Power-Tool Use in Orthopaedic Surgery
Iatrogenic Injury, Its Detection, and Technological Advances: A Systematic Review

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Background: Power tools are an integral part of orthopaedic surgery but have the capacity to cause iatrogenic injury. With this systematic review, we aimed to investigate the prevalence of iatrogenic injury due to the use of power tools in orthopaedic surgery and to discuss the current methods that can be used to reduce injury.

Methods: We performed a systematic review of English-language studies related to power tools and iatrogenic injuries using a keyword search in MEDLINE, Embase, PubMed, and Scopus databases. Exclusion criteria included injuries related to cast-saw use, temperature-induced damage, and complications not clearly related to power-tool use.

Results: A total of 3,694 abstracts were retrieved, and 88 studies were included in the final analysis. Few studies and individual case reports looked directly at the prevalence of injury due to power tools. These included 2 studies looking at the frequency of vascular injury during femoral fracture fixation (0.49% and 0.2%), 2 studies investigating the frequency of vertebral artery injury during spinal surgery (0.5% and 0.08%), and 4 studies investigating vascular injury during total joint arthroplasty (1 study involving 138 vascular injuries in 124 patients, 2 studies noting 0.13% and 0.1% incidence, and 1 questionnaire sent electronically to surgeons). There are multiple methods for preventing damage during power-tool use. These include the use of robotics and simulation, specific drill settings, and real-time feedback techniques such as spectroscopy and electromyography.

Conclusions: Power tools have the potential to cause iatrogenic injury to surrounding structures during orthopaedic surgery. Fortunately, the published literature suggests that the frequency of iatrogenic injury using orthopaedic power tools is low. There are multiple technologies available to reduce damage using power tools. In high-risk operations, the use of advanced technologies to reduce the chance of iatrogenic injury should be considered.

Level of Evidence: Therapeutic Level IV. See Instructions for Authors for a complete description of levels of evidence.
patients undergoing orthopaedic surgery and to discuss the current methods to reduce injury and thus improve patient safety.

**Materials and Methods**

**Search and Information Sources**

The methodology of this review is reported according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines\(^{16}\). A systematic review of published literature relating to a power tool and iatrogenic injury was undertaken via MEDLINE, Embase, PubMed, and Scopus databases up to April 1, 2020. We used a combination of the search terms “overdop,” “oversaw,” “tool,” “injury,” “danger,” “safe,” “damage,” “overshot,” “risk,” “drill,” “saw,” “iatrogenic,” “hospital acquired condition,” “medical errors,” “medical mistake,” and “orthopaedic.” The electronic database search was further supplemented by manual review of the references within key relevant studies.

**Eligibility Criteria**

Studies were included if they reported on an orthopaedic procedure that featured the use of a power tool. All study types were eligible, including case reports, animal research and simulation studies, cohort studies, and literature reviews. Included studies were either written in, or translated to, the English language.

Studies were excluded if they involved injuries related to cast-saw, arthroscopic trocar, diathermy, needle, scissors, and blade use. Studies relating to complications outside the scope of orthopaedic surgery, injuries not clearly related to intraoperative power-tool use, or injuries related to temperature-induced damage or infection were also excluded.

The 2 outcomes measured were the prevalence of iatrogenic injury related to power-tool use and the methods or safety mechanisms present to reduce iatrogenic injury.

The first 2 authors (M.C.A.A. and S.Z.) independently conducted the search, screened abstracts, and selected studies for review. Any discrepancies regarding article inclusion were resolved via discussion as recommended by the Cochrane Collaboration guidelines\(^{17}\).

**Data Collection Process**

Relevant data items were extracted from each included article and are presented in Table I. Items included were type of bone, type of iatrogenic injury, power tool used, type of operative procedure, and outcome/recommendation by the authors. The papers were then categorized according to prevalence of iatrogenic injuries, methods to reduce damage using power tools, methods to detect damage when using power tools, and recommendations for power-tool settings.

**Statistical Analysis**

Statistical analysis was not possible because of the heterogeneity of the study types and clinical data mostly coming from case series. Therefore, descriptive statistics were used where possible.

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**Source of Funding**

This study was supported by a grant from the Wellcome Trust (208858/Z/17/Z). General laboratory funding was provided by the U.K. National Institute for Health Research, The Royal College of Surgeons of England, the Dunhill Medical Trust, and the Michael Uren Foundation.

**Results**

A total of 3,689 abstracts were retrieved via the electronic databases using the search criteria. Five abstracts were included from the manual reference search of relevant papers. Following duplicate removal and abstract screening, a total of 460 eligible full-text studies remained. After review of these full manuscripts, 88 papers were deemed to fit the inclusion criteria and were subsequently included in the systematic review. Figure 1 shows the study selection flow, according to the PRISMA guidelines\(^{16}\). Table I lists data collected from all selected studies, with relevant findings and recommendations.

