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(54) ROBOTICALLY CONTROLLED WATER JET CUTTING

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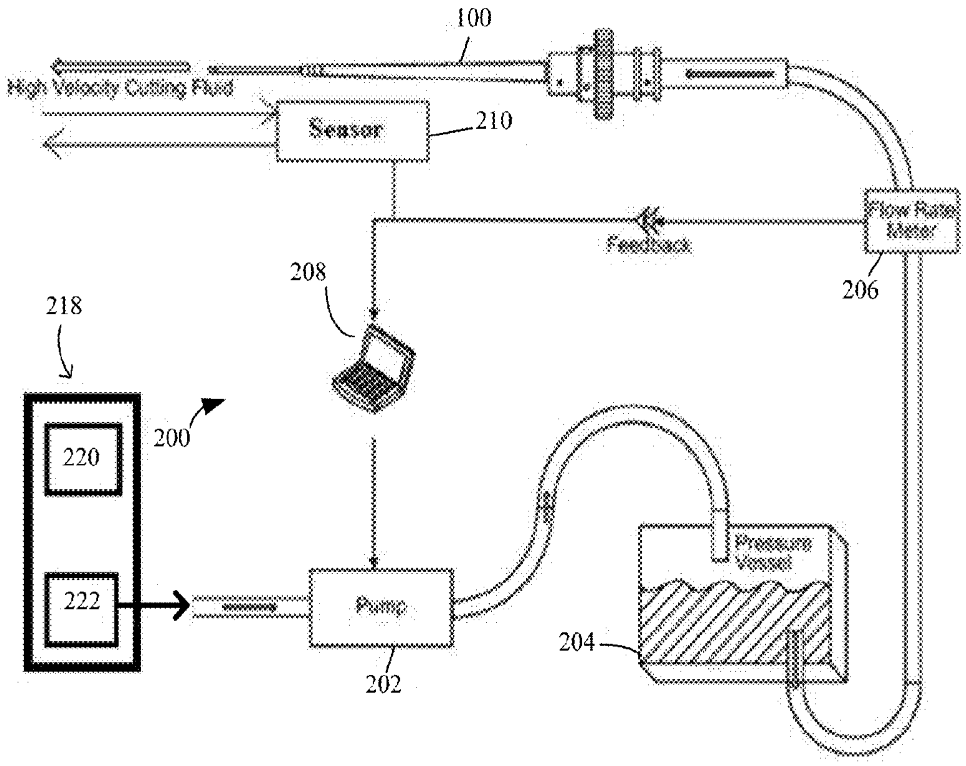
(57) **ABSTRACT**

A cutting system includes a material removal tool having a fluid nozzle with an adjustable diameter, a workpiece including a target shape for removal, and a controller operable to adjust the diameter of the nozzle to vary fluid flow and control an amount of material removed by the material removal tool. The controller is adapted to adjust the nozzle to vary the fluid flow based on a position of the nozzle and workpiece data preoperatively obtained from the workpiece via a continuous feedback loop. A method of cutting a bone is also provided.



