Bone Biomechanics: Orthopaedic screws

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Orthopaedic Screws

The **most commonly used orthopaedic implant** is the surgical screw. **Screws function as fixation devices** that stabilize bony abnormalities and injuries. **Understanding the biomechanical principles of screw fixation and its stabilizing features**, such as compression generation, can help reduce failure rates.

The function of the screw is to change **rotational motion into translational motion** while providing mechanical stability to the injured site. In order to achieve correction of the deformity in bone, there are some basic design features of the screw that contribute to maintaining the mechanical stability within bone.
Bone screws

FIGURE 1-32 A. Cross section through the head of a bone screw and the hole in a fracture plate showing the geometry. B. As the screw is tightened, the head slides down the inclined border of the plate, which displaces the screw sideways, and therefore the screw and the bone fragment to which the screw is attached are displaced toward the opposite fragment.

FIGURE 1-34 A demonstration of the gapping that occurs on the opposite cortex when a flat plate is applied to a flat bone surface. Slightly prebending the plate causes the ends of the opposite cortices to be driven together when the plate is applied.
Orthopaedic Screws

The main components of the screw consist of the head, the core, and the threads. Each component plays a crucial role in the performance of the screw. The head of the screw serves to transmit the insertion torque to the core and threads. It also functions as a stop when it comes into contact with the surface of the bone, hence ceasing the translational motion of the screw. Once the translational motion has stopped, the screw generates a compressive force.

The major diameter is the outer diameter of the screw measured at the crest of the threads. Length of the engagement of the screw is measured by the number of threads seated in the material.
Orthopaedic screws

In the lower limb of the adult, a screw may be highly stressed. Screw may break on insertion, during use, or when it is being removed from the patient. The force applied to a screw during its insertion should be below the yield stress of the screw, but to ensure this a torque limiting device must be used. The lead is the distance a screw advances with one turn, and it is equal to the pitch (distance between threads). The single depth of the thread is calculated from the root to the crest of the thread. The depth of the thread influences the purchase of the screw into the bone and can significantly influence pullout resistance.
Pedicle screws

PSc implanted in the back of the vertebrae to stabilize a spine and correct spinal deformities.
Screw’s materials

Bone screws can be fabricated from one of the following materials:

- Stainless steel alloy,
- Titanium-aluminum-vanadium alloy,
- Titanium-aluminum-niobium alloy,
- Titanium-niobium-zirconium alloy,
- Cobalt-chromium-molybdenum alloy,
- Nitrogen-strengthened stainless steel alloy,
- Unalloyed titanium,
- Titanium-molybdenum-zirconium-iron alloy.
The holding power of a screw in bone depends on two main factors: the shear strength of the bone itself, and the thread geometry. Holding power, otherwise known as stripping/pullout strength, is normally considered to be the axial load required to strip the screws intact from the bone. Other variables, however, contribute to the pullout behavior of the screw, such as the extent of cortical purchase, depth of screw penetration, thread angulation, pitch diameter, screw placement within the bone, physical changes to the screw or bone between the time of insertion and the time of withdrawal, speed at which the screw is withdrawn, the occurrence of predrilled holes, and the quality of the bone.
The holding power of screws in bone

Holding power depends on the shear strength of the material into which the screw was inserted, but was independent of screw material and pilot hole diameter up to a critical value of approximately ninety per cent of the screw major diameter. Consideration of all of these variables will minimize screw failure and loss of bone stabilization.

When a screw is inserted into a material such as bone, pullout failure of the screw implies failure of the bone as well. As the screw is loosened and begins to back out, the bone breaks and the screw toggles within the bone yielding a large void.
In general, bone has a **smaller modulus of elasticity than the screw** and is therefore weaker than the various metals used in screw constructs. Screw loosening as a result of bony failure can significantly compromise the stabilizing effect of the implant. Differences between the elastic moduli of bone and metal can have detrimental effects regarding stability. Placement of a significantly stiffer penetrating implant into bone disperses the forces nonuniformly, and regions of increased stress result within the screw and within the bone. Eventually, the bone will fail due to microfracturing of the trabeculae or fracturing within the cortical bone, or the screw will break at the region of peak stress. Therefore, the quality of the bone and the biomechanics of screw fixation must be respected when using instrumentation to stabilize an injury.
Holding strength of screw