**Prevalence of Iatrogenic Injury Using Power Tools**

There were few studies exploring the prevalence of iatrogenic injuries due to power tools. The majority looked at vascular injury, including 2 studies involving femoral fracture fixation\(^{18-19}\), 2 involving spinal surgery\(^{20-21}\), and 4 involving total joint arthroplasty\(^{22-23}\). Two of these were systematic reviews that investigated proximal femoral fractures\(^{24}\) and total hip arthroplasty\(^{25}\), with the majority being retrospective studies and 1 questionnaire sent to vascular surgeons\(^{26}\). In addition, there were multiple case reports of arterial, nervous, and ureteric injury due to screw placement and drill bit use\(^{27-29}\).

**Novel Methods to Reduce Damage When Using Orthopaedic Power Tools**

Nine papers involved robotic systems for use during knee arthroplasty\(^{30}\), femoral neck fractures\(^{31}\), and spinal surgery\(^{32-33}\), or in conjunction with sawing\(^{34}\) and in laboratory studies\(^{35-36,37}\).

Six papers studied simulation\(^{37-42}\), with the different types summarized effectively by Vanikipuram et al.\(^{43}\). These studies showed that simulation can successfully be used to reduce plunging depth in trainee surgeons\(^{38-39}\) and that computer-based simulation was found to provide effective and transferable skills for inexperienced surgeons\(^{40-41}\).

Six papers investigated piezoelectric/vibrational drilling\(^{42-48}\), 2 studies looked at dual motor drilling\(^{49}\), and 4 papers were on recommendations for drill bits\(^{50,52}\). Two studies by the same authors investigated the Taguchi method and suggested a lower rotational speed of 1,000 rpm and feed rate of 50 mm/min with a twist drill to reduce surface roughness and improve drill-hole quality\(^{53,54}\).

Six papers looked at imaging techniques in orthopaedic surgery. These include fluoroscopy\(^{55}\), magnetic resonance imaging (MRI)\(^{56-57}\), fluoroo-free navigation techniques\(^{58}\), computer-assisted navigation, and 3D image-guided placement\(^{59-60}\).
| Year | Study | Type of Bone | Type of Study | Type of Injury | Tool Use | Operative Procedure | Recommendation or Outcome |
|------|-------|--------------|---------------|----------------|----------|---------------------|--------------------------|
| 2012 | Alajmo et al. | Artificial bone | Laboratory | NA | Synthes | Drilling | Blunt drill bits significantly worsen plunging compared with sharp drill bits |
| 2019 | Alam et al. | Bovine femur | Laboratory | Bone stress/necrosis/cracks, drill breakage | Vibrational drilling | Drilling | The drilling force, torque, temperature, and cell loss could be minimized when the drill speed was maintained at 1,000 rpm, the feed rate at 30 mm/min, and the frequency at 20 kHz |
| 2015 | Alshameer et al. | Hip joint | Systematic review | Vascular | NA | Total hip arthroplasty | Femoral and external iliac arteries have the highest incidence of vascular injury |
| 2012 | Aziz et al. | Bovine femur | Laboratory | NA | CRS Catalyst-5 robot (Thermo CRS) | Drilling | The algorithm can be used to prevent any drill-bit breakage, unnecessary drill-bit insertion, and any mechanical damage to the bone |
| 2010 | Bail et al. | Talus | Cadaveric | NA | 3.4-mm titanium spiral drill bit | Drilling of osteochondral lesions | MRI appears to be a viable imaging technique |
| 2015 | Barquet et al. | Femur | Systematic review | Vascular | NA | Internal fixation (varying types) | Incidence of morbidity and mortality of vascular injury from femoral fracture fixation was 11.44% and 6.62%, respectively |
| 2013 | Boiadjiev et al. | Bovine femur | Laboratory | NA | Passive navigation principle for orthopaedic interventions with MR fluoroscopy | Nonspecified drilling | Robotic use in surgery is still under development but could be a useful tool in the future |
| 2006 | Bolger et al. | Porcine spine | Laboratory | Pedicle breach | Custom-made device | Pedicle drilling | Use of impedance measurement with drill tool allows real-time detection of pedicle perforation |
| 2007 | Bolger et al. | Spine | Clinical trial | Pedicle breach | PediGuard (SpineVision) | Pedicle-screw fixation | Electrical conductivity measurement may provide a simple, safe, and sensitive method of detecting pedicle breaches |
| 2019 | Butler and Halter | Swine femur | Laboratory | Not specified | OsseoSet 200 system (Nobel Biocare) | Drilling | The system can prevent iatrogenic injury associated with breaching the inferior alveolar nerve or maxillary sinus | continued |
| Year   | Study                         | Type of Bone          | Type of Study      | Type of Injury   | Tool Use                           | Operative Procedure                              | Recommendation or Outcome                                                                                   |
|--------|-------------------------------|-----------------------|--------------------|------------------|------------------------------------|---------------------------------------------------|-------------------------------------------------------------------------------------------------------------|
| 2010   | Butt et al.                   | Knee joint            | Review             | Vascular         | NA                                 | Total knee arthroplasty                           | There are 4 mechanisms for arterial injury during total knee arthroplasty, 1 of which includes direct injury to the vessel with power tools |
| 2013   | Bydon et al.                  | Spine                 | Retrospective case series | Durotomy         | Ultrasonic bone curette and high-speed drill | Spinal decompression                              | The ultrasonic bone curette has a safety profile similar to that of the high-speed drill                  |
| 2003   | Calligaro et al.              | Hip and knee joint    | Retrospective case series | Vascular         | NA                                 | Hip and knee arthroplasty                         | There were acute arterial complications in 32 patients (0.13%)                                              |
| 2010   | Cartiaux et al.               | Artificial bone       | Laboratory         | NA               | Compact Air Drive II (Synthes)      | NA                                                | There was a significant increase in accuracy when a robotic device was used in conjunction with an oscillating saw |
| 2012   | Clement et al.                | Artificial bone       | Laboratory         | NA               | Small fragment drill and air drill (Synthes) | NA                                                | Experienced surgeons penetrated the far cortex by a mean of 6.33 mm                                         |
| 2003   | Da Silva et al.               | Knee joint            | Survey             | Popliteal artery | NA                                 | Total knee arthroplasty                           | Popliteal artery injury during total knee arthroplasty is primarily the result of direct trauma to the vessel |
| 2014   | Dai et al.                    | Porcine spine         | Laboratory         | NA               | Laser displacement sensor measuring vibration | Drilling                                          | Minimizes radiation exposure and allows real-time feedback                                               |
| 2016   | den Dunnen et al.             | Porcine talus and femur | Laboratory         | NA               | Custom-made water jet               | Drilling                                          | The most accurate results in drilling depth can be achieved by applying a nozzle of 0.4 mm, a pressure of 50 MPa, and jet times between 1 and 5 s. |
| 2019   | Di Martino et al.             | Cervical spine        | Systematic review  | Neurovascular injury | NA                                 | Cervical spine decompression                      | Evoked-potential monitoring has a high sensitivity and specificity for detecting neural damage, but it is unclear which patients it is indicated for |
| 2019   | Duan et al.                   | Femur                 | Prospective case series | NA               | TiRobot system (TINAVI Medical Technologies) | Percutaneous cannulated screw fixation           | Robot-assisted screw fixation allows accurate screw insertion, less invasion, and less radiation exposure |
| 2019   | Duperron et al.               | Bovine femur          | Laboratory         | NA               | Modified version of surgical hand-drill (CD4; Stryker U.S.A.) | Intramedullary nailing                           | Diffuse reflectance spectroscopy can be successfully integrated into a handheld drill |