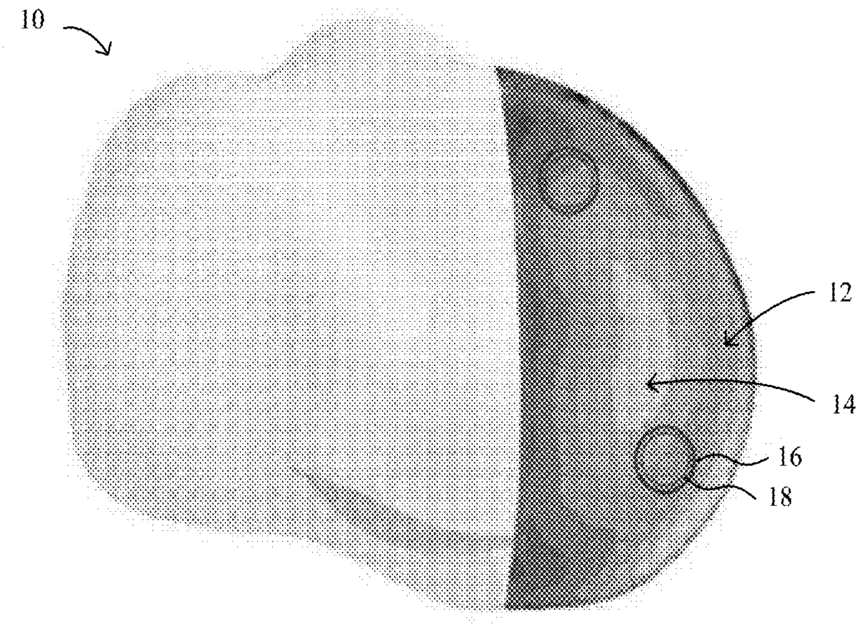


FIG. 1

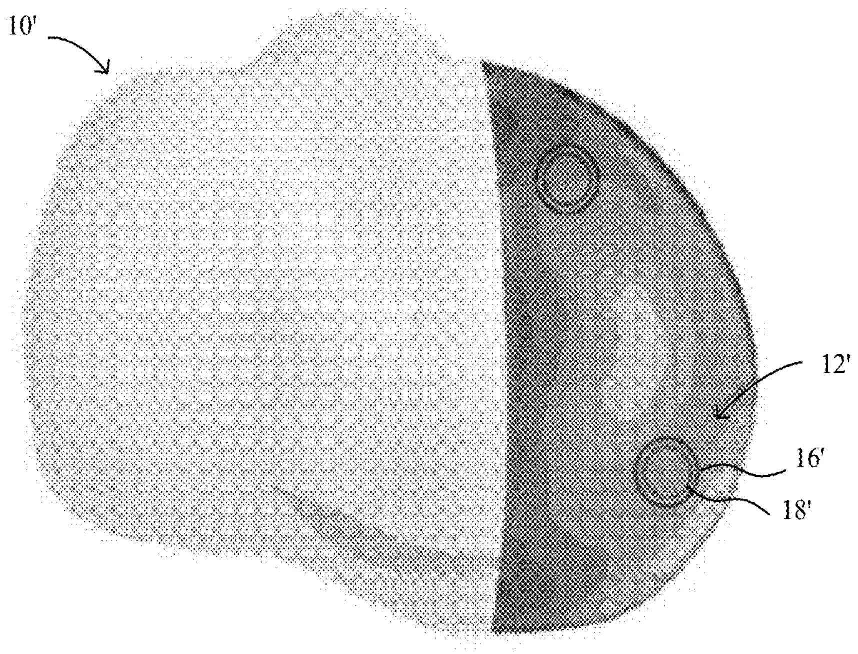


FIG. 2

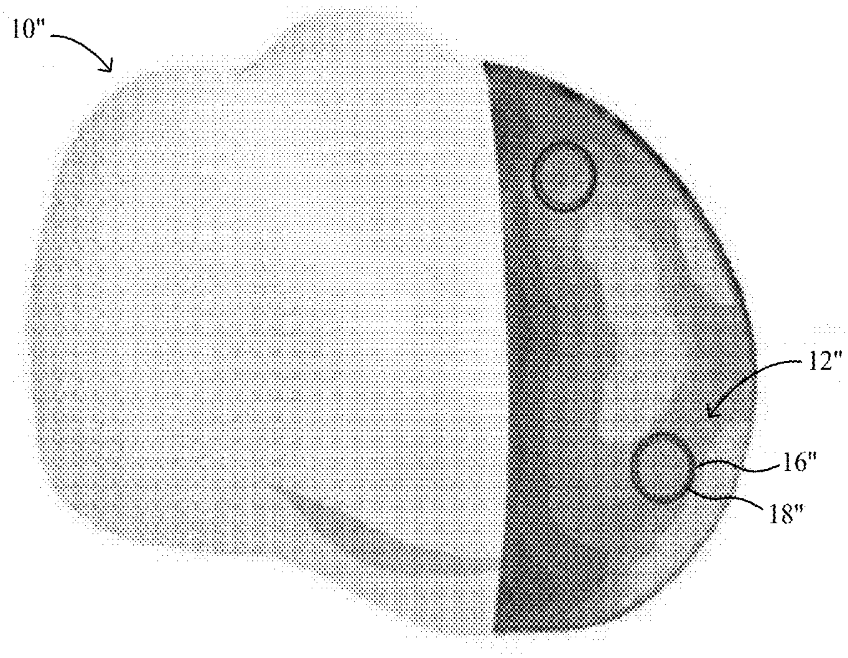


FIG. 3

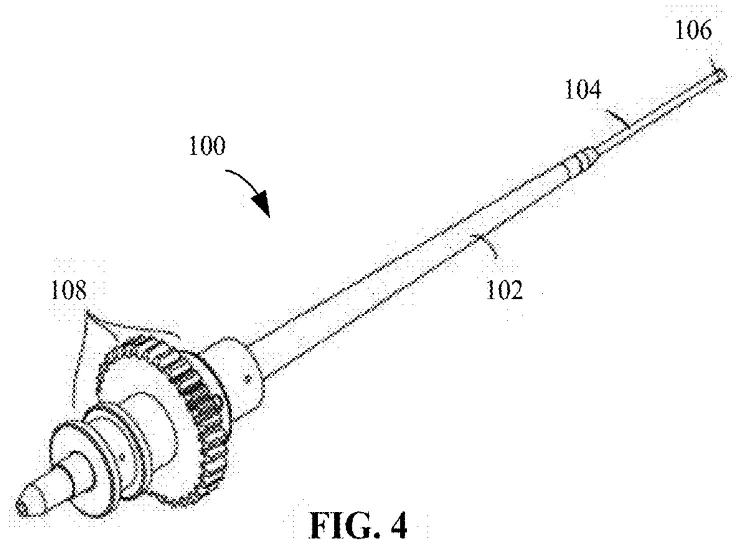


FIG. 4

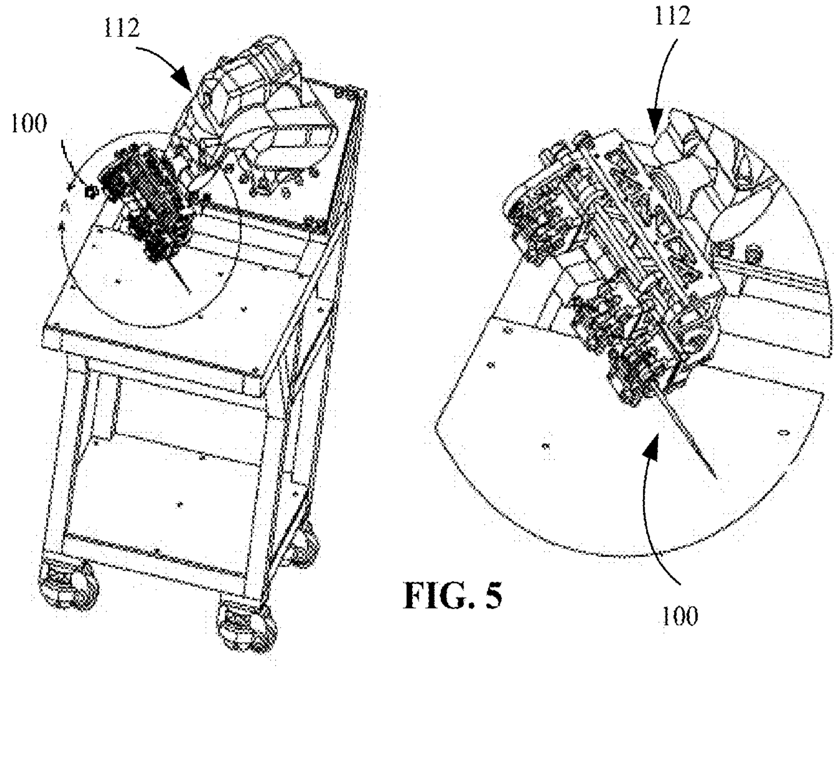


FIG. 5

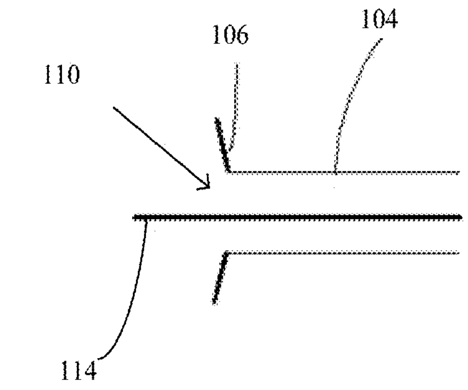


FIG. 6A

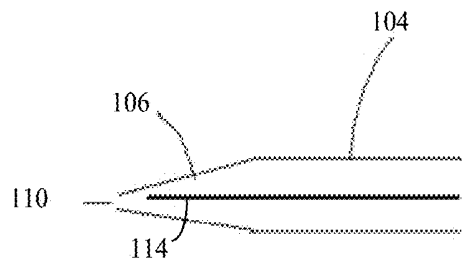


FIG. 6B

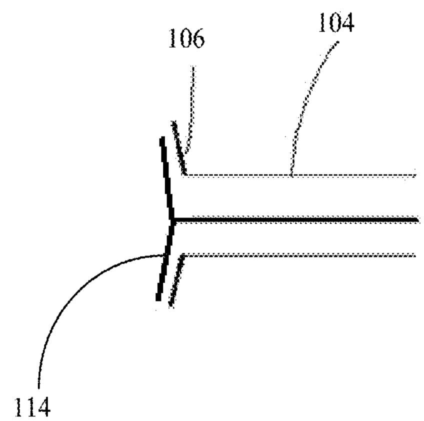


FIG. 6C

