Research Article

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Dual Motor Drill Continuously Measures Drilling Energy to Calculate Bone Density and Screw Pull-out Force in Real Time

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Abstract

Introduction: Low bone density complicates the surgical management of fractures. Screw stripping in osteoporotic bone leads to decreased fixation strength and weakening of the fixation construct. If low density could be detected during drilling, augmentation may be performed to prevent screw stripping. Furthermore, continuous monitoring of the drill bit depth and bone density can allow detection of the far cortex where density suddenly increases, providing immediate and accurate screw length measurement and reducing the risk of overpenetration or plunge in osteoporotic bone. Therefore, a dual motor drill was created to calculate bone density and pull-out force in real time. The purpose of this study was to determine whether real-time monitoring of drill bit torque and depth could be used to estimate bone density and pull-out force. We hypothesized that the calculated drilling energy could be used to determine density and would correlate with pull-out force.

Methods: Drilling and screw insertion were performed using a validated composite unicortical bone model. Screws of 5-, 10-, and 20-mm length were placed into blocks of known densities (10, 20, 30, and 40 pounds per cubic foot). During creation of holes by the dual motor drill, drilling energy was recorded and used to calculate density. Calculated bone density was then compared with the known density of the block. The drill bit was exchanged for a screwdriver, and screw insertion energy was recorded in a similar fashion during screw placement. Screws were then subjected to maximal axial pull-out force testing with a material testing device. Recorded drilling energy and screw insertion energy were then correlated with the measured pull-out force.

Results: Calculated bone density correlated very strongly with the known control density, confirming the accuracy of density calculations in real time. Drilling energy and screw insertion energy correlated very strongly with the measured pull-out force by destructive testing confirming ultimate pull-out force could be quantified during drilling or placement of a screw.

Discussion: Our results confirmed that a dual motor drill can accurately and immediately allow determination of bone density and screw pull-out force before placing a screw. This knowledge could allow a surgeon to perform augmentation or alter surgical technique to prevent screw stripping and loss of fixation as well as detect the far cortex and prevent overpenetration in osteoporotic bone.

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Osteopenia and osteoporosis are the most common causes of metabolic bone disease resulting in low bone density.[1-3] Furthermore, fragility fractures are a significant source of morbidity and mortality.[4,5] Poor bone density is a clinical challenge for orthopaedic trauma surgeons managing fragility fractures because of the increased risk of fixation failure.[6]

When low bone density is encountered intraoperatively, the result can be drill bit overpenetration, plunge, or screw stripping during screw insertion. Overpenetration is a problem inherent to drilling regardless of surgeon experience.[7] Drill bit overpenetration can result in clinically relevant damage to nerves, tendons, and vessels, which negatively impact and complicate surgical outcomes.[8-13]

Biomechanically, inadvertent stripping of a screw reduces pull-out strength by approximately 80%, dramatically weakening a fixation construct, which can be problematic in the setting of low bone density.[14] Unfortunately, attempts to identify risk factors for screw stripping identified no significant predictors of impending overtightening and loss of fixation.[15]

Typically, a patient's bone density is unknown before sustaining a fracture. Obtaining a dual-energy x-ray absorptiometry (DEXA) in the setting of acute injury is uncomfortable and impractical. Therefore, knowledge of intraoperative, in vivo, bone density in real time before placement of the implant would be potentially beneficial to surgeons managing fractures in osteoporotic bone by minimizing the risk of overpenetration to prevent iatrogenic damage and decreasing the risk of screw stripping to optimize fracture fixation stability.

According to the work-energy theorem, the work it takes to remove a volume of bone in the path of a drill bit correlates with the energy expended by the drill bit. According to material science and engineering principals, the work required to remove this aliquot of bone (drilling energy) should correlate closely with bone density. Also, the energy used to drive a screw (screw insertion energy) into a hole should similarly correlate with bone density.