**TABLE I (continued)**
| Year | Study | Type of Bone | Type of Study | Type of Injury | Tool Use | Operative Procedure | Recommendation or Outcome |
|------|-------|--------------|---------------|---------------|----------|---------------------|--------------------------|
| 1992 | Elliott\(^1\) | Tibia | Laboratory | NA | AO Small Air Drill (Straumann U.K.) | Dynamic hip screw | Drills do not increase risk of damage and increase operative time by 30 s per screw |
| 2011 | Flannery et al.\(^{53}\) | Tibia | Cadaveric | Plunging and nerve overwrapping | Handheld cordless drill (Standard Stryker drill) | Screw placement | Structures are at higher risk when using a threaded pin versus a smooth pin |
| 2018 | Franzini et al.\(^{44}\) | Spine | Case series | Spinal root, dura mater, venous plexus spinal cord injury | Mectron piezosurgery device (Mectron Medical Technology) | Laminoplasty | Piezoelectric device has good safety and precision profile |
| 2018 | Gilmer and Lang\(^{14}\) | Artificial bone | Laboratory | Fracture | Custom made dual motor drill | Screw placement | Measurement of drilling energy allowed for calculation of bone density, which correlated very strongly with the known density |
| 2010 | Gras et al.\(^{55}\) | Pelvis | Radiographic | Prevesical hematoma | 2D fluoroscopic navigation | Screw placement | Provides high accuracy of screw placement, but for bilateral iliosacral screw fixation, 3D fluoroscopy is preferred |
| 2011 | Gras et al.\(^{58}\) | Knee and talus | Case series | NA | Optoelectronic system for navigation of the drill and target reference pointer | Drilling | Increase drilling precision and reduce radiation exposure by reducing use of fluoroscopy |
| 2004 | Grauer et al.\(^{79}\) | Spine | Cadaveric | Neurological injury | SafePath cannulation device | Pedicle-screw insertion | May be better for pedicle-screw insertion cannulation in lumbar spine compared with standard techniques |
| 2019 | Hampp et al.\(^{13}\) | Knee | Cadaveric | Soft-tissue injury | The RATKA (robotic arm-assisted total knee arthroplasty) system (Mako Surgical Corp. [Stryker]) | Total knee arthroplasty | Robotic-assisted total knee arthroplasty may reduce soft-tissue injury, particularly the posterior cruciate ligament |
| 2020 | Herregodts et al.\(^{72}\) | Knee | Cadaveric | Soft-tissue injury | Dyonics power oscillating saw (Smith & Nephew) | Total knee arthroplasty | The oscillating saw significantly passes the edge of the bone during tibial resection in total knee arthroplasty |
| 2019 | Itoh et al.\(^{24}\) | Tibia | Case report/cadaveric study | Deep peroneal nerve injury | Not specified | Medial open-wedge high tibial osteotomy | Deep peroneal nerve has a risk of injury during distal locking-screw placement in this procedure |

