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3-Fluted orthopaedic drills exhibit superior bending stiffness to their 2-fluted rivals: Clinical implications for targeting ability and the incidence of drill-bit failure

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Summary Non-perpendicular drilling of bone is commonplace in orthopaedic surgery. In the absence of drill-jigs and guides, the drill-tip is prone to skiving along the bone. Skiving can alter the position of the intended hole or result in damage to surrounding tissues. We hypothesised that the acute point-angle and increased flexural rigidity of 3-fluted drills — in certain clinical scenarios — can increase a surgeons' ability to accurately position a hole. This study examined differences in drill-tip geometry (point-angle) and mechanical properties (flexural rigidity) between 2.8 mm diameter 2-fluted and 3-fluted surgical drills. Our results show that the 3-fluted design offers a significant improvement over the 2-fluted design not only in terms of accuracy; at 15° and 30° approach angles the 3-fluted drill skived significantly less than the 2-fluted drill in the hands of our surgeon, but also in the range of permissible approach angles; the 3-fluted drill was able to drill at a 45° approach angle with skiving equivalent to that experienced by the 2-fluted drill at 15°. Mechanical testing showed that bending stiffness (N/mm) of the 3-fluted drill (9.5 ± 2.1 N/mm) is more than double that of the 2-fluted drill (3.5 ± 0.6 N/mm) during operation. Computer modeling of the drills supported this finding and demonstrated that bending stiffness (I_X) for the 2-fluted drill varies dynamically during operation whilst remaining constant for the 3-fluted drill. Our study confirms a correlation between mechanical properties, point-geometry and targeting capability for surgical drills. Increased I_X of 3-fluted drills may account for the clinical prevalence of rotational bending failure amongst 2-fluted drills.

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Introduction

Drilling of bone is routine during fracture fixation and reconstructive surgery in a variety of anatomical sites. Surgical drills are the instruments used to remove a controlled amount of bone prior to the placement of a screw or graft material. They are available in either 2- or 3-fluted configurations, where the flutes are that portion of the drill used to channel debris away from the cutting surface. In reality, a surgeon is often required to drill at non-perpendicular orientations and on a highly curved and irregular surface to achieve the surgical goals. This can be difficult and result in skiving of the drill-tip along (or off) the bone and may result in adjacent soft tissue damage, improper placement of the drill hole or a hole that does not meet the original requirements in geometric terms. Unnecessary removal of bone stock can decrease screw pullout strength and have a negative effect on defect healing.[5] Little has been reported on the effects which drill-bit geometry and mechanical properties have on the ability of a surgeon to accurately place a drill hole in bone.

Breakage of orthopaedic drill-bits due to excessive bending rates highly amongst the reported incidences of drill-bit failure.[2–4] Bending failure of surgical drills is most commonly encountered with 2-fluted drills during bi-cortical drilling of long bones, such as in the placement of a lag screw across a fracture site.[1] This can occur due to skiving — or wandering — of the drill-tip along the far cortex prior to purchase which deforms the rotating drill-bit and induces a concentrated moment load causing failure. Where rotational bending failure has previously been reported the broken portion of the drill has been left in situ due to complications associated with removal of the broken portion from the medullary cavity.[2–4]

This study examined differences in tip geometry (point-angle) and flexural rigidity (EI_X) of diameter-matched 2- and 3-fluted surgical drills. We hypothesised that the acute-tip geometry and increased flexural rigidity of 3-fluted drills can — in certain clinical scenarios — equate not only to improved targeting ability for the surgeon, but also account for the clinical prevalence of rotational bending failure amongst 2-fluted drills.

Methods

2.8 mm diameter 2-fluted (Acumed, CA) and 3-fluted (Orthopaedic Innovation, Sydney, Australia) surgical drills were used in this study (Fig. 1). This study consisted of 3 components: (1) examination of accuracy; (2) examination of mechanical properties; (3) mathematical and computer modeling.