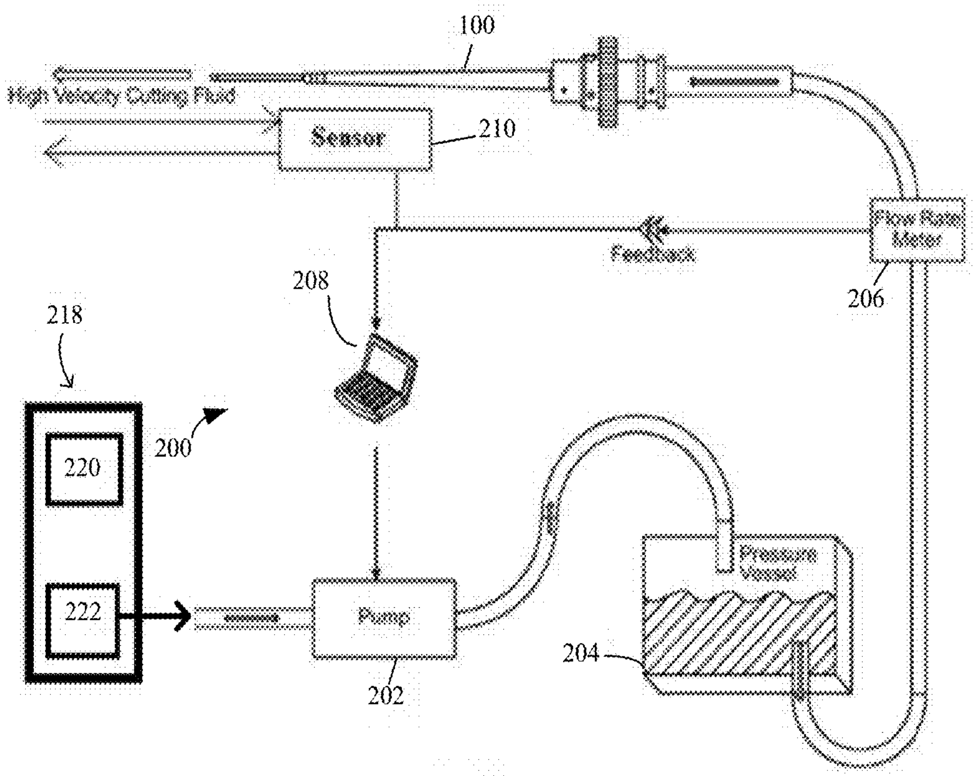

100
High Velocity Cutting Fluid
Sensor
210
Flow Rate Meter
Feedback
206
208
218
200
220
222
Pump
202
Pressure Vessel
204

FIG. 7A

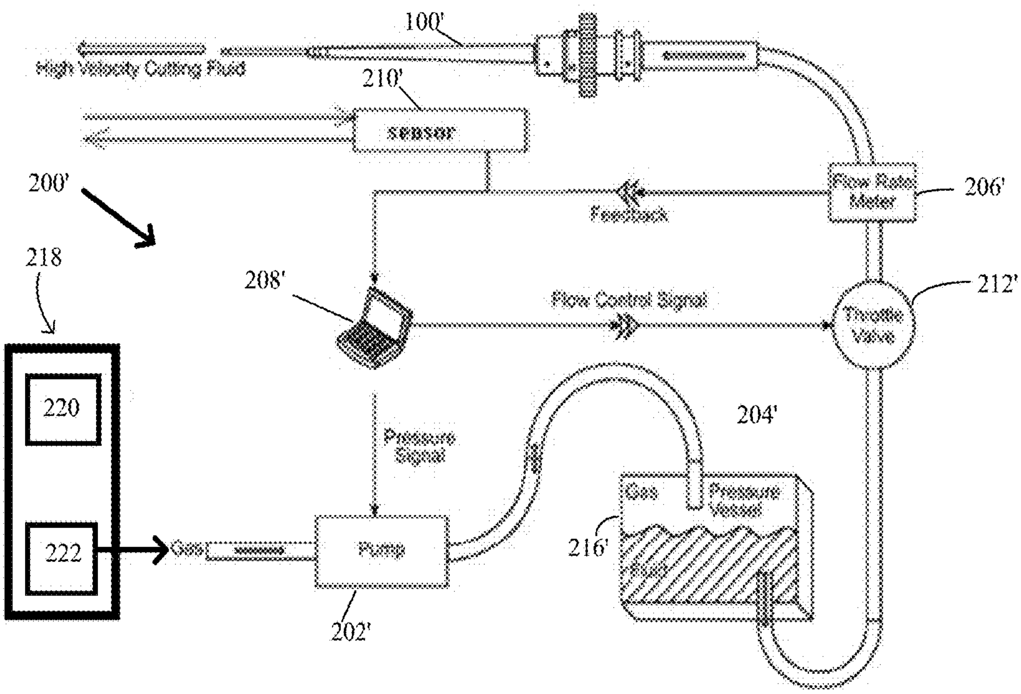

100'
High Velocity Cutting Fluid
210'
sensor
200'
206'
Flow Rate Meter
Feedback
218
208'
Flow Control Signal
212'
Throttle Valve
220
204'
Pressure Signal
Gas
Pressure Vessel
216'
222
Gas
Pump
202'