continued
| Year | Study                                      | Type of Bone | Type of Study       | Type of Injury                              | Tool Use                                                                 | Operative Procedure                          | Recommendation or Outcome |
|------|-------------------------------------------|--------------|---------------------|---------------------------------------------|--------------------------------------------------------------------------|-----------------------------------------------|----------------------------|
| 1993 | Jackson et al. 25                         | Femur        | Case report         | Popliteal artery, tibial/common peroneal nerves | Not specified                                                            | Posterior cruciate ligament reconstruction     | Square-shouldered drill bit causes higher risk of neurovascular injury as guide pins are used in more distal anatomical insertion |
| 2013 | James et al. 80                           | Bovine femur | Laboratory         | NA                                          | Saw blades (KM-458, Brasseler U.S.A.)                                      | Sawing                                        | Thrust force will always be greater than cutting force for the range of velocities and depths of cut investigated |
| 2016 | Jiang et al. 83                           | Spine        | Case series         | Spinal canal entry                          | Not specified                                                            | Atlantoaxial pedicle-screw fixation           | Use of novel drill guide template for atlantoaxial pedicle-screw placement is feasible and has high accuracy |
| 2000 | Jingushi et al. 82                        | Femur        | Case series         | Perforation and femoral fracture            | High-powered drill with variable-sized metal donut attached 3 cm proximal to drill tip end | Removal of femoral cement                     | Use of high-powered drill equipped with centralizer to remove the distal cement during hip revision arthroplasty can lessen the incidence of femoral perforation |
| 2017 | Kamara et al. 83                          | Ilium, femur, tibia | Retrospective cohort study | Infection, neurapraxia, suture abscess | Not specified                                                            | Hip and knee arthroplasty                     | Pins required for navigation-assisted arthroplasty have a low complication rate; however, transcortical/juxta-cortical drilling is a possible risk factor for pin-site infection |
| 2019 | Kazum et al. 38                           | Synthetic femur model | Prospective observational study | NA                                           | Power drill, 2.7-mm drill bit (Synthes)                                    | Drilling                                      | Training surgeons on a reproducible and reliable drilling simulator can reduce plunging distance |
| 2009 | Khokhotva et al. 84                       | Lamb femur   | Laboratory         | Plunging                                    | Nitrogen-powered surgical drill AO Drill Reamer; Hall Series 4, Model 5067 (Zimmer) | Drilling                                      | Feedback related to plunging does not improve results |
| 2016 | Kim et al. 26                             | Tibia        | Case report         | Anterior tibial artery                      | Not specified                                                            | Anterior cruciate ligament (ACL) reconstruction | Drilling for tibial bicortical fixation during ACL reconstruction can directly injure the anterior tibial artery |
| 2016 | Kim et al. 85                             | Femur        | Laboratory         | Screw malposition                          | Antegrade Femoral Nail (Synthes)                                         | Intramedullary nailing                       | Targeting device malalignment can occur when placing the proximal reconstruction screws in a reconstruction nailing system |
| Year | Study | Type of Bone | Type of Study | Type of Injury | Tool Use | Operative Procedure | Recommendation or Outcome |
|------|-------|--------------|---------------|---------------|----------|---------------------|--------------------------|
| 2003 | König et al. | Ilium, femur, tibia | Case series | NA | Piezoelectric MRI drilling machine (MRI Devices Daum) | Transcortical bone biopsy | Piezoelectric drill is a safe method for transcortical bone biopsy |
| 2003 | Kotani et al. | Spine | Case series | Pedicle wall/anterior vertebral-body-wall perforation | Not specified | Screw insertion | Computer-navigation system can reduce complications related to pedicle-screw insertion |
| 2012 | Larson et al. | Spine | Retrospective study | NA | Not specified | Screw insertion | Navigation increases accuracy for spinal instrumentation in congenital spine deformity |
| 2019 | Lee et al. | Cervical spine | Retrospective case series | Vertebral artery injury | Not specified | Cervical spine surgery | Overall incidence of vertebral artery injury was 0.08%. C1-2 posterior fixation had the highest incidence (1.35%) |
| 2019 | Liebmnn et al. | Artificial bone | Laboratory | Neurovascular injury | NA | Pedicle-screw placement | Precise pedicle-screw insertion can be achieved using this method on synthetic bone |
| 2017 | Mahylis et al. | Upper limb | Cadaveric | Extensor tendon injury | Continuous or oscillating drill modes | Drilling | Complete extensor tendon failure due to drill-penetration injury is rare |
| 2019 | Massimi et al. | Cranium | Retrospective case series | Dural tears | Piezosurgery (Mectron) | Craniotomy/ laminotomy | Piezosurgery is a safe and effective alternative to traditional drilling systems |
| 1998 | Moed et al. | Pelvis | Case series | Neural injury | 2.8-mm drill bit (Synthes) and a 3.2-mm drill bit (Howmedica) | Iliosacral screw fixation of pelvic ring fractures | Electromyography has the potential to reduce neural injury during placement of iliosacral screws |
| 2019 | Naik et al. | Orbit | Case series | Infraorbital nerves and vessels | Synthes Piezoelectric System | Orbital floor decompression | Significantly lower chances of infraorbital nerve hypoesthesia when piezoelectric surgery was used |
| 2019 | Nam et al. | Spine | Case report | Sacroiliac joint syndrome | Sextant system (Medtronic) | Pedicle-screw insertion | When using the Sextant system, surgeons must be aware of iatrogenic sacroiliac joint syndrome |
| 2019 | Neubauer et al. | Femur | Cadaveric | Deep/superficial femoral artery | 4-hole DHS system (DePuy Synthes) | Dynamic hip-screw insertion | Deep femoral artery is more at risk than superficial femoral artery with insertion of dynamic hip screw |
| Year | Study | Type of Bone | Type of Study | Type of Injury | Tool Use | Operative Procedure | Recommendation or Outcome |
|------|-------|--------------|---------------|---------------|----------|---------------------|-----------------------------|
| 2013 | Pandey and Panda | Multiple | Systematic review | Many | Many | Review | Guidelines for bone drilling include high-speed drill with larger force, supply of coolant, high drill rake angle, use of split point, quick helix, 2-phase drill bit, and large point angle |
| 2014 | Pandey and Panda | Bovine femur | Laboratory | NA | MTAB Flexmill | Drilling | The best combination of bone drilling parameters for minimum thrust force is 30 mm/min of feed rate and 1,805 rpm of spindle speed |
| 2008 | Parvizi et al. | Hip and knee joints | Retrospective case series | Vascular | NA | Total knee and hip arthroplasty | 0.1% (n = 16) of patients were found to have a vascular injury after total hip/knee arthroplasty, with 6 cases attributed to direct arterial injury |
| 2010 | Podnar | Spine | Retrospective case series | Cauda equina damage | NA | Lumbar spinal surgery | Lumbar spinal surgery causes a low number of lesions to the cauda equina |
| 2001 | Prabhu et al. | Spine | Case report | Vertebral artery pseudoaneurysm | Not specified | Screw fixation | Techniques include immediate removal of the drill, packing with hemostatic agents, angiography, early anticoagulation, and coil embolization with parent vessel occlusion 4 weeks after injury |
| 2020 | Puangmali et al. | Nonspecific porcine bone | Laboratory | Not specified | Novel drill device | Drilling | This technique can prevent overdrilling and reduce tissue damage |
| 2010 | Qin et al. | Clavicle | Radiographic | Neurovascular bundle damage | NA | Drilling | This study suggests safe zone and optimal drilling depths/angles during internal fixation of clavicular fractures |
| 2017 | Ruder et al. | Generic synthetic bone model | Laboratory | Plunging | Not specified | Drilling | There is a reduction in plunging depth with use of a low-cost training model |
| 2004 | Safar et al. | Lower limb | Case series | Pseudoaneurysm of axillary artery, popliteal and anterior tibial artery injury, posterior tibial nerve injury, popliteal artery, popliteal vein, tibial nerve | Not specified | Orthopaedic screw placement | This study suggests that the patient should immediately be referred to a vascular surgeon if a high index of suspicion for arterial injury |

