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**Behzadi et al.**

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(54) **HYBRID PROSTHESIS INSTALLATION SYSTEMS AND METHODS**

(71) Applicant: **Kambiz Behzadi**, Pleasanton, CA (US)

(72) Inventors: **Kambiz Behzadi**, Pleasanton, CA (US);  
**Jesse Rusk**, Waltham, MA (US)

(73) Assignee: **Kambiz Behzadi**, Pleasanton, CA (US)

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**A61F 2/32** (2006.01)

(52) **U.S. Cl.**

CPC ..... **A61F 2/4609** (2013.01); **A61F 2/32** (2013.01); **A61F 2002/469** (2013.01); **A61F 2002/4619** (2013.01); **A61F 2002/4681** (2013.01); **A61F 2002/4694** (2013.01)

(58) **Field of Classification Search**

CPC ..... **A61F 2/46**; **A61F 2/4609**  
See application file for complete search history.

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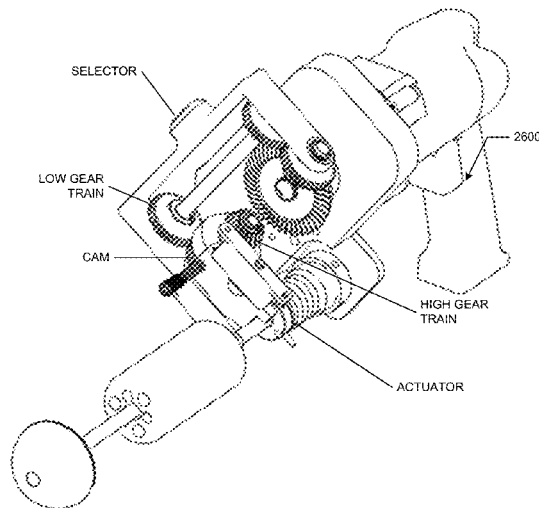
*Primary Examiner* — Christopher J Beccia

(74) *Attorney, Agent, or Firm* — Patent Law Offices of Michael E. Woods; Michael E. Woods

(57) **ABSTRACT**

A system and method for inserting and aligning an acetabular cup in the human pelvic bone, including selectively combining aspects of a vibratory BMD3 and an axially-impacting BMD4, including initially utilizing BMD3 vibratory insertion to partially insert and perfectly align the acetabular cup into the pelvis, and subsequently switching to a BMD4 controlled impaction technique to apply specific quantifiable forces for full seating and insertion, wherein the proven advantages of the vibratory insertion prototype with the advantages of the controlled impaction prototype are combined in a single device.

**6 Claims, 29 Drawing Sheets**



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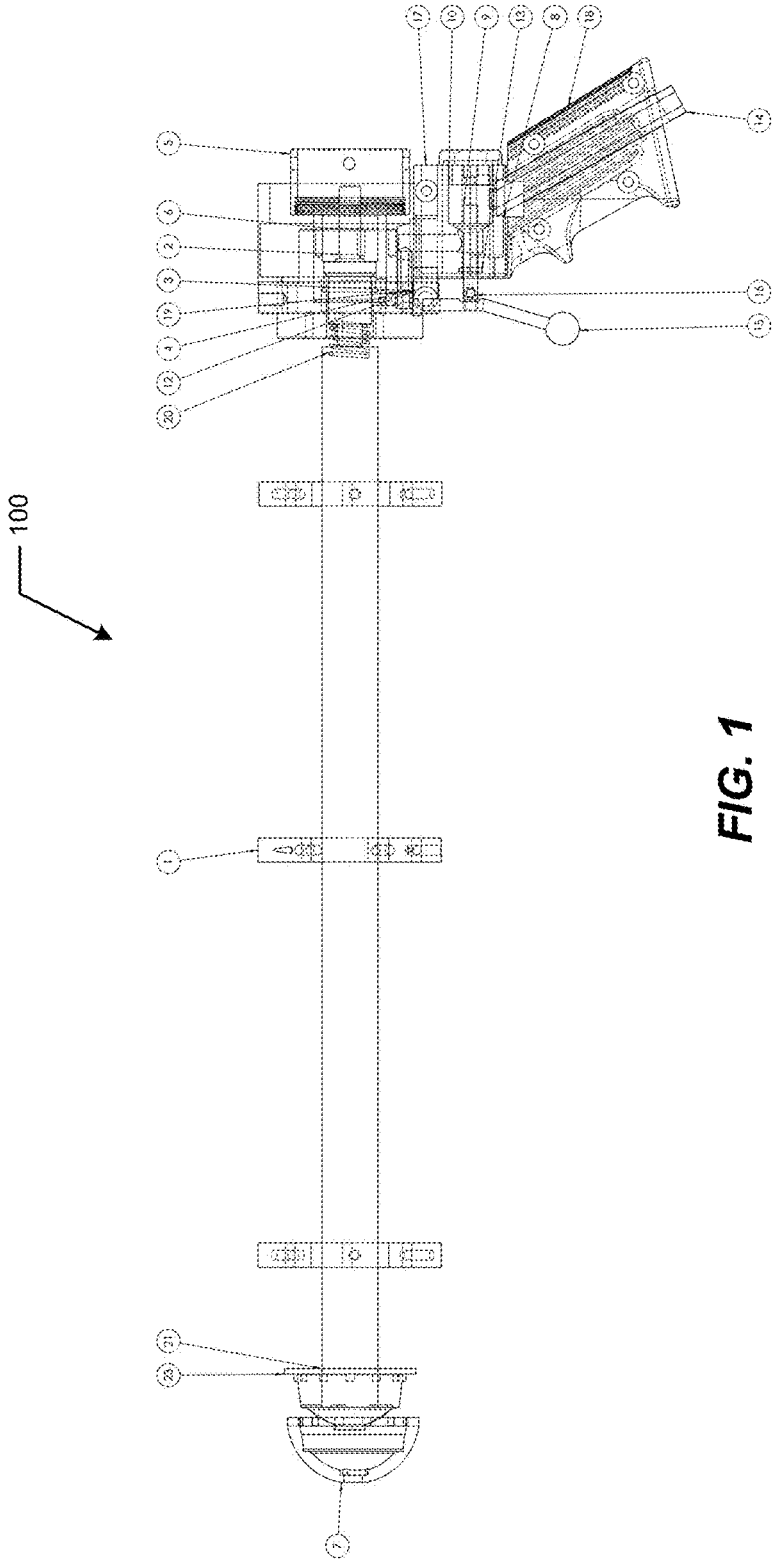