When the screw toggles, it breaks the individual trabeculae, disrupting the natural matrix, and enlarges the void between each trabecula. However, in soft uniform materials, the void is smaller and similar in size to the outer diameter of the screw. It is a concept best visualized by placing a screw into a soft uniform material, such as wax. When the screw is pulled out, a smooth cylinder is left inside the block of wax due to the screw threads shearing the wax from the side wall as it is pulled out. The area of the hole is that of a cylinder; area = depth × perimeter. Therefore, the maximum holding strength a screw can have is (area of the cylinder) × (shear strength of the material).
Increasing the holding strength of screw

The repetitive cyclical loading from motion in the human body can contribute to screw loosening in bone. Many factors can affect the loss of screw fixation in bone. Failures can be attributed to poor screw design, application of an improper screw type for the material of choice, misconception of the forces applied on the screw, shallow screw threads that do not grasp a sufficient amount of bone to prevent backout. Alterations in screw design and an understanding of the mechanical principles of the material used for screw fixation can provide better resistance to screw loosening and reduce the risk of stabilization failure (thread depth, depth of screw penetration, unicortical vs. bicortical purchase, triangulation of the screws).
Increasing the holding strength of screw

Screw pullout resistance can be greatly influenced by the thread design. The volume of bone the threads capture contributes to the pullout performance of the screw. The pitch can alter the amount of bone captured by changing the distance between one thread and the adjacent thread. The thread depth can alter the bone volume obtained by modifying the length of the thread. A deeper thread allows more bone to reside between each thread and increases pullout resistance.

\[
\text{Thread Depth} = \text{O.D.} - \text{I.D.}
\]

\[
\begin{align*}
\text{A} & \quad \text{Screw Thread} \\
\text{Material} & \quad \text{Thread Depth} = \text{O.D.} - \text{I.D.} \\
\end{align*}
\]

\[
\begin{align*}
\text{B} & \quad \text{Screw Thread} \\
\text{Thread Depth} & \\
\end{align*}
\]

* Pitch in A = Pitch in B

Volume of Material in A > Volume of Material in B
Increasing the holding strength of screw

The length of the screw has a dramatic effect on the pullout strength. Deeper screw insertion has been shown to increase pullout resistance and strength in flexion and extension loading. **The benefits of using a longer screw must be balanced against increased operative risk.**

Since cortical bone is denser than cancellous bone and has a significantly greater pullout strength, studies have shown bicortical screw purchase to be superior in pullout strength to unicortical screw purchase. The two layers of cortex surrounding the cancellous bone provide greater stability to the screw with respect to pullout than when only one cortical surface is purchased.
Increasing depth of screw penetration is achieved with longer screws. Screw pullout strength is significantly increased with longer screw penetration for both a unicortical or bicortical purchase. However, bicortical screw purchase is superior to unicortical purchase in pullout performance. The ideal situation is the use of a longer screw to obtain bicortical purchase, provided there are no neurological risks.
Increasing the holding strength of screw

Bone is a heterogeneous material. The trabecular architecture of cancellous bone varies and **tends to be denser proximal to the cortical margins**. Triangulation of the screws into these concentrated regions of bone will significantly increase pullout resistance. The toeing-in of the screws prevents backing out along the direction of the applied axial force. Triangulated constructs are biomechanically beneficial and offer stronger opposition to the forces that cause the screw to back out.

(A) Triangulation of the screws, or “toeing-in,” provides increased screw purchase and resistance to pullout. Angulation of the screw resists backing out along the direction of the applied load. (B) If the two triangulated screws are cross-linked, there is an even greater resistance to pullout. If the screws are angled toward the cortical margins while fixed to a plate, greater screw purchase will be acquired due to the increased density of the bone as it approaches the cortex. Resistance to pullout will be greater as well, due to the larger quantity of bone surrounding the angled screw.
Torque insertion

The torsional forces during screw insertion have been shown to correlate with pullout strength. Some studies have shown that high insertional torques measured during screw insertion into material correlate very well with high pullout strengths for certain screws and uniform materials such as synthetic bone blocks.