FIG. 7B

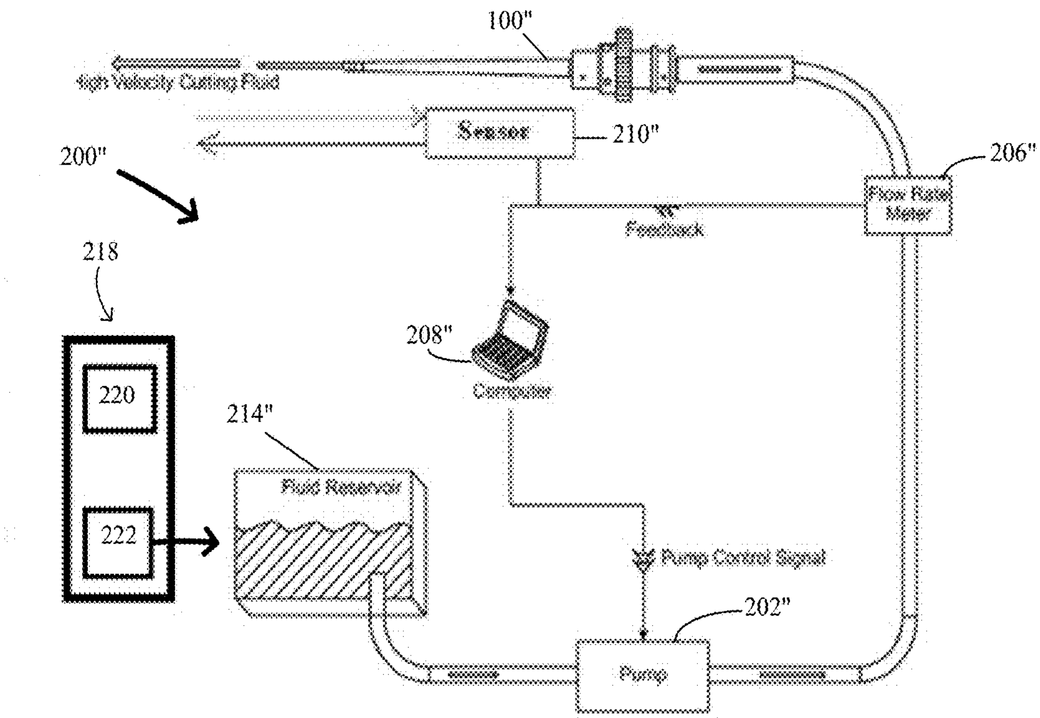

100"
High Velocity Cutting Fluid
Sensor
210"
200"
206"
Flow Rate Meter
Feedback
218
208"
Computer
220
214"
Fluid Reservoir
222
Pump Control Signal
202"
Pump

FIG. 7C

ROBOTICALLY CONTROLLED WATER JET CUTTING

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of the filing date of U.S. Provisional Patent Application No. 62/643,393 filed Mar. 15, 2018, the disclosure of which is hereby incorporated herein by reference.

FIELD OF THE INVENTION

[0002] The present invention generally relates to water-jet cutting tools for bone resection, and more particularly to a system and method for controlling the water-jet cutting tools.

BACKGROUND OF THE INVENTION

[0003] In cementless orthopedic procedures, robust ingrowth is one key element to long term implant stability and performance. Biologic ingrowth requires sufficient stability of the implant with respect to adjacent bones and/or tissues particularly during the first 6-8 months after implantation. During this time, bone growth onto a roughened, or into a porous surface may only occur if the implant is held in a generally stable position, relative to the bone.

[0004] Since bone is heterogeneous and bone properties including bone density, porosity, and elastic modulus, for example, vary throughout the thickness of a particular bone, especially from the hard cortical bone to the spongy cancellous bone surrounded by the cortical bone, the success of fixation is generally dependent upon the specific implant and the properties of the bone that engage fixation features of the implant. As is disclosed in U.S. Pat. Pub. No. 2015/0119987, assigned to Applicant and incorporated herein by reference in its entirety, implant stability can be improved by designing the fixation features of the implant based on a preoperative determination of the particular bone properties that the fixation features will engage upon implantation. Although this implant specific design technique has proven successful in reducing micro-motion, stability of the implant is limited, in part, by the accuracy of the system preparing the bone resection.

[0005] Cemented and revision surgeries could also benefit from a more precise system. Particularly, a system capable of precisely controlling the depth of a cut to create particular cement curing pockets.

[0006] Prior to performing an implantation procedure, for example, a knee, hip, or shoulder replacement, a surgeon must resect a target bone using a working cutting tool, e.g., a saw, a drill, an energy beam such as a laser beam or an electron beam. Soft tissue surrounding the target site is often susceptible to damage when these traditional cutting tools are utilized, either from direct contact with the cutting tool, or excess heat emitted from the cutting tool. As a result, various retracting/protecting devices are required for shielding ligaments and soft tissue adjacent a cutting site. These devices, which require fixation to anatomical structures, complicate and/or lengthen the time of the procedure, and thus, increase the likelihood of human error. Moreover, excess heat can lead to bone necrosis, preventing proper bone ingrowth, which is vital to implant fixation, and particularly, cementless fixation. Furthermore, broaching, tamps, and form tools prepare cancellous bone by compacting the bone. When bone is compacted along a longitudinal axis, complications such as embolisms may arise.

[0007] Thus, there is a need for further improvements to the systems and methods of cutting bone, and in particular, for safely and efficiently resecting a bone and promoting bone ingrowth. Among other advantages, the present invention addresses these needs by providing a precise fluid jet cutting system configured to continuously control fluid pressure to minimize damage to the surrounding soft tissue and prevent the bone from overheating during cutting.