Therefore, a dual motor drill was created to allow measurement of drilling and screw insertion energy to calculate bone density and pull-out force during drilling. The purpose of this study was to correlate calculated bone density and pull-out force from the dual motor drill to known control values. Our hypothesis is that drilling energy accurately determines bone density and drilling and screw insertion energy accurately determine pull-out force.

Methods

Dual Motor Drill

In standard drilling, advancement of the bit and revolution speed are controlled manually by the surgeon. A dual motor drill was created consisting of a drill with two-motors (Figure 1). The first motor spun a chuck similar to a standard orthopaedic drill but at a controlled revolution rate (rpm). The second motor moved a harp and drill guide parallel to the axis of the drill bit controlling advancement of the bit. During drilling, the drill guide was pressed against the bone holding the drill guide and harp static. Depression of the first trigger spun the chuck. Depression of a second trigger then allowed the drill bit to move forward at a controlled rate sliding through the drill guide and into the bone. This scenario allowed the drill to function like a handheld drill press in which the harp and drill guide function as a variable depth stop and the drill guide functions as a tissue protector.

During drilling, the dual motor drill measured the work done by the drill bit by isolating the torque on the bit and rpm as it cut through the bone model. The energy was plotted visually on a monitor with the drill bit depth on the x-axis and drilling energy on the y-axis (Figure 2) The process was similar for the insertion of a screw using a standard driving bit while demonstrating the energy and position on a monitor.

Testing Block Specimens

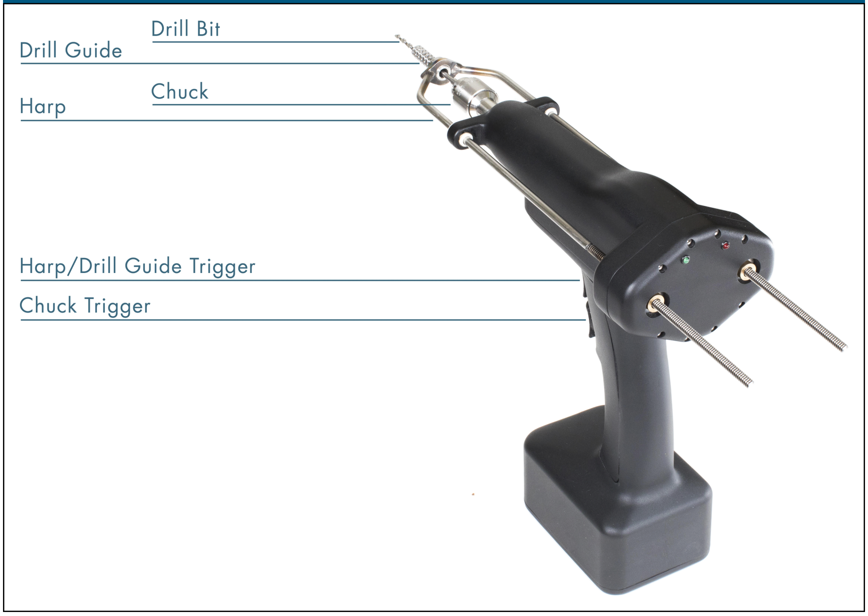
Uniform composite bone blocks of known densities (Sawbones part numbers 1522-01, 03, 04, 05; Pacific Research Laboratories) of 10, 20, 30, and 40 pounds per cubic foot (pcf) were cut to 130 × 40 × 40 mm for testing. Pilot testing was performed to determine the minimum distance to prevent fractures from propagating to an adjacent screw hole or deforming the specimen during pull-out testing in all cases. This testing confirmed that a zone of 15 mm was adequate. The use of composite bone block models for this type of testing has been previously reported and validated.[16]

Screws lengths of 5, 10, and 20 mm were selected for testing from a Synthes Large Fragment Standard 4.5-mm Cortical Screw Set (VS402.005, VS402.010, VS402.020; Synthes USA). Using the blocks described above, a centerline was placed down the length of each block, and three holes corresponding to one of each selected screw length were planned in each block evenly spaced from each other and from the edges of the block. Two blocks per density were used to validate consistency of the experimental model creating a total of 24 planned holes. All screw lengths were markedly less than the block thickness to ensure a uniform drilling model for all specimens. Each block was stabilized by hand for drilling to mimic clinical use, and a single examiner performed all testing.