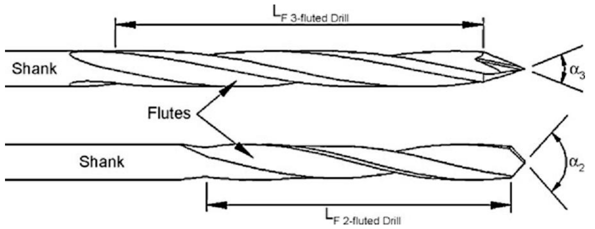

Figure 1 ProEngineer models of the Orthopedic Innovation 3-fluted (above) and Acumed 2-fluted (below) Ø2.8 mm surgical twist drills used in this study. Point-angle, α, and flute lengths, L_F, were some of the parameters used to compare and model the drills.

Examination of accuracy

In this experiment our orthopaedic surgeon (TKG) drilled a series of holes through the cortex of a Sawbone composite femur (item# 1130: foam with cortical shell. Pacific Research Laboratories, Vashon Island, WA) at locations marked with crosshairs (non-etched) at 15°, 30° and 45° approach angles. The surgeon was instructed to apply only axial force to the surgical handpiece (MicroAire, Smith & Nephew Surgical, North Ryde, Australia) and not loads which would otherwise cause the drill to bend. Prior to the commencement of a drilling episode the drill-tip was brought into contact with the target by the surgeon. An assistant using a hand-held goniometer assisted in attaining the desired approach angle. Skiving from the non-etched crosshair to the centre of the drilled hole was subsequently measured using calibrated digital calipers and recorded as the accuracy measure. A fresh drill was used to drill a total of six holes ($n = 6$) at each of the three approach angles.

Mechanical properties

In this experiment the surgical handpiece was rigidly mounted to the actuator of a Bionix 858 closed loop servo-hydraulic mechanical testing machine (MTS Systems, Minneapolis, MN) using a specialised jig (Fig. 2). Motion of the drill-bit was confined to 2-degrees of freedom (vertical translational and rotation). Porcine femurs were held in simple vice grips attached to a calibrated 6-DOF load cell (Advanced Mechanical Technologies Inc., Watertown, MA) and were adjusted using a hand-held goniometer to the same series of approach angles. The relation between lateral force, F_Y, and coupled skiving encountered whist drilling through the femurs at a constant feed rate of 5 mm s^{-1} was examined. Skiving distance — from the centre of the drilled hole to the centre of the drill piece — was measured in the horizontal plane at the

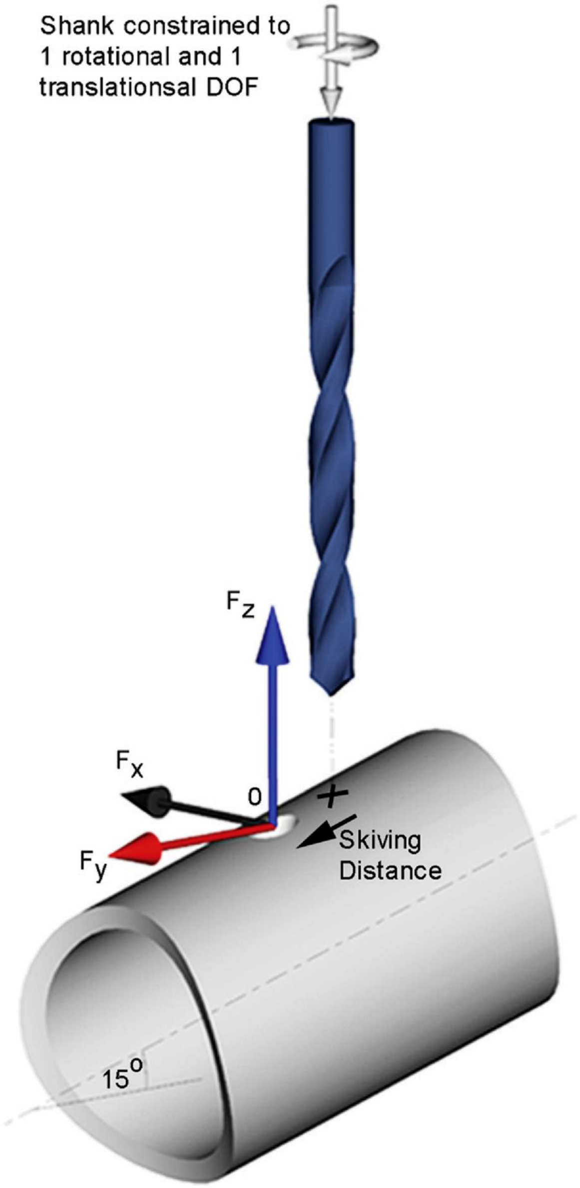

Figure 2 Experimental design. Orthogonal forces imparted to the drill. 15° approach angle is depicted. Crosshair marks the target point. Skiving distance measured from the crosshair to the centre of the drilled hole, 0.