SUMMARY OF THE INVENTION

[0008] The fluid cutting system disclosed herein is particularly advantageous in cutting bone prior to a cementless implant procedure as the system minimizes, if not alleviates, several of the previously mentioned drawbacks associated with traditional saw and laser cutting. Specifically, fluid cutting systems are capable of creating a more precise and reproducible cut, especially when cutting a curved trajectory normal to a surface, than traditional saw or laser cutting systems. The fluid jet also keeps a cutting region of the bone cool during cutting, and therefore, greatly diminishes the risk of bone necrosis.

[0009] As is explained in detail hereinafter, the system is configured to control fluid cutting pressure via a continuous feedback loop such that a minimum pressure sufficient to cut through a particular section of bone can be utilized. By controlling fluid jet pressure in this manner, the depth of the cut can be precisely controlled to minimize damage of the soft tissue surrounding the cutting site such that fewer, if any, retracting/protecting devices are required. By adjusting the fluid nozzle, the system can direct the fluid radially outward, relative to a longitudinal axis of the bone, thus reducing the likelihood of an embolism arising from compacting bone along a longitudinal axis of the bone. The adjustability and versatility of the present system replaces the need for the use of numerous instruments, trials, and size specific cutting tools.

[0010] In one embodiment, the cutting system includes a material removal tool having a fluid nozzle with an adjustable diameter, a workpiece including a target shape for removal, and a controller operable to adjust the diameter of the nozzle to vary fluid flow and control an amount of material removed by the material removal tool. The controller is adapted to adjust the nozzle to control the fluid flow (i.e. cutting area, shape, and pressure) based on a position of the nozzle and workpiece data preoperatively obtained from the workpiece via a continuous feedback loop. The fluid utilized in the present invention may be water and/or a saline solution including antimicrobial agents, for example.

[0011] The cutting system may further include a sensor for continuously providing cut depth information. The controller is configured to adjust the nozzle to control the fluid flow based upon the cut depth information.

[0012] In a preferred embodiment, the material removal tool is coupled to a robotic arm via a drive mechanism provided on the material removal tool. Alternatively, the material removal tool may be manually operated.

[0013] The continuous feedback loop for controlling the fluid flow further includes at least one of a flow rate meter, a pump, a pressure gauge, and a throttle valve. The system further includes a fluid reservoir adapted for containing a fluid therein. The fluid reservoir is coupled to the material removal tool. The fluid reservoir may be filled with water or a saline solution.

[0014] A method of cutting a bone is also provided herein. The method includes obtaining bone quality data, operating a material removal tool including a nozzle having an adjustable diameter, and controlling the diameter of the nozzle to vary fluid flow based on a position of the nozzle and the obtained bone quality data via a continuous feedback loop. In a preferred embodiment, the material removal tool is coupled to a robotic arm via an instrument drive mechanism such that the nozzle of the material removal tool is spatially moveable relative to the bone. The bone may be a distal end of a femur bone.

[0015] The method may optionally include sensing cut depth information in real-time via a sensor such that the fluid control can be verified and modified if needed based on the cut depth information. The sensor may be an optical sensor or an ultrasonic sensor.

[0016] Tissue quality data, which may refer to bone quality data, being at least one of bone density, porosity, and elastic modulus, is obtained preoperatively. The bone quality data may be preoperatively derived from CT image data. In one particular embodiment, derivation of the bone quality data includes calculating one or more Houndsfield values from the CT image data with a density phantom to calculate real density values from any given scanning machine regardless of the radiology center scanning protocols.

BRIEF DESCRIPTION OF THE DRAWINGS

[0017] The present disclosure will be better understood on reading the following detailed description of embodiments thereof, and on examining the accompanying drawings, in which:

[0018] FIG. **1** is an example of an average bone density profile with a corresponding designed implant preparation;

[0019] FIG. **2** is an example of a bone density profile exhibiting decreased density, and a corresponding implant preparation;

[0020] FIG. **3** is an example of a bone density profile exhibiting increased density, and a corresponding implant preparation;

[0021] FIG. **4** is a perspective view of a fluid jet device according to an embodiment of the present invention;

[0022] FIG. **5** is a perspective view of a robotic arm coupled to the water jet device of FIG. **4**;

[0023] FIG. **6**A is a cross-section view of a nozzle of the fluid jet device of FIG. **4** with the nozzle in a first position and the deflector in a first position;

[0024] FIG. **6**B is a cross-section view of a nozzle of the fluid jet device of FIG. **4** with the nozzle in a second position and the deflector in the first position;

[0025] FIG. **6C** is a cross-section view of the nozzle of the fluid jet device of FIG. **4** with the nozzle in the first position and the deflector in the second position; and

[0026] FIGS. **7**A-**7**C are block diagrams of a water jet system, according to multiple embodiments of the present invention.

DETAILED DESCRIPTION

[0027] Although the disclosure set forth herein focuses on the use of cutting tools to cut and/or shape bone during surgery, it will be understood that the present invention may be used for a wide variety of applications where material is removed from a medium or stock workpiece.

[0028] By taking into account heterogeneous bone properties and preoperatively determining these properties, parameters of a bone resection can be designed to optimize a press-fit connection between a resected bone and an implant, such as an articular implant. An optimized press-fit between the resected bone and an articular implant may, for instance, reduce undesirable qualities, including excess micromotion, or maintain a desirable range for other qualities, including stress transmission and strain. The optimized press-fit is obtained by determining ideal engagement characteristics of fixation features of the articular implants, determining the parameters of a bone resection that would achieve the determined ideal engagement characteristics, and then safely and efficiently resecting the bone in view of these parameters.

[0029] FIG. **1** illustrates a bone having an exemplary average bone density profile **10**. The bone density profile **10** exhibits areas of both relatively low density **12** (indicated by relatively dark shading) and relatively high density **14** (indicated by relatively light shading). FIG. **1** also illustrates an exemplary planned parameter of a bone resection **16** in order to achieve a press fit with a fixation feature having a corresponding shape. Outline **18** represents the size and shape of the fixation feature of the implant. Here, the planned parameter of the bone resection **16** is shown as having a circular cross-section. This particular resection may be made by plunging a rotating burr into the bone to a desired depth. In another embodiments (not shown), the resection **16** may be, for example, ovular in cross-section when viewed in the same plane, and formed if a rotating burr, for instance, is plunged into the bone at a preoperatively planned angle relative to the plane, or any other desirable cross-sectional shape. For instance, a planned parameter may include designing the resection based on preferred clearances and tolerances with particular fixation features that facilitate stability for cementless implants to improve long-term bone ingrowth/ongrowth to the implant.