FIG. 1

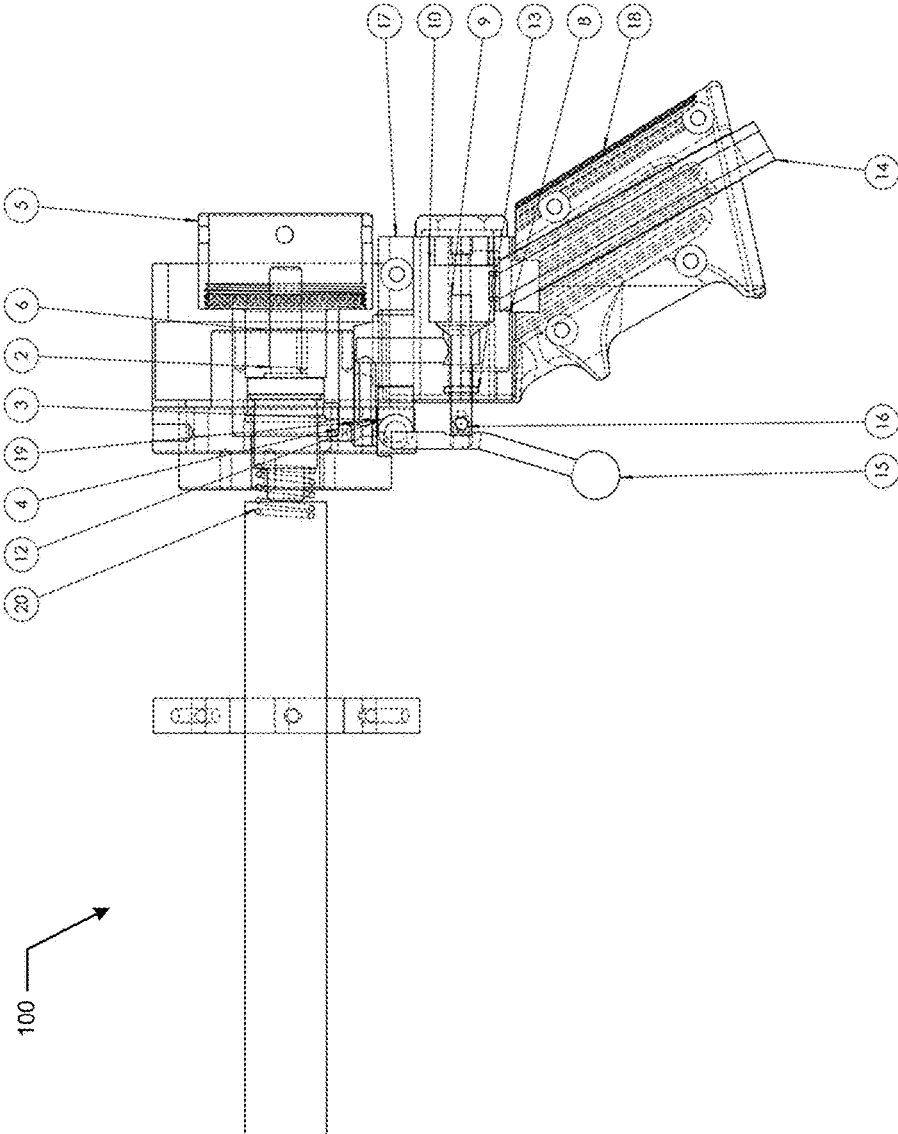


FIG. 2

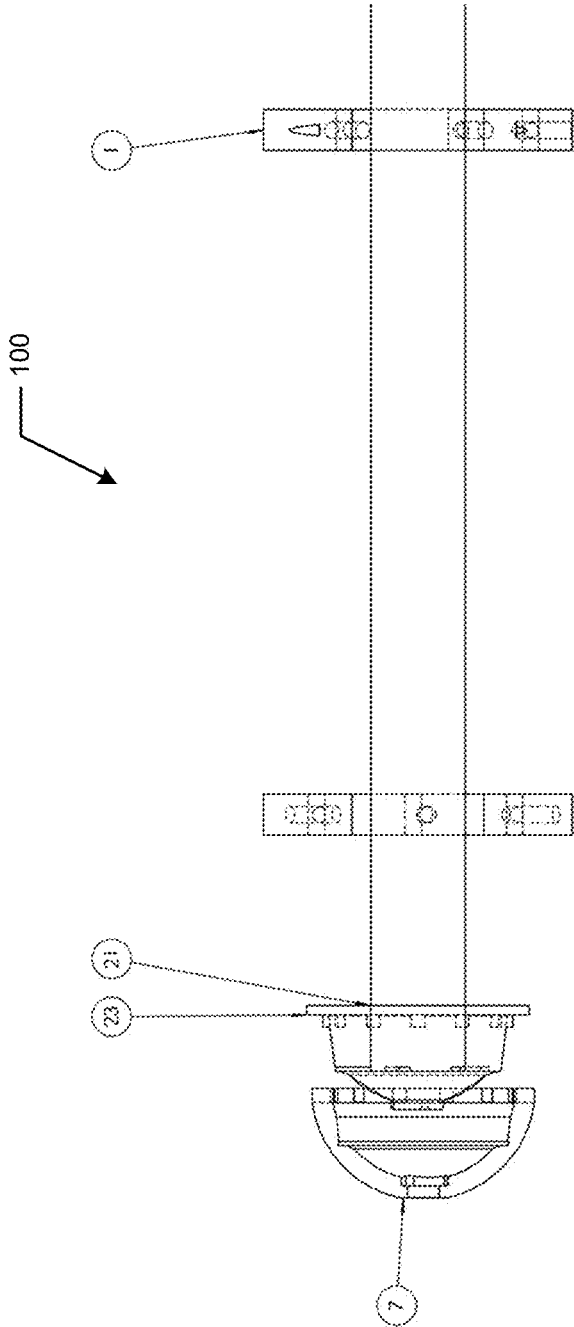


FIG. 3

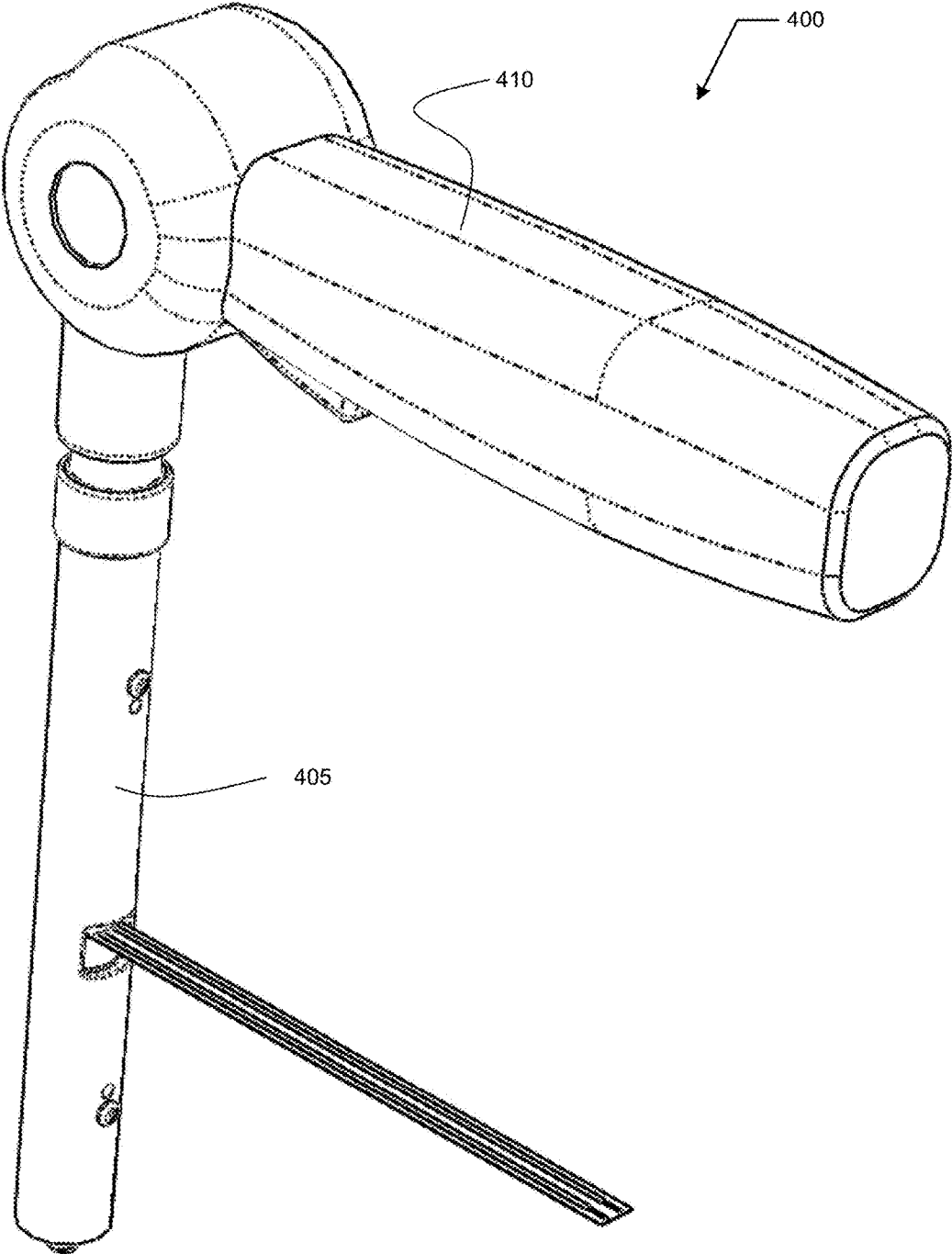


FIG. 4

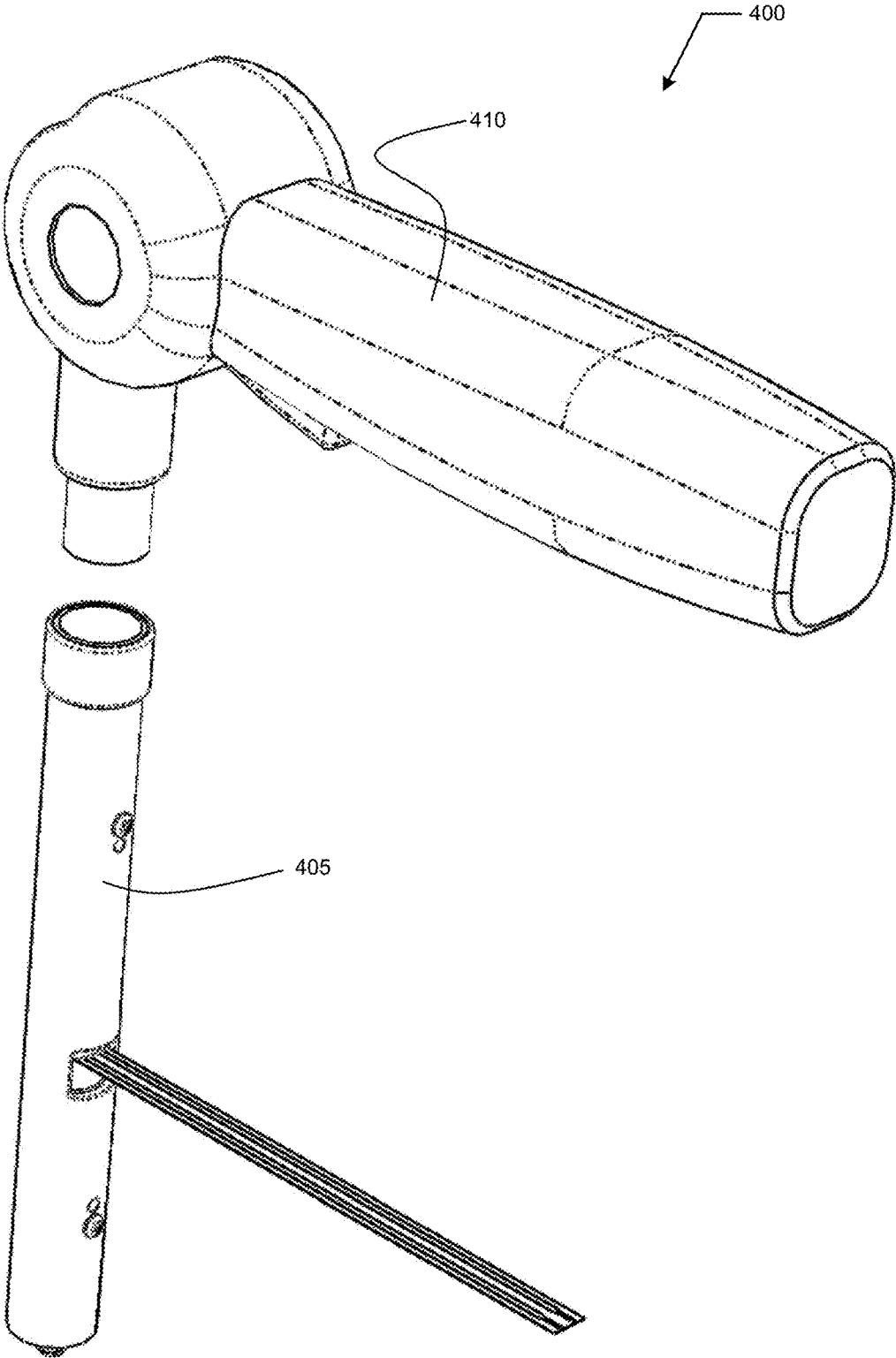


FIG. 5

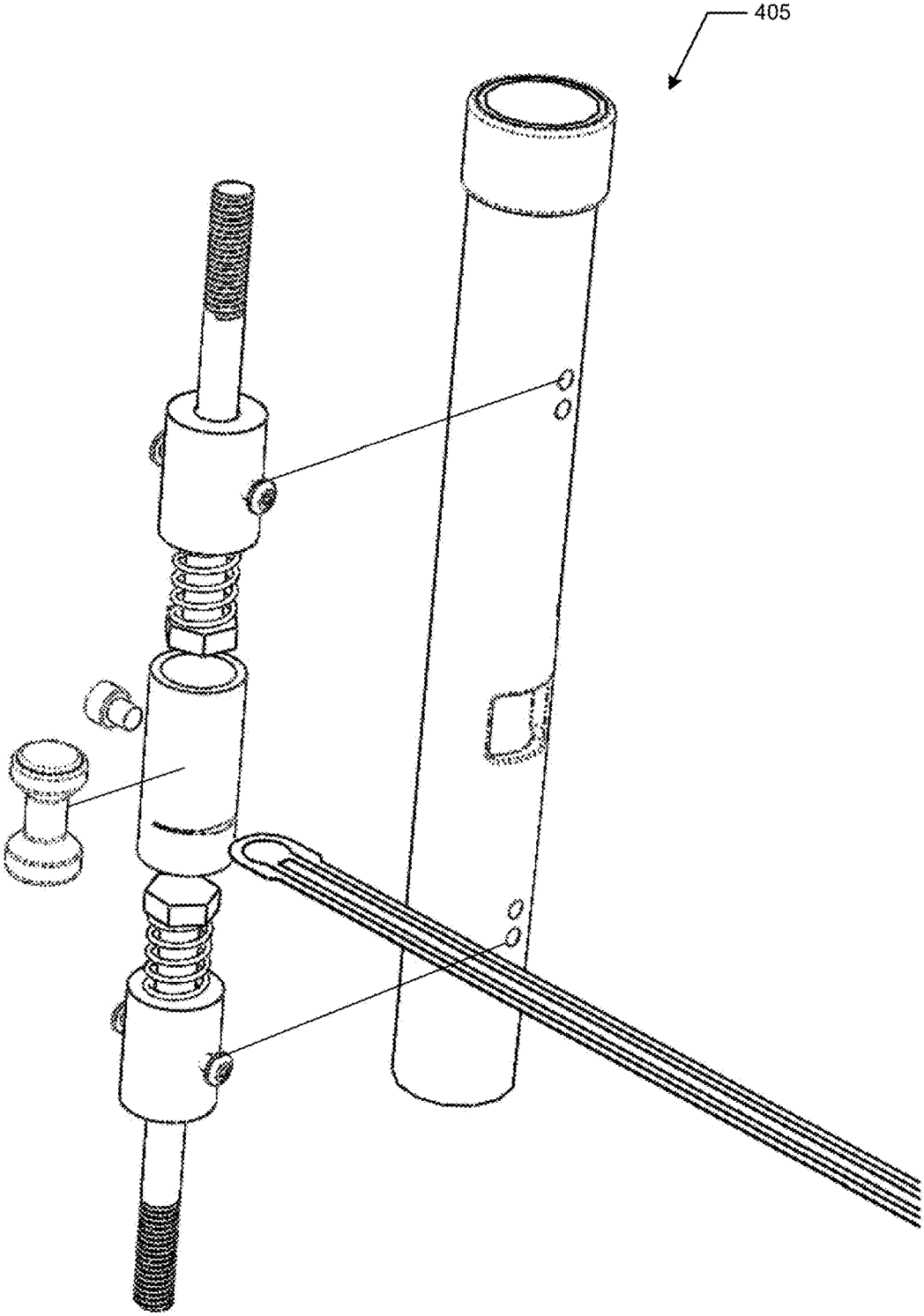


FIG. 6



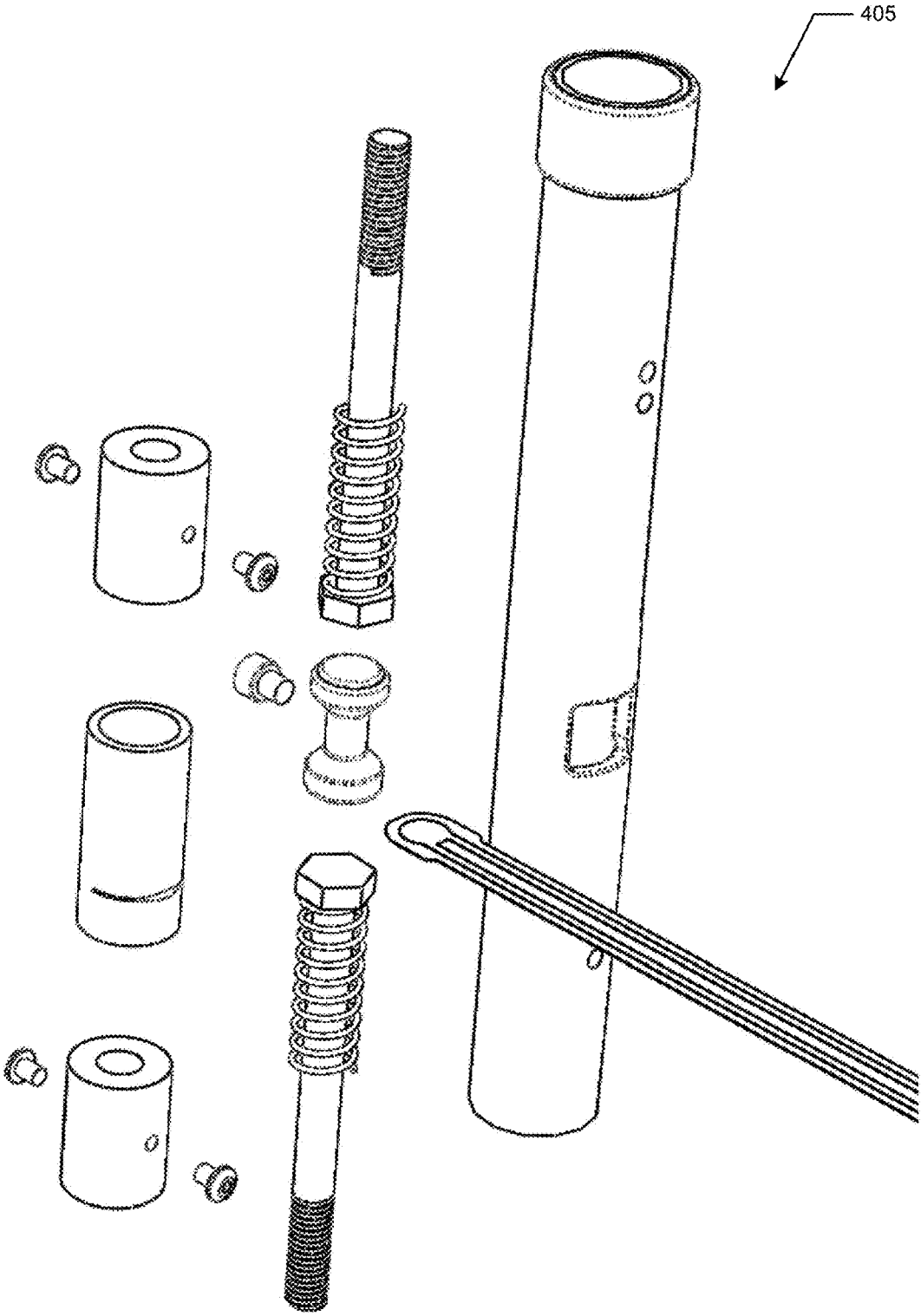


FIG.7

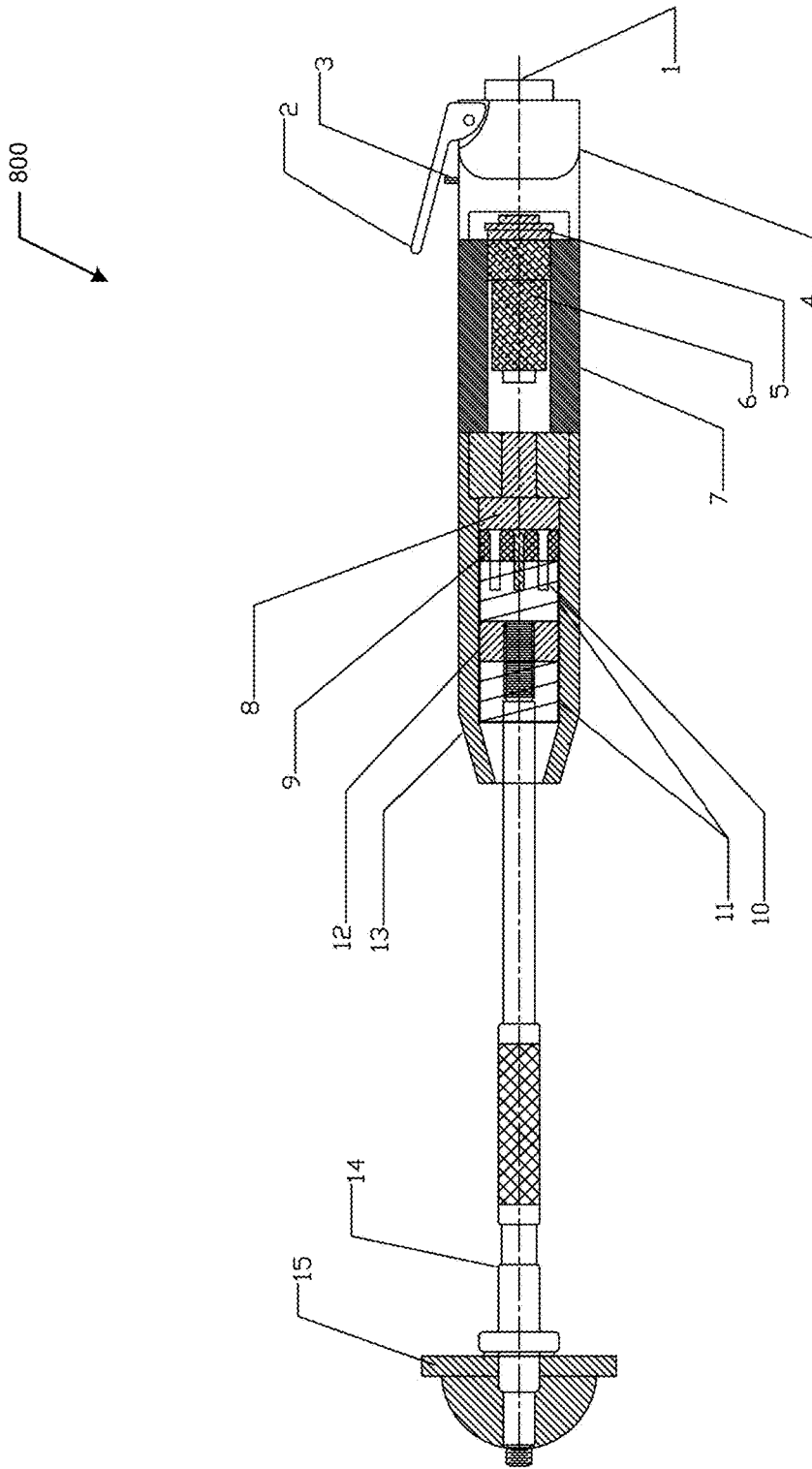


FIG. 8

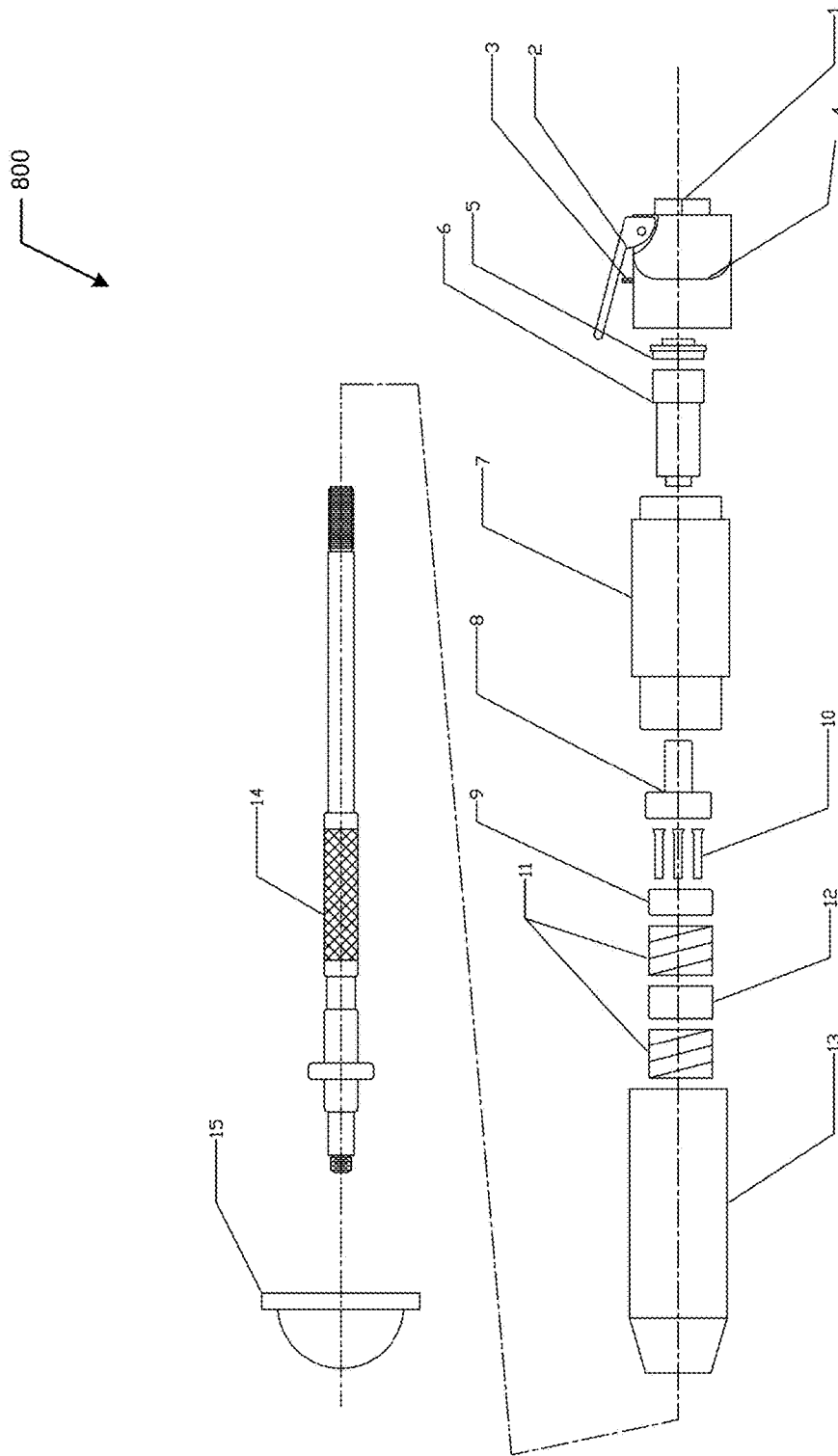


FIG. 9

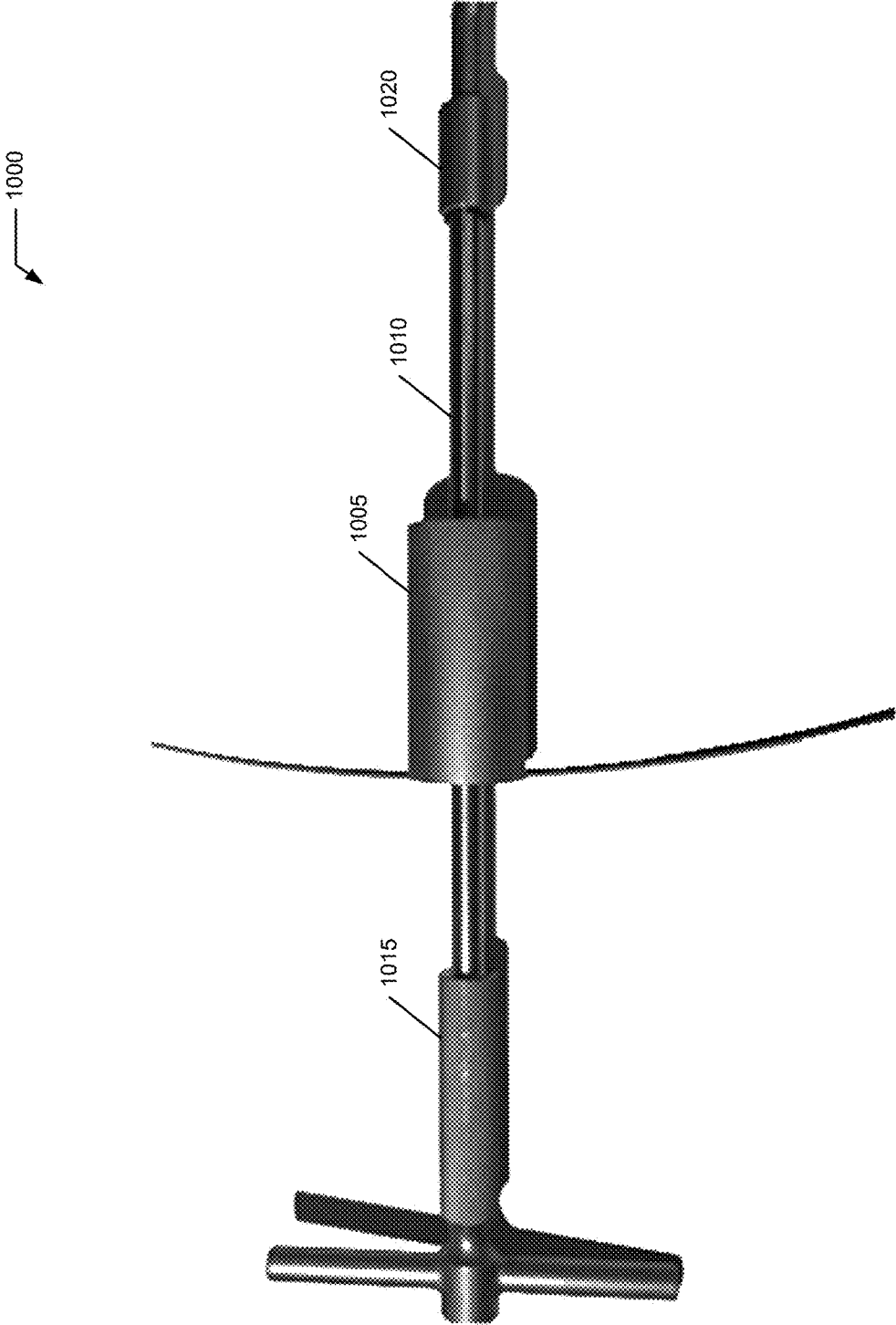


FIG. 10

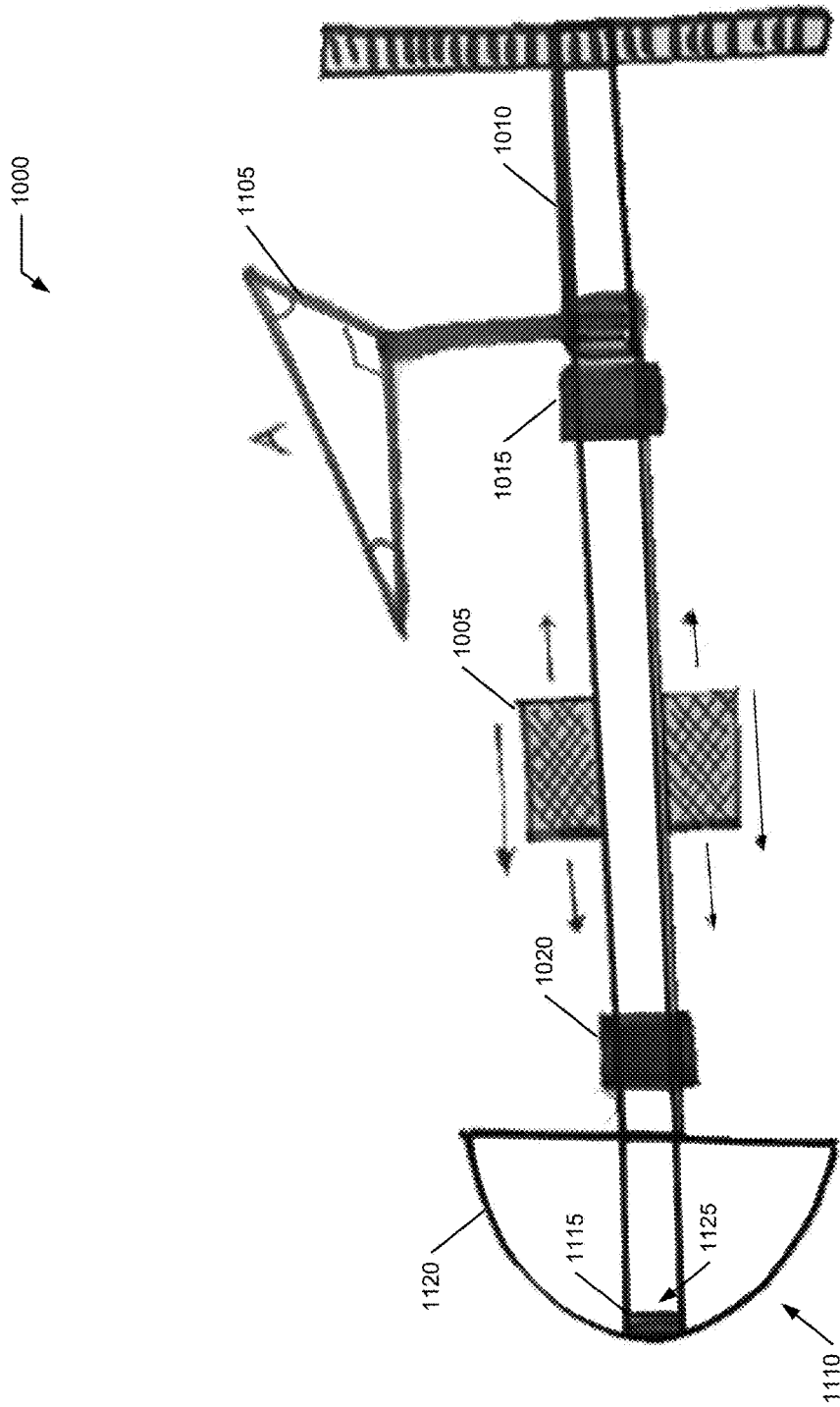


FIG. 11

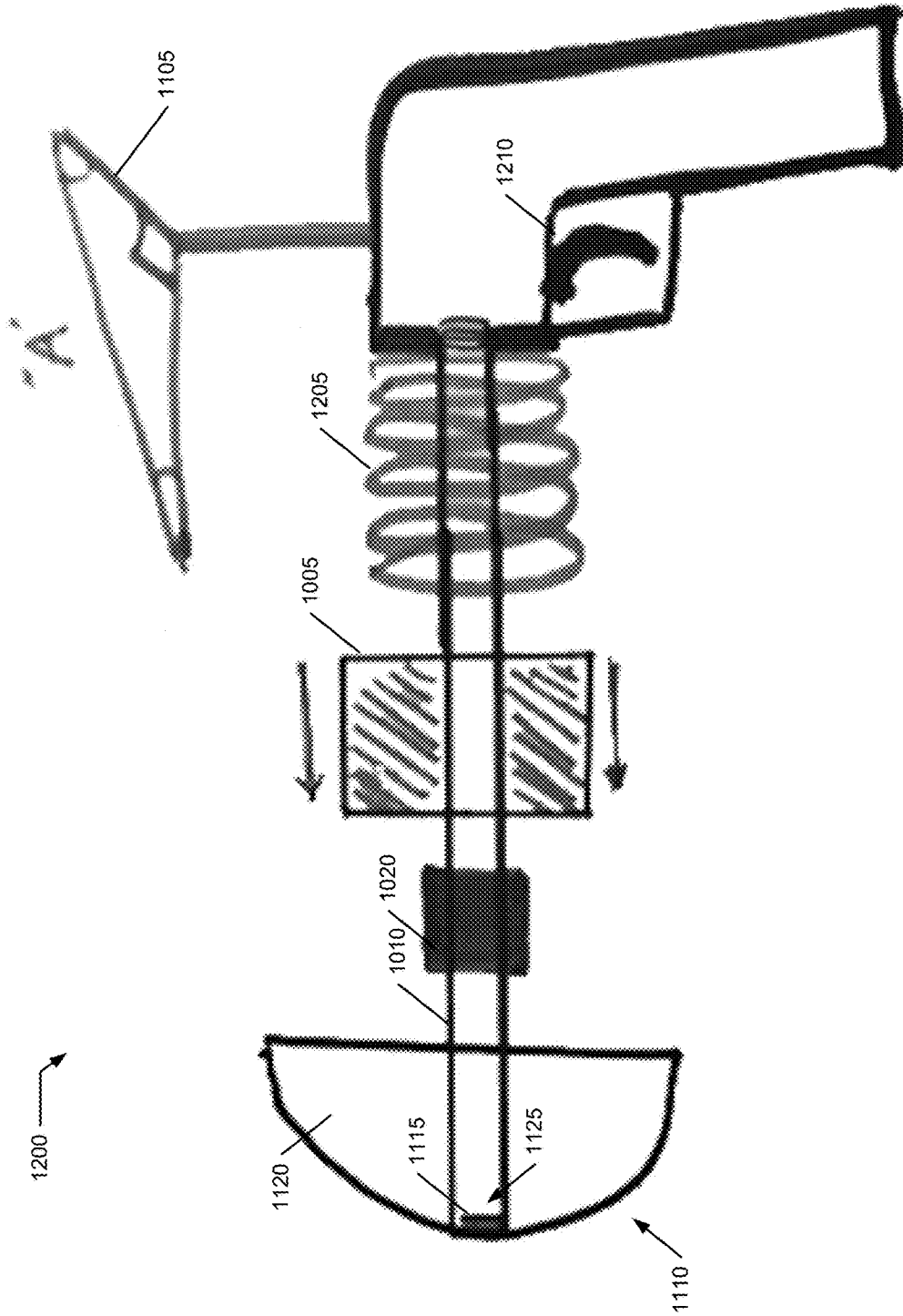


FIG. 12

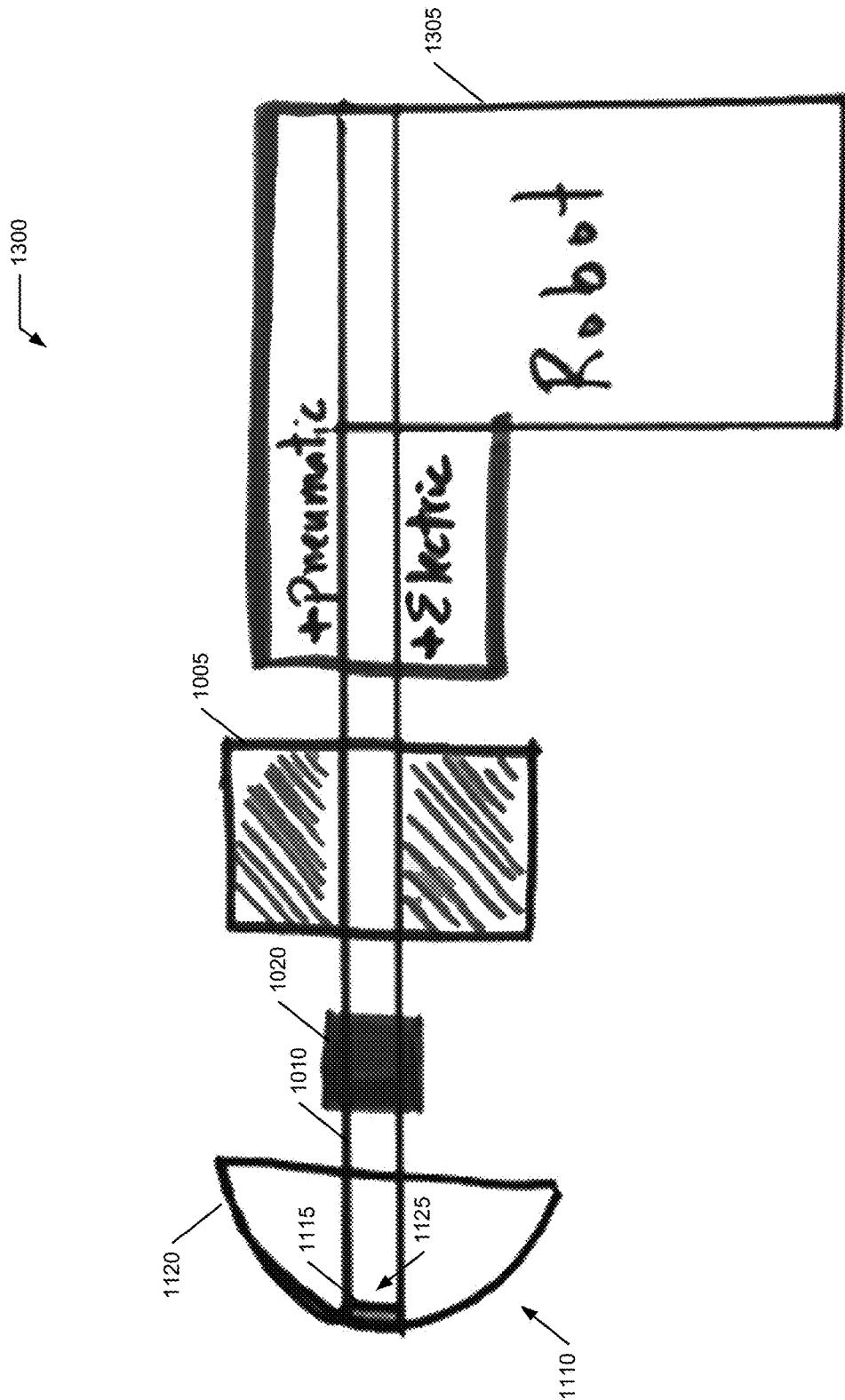


FIG. 13

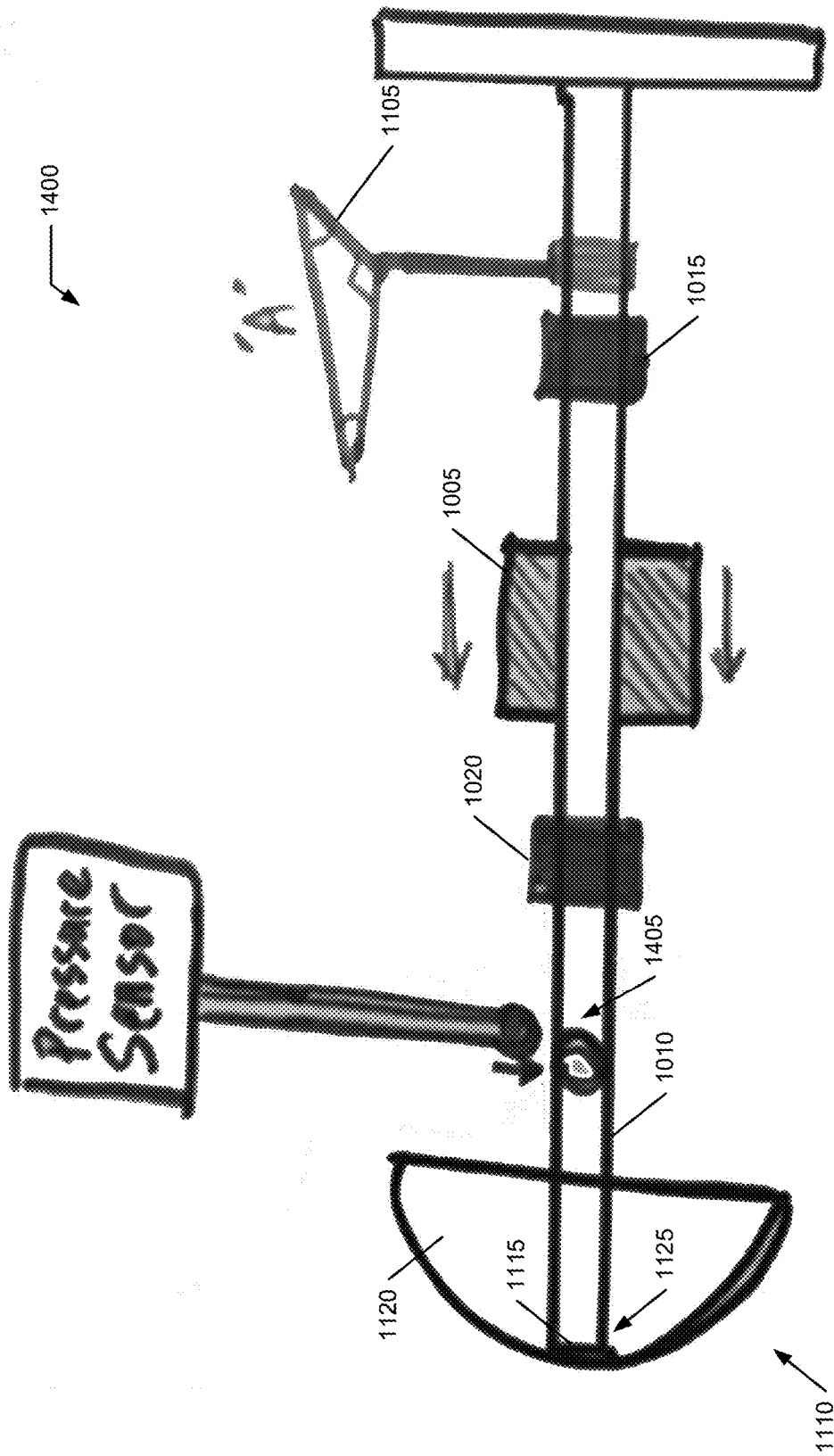


FIG. 14



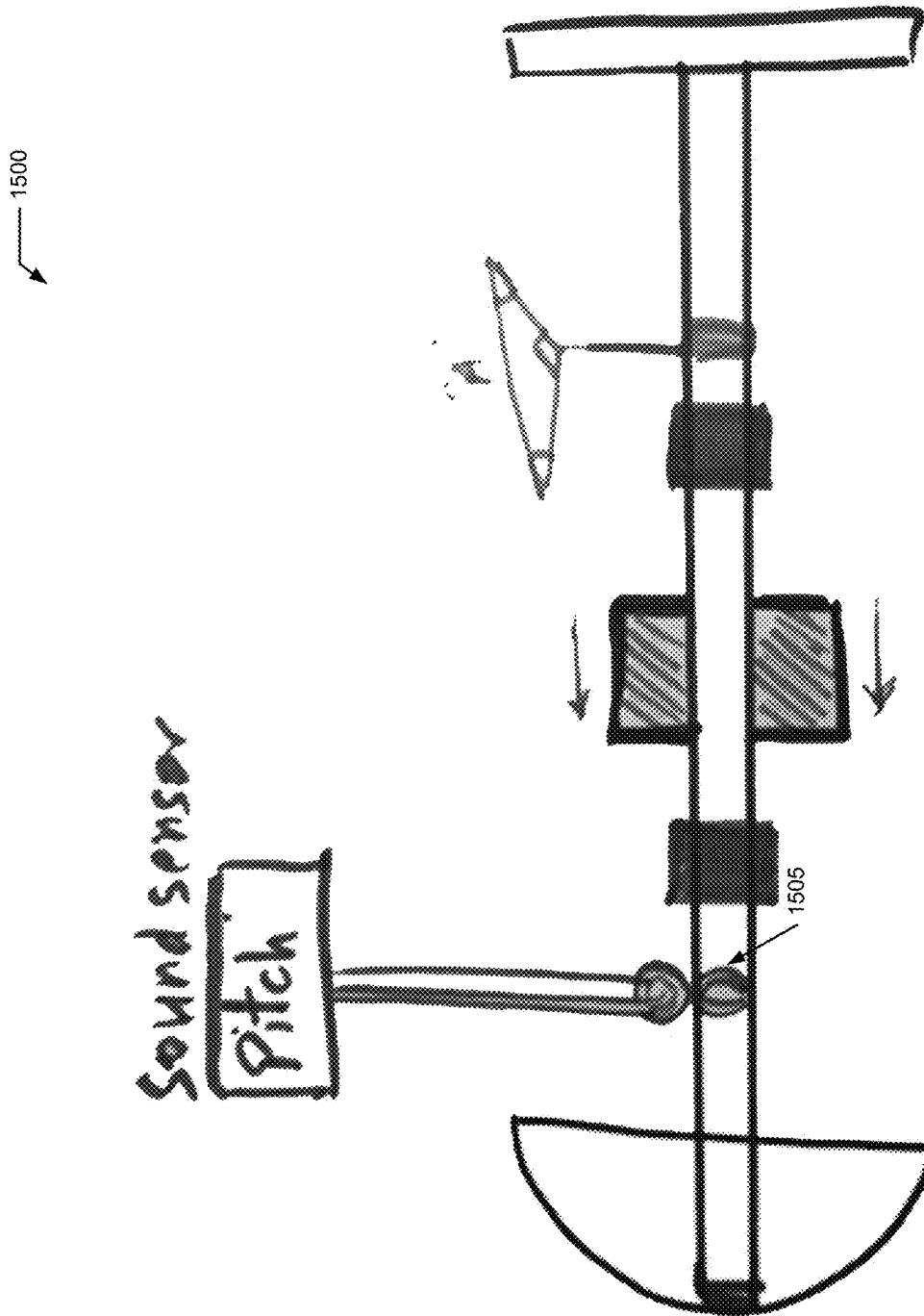


FIG. 15

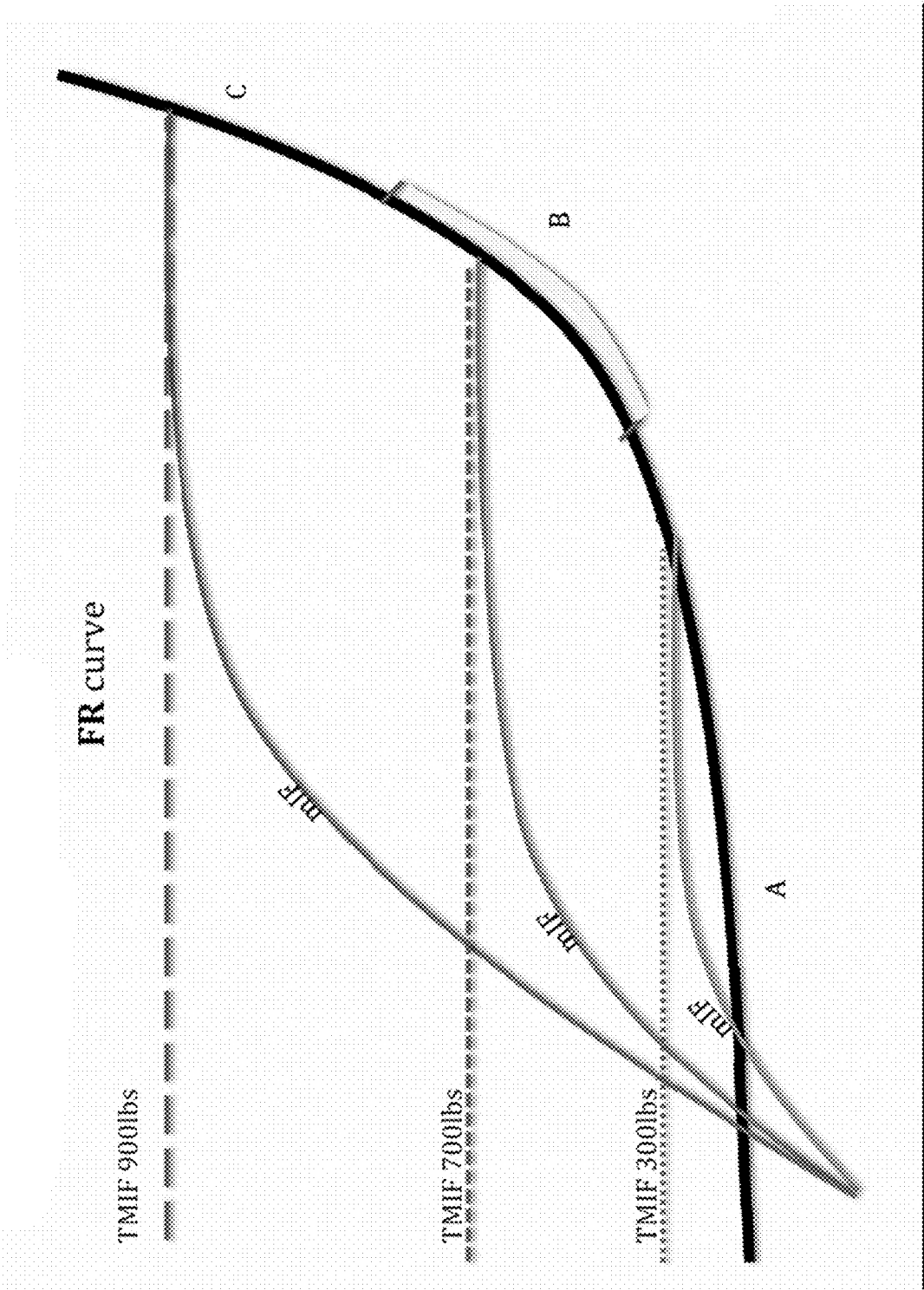


FIG. 16

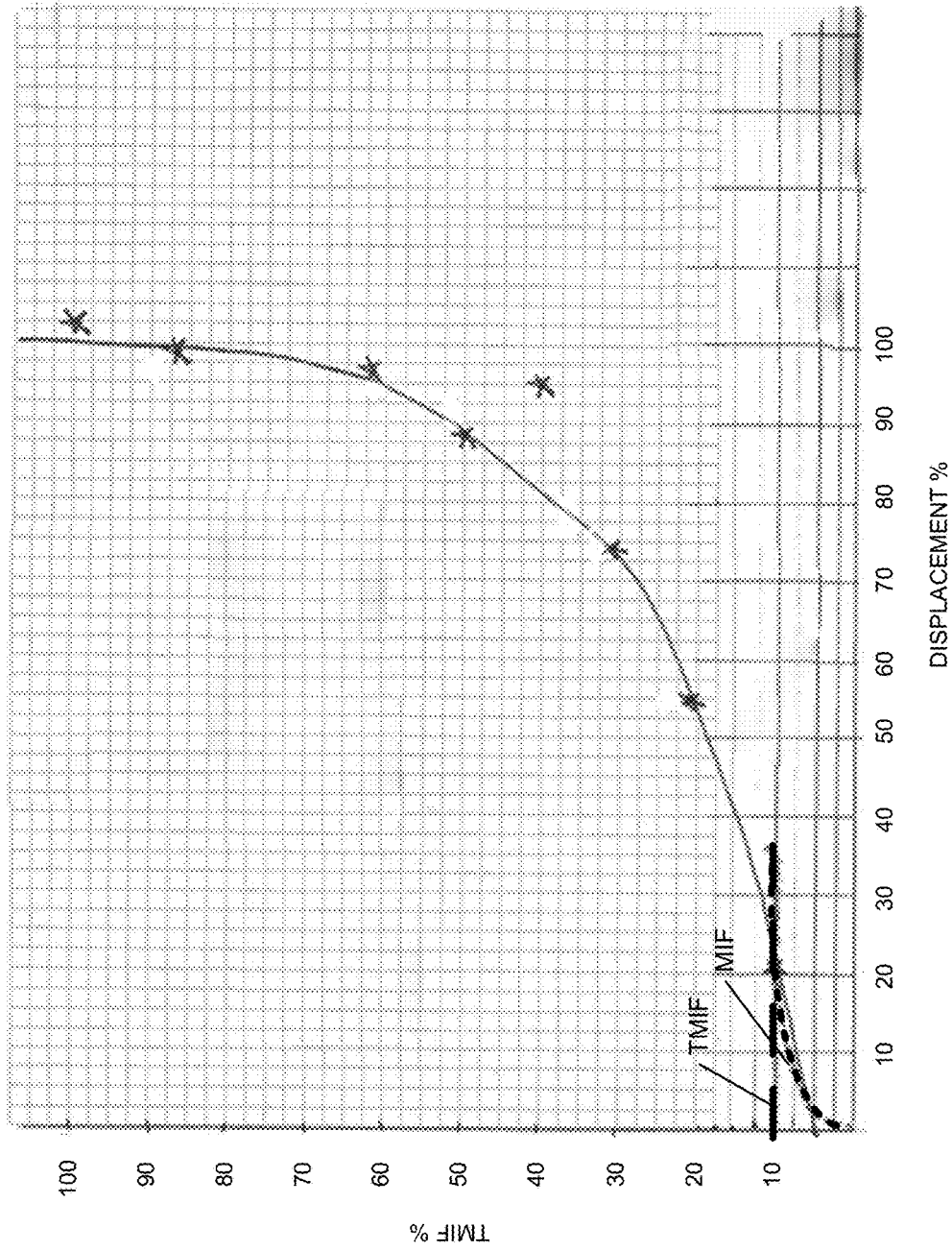


FIG. 17

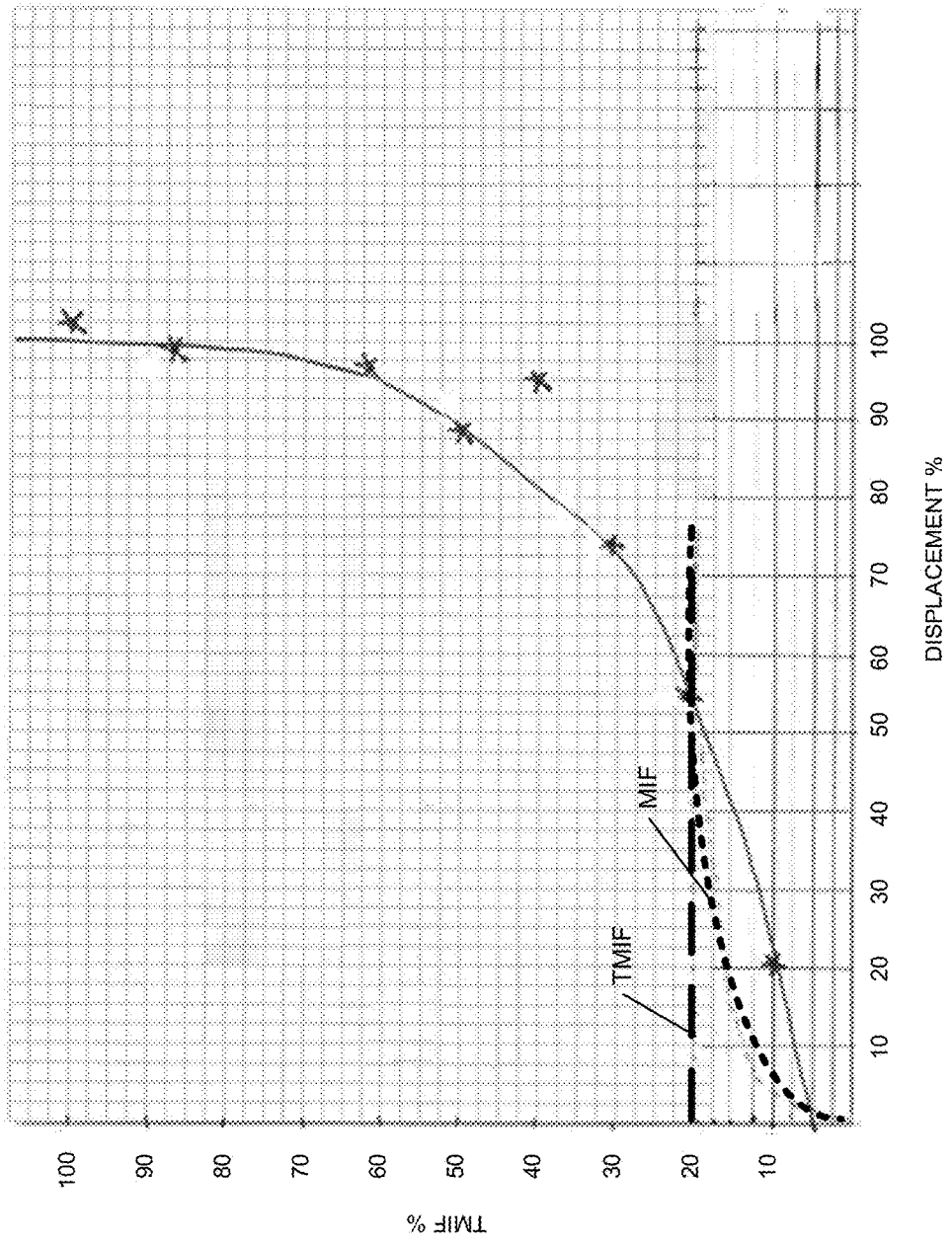


FIG. 18

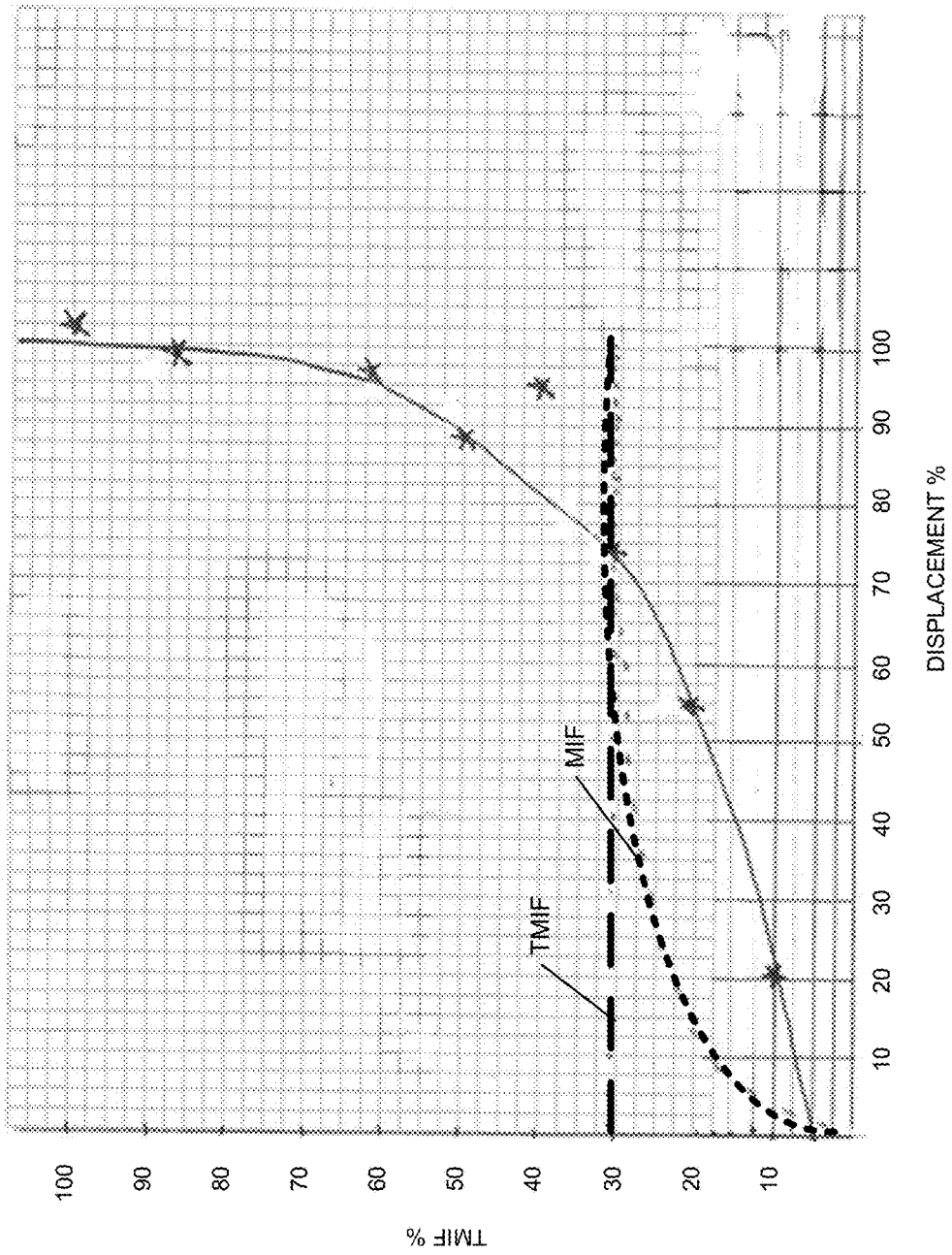


FIG. 19

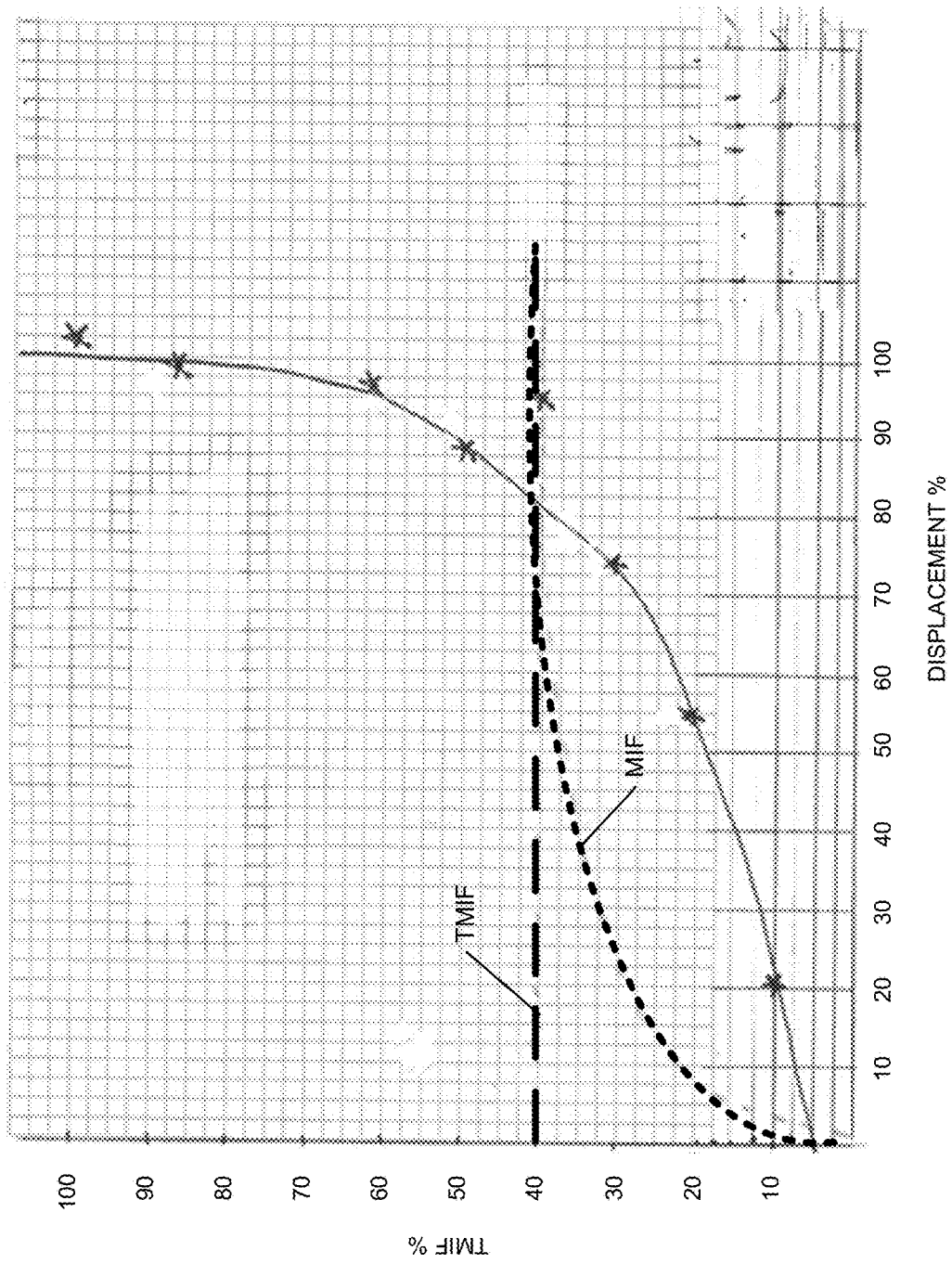


FIG. 20

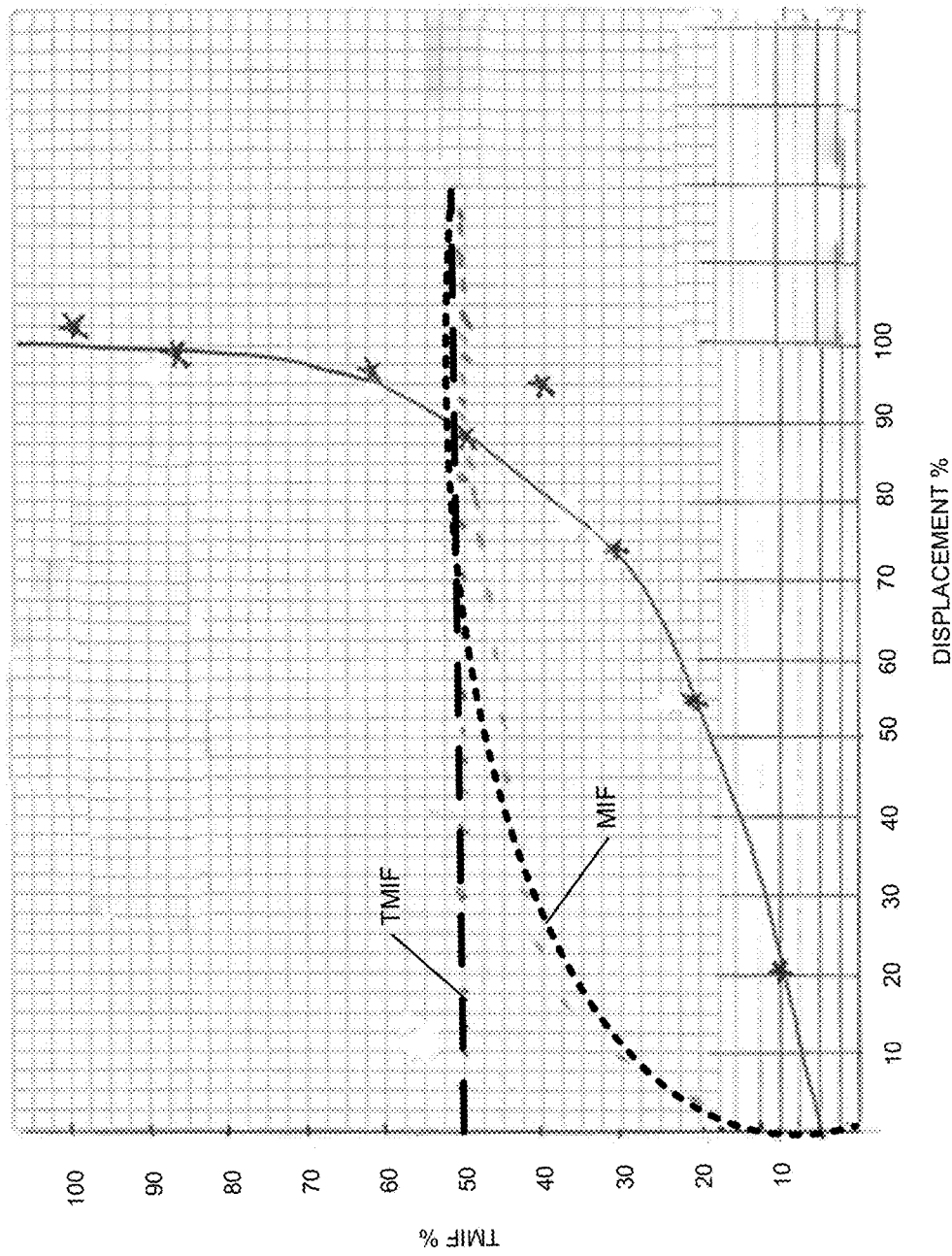


FIG. 21

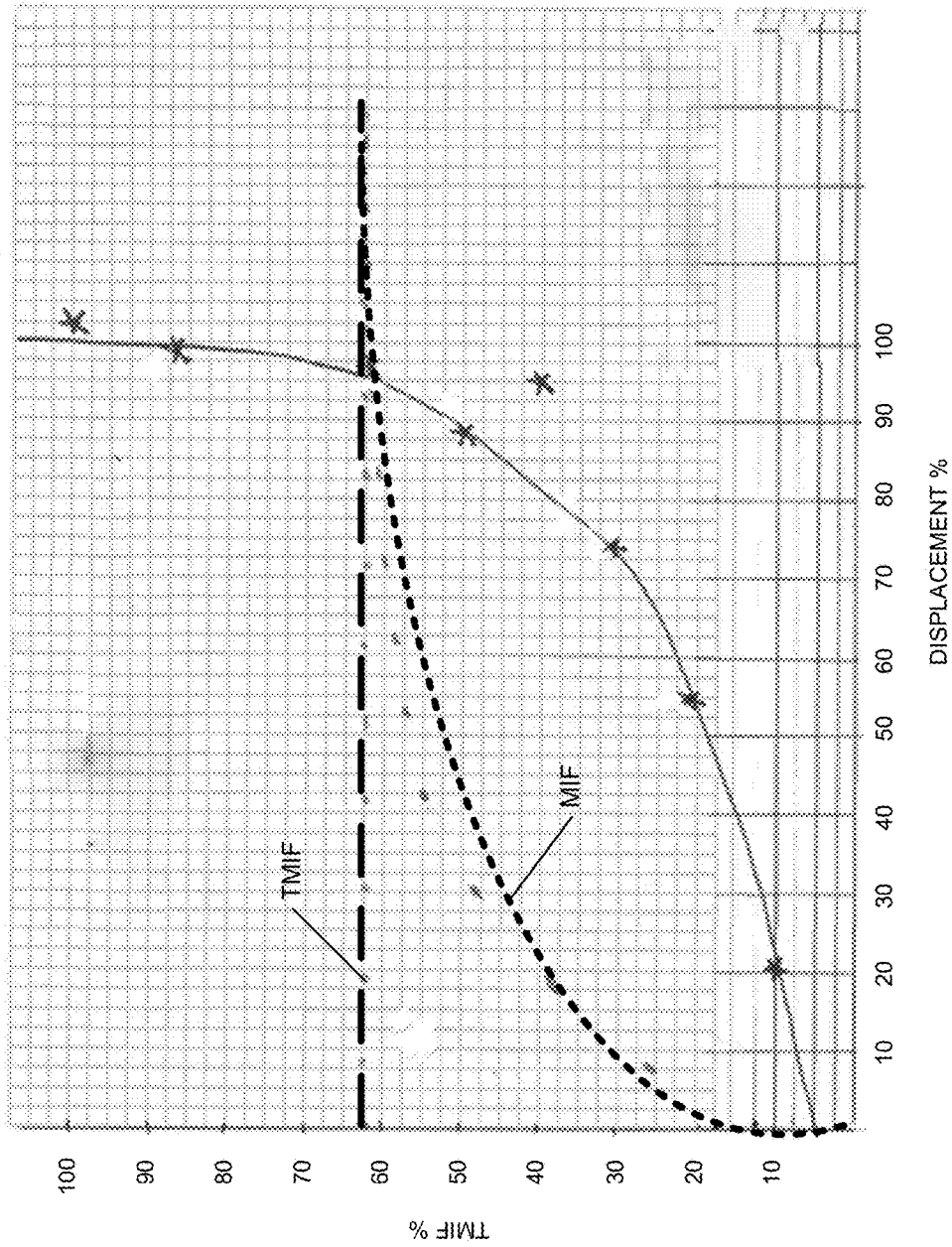


FIG. 22



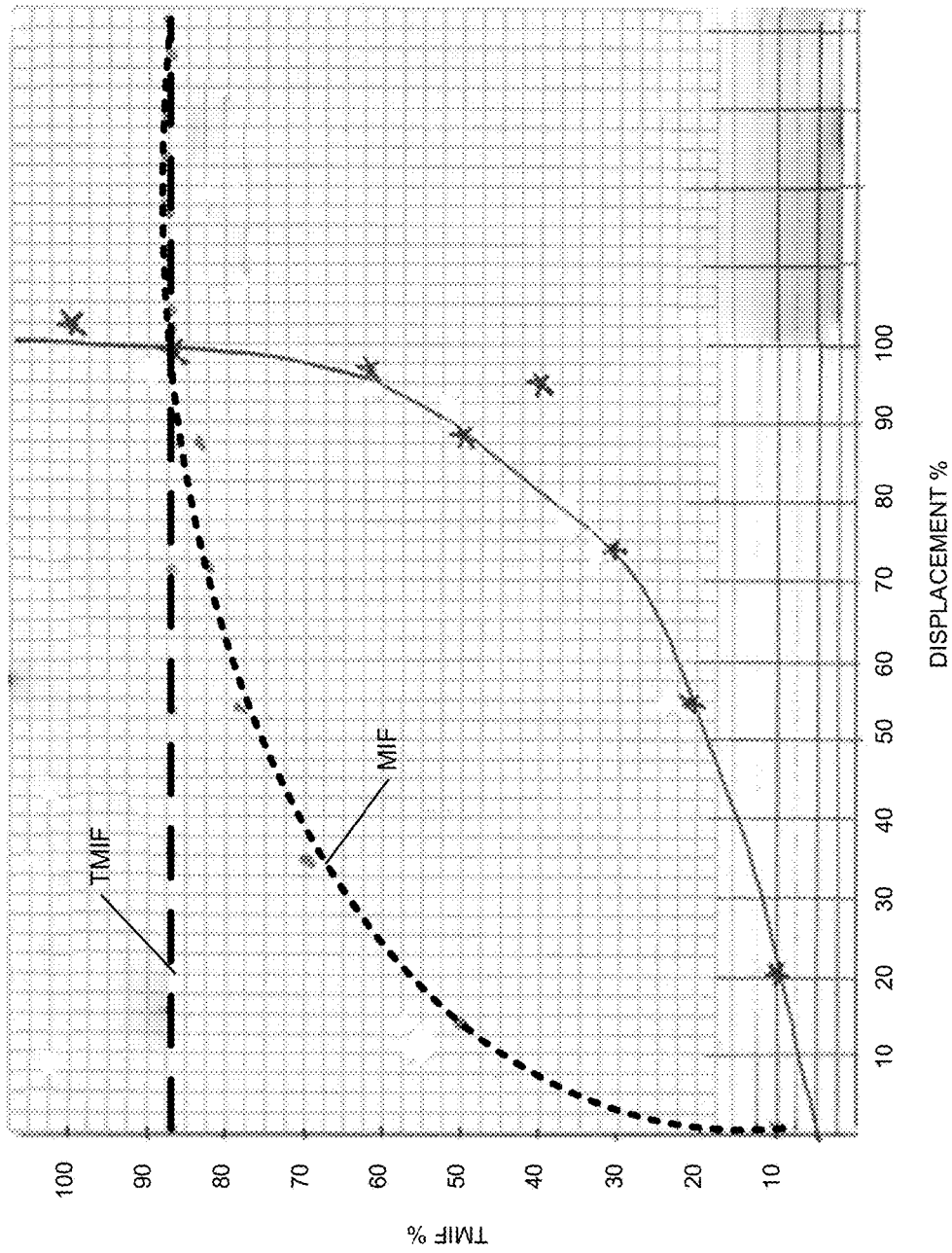


FIG. 23