completion of each drilling episode and adjusted for the simulated approach angle. A fresh drill was used to drill a total of six holes ($n = 6$) at each of the three approach angles. Distance from the drill chuck to the tip of the drill-bit was maintained at 56 mm for both drills in both experiments. Specimens were kept moist with saline solution and all testing was performed at room temperature. Accuracy and mechanical properties data was analysed using ANOVA with SPSS for Windows V14 (SPSS, Chicago, IL) at a 5% significance level.

Mathematical & computer modeling

A fresh sample of each drill was sectioned using a diamond wafer blade saw at regular intervals coinciding with 0, 25, 50, 75 and 100% of the length of the fluted portion, L_F, of each drill. Geometrical approximations of the cross-sections were then generated using ImageJ (NIH, USA). Using these approximations, three-dimensional models of the 2-fluted drill and 3-fluted drill were reconstructed using ProEngineer (Parametric Technology Corporation, MA). Variable section sweeps along a combination of linear, helical and conical helical (in the case of the 3-fluted drill) trajectories were used to model the fluted portion of the drills, the parameters of which were adjusted on a best-fit basis. Geometry of the tip and transition zones of the drills (defined as the zone between the shank and the fluted portion) were approximated based on measurement and visual observation. We justified this approach as the mechanical properties of the drills' fluted portions were the main focus of this study. Point-angles were subsequently measured from the models. Model analysis within ProEngineer involved the computation of principal area (second) moment of inertia (I_{max}, I_{min}), product of inertia (I_{XY}), polar moment of inertia (I_Z), cross-sectional area (A), and bending stiffness values (I_X) at equally spaced points along the length of the drill.

Results

Results from the accuracy experiment, shown in Table 1, revealed that the 3-fluted drill outperformed the 2-fluted drill not only in terms of accuracy, but also in the range of allowable approach angles. Our surgeon was unable to drill holes at approach angles beyond 30° using the 2-fluted drill but was able to drill at all angles up to and including 45° using the 3-fluted drill. Mean skiving was contained to within one diameter of the drill (2.8 mm) for both drills at all approach angles. Skiving of the 2-fluted drill was significantly greater than for the 3-fluted drill at both 15° and 30° ($P < 0.05$).

Results for skiving and coupled lateral force (F_Y) from the mechanical experiment are presented in Table 1. The value of F_Y was the maximum value occurring prior to the peak value of F_Z, since peak F_Z corresponds to the instance where the drill-tip has embedded itself in the cortex of the bone completely and no further skiving can occur. Both drills were able to successfully purchase the porcine bone at 15° and 30°, with only the 3-fluted drill able to purchase at 45°, 100% of the time. F_Y was significantly greater for the 2-fluted drill than the 3-fluted

Table 1 Results from accuracy and mechanical testing experiments. Mean (S.D.)

Experiment	Parameter	Approach angle					
		15°		30°		45°	
		2-Fluted	3-Fluted	2-Fluted	3-Fluted	2-Fluted	3-Fluted
Accuracy	Deviation (mm)	0.98 (0.15) *	0.20 (0.22) *	1.14 (0.29) *	0.48 (0.22) *	—	0.98 (0.26)
Mechanical	Lateral force, F_Y (N)	5.49 (1.02)	5.11 (0.72)	11.60 (0.96) ^	7.72 (0.90) ^	—	11.75 (2.05)
	Deviation (mm)	2.0 (0.56) *	0.55 (0.22) *	3.31 (0.79) *	1.14 (0.17) *	—	3.35 (0.79)

^ and * denote significant differences in F_Y and/or deviation, respectively, at that approach angle. The 2-fluted drill was unable to purchase the bone at 45° in both experiments, whilst the 3-fluted drill was successful at this angle 100% of the time.

drill at 30° ($P < 0.05$). No significant difference in F_Y was observed at 15° ($P > 0.05$). At both 15° and 30°, skiving of the 2-fluted drill was significantly greater than that experienced with the 3-fluted drill ($P < 0.05$). Further to this, skiving of the 3-fluted drill at both 15° and 30° was contained to within one diameter of the drill. At 15°, and for approximately the same level of F_Y ($P > 0.05$), the 2-fluted drill skived significantly more that the 3-fluted drill. The lateral force (F_Y) divided by the skiving distance (measured in the horizontal plane) at this approach angle was calculated and defined as stiffness. Stiffness (F_Y/skiving distance) for the 3-fluted drill (9.5 ± 2.1 N/mm) is more than double that of the 2-fluted drill (3.5 ± 0.6 N/mm) at 15°.

