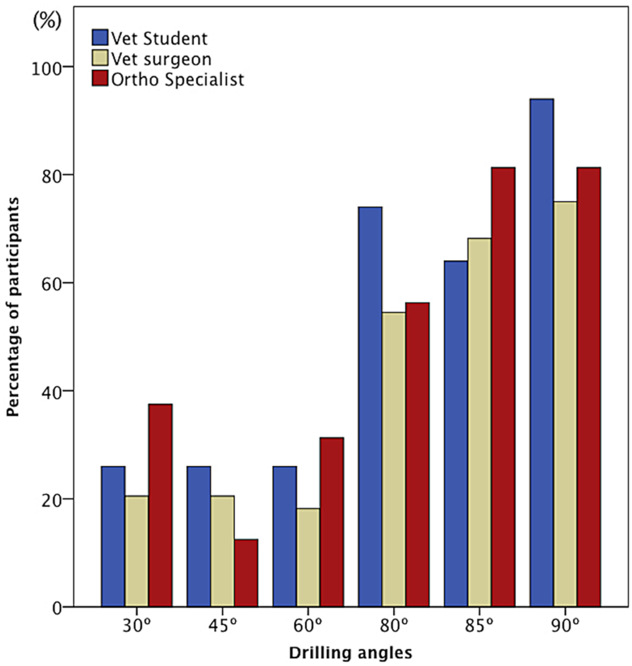

FIG 2: Percentage of participants within groups achieving error margin ≤4°

error; perceived difficulty across the range of specified angle was significantly different. Perception of difficulty was the same for participants of different experience levels.

DISCUSSION

In investigating whether a surgeon can drill at a specified angle, the authors failed to reject two of the four null hypotheses and refuted the other two.

Effect of drill bit size and experience on drilling accuracy

Using this experimental set-up, both drill bit size and operator experience had no statistically significant effect on the ability to drill accurately. While common sense might make it unsurprising that drill bit size does not influence drilling accuracy, it might be expected that a surgeon with greater orthopaedic experience would have greater ability to assess an angle and drill it free hand, but this study showed no benefit of experience over ability to drill accurately.

This challenges the question whether assessing an angle and performing freehand drilling is an innate ability or a skill that can be improved with time and targeted training. To the author's knowledge, no studies have assessed if or how such a skill is acquired; however, two main theories have been reported in the literature regarding expert performance in a domain. The 'skill acquisition view' of Ericsson (2004) postulates that practice is necessary for an individual to be able to master a certain skill. On the contrary, the 'talent view' states that the difference in skills noted among practising surgeons reflects limits of achievement determined by innate abilities; thus, quality of performance can increase with practice but only up until a fixed upper plateau reflecting these innate traits (Lombardo and Deaner 2014).

Van Bruwaene and others (2015) found that both innate ability and practice contribute to the acquisition of laparoscopic surgery skills in medical students. They drew this conclusion based on assessment of baseline laparoscopic psychomotor and visual-spatial aptitude in a group of 68 final-year medical students and on assessment of the same variables after a three-hour laparoscopy training followed by two weeks of individual practice.

The authors found that experienced surgeons did not perform better compared with final-year students when attempting to drill at a specified angle, which suggests indirectly that innate ability may contribute more than practice to the acquisition of this skill. However, care was taken in this study design to eliminate limited potential learning component; therefore, we cannot assess the effect of training on task performance. It would be interesting to evaluate the effect of targeted training (repetition of drilling attempts at a set angle followed by feedback) on freehand drilling performance as it would demonstrate whether dry lab practice would be beneficial for individuals interested in orthopaedics and neurosurgery.

How accurately a specified drilling angle can be achieved

The null hypothesis that all angles could be drilled with equal accuracy was refuted. The authors found that greater accuracy was achieved at angles closer to 90°; however, only approximately 85 per cent of participants could drill with error less than 4° at a 90° angle and the percentage was even lower for more acute angles and when a narrower error margin (less than 2°) was permitted (Table 2).