[0030] FIG. **2** illustrates a bone having an exemplary density profile **10'** exhibiting decreased bone density compared to the bone density profile shown in FIG. **1**. The bone density profile **10'** exhibits increased areas of lower density **12'** in planned fixation feature implant areas relative to bone **10** shown in FIG. **1**. In order to achieve the designed press-fit between the fixation feature and the lower density bone **12'**, the planned parameter of the resection **16'** is adjusted with respect to the shape of the fixation feature shown as outline **18'**. Here, the parameter resection **16'** has a smaller diameter compared to resection **16**, thus increasing the interference between the fixation feature of the implant and the bone.

[0031] FIG. **3** illustrates a bone having an exemplary density profile **10"** exhibiting an increased bone density compared to the bone density profile shown in FIG. **1**. The bone density profile **10"** exhibits increased areas of higher density bone **14"** in planned fixation feature implant areas relative to the bone shown in FIG. **1**. In order to achieve the designed press-fit between the fixation feature and the bone, the parameters of the resection **16"** are adjusted with respect to the shape of the fixation feature shown as outline **18"**. Here, the planned parameter of the resection **16"** is modified to a larger diameter, thus decreasing the interference between the fixation feature and the bone.

[0032] Bone quality data, including bone density, of the heterogeneous bone may be derived from an image (or data relating to an image) of at least one joint. The image (or image data) can be obtained in a variety of manners, including by performing any medical imaging method known in the art, or by obtaining the image data from a collection and/or database. For example, the image data may be obtained by performing a CT scan. Additional suitable imaging methods include MRI, Electrical Impedance Tomography ("EIT"), Dual-Energy X-ray Absorptiometry ("DXA" or "DEXA"), X-ray, ultrasound, and nuclear imaging, for example. The image data may further comprise a combination of one or more different kinds of image data, for instance a composite image data that comprises both CT and MRI image data.

[0033] The image data obtained may correspond to either a single individual or to a population of individuals. For instance, the image data may correspond to a joint of the individual for whom the press-fit is being optimized. In this case, the parameters of the bone resection are determined on a patient-specific basis such that the parameters optimize the press-fit between the individual anatomy and the articular implant.

[0034] Bone quality may alternatively be derived from data representative of a population, for instance, a representative or average data corresponding to a particular population of individuals. The population may represent a class or sub-class of individuals, such as members of an age-range, a gender, a class of individuals who suffer from a particular joint or knee ailment, or any other relevant population. For example, the Stryker Orthopaedics Modeling and Analytics system ("SOMA") is a population-based design environment featuring a large database of bone morphology, including size, shape, density, and inner and outer cortical boundaries, drawn from diverse populations. Such a database may be used, for example, by normalizing a set of data relevant to the patient of interest onto a phantom tissue model. In this way, image data taken from a population may be used to derive the relevant bone quality and to optimize the engagement between the implant and the patient's bone.

[0035] Once the image data of at least one joint is obtained, bone quality information can be derived by a variety of methods for calculating or estimating bone properties from the imaging modalities previously described, including CT, X-ray, MRI, DEXA, etc.

[0036] By way of example, bone density and elastic modulus can be derived from a CT image (or data relating to the image) by correlating CT brightness to bone density and then to elastic modulus using Hounsfield values (also known as CT numbers). Bone density of both the proximal end of the tibia and the distal end of the femur can be calculated from CT brightness values using the following equations:

[0037] A) Proximal Tibia:

[0038] Hounsfield unit to density conversion:

[0039] $p=1.14e^{-4}+(9.16e^{-7})*(CT\#)$, where p is in g/mm^3

[0040] B) Distal Femur:

[0041] Hounsfield unit to density conversion:

[0042] $p=1.39e^{-4}+(1.205e^{-6})*(CT\#)$, where p is in g/mm^3

[0043] The elastic modulus of both the proximal end of the Libia and the distal end of the femur can be calculated from the derived density values by the following equations:

[0044] A) Proximal Tibia:

[0045] Density to modulus conversion:

[0046] $E=(1.2965e^{8})*(\rho^{1.5})$, $0<p<0.001$ g/mm^3

[0047] $E=(3.790e^{12})*(p^{3})$, $0.001<p<0.00173$ g/mm^3

[0048] B) Distal Femur:

[0049] Density to modulus conversion:

[0050] $E=(1.283e^{9})*(p^{1.85})$, $0<p<0.001$ g/mm^3

[0051] $E=(3.790e^{12})*(p^{3})$, $0.001<p<0.00173$ g/mm^3

[0052] The aforementioned models are only exemplary manners of deriving bone property information from the image data of at least one joint. Alternative and additional methods such as those disclosed in U.S. Pat. Pub. No. 2015/0080717, assigned to Applicant and incorporated in its entirety herein, or any other methods known in the art may be employed.

[0053] After bone quality data has been determined, fluid jet **100**, as shown in FIG. **4**, may be operated by a surgeon to cut the bone, for example, to resect planned parameters **16**, **16'**, **16"**. Fluid jet **100** may also be used to remove an implant having a quantified and known density using a traditional saw type cutting technique to make room for a revision implant.

[0054] Fluid jet **100** is particularly advantageous in cutting bone in preparation of a cementless implant fixation procedure as the cutting fluid, which may be water for example, keeps the cutting region cool and prevents bone necrosis. Moreover, in previous studies, water jet cutting has been shown to be more accurate and reproducible than traditional saw cutting during which the blades are susceptible to deflection. It is also contemplated that the cutting fluid could contain a saline solution for fighting bacteria and preventing infection.