Gross parameters required to model the drills were measured prior to sectioning, including length of the fluted portion (L_F) and twist angle (ψ) (Table 2). The cross-sectional geometry and area (A) of the 2-fluted drills' fluted portion did not vary along its length (Fig. 3a). In contrast, land width (w) of the 3-fluted drill decreased linearly along its length ($R^2 = 0.9896$), from 1.15 mm nearest the shank to 0.73 mm nearest to the tip (Fig. 4a). A consequence of this linear decrease in w from shank to tip is a commensurate reduction in cross-sectional area, A, resulting in an increase in the combined cross-sectional area of the flutes, A_F (since $A_{Total} = A + A_F$). Flutes of a drill are that portion of the drill which evacuate and channel debris away from the cutting surface during operation (Fig. 1). The ratio of flute areas between the two drills ($A_{F\ 3\text{-fluted}}/A_{F\ 2\text{-fluted}}$) varies linearly from 1.52 closest to the shank to 1.0 at the tip.

Table 2 Drill design parameters

Design parameter	2-Fluted drill	3-Fluted drill
Length of fluted portion, L_F	23.4 mm	28.6 mm
Twist angle, ψ	270°	270°
Point-angle, α	97°	44°
Principal (area) moment of inertia, I_{min}	0.296 mm^4	1.501—0.846 mm^4
Principal (area) moment of inertia, I_{max}	1.650 mm^4	1.501—0.846 mm^4
Polar moment of inertia, I_Z	1.946 mm^4	3.00—1.692 mm^4

For both drills the flute contours were modeled as parabolic. Symmetry of cross-sections was observed at all locations along the length of the fluted portion for both drills; about the x''-axis and y''-axis for the 2-fluted drill (Fig. 3b) and the x''-axis for the 3-fluted drill (Fig. 4b). Note that each of the 'webs' in the 3-fluted section displays symmetry about the x''-axes which are each separated by 120°. These rectangular axes are known as the principal axes of inertia, as they represent axes relative to the section about which maximum (I_{max}) and minimum (I_{min}) values of second (area) moment of inertia occur. Principal area moments of inertia values of the 2- and 3-fluted sections generated within ProEngineer are given in Table 2.

The effect which rotation (θ) of the approximated cross-sections relative to a theoretical plane of bending (y—z plane in Fig. 7) has on the second (area) moment of inertia (I_X) is shown in Table 2. I_X of the 2-fluted section varies as a function of cosine between principal values with rotation, θ. Conversely, I_X of the 3-fluted cross-section is independent of rotation, θ. Models of the drills generated in ProEngineer using the data obtained from sectioning are shown in Figs. 3c and 4c. To cater for the linear decay in land width, w, of the 3-fluted drill a third trajectory was introduced taking the form of a conical helix. Point-angles measured directly from the models (Fig. 1) are shown in Table 2.

I_X and I_Z profiles for the 2- and 3-fluted drills are shown in Figs. 5 and 6, respectively. It can be seen that the I_X profile of the 2-fluted drill (and, in