The drilling angles chosen in this study focused on those in the region that would be attained in a successful sacroiliac luxation repair in cats and surgical stabilisation of vertebral fractures/luxations (Watine and others 2006, Shales and others 2009, Hettlich and others 2010). Only 55 per cent of qualified veterinary surgeons in this study could drill at the required 90°±2° angle for feline sacroiliac luxation repair suggested by Shales and others (2009),

TABLE 3: Kruskal-Wallis test results for difference in mean error between groups

Specified angle:	30°	45°	60°	80°	85°	90°
χ^2	2.99	2.99	2.09	2.84	1.26	4.61
P value	0.224	0.228	0.352	0.242	0.532	0.100

assuming a lateral approach to the sacrum with the patient in lateral recumbency. This suggests that to improve chances of successful screw placement surgeons may choose to rely on additional aids. A recent clinical research abstract reported the use of intraoperative radiography to improve drilling accuracy in placing sacroiliac lag screws in cats. In this study, sacroiliac screw placement under intraoperative radiography guidance resulted in premature exit of the screw from the sacral body in 15 per cent of cases as opposed to 47 per cent of cases when intraoperative radiography was not used (Silveira and others 2015). In situations where intraoperative imaging is not available, some guidance from an experienced surgical assistant regarding drill positioning in relation to prediscussed anatomic landmarks may be of aid to the surgeon in achieving a specified drilling angle; however, no scientific evidence is available at present to evaluate whether this arrangement provides an actual improvement in drilling accuracy.

The percentage of qualified veterinary surgeons that were able to drill at angles relevant for surgical stabilisation of vertebral fracture/luxation (30°, 45° and 60° angles) was only 20 per cent when considering a 4° error margin and 6–10 per cent when considering a 2° error margin. These results suggest that surgeons should be very careful in relying on their own ability to estimate and freehand drill for screw/pin placement in vertebral bodies, and that intraoperative imaging would likely be highly beneficial in performing these surgical procedures. Fluoroscopically assisted percutaneous vertebral pin placement has been described in dogs (Leasure and others 2007). Fluoroscopic guidance resulted in more accurate percutaneous pin placement in the lumbar vertebral bodies compared with freehand drilling in a cadaveric study (Wheeler and others 2002). If intraoperative fluoroscopy is not available, a technique based on creation of a bone tunnel by advancing a blunt-tipped pedicle probe and careful assessment of medial pedicle wall violation before pin insertion has also been described in order to minimise aiming error and iatrogenic damage to neurovascular structures (Weh and Kraus 2012). A similar freehand technique for insertion of pedicle screws in people has been reported to have a low complication rate (6 per cent pedicle cortical penetration rate, no vascular, neurological or visceral complications) when anatomic landmarks and specific entry sites were used to guide the surgeon as well as a stepwise, careful and accurate surgical technique (Kim and others 2004).

The use of computer-assisted navigation and rapid prototyping custom-made drill guides to improve accuracy of pedicle screw placement have also been described in people; however, they have not been reported in veterinary medicine yet (Amiot and others 2000, Lu and others 2009).

Perceived difficulty: effect of drilling angle, error attained and experience

The results of this study refuted the null hypothesis that the perceived difficulty of drilling would be equal for all drilling angles: participants found more acute (lower) angles more difficult to drill. They also found it more difficult to drill those angles where they attained greater drilling error. Perception of difficulty was the same for participants of different experience levels. This indicates that the participants were aware of their limitations and experienced a perception of difficulty consistent with their ability to achieve the angle required. It might be assumed that a more experienced surgeon would have greater confidence in their ability, and therefore, the more experienced group would score a lower median perceived difficulty score. In this study, though, students recorded only a marginally higher median perceived difficulty compared with non-orthopaedic veterinary surgeons and orthopaedic specialist veterinary surgeons, with no statistically significant difference detected between groups.

STUDY LIMITATIONS

There are several improvements that could be made to the study. The number of orthopaedic specialists was small compared with qualified veterinary surgeons and students. More even and increased sample sizes in the three groups would be beneficial for statistical analysis; a difference in error attained by orthopaedic specialists and non-orthopaedic veterinary surgeons may be discovered in a larger sample as currently very few outlying values have the potential to skew the results in this group.

With regard to determining the difference in drilling accuracy between experience levels, a power calculation was not performed in advance of the study as the authors had little useful starting information as to how accurately participants of any experience level were likely to be able to drill. This study reports outcome data that are continuous, do not report a binary outcome and challenge a number of different discrete variables, that is, operator experience and drilling angles. Therefore, it is challenging to make a meaningful post hoc calculation. As a consequence, and particularly given the small number of experienced surgeons recruited (n=8), the authors' failure to demonstrate improved accuracy in experienced surgeons could simply be a type II error, that is, insufficient sample size.