Dual Motor Drilling Technique

To zero the drill and synchronize software, the tip of the drill bit was aligned to the tip of the drill guide, and software was zeroed. Once the drill was placed on the target specimen, the chuck trigger was depressed to spin the drill bit. Then, the harp and drill guide triggers were depressed together to allow the drill bit to move past the tip of the drill guide to penetrate the specimen. The drill was set to a continuous feed rate of 1 mm/s and 600 rpm. Then, 3.2-mm drill bits were used for all holes, and bits were changed for each block. During drilling, the curve was continuously monitored, and drilling was stopped once the bit depth reached the desired screw length plus 2 mm (7, 12, 17, and 22 mm, respectively). Holes were overdrilled by 2 mm to ensure the screw tip would not reach the bottom of the hole because this can alter screw insertion energy and axial pull-out force testing.

Figure 1



Photograph of the dual motor drill. Collectively, the drill functions like a handheld drill press. Depression of the chuck trigger engages the first motor to spin the chuck similar to any standard orthopaedic drill. Depression of the harp and drill guide trigger engages the second motor to move the harp and drill guide parallel to the axis of the drill bit. During drilling, the drill bit moves forward at a controlled rate, whereas the harp and drill guide remain fixed. The harp and drill guide function as a variable depth stop, whereas the drill guide functions as a tissue protector.

Determination of Calculated Bone Density

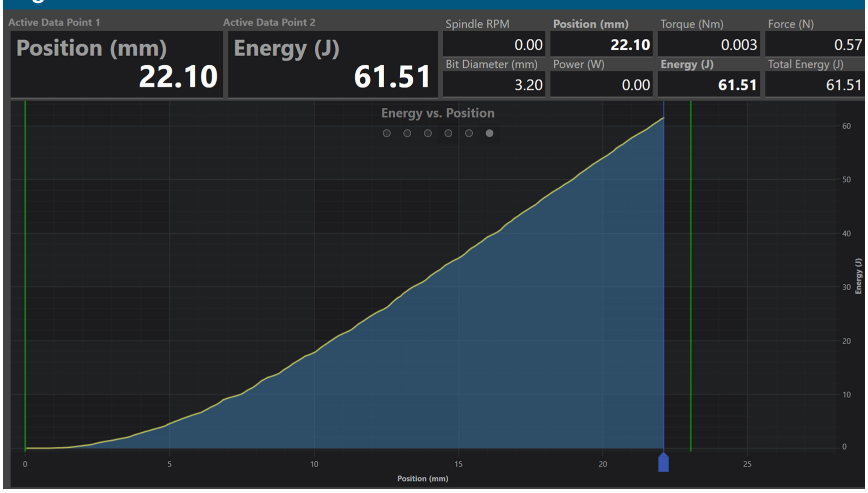
The monitor screen was then inspected. The point on the x-axis corresponding to the planned screw length was selected, and the energy value at the point was recorded. This point represented the total drilling energy required to reach the planned screw depth.

Using the data obtained during drilling, the following formula was applied to obtain the calculated bone density:

$$6.4 \times \text{drill energy/screw depth} + 4 = \text{calculated bone density}.$$