**Table I (continued)**
| Year | Study              | Type of Bone | Type of Study       | Type of Injury       | Tool Use                  | Operative Procedure                              | Recommendation or Outcome                                                                                                                                 |
|------|--------------------|--------------|---------------------|----------------------|---------------------------|---------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------|
| 2014 | Schatlo et al.     | Spine        | Retrospective case series | Neurological injury | SpineAssist (Mazor)       | Pedicle screw insertion                           | Robotic pedicle-screw placement is safe, but there are technical difficulties and, hence, fluoroscopy should also be used                                                                                   |
| 2010 | Seebauer et al.    | Femur        | Cadaveric           | NA                   | MRI-compatible drill and a 3.4-mm titanium drill bit (Invivo) | Osteochondral defect repairs                      | MRI-assisted navigation method with a passive-navigation device is potentially applicable in the treatment of osteochondral lesions of the knee                                                                 |
| 2017 | Segal et al.       | Femur        | Retrospective case series | Vascular             | Multiple                  | Internal fixation of intertrochanteric fracture (intermedullary nail or dynamic hip screw) | The rate of iatrogenic vascular injury occurring in internal fixation of intertrochanteric femoral fractures was 0.2% in this study                                                                       |
| 2019 | Shepard et al.     | Spine        | Cadaveric           | Pedicle injury       | IntelliSense drill (McGinley Orthopedics) | Pedicle screw insertion                           | This computerized drill is comparable with a freehand technique at a junior and senior level                                                                                                                         |
| 2018 | Shim et al.        | Swine femur  | Laboratory          | NA                   | Custom-made robotic system | Nonspecific drilling                               | The rolling friction mechanism allows immediate drill-tip detachment and enables the robot to have a compact structure                                                                                       |
| 2013 | Shin et al.        | Pelvis       | Case report         | Ureter injury        | Not specified             | Internal fixation of multiple pelvic fractures    | When operating on the pelvis, it is important to understand anatomy of the ureter and surrounding structures                                                                                                  |
| 2018 | Shu et al.         | Bovine femur | Laboratory          | Bone necrosis        | Novel elliptical vibration-assisted orthopaedic oscillating saw | Osteotomy                                         | Elliptical vibration saw may reduce cutting forces during sawing                                                                                                                                           |
| 2017 | Singh et al.       | Bovine femur | Laboratory          | NA                   | A twist drill             | Nonspecific drilling                               | Lower rotational speed and low feed rate with twist drill provides optimum force and surface roughness                                                                                                       |
| 2016 | Singh et al.       | Bovine femur | Laboratory          | NA                   | CNC vertical milling machine | Nonspecific drilling                               | Optimal result can be achieved with lower rotational speed (1,000 rpm) and low feed rate (50 mm/min) with twist drill                                                                                       |
| 1993 | Smith et al.       | Spine        | Retrospective case series |Vertebral artery injury| Air drill responsible for most injuries | Vertebral body resection                           | Provided recommended operative procedure technique                                                                                                                                                    |