[0055] Fluid jet **100** generally includes a body **102**, a hose **104** at least partially disposed within body **102**, a nozzle **106** provided at a distal end of the hose, and an instrument drive coupling mechanism **108** provided at a proximal end of the body. The drive coupling mechanism is configured to couple fluid jet **100** to a robotic arm **112** as depicted in FIG. **5**. For example, fluid jet **100** may be coupled to the RIO® robotic system, provided by MAKO Surgical Corp., the da Vinci® Surgical System, provided by Intuitive Surgical, Inc., the Magellan™ Robotic System, provided by Hansen Medical, Inc., Carnegie Mellon's Micron, or John Hopkins University's Steady Hand. In this preferred embodiment, placement of nozzle **106** is optimized by the robotic arm. However, fluid jet **100** may be manually operated in some instances, and therefore, need not include coupling mechanism **108**. If manually operated, fluid jet **100** may instead include a navigation tool for spatial recognition.

[0056] Referring to FIGS. **6**A and **6**B, nozzle **106** is illustrated in more detail. A proximal end of nozzle **106** is pivotally connected to hose **104** such that a diameter of the nozzle opening **110** is adjustable. Specifically, nozzle **106** is moveable between a first position as shown in FIG. **6**A to a second position as shown in FIG. **6**B. The second position being relatively closed compared to the first position. By adjusting the diameter of the nozzle opening **110**, a surgeon will have greater control over parameters such as a fluid cutting area, fluid cutting shape, fluid pressure levels, cut depth, and nozzle orientation. Nozzle **106** may be made from stainless steel or any other suitable medical grade metal or plastic known in the art.

[0057] Nozzle **106** may optionally include an adjustable deflector **114** for directing fluid flow radially outward.

Deflector **114** is moveable between a first position (FIGS. **6**A and **6**B), in the deflector is arranged along, or parallel to, a longitudinal axis of nozzle **106**, and a second position (FIG. **6**C), in which the deflector has pivoted to a position transverse to the longitudinal axis of the nozzle. Deflector **114** may be adjusted from a position parallel to the longitudinal axis of nozzle **106** to a position perpendicular thereto, or any position in between. When deflector **114** is in the first position (e.g., parallel to the longitudinal axis of the nozzle), fluid flow is directed exclusively by nozzle **106**. However, when deflector **114** transitions to the second position, transverse to the longitudinal axis of the nozzle, fluid flow is directed radially outward as a result of the deflector and nozzle **106** acting in concert. Nozzle **106** is thus advantageously capable of performing a variety of cuts, for example, straight or flat cuts and compacting/resecting an interior canal of the bone in the shape of the keel and pegs to support an implant, without compacting the bone along an axis of the long bone.

[0058] FIGS. **7**A-**7**C illustrate exemplary block diagrams of a fluid jet system **200**, **200'**, **200"**. Fluid jet device **100** may be incorporated into any of the fluid jet systems **200**, **200'**, **200"** shown in FIGS. **7**A-**7**C.

[0059] In a preferred embodiment, in which fluid jet device **100** is controlled by robotic arm **112**, further components of fluid jet systems **200**, **200'**, **200"**, as explained hereinafter, are also coupled to robotic arm **112**. In the manually controlled embodiment, fluid jet device **100** may be coupled to other components of fluid jet systems **200**, **200'**. **200"** via an interface.

[0060] With specific reference to FIG. **7**A, depicting fluid jet system **200**, fluid enters a pump **202** and is forwarded to a pressure vessel **204** via a tube. An output of the pressure vessel is forwarded to the flow rate meter **206**. An output of flow rate meter **206** and adjustment of the diameter of nozzle **106** is controlled by a feedback loop including controller **208** and pump **202**. Controller **208** may be a computer, a central processing unit, a microcontroller, ASIC, or other control circuitry. Based upon the preoperatively obtained bone quality information, fluid flow is controlled throughout the cut of a particular section of bone. More particularly, cutting area, shape of the jet, and pressure, for example, of the cutting fluid can be precisely controlled via the continuous feedback loop and the preoperatively obtained bone quality data.

[0061] Since the bone quality data is preoperatively determined, the fluid jet pressure for cutting a particular section of bone can also be preoperatively determined. Advantageously, cutting pressure can be controlled via the feedback loop and the adjustable nozzle **106** such that flow rate meter **206** outputs a minimum pressure sufficient to cut a particular section of bone in order to minimize damage to the surrounding soft tissue. As bone is heterogeneous, the flow rate can be continuously adjusted to maintain minimum sufficient pressure throughout the depth of the cut as different density of bone is encountered.

[0062] Although fluid flow, including fluid pressure and the length of time the pressure must be applied to a particular cutting region to make a cut, can be preoperatively determined from the bone quality data, system **200** may optionally further include a sensor **210** for determining a cut depth. The sensor may be, for example, an ultrasonic sensor or an optical sensor for verifying the cut depth. A signal may be sent from the sensor **210** and reflected off of the cutting region of the bone such that real-time cutting depth information can be transmitted to controller **208** to verify accuracy and/or adjust the fluid flow, if necessary. Since the robot or a navigation system can track the locations at which the nozzle previously 'fired', the closed loop system is also capable of showing the user the resected bone and remaining bone sections, similar to the manual burr and saw tools used in the MAKO system.

[0063] Modified system **200'**, shown in FIG. **7**B, is substantially similar to system **100'** shown in FIG. **7**A, in that the modified system includes a pump **202'**, a pressure vessel **204'**, a flow rate meter **206'**, a controller **208'** and optionally, a sensor **210'**. However, modified system **200'** additionally includes of a throttle valve **212'** that aids in regulating flow rate. In modified system **200'**, throttle valve **212'** receives the control signal from controller **208'**. Furthermore, modified system **200'** may utilize a gas for controlling fluid flow, and thus, may include a pressure gauge **216'** coupled to pressure vessel **204'**.

[0064] Restructured system **200"**, shown in FIG. **7**C, is substantially similar to system **200** shown in FIG. **7**A, in that the restructured system includes a pump **202"**, a flow rate meter **206"**, a controller **208"** and optionally, a sensor **210"**. However, restructured system **200"** removes pressure vessel **204**, **204'** such that the feedback loop is only involves pump **202"**, flow rate meter **206"** and controller **208"**.