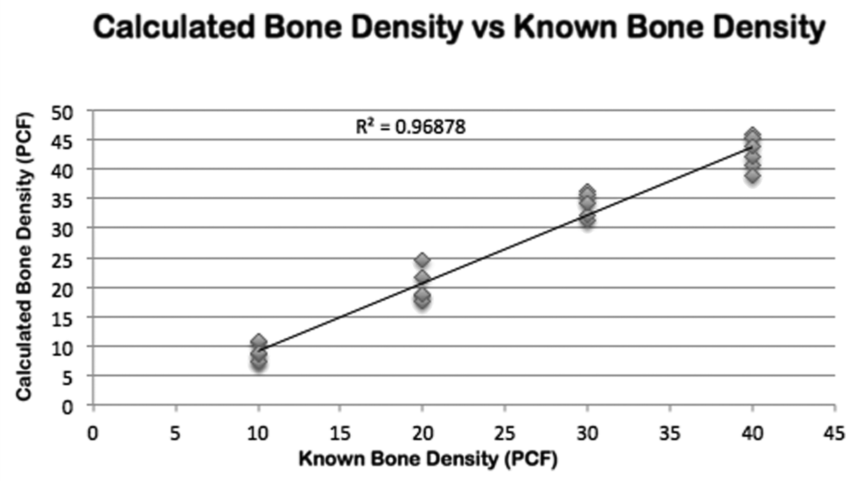
The calculated bone density was then compared with the known density of the blocks.

Figure 2



Example of visual monitor demonstrating the energy plot with energy (y-axis) in joules and position (x-axis) in millimeters for a 22-mm hole drilled in a 20-pcf block. When the drill bit reaches the desired depth (position), the operator stops drilling by letting go of the triggers. The total energy can be recorded for any given depth (position) on the plot.

Figure 3



Measured density in pounds per cubic foot (pcf) using the dual motor drill (*y*-axis) compared with known block density (*x*-axis). A very strong linear correlation was identified (R^2 = 0.969).

Screwdriver Testing

The process for screw insertion was similar to that of the dual motor drilling technique described above except that the drill bit was exchanged for a standard screwdriver bit. Then, 4.5-mm self-tapping cortical screws were inserted using the same handheld drill with a screwdriver bit set to 30 rpm. Screws were inserted until the flare of a prefashioned depth marker first contacted the surface of the block to minimize the risk of overtightening. During screw insertion, the graphical user interface was continuously monitored. When the screw reached the planned depth, the driver was stopped and the screw insertion energy was recorded.

Pull-out Force Testing

All screws were then subjected to maximal axial pull-out force testing. Pull-out force was measured using a Mark-10 ESM301 Motorized Test Stand with a Mark-10 Series 5 M5-005 Force Meter with a custom jig to secure the blocks and allow for coupling to the screw heads without applying an off-axis load. Pull-out speed was set at 5 mm/min as previously described in the literature, and the maximal axial pull-out force obtained was recorded for each screw.[17] Order of pull-out testing was randomized for screw depth. Previously recorded drilling energy and screw insertion energy were then compared with the maximal axial pull-out force obtained from mechanical testing.

The primary outcome measure was the correlation of calculated bone densities with known standards. Secondary outcome measures were correlation of drilling energy and screw insertion energy with pull-out force.

Statistical Analysis

A Pearson product-moment correlation coefficient was computed to assess the relationship between the calculated bone density and the known density and between drilling and screw insertion energies and maximal axial pull-out force. Strength of correlation was classified as being strong (R > 0.66), moderate (0.33 ≤ R ≤ 0.66), or weak (R < 0.33). Any coefficient value of 0.80 or greater was considered indicative of very strong correlation. Statistical significance was set at $P < 0.05$. Data were recorded and analyzed using Microsoft Excel (Microsoft).

Results

During pull-out testing, the Mark-10 Series was determined to be not capable of pulling out the 20-mm screws from the 40-pcf blocks. Thus, the two 20-mm screws in the 40-pcf blocks were excluded. There were no other drilling, screw insertion, or pull-out force testing errors, and all remaining (22/24 screws) were included in final analysis.

A very strong positive correlation was found between calculated bone density and known bone density (R^2 = 0.969; n = 22; $P < 0.00001$), indicating accurate calculation of density for all screw lengths and bone densities (Figure 3).

A very strong positive correlation was found between drilling energy and pull-out force (R^2 = 0.946; n = 22; $P < 0.00001$) (Figure 4).