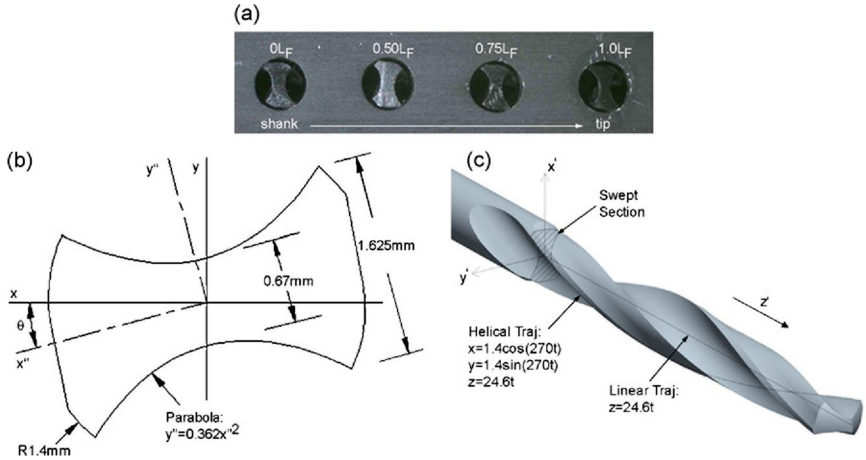

Figure 3 Cross-sectional properties and modeling of the 2-fluted drill. (a) Cross-sections obtained from sectioning. (b) Cross-sectional approximation displaying symmetry about the x''- and y''-axes. Equation for parabola based on parameters; b = 0.47 mm, a = 1.14 mm. (c) ProEngineer model.

particular the points of minimum I_X) migrates towards the shank with rotation of the drill during operation. That is, I_X varies along the length of the fluted portion as a function of drill rotation (θ) between 9.8% and 54.8% of the principal value of the solid shank (3.014 mm^4). Conversely, I_X of the 3-fluted drill remains constant and is independent of rotation (θ) representing 49.8% and 28.1% of the principal value of the solid shank at the commencement and termination of the fluted portion, respectively. Linear decay in land width (w) for the 3-fluted drill results in a parabolic decay of I_X (moving from shank to tip). At the commencement of the fluted portion (closest to the shank), I_X of the 2-fluted drill varies cyclically between 19.7% and 109.9% of the value for the 3-fluted drill. In other words, at this location, the stiffness property (I_X) of the 3-fluted drill is approximately 5.1 times greater than that of the 2-fluted drill. I_Z (which is related to torsional rigidity) is independent of rotation for both drills.

Discussion

Flexural rigidity (EI_X) of a member rotating through a stationary bending moment (such as a surgical drill subjected to a net bending moment) is a function of the principal second (area) moments of inertia (I_{max}, I_{min}), Young's modulus (E) of the material, rotation

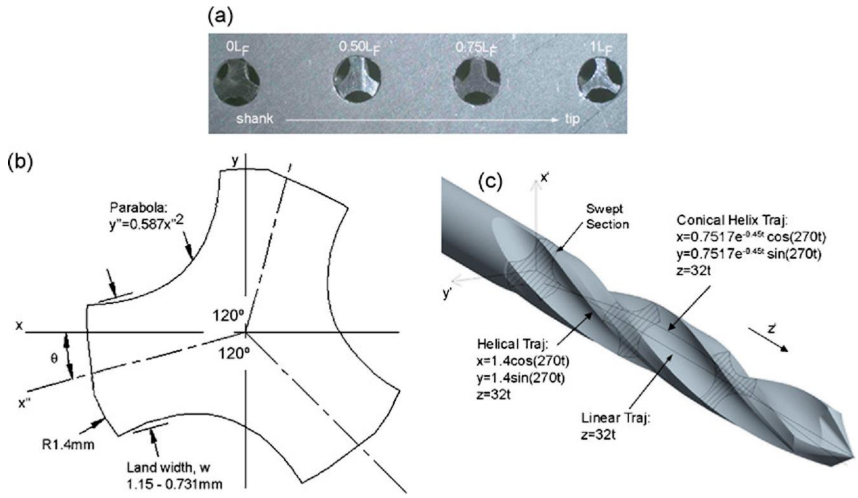

Figure 4 Cross-sectional properties and modeling of the 3-fluted drill. (a) Cross-sections obtained from sectioning. (b) Cross-sectional approximation displaying symmetry about the x''-axes (each separated by 120°). Equation for parabola generated based on parameters; b = 0.39 mm, a = 0.815 mm. (c) ProEngineer model.