The peak torque that is generated during screw insertion can depend on screw type, screw diameter, screw design, and whether the screw hole was tapped prior to insertion. A screw with a larger diameter in composite bone is more likely to engage the region of denser cortical bone. In contrast to this, a smaller diameter screw placed in composite bone would yield lower insertional torques because it primarily engages cancellous bone. Tapping of the screw hole prior to insertion also yields lower peak torques during insertion.
Screw mechanics

When a metal screw is inserted into bone, the shear strength of the screw is considerably greater than the bone. Thus, it is the bone that fails initially in pullout testing. The more dense the bone, the smaller the risk of bone failure, and the higher the pullout resistance. A bending force applied to a screw in any material creates a stress concentration at the initial two or three threads of the screw. This region is often the area where screw breakage or failure (pullout) will occur. It is the superficial two or three threads of the screw that are responsible for the transfer of the load to the bone. Therefore, thread configuration and bone density correlate well with pullout resistance, especially at the bone–screw interface.
Screw mechanics

Screw material can significantly impact performance. Currently, 316L stainless steel with a 480MPa ultimate tensile strength is the conventional material used in biological implants. Titanium has gained popularity due to its resistance to corrosion within the human body and the similarities in terms of mechanical properties to that of stainless steel. Bioabsorbable screws have been developed in an effort to increase patient rehabilitation time postoperatively. Polylactic acid is a common component of these types of screws. *In vivo* degradation of these screws occurs over time by the process of hydration, depolymerization, loss of morphological supporting structure, absorption, and elimination. The metal screws performed favorably and had significantly higher insertional forces than the bioabsorbable screws. They also demonstrated significantly greater failure loads than the bioabsorbable screws.
Insertion and extraction of a screw

There is always a degree of human error in the drilling of holes and this should be minimized. If the bone is split during drilling, its strength is greatly reduced and too great a drilling speed may cause fragmentation or burning of the bone with subsequent necrosis and screw loosening. The quality of a fixation depends on the contact between the screw head and plate. Some proposed that disproportion between drill and screw diameter is the commonest cause of fixation failure.

The Swiss Association for Osteosynthesis (AO) system recommends a drill identical in size to the core diameter of the screw. To meet these various requirements, a pilot hole should not exceed ninety percent of the major screw diameter to ensure good holding power, nor should it fall below the core diameter of the screw as this would result in high insertion stresses being imposed on the screw.
Failure of a surgical screw

The bending or **breaking of a screw on insertion** is usually caused by the application of **a torque greater than the particular screw can withstand**; because of:

- (a) the use of the incorrect size of drill in relation to core diameter of screw
- (b) the incorrect alignment of a screw in a hole - this is particularly relevant when the opposite cortex is being engaged;
- (d) the seizing of a screw when the distal cortex is engaged, when no clearance hole is drilled in the proximal cortex.
Failure of a surgical screw

Screws which appear to have been inserted correctly may fail in the patient because:

– (a) the elastic limit of the metal was exceeded during insertion;
– (b) the load on the screw is greater than that which it was designed to withstand;
– (c) the screw is subject to fatigue stressing.

A screw may be bent or broken when it is being removed from a patient because:

– (a) bone has grown into intimate contact with the thread;
– (b) with self-tapping screws, the bone has grown into the flutes.
Pullout strength

The clinical objective is, theoretically, to increase the volume of bone the screw can hold between the threads. This relationship of bone volume to screw thread contributes to the degree of purchase the screw has to the bone. Many types of screws are used in bone fixation. Cortical screws are used in hard, compact, dense bone. The bone–implant interface in screw fixation is the site of greatest load transfer. The load is transferred from the head of the screw along the core and into the material in which the screw is placed.
Cancellous bone screw

Cancellous bone screw’s deep thread design and tapering permits easy insertion into the material. This design forms threads within the material by compressing the surrounding material during the insertion process. Tapping (threading) is not recommended in cancellous bone because it can weaken the bone–implant interface and decrease the pullout strength of the screw. Screw insertion into cancellous bone and resistance to pullout requires that an optimal amount of bone be captured between the screw threads. **The structural characteristics of the screw and the integrity of the cancellous bone can significantly alter the performance of the screw.** Enhancement of the screw performance within the bone can be achieved by altering the thread depth, shape, and inter-thread distance of the screw. This enables a larger volume of bone to surround the screw, thereby increasing the resistance to backout.