The ability to judge a specified angle and the ability to drill the angle accurately were jointly assessed in this study as both skills are necessary in order to achieve accurate freehand surgical bone drilling. However, separate assessment of the two skills may have provided additional information in regard to developing aimed training for individuals to improve their skills.

It is possible that asking participants to drill in a sequence of increasing or decreasing drill angles may have influenced the results; such a pattern may have caused confusion or may have aided in inferred learning. This is unknown and a separate study would be needed to investigate this.

No time restriction was placed on how long participants could take to drill as surgeons generally take as much time as they need to drill holes accurately in surgery, and there was no known benefit to imposing a time restriction.

Sections of oak wood were selected as a drilling substrate for the study due to convenience and the consistent high density of the material. The density of oak wood sections has been reported to be approximately 0.68 g/cm^3, which is comparable to the average bone mineral density of canine femoral cortical bone (0.84 g/cm^3) (Silbernagel and others 2002, Askeland and Wright 2016). Alternative substrate of canine or feline cadaveric bone was considered; however, the option was rejected since cadaveric bone cannot be considered a uniform test medium because of differences in size, shape, age, bone mineral density, preservation techniques and anatomic variations, even among matched pairs (Silbernagel and others 2002, Kunkel and others 2011).

In addition, acquisition, handling and transport of cadaveric specimens can involve significant financial, ethical and biohazard issues. Furthermore, the contoured surface of cadaveric bone would add a novel and inconsistent difficulty to the drilling task and decrease accuracy of measurement of achieved angles. In this study, the authors have created a simplified case scenario by asking participants to drill on a flat and uniform surface. Further studies could be developed to consider the difficulty in freehand drilling at a specified angle on a contoured surface of a shape and density analogue to a specific skeletal segment (i.e. lateral aspect of the canine or feline sacrum or the canine humeral condyle or the canine lumbar vertebrae). Additionally, varying the visual field and reducing the area available in which to drill would make the task more realistic as exposure of the bone surface during surgery is generally very limited (Tomlison 2002). Experimentally, this might be achieved by using sham surgical drapes with various-sized fenestrations to provide a varied level of exposure, and so visualisation, of the plane by which the angle of drilling can be judged. Reduced visualisation of the area surrounding the drilling target may hide external cues, which one would expect could make accurate drilling more difficult. However, the effect of external cues on drilling accuracy is not known, and therefore, further studies would be necessary to establish whether obscuring them has a negative impact on operator drilling performance.

Using wood as a drilling substrate may have contributed to creating a simplified case scenario by facilitating the drilling task compared with drilling in a clinical setting. When drilling is performed on wood, the authors' observation is that it is easier to create an indentation on the surface by applying pressure onto the drill bit before running the drill, thus avoiding skimming of the drill bit. In the clinical situation, it is often necessary to start drilling at a steeper angle to make an indentation in the cis cortex before the surgeon's hand is dropped and the intended angle is drilled, making it harder for the operator to attain the intended drilling angle. The participants were not prevented from doing this, but they were not directly observed as doing so. Regardless, this study may underestimate the difficulty and therefore the error in accuracy of drilling cortical bone, particularly with increasing angles from vertical.

Finally, the authors assessed drilling angle in a single plane (i.e. parallel to the long axis of the section of wood); however, when performing freehand drilling at a specified angle, the surgeon should be aware that aiming bias may be present in the orthogonal plane as well.

CONCLUSION

In conclusion, the ability of a surgeon to drill safely at a specified angle depends largely on the angle at which they must drill and the acceptable margin of error.

This study shows that surgeon's ability to drill accurately (within ±4° error) is limited, particularly at angles ≤60°.

The ability to drill accurately appears to vary on an individual basis, and in this study was not influenced by surgeon experience.

In situations where it is critical to drill accurately at a specified angle, use of intraoperative imaging, computer-assisted navigation or custom-made drill guides may be preferable.

Acknowledgements The authors thank Professor Adrian Boswood for his help with statistics and the surgery department of the Queen Mother Hospital for Animals (Royal Veterinary College, University of London) for allowing access to equipment.

Competing interests None declared.

Provenance and peer review Not commissioned; externally peer reviewed.

Data sharing statement No additional data are available.

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*Vet Rec Open*2016 3:
doi: 10.1136/vetreco-2016-000172