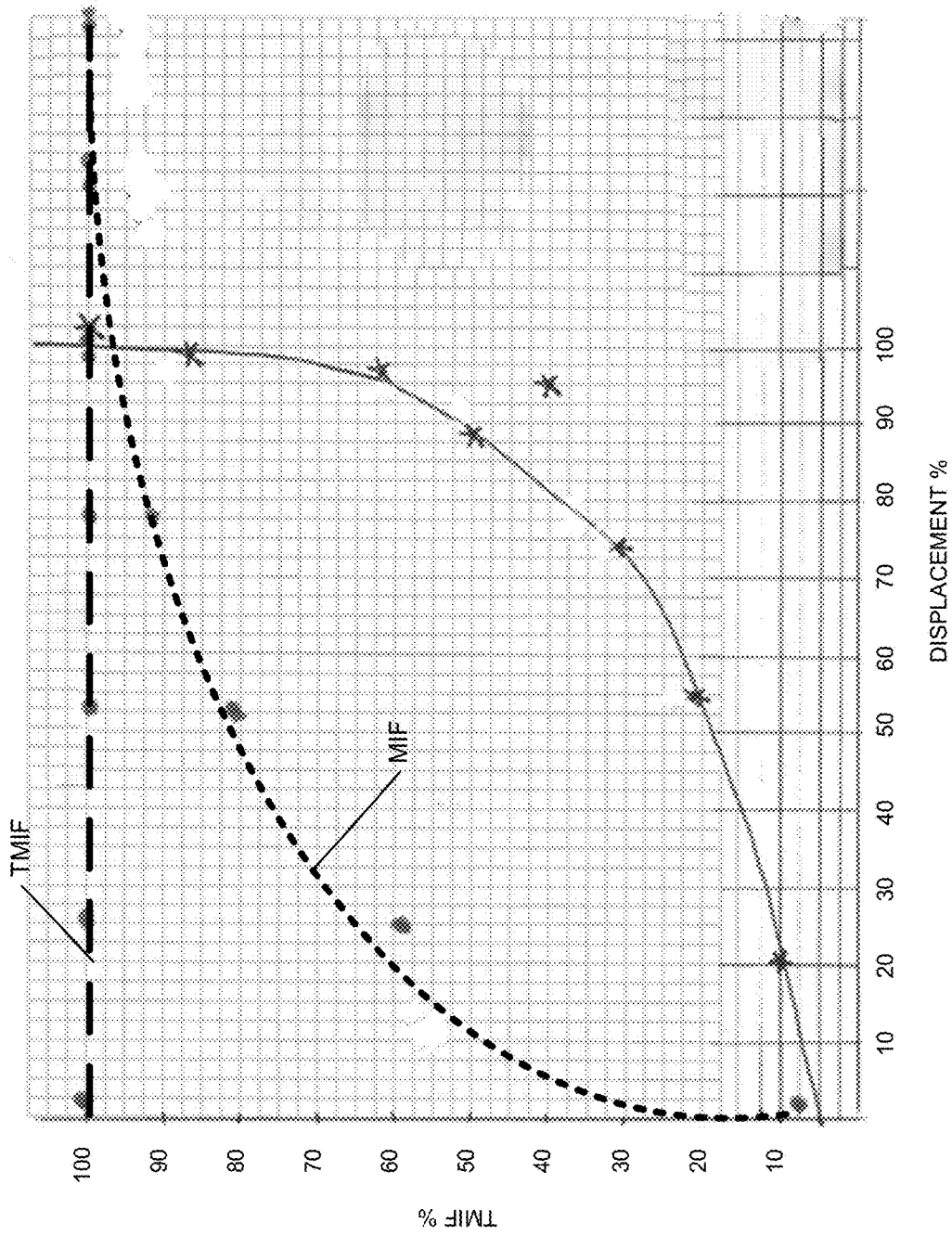


FIG. 24

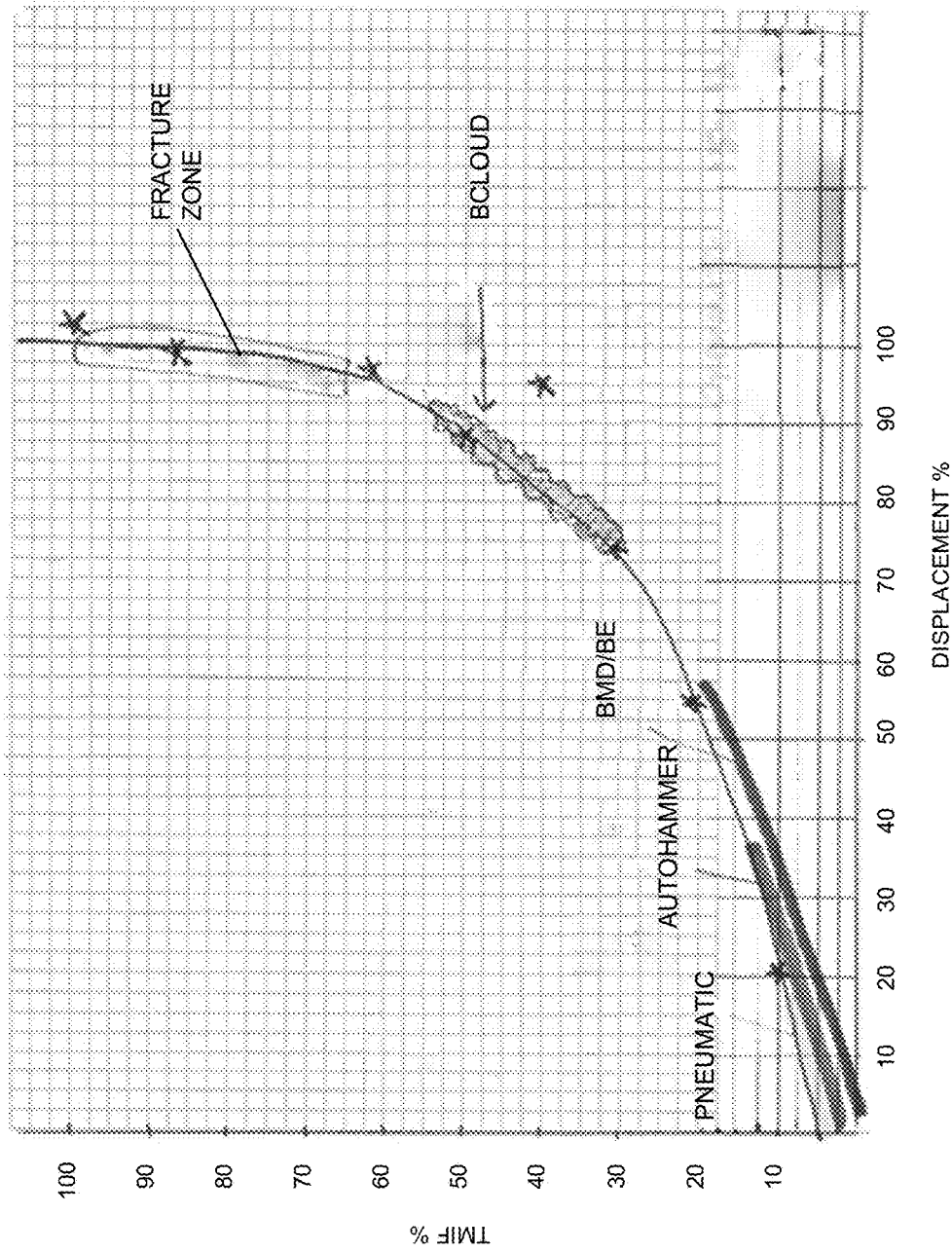


FIG. 25

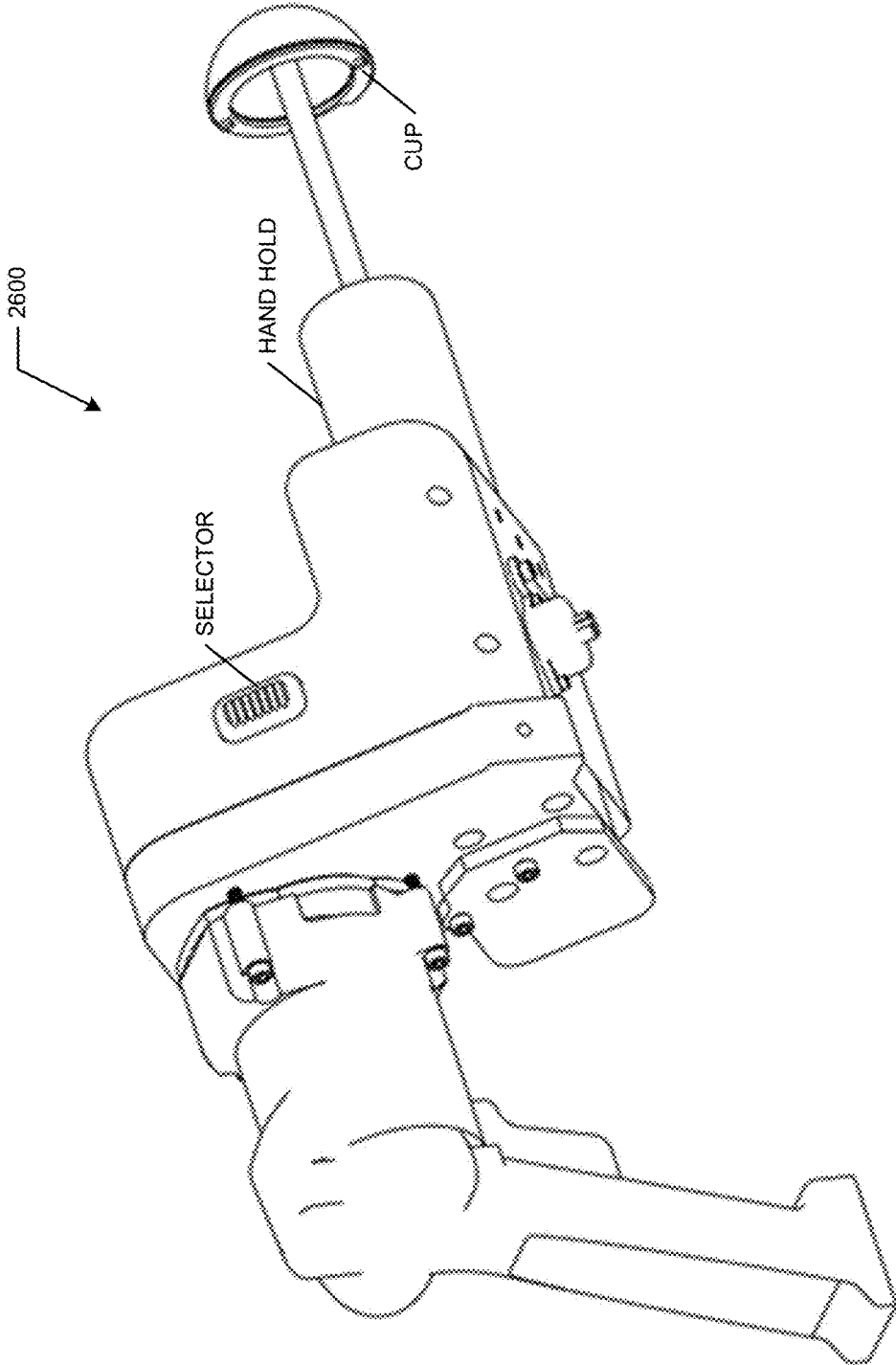


FIG. 26

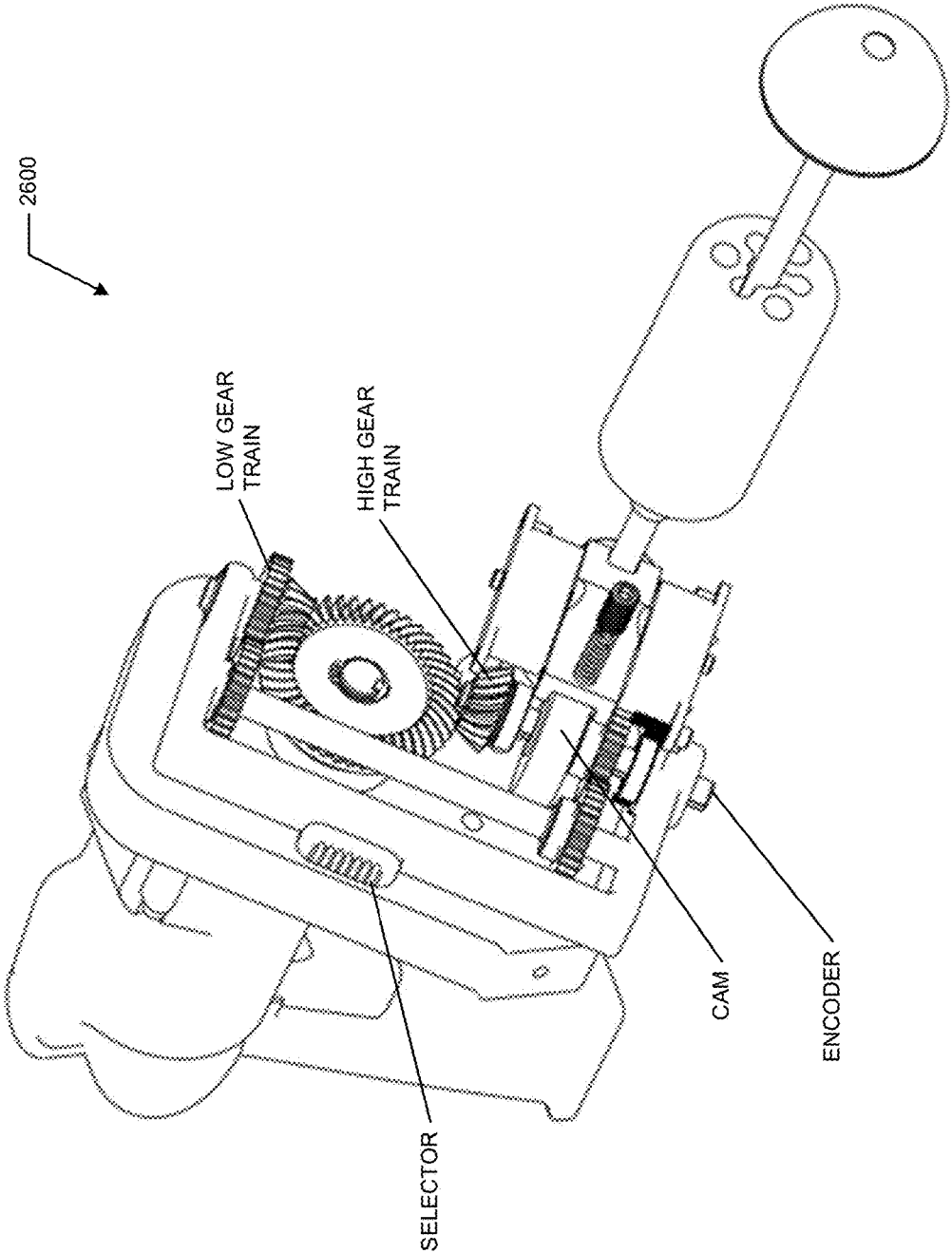


FIG. 27

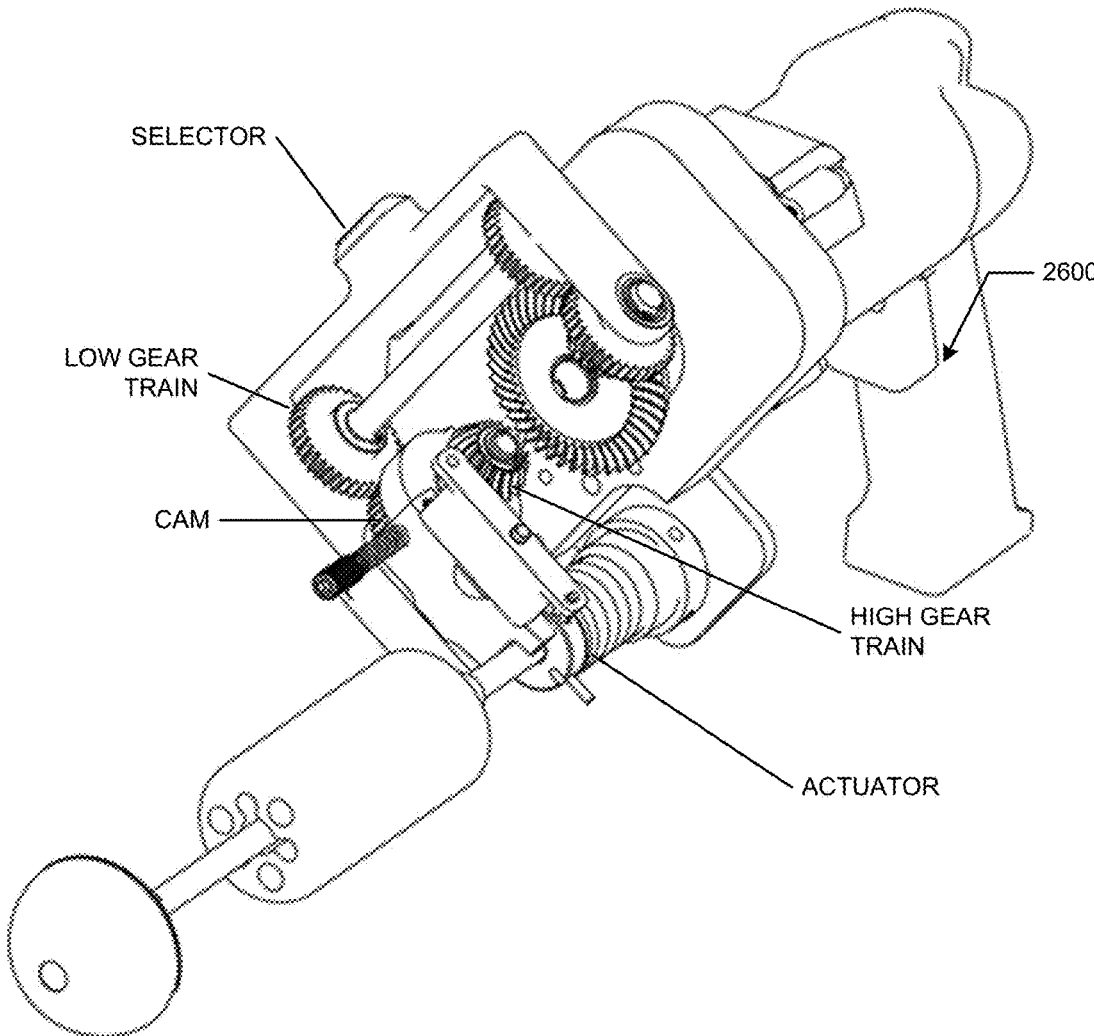
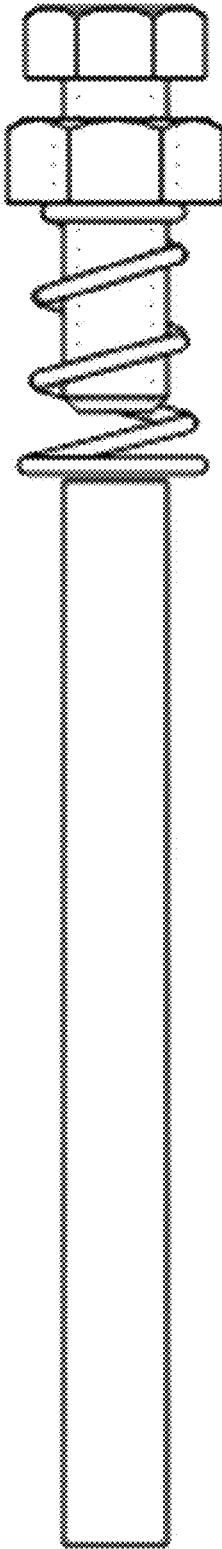
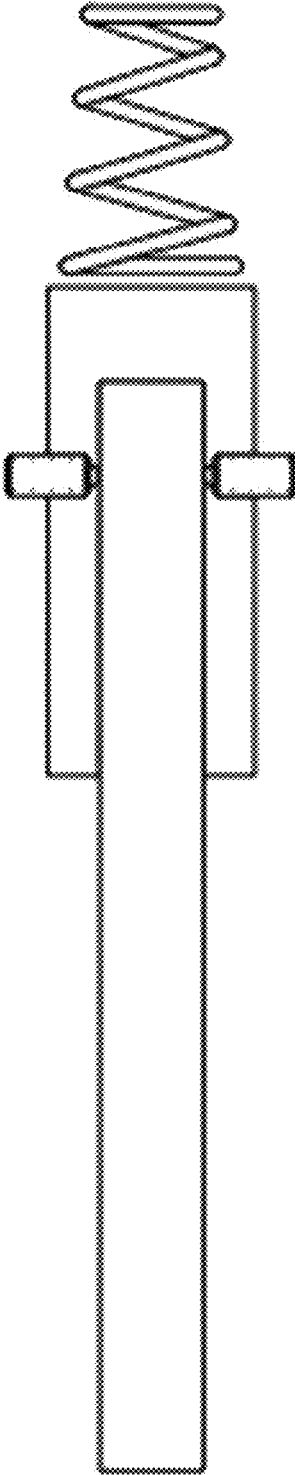


FIG. 28



**FIG. 29**



**FIG. 30**

## HYBRID PROSTHESIS INSTALLATION SYSTEMS AND METHODS

### CROSS REFERENCE TO RELATED APPLICATIONS

This application claims benefit from U.S. Patent Application No. 62/353,024 and is related to the following: a) U.S. Patent Application No. 61/921,528, b) U.S. Patent Application No. 61/980,188, c) U.S. patent application Ser. No. 14/584,656, d) U.S. patent application Ser. No. 14/585,056, and e) U.S. Patent Application No. 62/277,294, the contents of each of these applications in their entirety is hereby expressly incorporated by reference thereto for all purposes.

### FIELD OF THE INVENTION

The present invention relates generally to orthopedic surgical systems and procedures employing a prosthetic implant for, and more specifically, but not exclusively, to joint replacement therapies such as