Complex forces act upon a screw once it is inserted into bone. It is essential that the screw be of sufficient strength to accommodate these forces. **In bending, the strength of a screw is proportional to the third power of its minor diameter.** Thus, the core diameter of a screw significantly affects the bending strength of the screw. A small increase in the diameter can yield a large increase in the bending strength of the screw.
Unicortical vs. bicortical purchase

Since cortical bone is denser than cancellous bone and has a significantly greater pullout strength, studies have shown bicortical screw purchase to be superior in pullout strength to unicortical screw purchase. The two layers of cortex surrounding the cancellous bone provide greater stability to the screw with respect to pullout than when only one cortical surface is purchased. Bicortical screw purchase increases the pullout strength in many constructs. Penetrating bicortical screws may, however, increase the risk of neurovascular injury.
Thread angulation

The thread angle defines the shape of the thread. Altering this angle changes the shape of the threads and alters the amount of bone that the screw grasps directly. The larger the bone volume the screw carries within each thread, the greater the pullout resistance. However, there is a balance between optimal thread depth, shape, pitch, and thread angle. A large thread depth with few threads per inch may not provide optimal resistance to screw back-out.

Buttress Screw Threads - Basic Profile

\[ H = 1.5878P \]
\[ H_s = 0.7939P \]
\[ H_t = 0.7500P \]
\[ \omega = 0.23384P \]

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Biomechanics of screw fixation

To increase pull out strength of screw in bone:
- Increase outer diameter
- Decrease inner diameter
- Increase thread density
- Increase thickness of cortex
- Use cortex with more density.

To increase strength of the screw & resist fatigue failure: Increase the inner root diameter
Dear Students: Please note that parts of the following slides were taught in the class, and the rest is just for your information. However, you’re advised to read the following slides and take benefit of all points raised in the following slides. Good luck with your final exams!
The purpose of quantifying the pullout strength of screws is to measure their ability to attach and hold an object. There are several ways to quantify screw performance and the holding strength of the screw. Quantification of the tensile forces required to pull a screw out of a particular material determines the pullout strength of that screw. Measurement of the axial forces necessary for insertion of the screw as it is tightened into a material will also describe biomechanical characteristics of the screw.

A “uniaxial materials testing system” capable of operating in tension and compression is the highest-quality testing apparatus. The fixtures that are used to grip the screw and the material into which it is inserted can dramatically affect the results of a pullout study. According to the American Society for Testing and Materials standards (ASTM), a true pullout assessment of a screw would require that the grips used to grasp the screw head be shaped to fit accurately and that the grips provide a true axial load. An ideal withdrawal study performed on screws should allow the grips to pivot or toggle. This would reduce any residual stresses that may occur within a rigid gripping device and diminish the transfer of these stresses to the screw during the pullout. Universal ball joints and pinned joints are commonly used as mounting devices because of their mobility, standard design, and ease of use.
Experimental methodology for screw pull out testing

Illustration of pullout fixtures: (A) universal ball joint for the top grip with the bottom grip fixed to the platen of the testing apparatus, allowing the top grip to toggle during the application of tensile forces, and (B) universal ball joint for the top and bottom grip allowing both to toggle during the application of tensile forces. Use of these devices eliminates residual stresses that occur within the pulling fixtures during tension.
Insertion of the test specimen