[0065] Any of the fluid jet systems **200**, **200'**, **200"** may further include a reclaim system **218**, including a vacuum **220** and a filter **222**. Reclaim system **218** may be either integrated into fluid jet systems **200**, **200'**, **200"** or coupled thereto. Vacuum **220** being capable of suctioning excess water, bone chips/debris, blood and other waste products (collectively debris) from the surgical site during a resection. After removal from the surgical site, the water and debris is then forwarded to filter **222** where the water is separated from the debris. The debris is discarded and the water recycled to the fluid reservoir for re-use in the same surgery.

[0066] In use, system **200**, **200'**, **200"** is capable of cutting various types of bone and is particularly advantageous in preparing bone, for example, for knee, hip, and shoulder implants. After bone quality data, such as bone density, is preoperatively obtained, a specific fluid flow (e.g., cutting area, cutting shape, and fluid pressure) can be calculated for performing each of the desired resections.

[0067] Referring to FIG. **5**, fluid jet **100** is then coupled to robotic arm **112** via instrument drive mechanism **108**. Here, fluid jet **100** is precisely positioned via arm **112** coupled to a robotic system, for example, the RIO® robotic system, provided by MAKO Surgical Corp.

[0068] To perform a knee replacement, a series of flat cuts are made to remove the target bone from the femur using system **200**, **200'**, **200"**. After the planar cuts have been made, nozzle **106** may be adjusted and the bone of the tibia can be radially compacted in the shape of the keel and pegs to prepare the metaphyseal bone to receive the implant.

[0069] To perform a hip replacement, system **200**, **200'**, **200"** may be used to etch through cartilage and bone and subsequently to cut though the femoral neck. Depending on the type of implant being used, cemented or cementless, bone will either need to be compacted or removed to allow for cement integration. By controlling fluid jet **100**, and particularly, the fluid cutting area, shape, and any of the numerous desired resections can be performed. Based in part on the preoperatively obtained bone quality data, and the previously described feedback loops, system **200**, **200'**. **200"** is capable of continuously controlling the fluid flow throughout the depth of a cut. Increasing and decreasing fluid pressure, for example, throughout the cut allows system **200**, **200'**, **200"** to utilize a minimum pressure sufficient to cut through different densities of the heterogeneous bone so as to minimize damage to the ligaments and soft tissue surrounding the cutting site.

[0070] During the resection, vacuum **220** may be placed proximate the surgical site for removing water and debris therefrom. Although reclaim system **218** is advantageous in any surgery, reclaim system **218** is particularly critical in total hip replacements for ensuring that bone chips are removed from the surgical site and not deflected into areas between soft tissue which could result in heterotopic ossification.

[0071] Although the invention herein has been described with reference to particular embodiments, it is to be understood that these embodiments are merely illustrative of the principles and applications of the present invention. It is therefore to be understood that numerous modifications may be made to the illustrative embodiments and that other arrangements may be devised without departing from the spirit and scope of the present invention as defined by the appended claims. For example, features or steps described in relation to one aspect of the disclosure may be combined with features or steps described in relation to another aspect of the disclosure. In addition, although methods may be described as having a number of steps, the steps do not need to be completed in the exact order described, unless explicitly noted otherwise or required by the context of the steps.

1. A surgical cutting system comprising:

a material removal tool including a nozzle having an adjustable diameter,

a registered workpiece including a target tissue shape for removal; and

a controller operable to adjust the diameter of the nozzle to vary fluid flow and control an amount of tissue removed by the material removal tool,

wherein the controller is adapted to adjust the nozzle diameter based on a position of the nozzle and workpiece data preoperatively obtained from the workpiece via a continuous feedback loop.

2. The system of claim **1**, wherein the material removal tool is coupled to a robotic arm via a drive mechanism.

3. The system of claim **1**, further comprising a sensor continuously providing cut depth information and wherein the controller is further adapted to adjust the nozzle to vary the fluid flow based upon the cut depth information.

4. The system of claim **3**, wherein the continuous feedback loop further comprises at least one of a flow rate meter, a pump, a pressure gauge, and a throttle valve for facilitating control of the fluid flow.

5. The system of claim **1**, wherein the workpiece is a bone.

6. The system of claim **5**, wherein the preoperatively obtained workpiece data comprises bone quality data including at least one of bone density, porosity, and elastic modulus.

7. The system of claim **6**, wherein the bone quality data is derived from image data.

8. The system of claim **7**, wherein the image data is CT image data.

9. The system of claim **6**, wherein the bone quality data is derived from a single individual.

10. The system of claim **1**, further comprising a fluid reservoir coupled to the material removal tool.

11. The system of claim **10**, further comprising a saline solution disposed in the fluid reservoir.

12. The system of claim **1**, wherein the nozzle further comprises a deflector for directing fluid flow radially outward.

13. A method of cutting tissue comprising:

obtaining tissue quality data;

operating a material removal tool including a nozzle having an adjustable diameter, the material removal tool coupled to a robotic arm via an instrument drive mechanism; and

controlling the diameter of the nozzle to vary fluid flow based on a position of the nozzle and the obtained tissue quality data via a continuous feedback loop.

14. The method of claim **13**, further comprising continuously sensing cut depth information via a sensor and wherein the controlling step is further based on the cut depth information.

15. The method of claim **14**, wherein the sensor is an ultrasonic sensor or an optical sensor.

16. The method of claim **13**, further comprising deflecting the fluid flow in a radially outward direction.

17. The method of claim **13**, wherein the tissue quality data is obtained preoperatively.

18. The method of claim **13**, wherein the tissue quality data comprises at least one of tissue density, porosity, and elastic modulus.

19. The method of claim **13**, wherein the step of operating the material removal tool comprises spatially moving the nozzle relative to the tissue.

20. The method of claim **13**, wherein the step of obtaining tissue quality data includes calculating one or more Houndsfield values from CT image data.

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摘要(译)

一种切割系统包括：材料去除工具，具有可调直径的流体喷嘴;工件，包括用于移除的目标形状;以及控制器，可操作以调节喷嘴的直径以改变流体流动并控制由所述材料移除的材料量。材料清除工具。控制器适于调节喷嘴以基于喷嘴的位置和通过连续反馈回路从工件预先获得的工件数据来改变流体流量。还提供了一种切割骨头的方法。