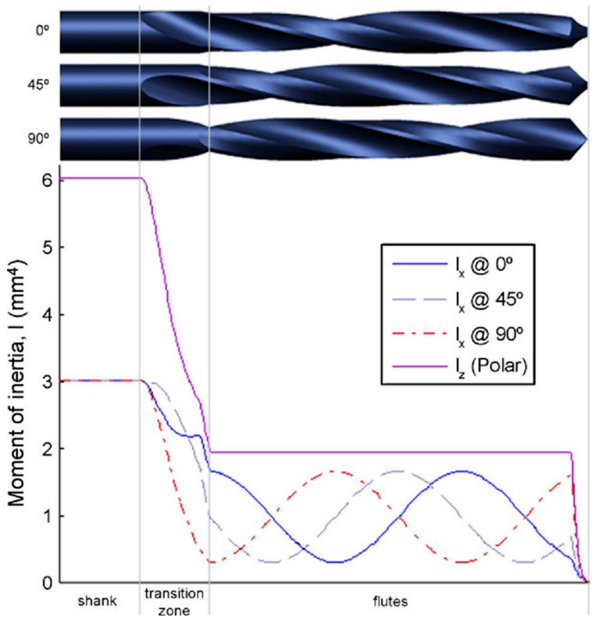

Figure 5 I_X and I_Z profile—2-fluted drill. I_X varies with rotation relative to a theoretical plane of bending. Maximum and minimum values of I_X represent 54.82% and 9.82% the principal value of the solid shank. Points of lowest I_X (maximum 2, minimum 1) migrate towards the shank with drill rotation. I_Z is constant and independent of rotation.

(θ) of the principal axes of the given cross-sectional area relative to the plane of bending according to the following relation:

$$EI_X = E\int_A y^2 dA = E\left[\frac{I_{max}+I_{min}}{2} + \frac{I_{max}-I_{min}}{2}\cos 2\theta - I_{xy}\sin 2\theta\right] \quad (1)$$

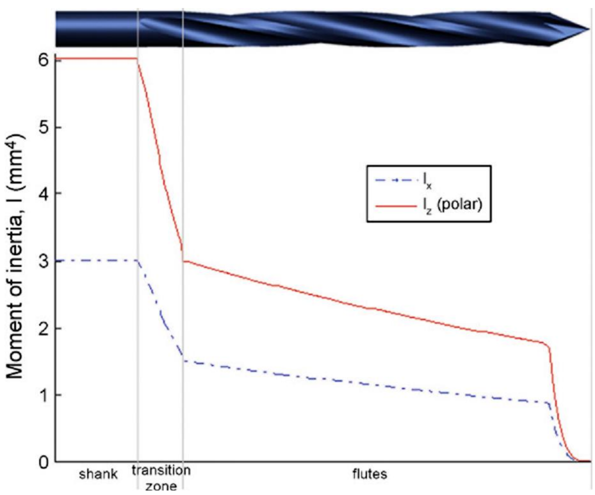

Figure 6 I_X and I_Z profiles—3-fluted drill. The effect of the linear decay in web-width, w, along the length of the fluted portion results in a parabolic decay of I_X which does not vary as a function of rotation of the drill.

For surgical drills — and twist drills in general — the product of inertia, I_{XY}, tends to zero due to cross-sectional symmetry about the principal axes (x''- and y''-axes in Figs. 3b and 4b). Bending stiffness, I_X, of a surgical drill at any point along its length is therefore given by

$$I_X = \frac{I_{max}+I_{min}}{2} + \frac{I_{max}-I_{min}}{2}\cos 2\theta \quad (2)$$

Principal moments of inertia for a 3-fluted drill are equal ($I_{max} = I_{min}$) due to the symmetrical and radial arrangement of the individual flutes at 120° to one another (Table 2). That is, I_X of a 3-fluted drill is constant and independent of rotation (θ) of the drill relative to the plane of bending (Fig. 6). Conversely, I_X of a 2-fluted drill varies along its length as a function of cosine between values in the principal direction (I_{max}, I_{min}) with rotation (Fig. 5). In this study we have demonstrated that there is a fundamental difference in the bending stiffness properties of 2-fluted and 3-fluted drills.

Mathematical modeling of the drills revealed that I_X of the 2-fluted drill varies along the length of the drill with rotation (as opposed to the 3-fluted drill which remains constant), being between 0.2 and 1.1 times the strength of the 3-fluted drill in bending at the commencement of the fluted portion (Table 2). Bending stiffness (I_X) of a 2-fluted drill is therefore a truly dynamic entity and for this reason it follows that diameter-matched 2- and 3-fluted drills exhibit fundamentally different deformation responses (in terms of deflection) to bending moments whilst in operation. That is, under the action of a lateral force acting at the drill-tip, deflection of the 2-fluted drill would be greater than that for the 3-fluted drill, on the basis, of course, that both drills were manufactured from the same material. In our case, both drills were manufactured from surgical grade stainless-steel (E = 200 GPa).