total hip replacement including controlled installation and positioning of the prosthesis such as during replacement of a pelvic acetabulum with a prosthetic implant, and relates generally to installation of a prosthesis, and more specifically, but not exclusively, to improvements in prosthesis placement and positioning, and relates generally to a hybridization of the vibratory and axially-impactful aspects of such systems.

### BACKGROUND OF THE INVENTION

The subject matter discussed in the background section should not be assumed to be prior art merely as a result of its mention in the background section. Similarly, a problem mentioned in the background section or associated with the subject matter of the background section should not be assumed to have been previously recognized in the prior art. The subject matter in the background section merely represents different approaches, which in and of themselves may also be inventions.

Total hip replacement refers to a surgical procedure where a hip joint is replaced using a prosthetic implant. There are several different techniques that may be used, but all include a step of inserting an acetabular component into the acetabulum and positioning it correctly in three dimensions (along an X, Y, and Z axis).

In total hip replacement (THR) procedures there are advantages to patient outcome when the procedure is performed by a surgeon specializing in these procedures. Patients of surgeons who do not perform as many procedures can have increased risks of complications, particularly of complications arising from incorrect placement and positioning of the acetabular component.

The incorrect placement and positioning may arise even when the surgeon understood and intended the acetabular component to be inserted and positioned correctly. This is true because in some techniques, the tools for actually installing the acetabular component are crude and provide an imprecise, unpredictable coarse positioning outcome.

It is known in some techniques to employ automated and/or computer-assisted navigation tools, for example, x-ray fluoroscopy or computer guidance systems. There are computer assisted surgery techniques that can help the surgeon in determining the correct orientation and placement of the acetabular component. However, current technology provides that at some point the surgeon is required to employ a hammer/mallet to physically strike a pin or align-