continued
| Year | Study | Type of Bone | Type of Study | Type of Injury | Tool Use | Operative Procedure | Recommendation or Outcome |
|------|-------|--------------|---------------|----------------|----------|---------------------|--------------------------|
| 2014 | Soriano et al. | Bovine femur | Laboratory | Thermal damage | Multiple | Drilling | A drill bit with 18° rake angle and 0.1-mm margin width reduced temperatures by 50% as well as feed forces and cutting torque by 60% and 50%, respectively. |
| 2017 | Staats et al. | Multiple sites | Retrospective case series | Nil | Not specified | Tumor resection | Computer-navigated surgery offers a safe tool for resection of musculoskeletal tumors. |
| 2017 | Stillwell et al. | Clavicle | Cadaveric | Injury to brachial plexus, pseudoaneurysm, arteriovenous fistula, subclavian vein injury | Standard Stryker drill | Plunge depths | Plunging depths were greater for inexperienced surgeons. Medial clavicle most at risk for damage to neurovascular structures. |
| 2017 | Stranix et al. | Pelvis | Radiographic | Iliac crest bone graft harvest | Simulated drilling | Pelvic visceral injury | Acumed drill-assisted iliac crest bone-graft harvest is a safe technique for obtaining cancellous bone. |
| 2019 | Sui and Sugita | Bovine femur | Laboratory | Not specified | OKK VM4-2 Machining Center | Drilling | Drilling forces are affected by bone type. |
| 2018 | Sui and Sugita | Bovine femur | Laboratory | Not specified | OKK VM4-2 Machining Center | Drilling | Optimized drill bits can reduce drilling forces and temperature rise. |
| 2016 | Synek et al. | Frozen cadaveric radius | Laboratory | Extensor tendon irritation | Not specified | Drilling/screw placement | Self-drilling locking screws can help eliminate overdrilling and distal screw protrusion during fixation of distal radial fractures. |
| 2009 | Tonetti et al. | Model spine | Laboratory | Not specified | Simulator | Simulation: percutaneous sacroiliac joint screw fixation | Useful simulation for familiarizing surgeons with 2D fluoroscopic guidance in a 3D operating environment. |
| 2020 | Torun and Pazarci | Artificial bone | Laboratory | Not specified | TRMAX-RTM134 with a MAIER HSS 3.5-mm-diameter and 70-mm-length drill bit | Drilling | This technique could be integrated with the use of conventional drills with minimum configuration changes and allow increased safety when drilling. |
| 2017 | Tsai et al. | Femur | Cadaveric | Subtrochanteric femoral fracture | Not specified | Drilling | Drilling inferior to the lesser trochanter does not cause an increased chance of fracture compared with drilling at the level of lesser trochanter. |
Methods for Detecting Damage When Using Orthopaedic Power Tools
Numerous papers investigated novel technology to detect damage during orthopaedic surgery. This includes spectroscopy\(^1\), electrical conductivity devices\(^61,62\), electromyography\(^63\), stimulus-evoked potential\(^64\), bioimpedance drills\(^25\), and acoustic emission-signal analysis\(^66\).