The bone screws shall be inserted into the standard material in accordance with the insertion torque test method. **The screws shall be inserted at a rate of 3 r/min to a depth of 20 mm.** For fully threaded screws with threaded lengths less than 20 mm, the insertion depth should be 60% of the threaded length of the screw. The test block and test block clamp shall be fixed to the base of the load frame so that the **longitudinal axis of the screw is aligned with the direction of the applied load.** The screw’s head shall be placed in the slot of the load fixture and seated in the spherical recess. The load fixture shall then be attached to the load frame. **A tensile load shall be applied to the test specimen at a rate of 5 mm/min** until the screw fails or releases from the test block. Load (Newtons) versus load fixture displacement (millimetres) shall be recorded on a data acquisition device, noting the maximum load applied and the mode of failure (screw shaft, screw threads, or material failure). The axial pullout strength (Newtons) of the test specimen from the load displacement curve: the maximum load which is reached during the test.
Synthetic bone specimens and bone specimens can be used. Often materials of uniform density are used during screw pullout studies to provide a standardized experiment. Currently, rigid polyurethane foams are used as bone substitutes for pullout studies. The uniformity of the material and consistent mechanical properties similar to that of human bone make it a good substitute for screw strength quantification. It can be purchased in a variety of densities that represent good bone integrity, as well as osteoporotic bone models. The uniform nature eliminates the variability that exists between normal bone samples and provides a standardized method for determining screw pullout resistance. Therefore, it can provide an accurate assessment of the pullout strength of the screw. Use of synthetic bone is limited in its clinical applicability because bone is an inhomogeneous substance in most regions of the body.
Experimental methodology for screw pull out testing

The size of the synthetic bone sample in order to maintain a constant pattern of failure within the synthetic bone, the screw diameter should be approximately less than 5% of the circumference of the synthetic bone block. When mounting the synthetic bone into the bottom grip on the testing apparatus, it is crucial to apply a uniform pressure across the material. This can be done by using plates that are similar in size to the synthetic bone block attached to the clamping arms of the vise. The plates distribute the forces applied by the vise screws over a larger surface area and transmit these forces uniformly across the block. The ideal situation is to have four plates clamping four sides of the block for a uniform application of pressure. This eliminates discrepancies in the screw pullout data due to regions of high stresses within the synthetic bone blocks caused by nonuniform clamping.
Experimental methodology for screw pull out testing

These fixtures are positioned into the machine grips and a tensile force is applied at a uniform rate. The platens separate and the top grip pulls the screw out of the material. The load cell of the testing apparatus records the force required to separate the screw from the material. **The peak force during pullout usually occurs within the first few threads that are pulled out of the material.** The manner in which the specimens are secured into the bottom fixture that sits in the grip of the testing apparatus can affect the pullout resistances of the screw. The fixture is responsible for holding the specimen in place and resisting the tensile forces placed on the screw. In contrast, the grip is attached to the testing apparatus and holds onto the fixture housing the testing specimen.
Experimental methodology for screw pull out testing

To initiate screw insertion, the screw holes can be drilled with bits that are approximately 10% larger than the minor diameter of the screw without compromising pullout strength. If the bone is cortical or has a cortical shell, it is suggested that the cortex be drilled and tapped to avoid microfracturing at this layer. Since the cortical shell is usually at the bone–screw interface and may surround the initial few threads of the screw, microfractures could reduce the pullout strength. If the screws are to be placed at an angle, special guides must be constructed to ensure the screw will follow the correct insertion angle. Radiographs can document the screw orientation and screw depth within the test sample. After insertion, the peak insertional torque should be quantified by using a finely graded torque wrench.
Experimental methodology for screw pull out testing

The test specimen should be placed onto the loading platform of the testing machine into a top and bottom grip that is in perfect alignment. **This avoids bending moments and additional stresses transferred to the screw as a result of misalignment.** Depending on the type of testing apparatus, the protocol for screw pullout should be withdrawal of the screw using an axial force in tension moving at a constant rate. Some common pull rates range from 0.1 to 5 mm/s depending on the type of screw and the material into which it is inserted. **It is recommended that a screw be used only once within a pullout study.** Repetition of pullout on a screw can weaken and dull the threads. Placement of this used screw into another piece of bone will reduce its purchase capability and may decrease its pullout resistance.
Experimental methodology for screw pull out testing

In order to assess the clinically relevant nature of screw fixation, pullout experiments are commonly conducted in various types of bone. Bone is not homogeneous in composition. In the vertebral bodies, the bone density is significantly higher at the cortical margins and lowest in the center of the body. Human cortical bone, such as that found in the long bones of the appendages, is extremely dense and can generate screw pullout strengths approximately four times greater than that of cancellous bone.