Results from the mechanical testing component of this study support this result, where it was shown that stiffness of the 3-fluted drill is more than double that of the 2-fluted drill. (The feed rate of 5 mm s^{-1} was chosen based on a previous unpublished study as it correlated well with the axial force typically exerted on the handpiece by a surgeon whilst drilling holes in this size range). If the drills were manufactured from a higher modulus material, such as Cobalt Chrome (E = 259GPa), the result of the deflection or skiving should be improved. Indeed, this would be one way of improving the bending stiffness of the 2-fluted drill, making it comparable with the 3-fluted drill.

Results from the our accuracy experiment show that the 3-fluted drill significantly out-performs the 2-fluted drill not only in targeting ability but also in

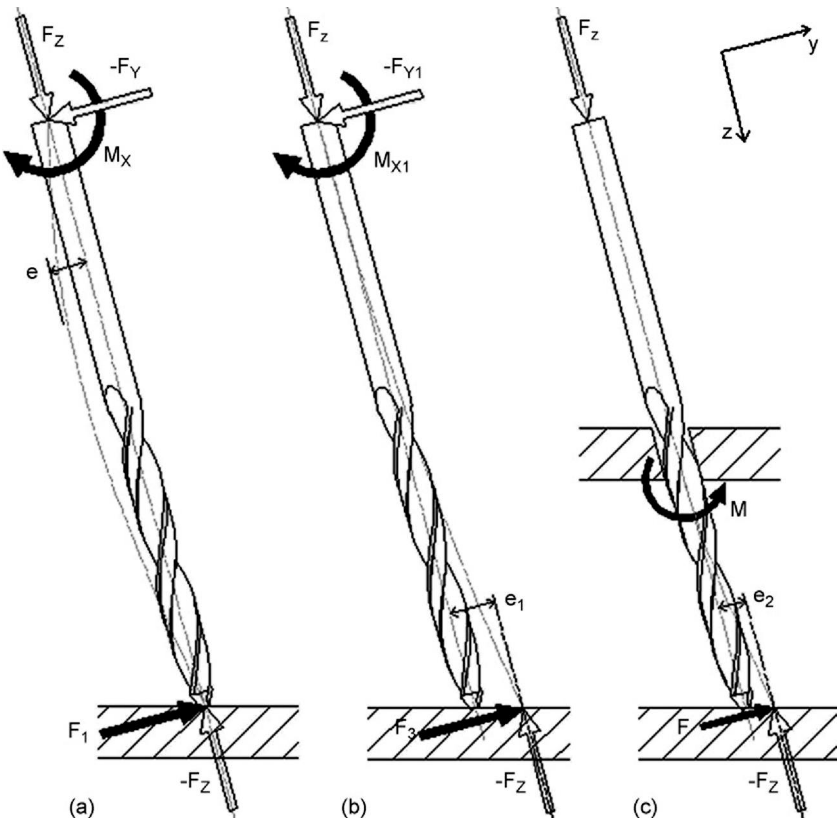

Figure 7 Typical Modes of bending for a surgical drill. (a) and (b) Drill-bit subjected to combined axial force, F_Z and bending moments, M_X and M_{X1}, with coupled lateral forces, $-F_Y$ and $-F_{Y1}$, respectively. Bending moments, M_X and M_{X1}, opposed by transverse shear forces, F_1 and F_3, acting at the tip and $-F_Y$ and $-F_{Y1}$ applied to the handpiece. (c) Drill-tip skives along far cortex inducing bending moment, M. Remainder of fluted portion constrained by hole in near cortex. Note: elastic curvature profiles for the drill in the three bending modes is an approximation for the deflection of a solid rod Ø2.8 mm under the respective loading conditions.

the range of permissible approach angles (Table 1). Although we have only the data from a single surgeon, it is probable that this improvement in accuracy is a direct function of the acute point-angle (Table 2). Improvement in the range of permissible approach angles using the 3-fluted drill is undoubtedly attributable to the acute point-angle as it allows for increased clearance. Although, whilst having a positive effect on approach angle, an acute-tip angle may have an adverse effect clinically, as the sharper the drill-bit, the further the drill-bit needs to extend beyond the far cortex in order to produce a clear hole with the proper diameter, which may cause unnecessary damage to adjacent tissues.