A very strong positive correlation was found between screw insertion energy and pull-out force (R^2 = 0.964; n = 22; $P < 0.00001$) (Figure 5).

Subgroup analysis revealed that the correlations were equally preserved for all tested densities and screw lengths.

Discussion

The primary finding of this study was a dual motor drill can accurately and immediately allow determination of bone density while drilling a variety of densities and screw hole depths. Furthermore, drilling or screw insertion energy obtained in real time correlates highly with maximal pull-out force.

The biomechanical properties of an osteosynthesis construct for fracture fixation primarily depend on the individual characteristics of the host bone for a given fracture pattern and stabilization construct.[18] Specifically, bone density and insertion torque have been validated as determinants of the strength of an osteosynthesis construct.[19-22] Using standard drilling and insertion of the implant for fracture fixation, these variables are unknown.

If low density could be detected during drilling, the surgical technique could be altered to prevent fracture fixation failure. Decreased pull-out force after a screw is stripped or exchanged has been well documented.[14]

Techniques for augmentation of screw fixation to salvage fixation are numerous and evolving.[23-25] Changing the surgical plan to use locking plate fixation is another option for improving fixation strength in osteoporotic bone.[26,27]

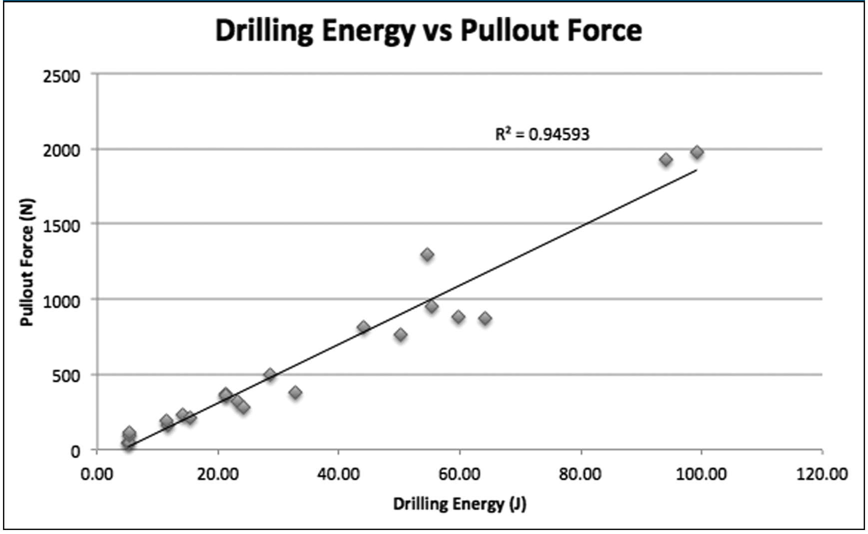
Furthermore, continuous monitoring of drill bit depth and bone density can allow detection of the far cortex where density suddenly increases. This method has two potential clinical advantages. First, it provides immediate and accurate screw length measurement if the depth of drilling is recorded and monitored. This obviates the need for the additional time and error introduced by using a manual depth gauge. Second, detecting the change in density at the far cortex reduces the risk of overpenetration or plunge in osteoporotic bone. Clinically, this has a wide variety of applications such as increased accuracy for screw placement in the humeral or femoral heads, which allows optimization tip apex distance to decrease the risk of screw cutout and failure after placement of a dynamic hip screw.

Reitman et al[21] evaluated the relationship between pull-out force, peak insertion torque, and bone density. They found that pull-out force correlates less with peak insertion torque than bone density. This finding is relevant because it suggests dominance of the host bone over the screw construct in determining overall construct strength, but more importantly, it suggests that the perceived insertion force of screw placement by a surgeon may be a less reliable marker of construct stability than previously thought.[28,29]

Thus, quantifying bone density in real time may provide a clinical advantage over estimating surgeon perceived insertion torque. In this study, both drilling energy and screw insertion energy highly correlated with pull-out force. This difference could be related to the use of drilling energy rather than peak insertion torque because drilling energy is measured in a continuous and cumulative fashion versus as a single static data point.