Recommended Settings for Power-Tool Use
Aziz et al. developed an algorithm that detects excessive force and breakthrough of the drill bit during bone drilling, whereby the drill will halt and return to a safe position once the algorithm is triggered\(^67\). Pandey and Panda calculated the point at which a drill had broken through bone. They found that the best combination of bone-drilling parameters for minimum...
thrust force is 30 mm/min of feed rate and 1,805 rpm of spindle speed.

**Discussion**

This systematic review aimed to determine the prevalence of iatrogenic orthopaedic injuries related to intraoperative power-tool use in the literature and current methods available for reducing the occurrence of these injuries. A total of 88 studies were retrieved and analyzed to help answer these questions, although a wide range of orthopaedic procedures were included. Where possible, we have given recommendations to reduce injury on the basis of the studies. However, our intention was to gain appreciation of the breadth of reported iatrogenic injuries in the literature; providing specific recommendations for each procedure is outside the scope of this review.

**Prevalence of Iatrogenic Injury**

Overall, there were few papers that specifically explored the prevalence of iatrogenic power-tool injuries in orthopaedic surgery. Where reported, types of iatrogenic injuries included vascular, nervous, and ureteral injury.
One systematic review from 2015 looked at vascular injuries that occurred during internal fixation of proximal femoral fractures. The authors estimated the incidence of these injuries to be 0.49%. They showed that, of 182 cases of injury identified, 175 were reported as iatrogenic injuries, mostly in the extra-pelvic vessels and specifically the profunda femoris artery. Interestingly, from their analysis, at least 28 of these cases had a confirmed mechanism of injury involving a drill bit. The authors make several recommendations related to power-tool use during internal fixation of proximal femoral fractures. These include encouraging the use of powered instruments under image-intensifier guidance, maintaining the leg in neutral with reduced traction, and keeping the drill bit sharp.

Another systematic review from 2015 investigated the incidence of vascular injury during total hip arthroplasty. The authors described 138 vascular injuries in 124 patients, mostly affecting the common femoral artery (23%) and with the most prevalent mechanism being laceration. However, there was no association between the type of blood vessel injured and surgical approach. The main contributing factors appeared to be aggressive medial retractor placement and injury from screw fixation of the acetabular component. Although not explored in depth during this review, it is important to recognize that the surgeon’s (and assistant’s) knowledge of anatomy and correct retractor placement is vital to reducing the chance of iatrogenic injury. Other retrospective studies looking at arterial injury in total hip/knee arthroplasty found an incidence of 0.13% and 0.1%, both noting direct laceration as a cause. In addition, a survey sent to vascular surgeons in the U.S. demonstrated 19 instances of popliteal artery injury during total knee arthroplasty (12 cases of which were due to direct injury). However, the response rate was low, with only 13 replies from 190 survey recipients, so underreporting is extremely likely.

Smith et al. conducted a retrospective review of 10 cervical decompression procedures performed by 9 spinal surgeons. They found that the incidence of iatrogenic injury to the vertebral artery was 0.5%, with all cases related to intraoperative motorized power-tool instrumentation. Four of these patients also suffered postoperative neurological deficit, which occurred as a direct result of the arterial injury. The authors give recommendations for avoiding injury, such as dissecting the bone/disc material as close to the midline as possible or using imaging to determine vertebral artery position and artery proximity to the lesion.

A retrospective multicenter study looking at iatrogenic injury to the vertebral artery demonstrated an overall incidence of 0.08%, with C1-2 posterior fixation having the highest incidence (1.35%). This study involved 15,582 surgeries in 21 centers, and 77% of the cases showed no permanent neurological deficit.

**Novel Methods for Reducing Damage When Using Orthopaedic Power Tools**

The range of robotic systems in surgery is increasing, with numerous systems developed in the last decade to overcome the inaccuracy of manually navigating orthopaedic tools. The benefits of robotic systems include increased safety and a reduced rate of iatrogenic injuries.