The surgical drill is a versatile instrument and is routinely subjected to bending loads in the clinical setting. Since surgical drill-bits are highly susceptible to skiving prior to entry it is often difficult to drill a hole at an oblique orientation to the cortical surface in the absence of accompanying targeting aids such as drill-jigs and guides. To counter the potential for skiving and improve accuracy in the absence of such aids the surgeon can apply a counter-moment (M_X), and coupled lateral force ($-F_Y$) — in addition to the axial force (F_Z) — to the surgical handpiece, the sum of which results in a net bending moment acting on the drill-bit (Fig. 7a). Alternatively, the surgeon may drill out a pilot indentation to constrain the drill-tip by first orienting the handpiece and drilling perpendicular to the bone after which the handpiece can be toggled to the desired oblique orientation. However, this may result in unnecessary bone removal which can adversely effect screw pullout strength and defect healing.[1] Another likely scenario involving the application of a counter-moment and coupled lateral force to the handpiece, albeit delayed, is whilst attempting to purchase the bone at an oblique orientation the drill-tip skives either unexpectedly or within tolerable limits (shown as M_{X1} and $-F_{Y1}$ in Fig. 7b). A third scenario involving deformation of the drill is the so-called rotational bending failure scenario where the drill-tip skives along the far cortex, which places a concentrated moment (M) on the drill-bit causing it to fail (Fig. 7c). This moment is generated due to the constraint imposed on the drill by the hole produced in the near cortex, and is exacerbated by the surgeon who is unaware of the extent of the skiving and cannot, therefore, compensate by toggling the handpiece. Magnitude of this moment is reduced if the flutes are able to 'ream out' the hole in the near cortex, resulting in a hole exhibiting misshapen geometry. If the hole in the near cortex is not reamed out but the drill skives along the far cortex then the result is 2 non-collinear holes, potentially causing complications for placement and fixation of screws.

In all 3 bending scenarios both the profile of deformation (deflection) and potential for failure is governed by I_X. In these scenarios the stiffer 3-fluted drill (coupled with increased tip angle) would be seen to offer an advantage over the 2-fluted drill in terms of accuracy, specifically where the loads applied to the surgical handpiece resulted in a net bending moment acting on the drill-bit. In particular, where a moment and coupled lateral force are applied to the handpiece to counter skiving of the drill-tip the weaker 2-fluted drill would deflect more than a 3-fluted drill, thereby augmenting the approach angle and further increasing the potential for skiving (Fig. 7a and b). The 2-fluted drill would also be more likely than a 3-fluted drill to fail in bending (Fig. 7c).

A reduction in L_F of the 2-fluted drill would have an effect in all three bending scenarios, resulting in a stiffer drill, which would then deflect less under the action of a net bending moment. For example, if a 2.8 mm diameter drill is used to drill a hole (3 mm bone screw) in bone cortex which is no more than 7 mm thick, L_F could be reduced from 23.4 to 14 mm or possibly less, without compromising functionality. Likewise, manufacturing the drill from a higher modulus material would have a similar effect.

This study is not without limitations. Our study did not investigate whether the decreasing flute area, A_F, of the 3-fluted drill (as a function of the increasing land width, w) increases the incidence of bone chips becoming lodged in the flutes. 3-Fluted drills tend to clog with debris when the depth of the hole becomes appreciable in relation to its diameter. The ratio of A_F between the drills varies from being similar at the drill-tip to approximately 1.52 closest to the shank.

A Sawbone composite femur was used in the accuracy study to provide a reproducible test material. Although the material does not mimic that of cortical bone it did allow a direct comparison between drills in terms of targeting ability. Porcine femurs were used in the mechanical study to provide a material similar to human bone. Although the sample size was small (n = 6) we were able to detect differences in bending stiffness properties between the drills.

In summary, the properties of 2- and 3-fluted drill-bits in terms of tip geometry as well as bending stiffness may influence accuracy/targeting ability as well as the potential for surgical complications.

Conflict of interest statement

None.

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