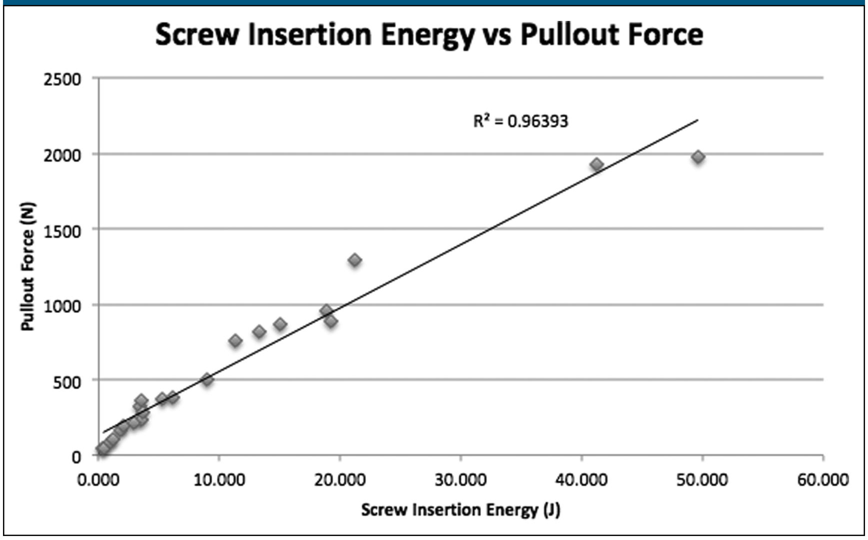
Ong and Bouazza-Marouf[30] examined drilling force as a means to

Figure 4



Drilling energy (*x*-axis) in joules was compared with pull-out force in newtons. A very strong linear correlation was identified (R^2 = 0.946).

Figure 5



Screw insertion energy (*x*-axis) in joules was compared with pull-out force in newtons. A very strong linear correlation was identified (R^2 = 0.964).

estimate bone density against the benchmark of DEXA measurements and found a high degree of correlation, suggesting that analysis of drilling force could provide useful information about the strength of bone. They measured drill force and extrapolated measurement of energy based on the work-energy theorem. Conversely, we directly measured drilling energy.

Notably, in some studies, bone density was obtained using DEXA, which creates an average area density over the region of interest.[17,21,30] This method is less clinically applicable for a given screw or construct because of the presence of regional variations in a given specimen. By contrast, we specifically elected to measure against a specimen of known density to minimize this variability and confirm the correlation between drilling energy and bone density at the point of testing.

The study was performed on composite bone block models instead of cadaveric bone. Although this is a limitation, this was an intentional portion of the study design. DEXA is considered the benchmark for determination of bone density clinically; however, it has notable limitations because measurement accuracy can be limited by a number of factors including the size of bone measured and differences between cortical and cancellous bone resulting in total error in measurement up to 5% to 6%.[31-34] In this case, we chose to specifically evaluate accuracy against a known standard to determine the true accuracy of density measurements of the dual motor drill.

Testing was performed by an operator with significant experience in placement of the orthopaedic implant, and results may not be generalizable to other levels of skill or experience. Biomechanical testing was performed with 4.5-mm cortical screws alone in a uniform bone model, and other common diameter screws in clinical use were not tested.

Conclusions

In this in vitro study using a composite foam bone block model, our hypothesis confirmed that real-time measurement of drilling energy allowed for calculation of bone density, which correlated very strongly with a known density. Furthermore, measurements of both drilling and screw insertion energy were strongly correlated with pull-out force testing. This information has potential implications for quantifying fracture fixation strength without destructive testing (see Video, Supplemental Digital Content 1, http://links.lww.com/JG9/A24).

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