It is essential to prepare each of the bone samples meticulously, especially when using cadaver bone samples. All soft tissue should be cleanly dissected off the bone in order to provide a better gripping surface. The oils secreted from the musculature can cause the bone sample to slip out of the grips during the tensile pull. Although some found no significant changes in pullout strength with cadaver bone that was allowed to undergo structural degradation, some others found that the process of freeze-drying the bone significantly weakened the pullout resistances of the screw. Therefore, it is best to conduct pullout studies with bone specimens that have been subjected to minimal thawing and freezing cycles and have not undergone any processing treatments.
Experimental methodology for screw pull out testing

A significant factor in the holding strength of bone instrumentation is the quality of the bone itself. There are many techniques currently used to assess the integrity of the bone samples. Dual X-ray absorptiometry (DEXA), quantitative computed tomography (QCT), and magnetic resonance imaging (MRI) are used clinically to study the bone mineral density for studies on osteoporosis. DEXA is a common scanning method for determining bone quality because of its ease of use, speed, and accurate assessment. However, it provides an overall average bone mineral density (BMD) for the regions of bone measured. QCT is another common method used for determining BMD. The advantage of this technique is the ability to measure distinct regions of bone for the quantification of BMD. This can yield a more localized BMD for the region where the screw will be placed. Proper CT algorithms should be used for cancellous and cortical bone and the regions measured within the bone can be calibrated against the phantom for each scan. MRI is an accurate method for BMD quantification and can be used to characterize trabecular architecture. The inhomogeneity of tissue induces signal intensity differences in response to the magnetic stimulation; thus differences in the trabeculae can be visualized and quantified for specific regions of interest.
The holding power of orthopedic screws \textit{in vivo}

Most published data to date have been limited to the investigation of a few variables affecting the holding power of screws in autopsied bone or in synthetic bone-like materials. While this has application in the design of screw threads for improved holding power \textit{in vitro}, it does not reflect the holding power \textit{in vivo}. In living bone the holding power of a screw is inseparably a function of the bone adjacent to the screw. Thus, the holding power will not only be dependent on the screw design, but also on the changes induced in bone by the trauma of insertion, the reaction of bone to the implant, and on the resorption and remodeling of bone as a result of healing.

The holding power of a screw in living cortical bone can be considered as a function of the weakest element in the bone screw composite system, that is the bone adjacent to the screw.

For screws of comparable dimensions and equivalent geometry, the factors considered most important for the integrity and strength of the local bone around the screw are; the tissue reaction to the trauma of insertion of the screw, the reaction of bone to the implant, and the reaction of the bone to the loading to which it is subjected.

In the unloaded system a loss resulted from the combination of the following; tissue trauma due to the drilling operation resulting in microvascular damage and/or thermal necrosis; tissue trauma associated with the insertion of the screw and relative differences in between the self tapping and non-self tapping screws; reaction to, and recovery from the trauma of insertion with proliferation, resorption and remodeling of the bone adjacent to the screw.
The holding power of orthopedic screws *in vivo*

When the time course of the holding power of any of the screw types is considered with reference to the histological changes occurring, its magnitude would be dependent on the following processes: *reinforcement by periosteal and endosteal callus and by the woven bone within the medullary canal surrounding the screws; reinforcement by new bone within the region of the cortex laid down between the drill hole and the screw core, and by the new osteons within the cortex; and hypothetical weakening by bone death, resorption or fibrosis.* It was evident during the *first zero to four-week* time period after insertion that the first of these processes was the major contributing factor to the observed increases in holding power of all screws. During the *fourth to twelfth week* period with the disappearance of this proliferative reaction, the second factor no doubt contributed to the increase observed.

The observed clinical failures by the pull out of screws as an integral part of a loaded system have three additional factors which may contribute to their cause:

- Firstly, remodeling of the structural elements of bone to align with local principle stresses adjacent to the screw may take place under the stimulus of sustained (static) or intermittent loading.
- Secondly, differential micromovements between bone and screw under intermittent loading conditions may result in fibrous replacement of bone adjacent to the screw.
- Thirdly, overload of the screw by the large forces occasionally acting on an implant may cause local bone failure and result in loosening of the screw and possible failure of the implant itself.