Oscillating saws have the potential to cause soft-tissue damage during total knee arthroplasty, and Cartiaux et al. showed that using robotic navigation in conjunction with these tools has the potential to significantly decrease iatrogenic injury compared with freehand techniques.

Another study looked at robotic-assisted cervical transpedicular screw placement, finding that it achieved 98.8% accuracy in Kirchner wire placement and improved functional outcomes compared with non-robotic-guided placement. Another study of robotic-assisted pedicle screw placement also found increased accuracy in spinal surgery when compared with fluoroscopy-guided techniques.

Shim et al. tested a compact robotic drill prototype using an automated “rolling friction mechanism,” which allowed safe removal of the drill tip in an emergency while not compromising the speed and accuracy of the drill.

Piezoelectric surgery uses high-frequency ultrasonic vibrations to cut bone tissue. When compared with conventional drilling, vibrational drilling aims to reduce force, torque, and thermal damage to bone. This is thought to be possible because of the increased precision and reduced bleeding due to a “microcoagulation” effect. For instance, it has been demonstrated that an elliptical vibration-assisted oscillating saw can minimize required cutting force and also reduce risk of soft-tissue injury. This technique can be applied safely in a low-field MRI environment and is a valuable method to facilitate transcortical bone biopsy, but there is minimal comparison of this and traditional methods in the literature. In contrast, another study evaluated the use of ultrasonic bone curette compared with a high-speed drill in spinal surgery. Both groups experienced dural tears, and this study concluded that one method was not significantly better than the other. The suggested optimal settings for vibrational drilling were noted in 1 study to be a drill speed of 1,000 rpm with a frequency of 20 kHz.

**Methods of Detecting Damage When Using Orthopaedic Power Tools**

To minimize iatrogenic injury, it is important to easily and rapidly identify when injury occurs intraoperatively. One novel example includes the use of a spectroscopy device integrated into a power drill to detect the bone-tissue boundary when drilling holes for intramedullary nailing. This helps to reduce breaching of the periosteum and unintentional soft-tissue injury.

The use of methods providing real-time feedback is increasing. Bolger et al. used an electrical conductivity device to detect iatrogenic spinal pedicle perforation. In 1 multicenter study, it demonstrated a sensitivity of >98% in the detection of breaches, 52% more when compared with the surgeon alone. Similarly, a systematic review of intraoperative somatosensory-evoked potential and transcranial motor-evoked potential methods in cervical spine surgery showed a high sensitivity/specificity for both (22% to 100%/100%, and 78% to 100%/100%, respectively). Another study used stimulus-evoked
Electromyography to detect proximity to neural structures during iliosacral screw placement. Four of 51 screws were redirected as a consequence of the technique, and all patients had normal neurological status postoperatively65. Other novel methods include the use of a bioimpedance-sensing drill to successfully differentiate between cortical and cancellous bone56 and acoustic-emission signal analysis, which is based on the principle that different bone types will produce varying sound signals when being drilled56.

Recommendations for Power-Tool Settings

With such a wide range of equipment, imaging modalities, and device settings available, there can be much heterogeneity in tools and settings used during orthopaedic procedures. Several papers have specific recommendations for power-tool equipment settings to help reduce the risk of iatrogenic injury.

With regard to drill bits, several papers agree that blunt drill bits cause higher damage to bone than sharp bits64,65, with 1 study demonstrating significant differences in plunging depth when sharp or blunt drill bits are used6. Smooth pins have also been shown to reduce the risk of overdripping compared with threaded pins and can reduce iatrogenic injury in the form of tissue entanglement66.

Two studies looked at dual motor drilling. Unlike use of a conventional drill, this involves a second motor that retracts an attached sleeve at a set rate, accurately advancing the drill bit, and measures the drill bit’s energy expenditure and the distance drilled, which is continuously communicated to the surgeon. Gilmer and Lang1 looked at a dual motor drill for real-time measurement of torque, depth, and bone density. They found that this tool could accurately determine these parameters and, thus, give indications of screw pull-out force and cortex boundaries to prevent screw stripping and overpenetration. The second study showed a mean plunging distance of <1 mm using a dual motor drill and found that there was no difference between novice and experienced surgeons using this technique6. It should be noted, however, that both were preliminary studies involving artificial bone specimens and the clinical applicability of the tool would need to be validated in vivo. Other methods in the literature on detecting real-time feedback of bone conditions included the use of laser displacement sensors in a laboratory study66.

Conclusions

Although iatrogenic injury in orthopaedic surgery has been described in the literature, it likely is vastly underreported. Despite this, it is important not to overlook the role of power tools in contributing to patient harm and techniques for reducing injury. Such methods should be considered in terms of equipment factors (e.g., drill speed, intraoperative imaging, use of robotic guidance), patient factors (e.g., anatomical variance, safe zones), and surgical factors (e.g., tools to increase haptic feedback, simulation training, and knowledge of critical anatomy).

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