ment rod. The amount of force applied and the location of the application of the force are variables that have not been controlled by these navigation tools. Thus even when the acetabular component is properly positioned and oriented, when actually impacting the acetabular component into place the actual location and orientation can differ from the intended optimum location and orientation. In some cases the tools used can be used to determine that there is, in fact, some difference in the location and/or orientation. However, once again the surgeon must employ an impacting tool (e.g., the hammer/mallet) to strike the pin or alignment rod to attempt an adjustment. However the resulting location and orientation of the acetabular component after the adjustment may not be, in fact, the desired location and/or orientation. The more familiar that the surgeon is with the use and application of these adjustment tools can reduce the risk to a patient from a less preferred location or orientation. In some circumstances, quite large impacting forces are applied to the prosthesis by the mallet striking the rod; these forces make fine tuning difficult at best and there is risk of fracturing and/or shattering the acetabulum during these impacting steps.

Earlier patents issued to the present applicant have described problems associated with prosthesis installation, for example acetabular cup placement in total hip replacement surgery. See U.S. Pat. Nos. 9,168,154 and 9,220,612, which are hereby expressly incorporated by reference thereto in their entirety for all purposes. Even though hip replacement surgery has been one of the most successful operations, it continues to be plagued with a problem of inconsistent acetabular cup placement. Cup mal-positioning is the single greatest cause of hip instability, a major factor in polyethylene wear, osteolysis, impingement, component loosening and the need for hip revision surgery.

These incorporated patents explain that the process of cup implantation with a mallet is highly unreliable and a significant cause of this inconsistency. The patents note two specific problems associated with the use of the mallet. First is the fact that the surgeon is unable to consistently hit on the center point of the impaction plate, which causes undesirable torques and moment arms, leading to mal-alignment of the cup. Second, is the fact that the amount of force utilized in this process is non-standardized.

In these patents there is presented a new apparatus and method of cup insertion which uses an oscillatory motion to insert the prosthesis. Prototypes have been developed and continue to be refined, and illustrate that vibratory force may allow insertion of the prosthesis with less force, as well, in some embodiments, of allowing simultaneous positioning and alignment of the implant.

There are other ways of breaking down of the large undesirable, torque-producing forces associated with the discrete blows of the mallet into a series of smaller, axially aligned controlled taps, which may achieve the same result incrementally, and in a stepwise fashion to those set forth in the incorporated patents, (with regard to, for example, cup insertion without unintended divergence).

There are two problems that may be considered independently, though some solutions may address both in a single solution. These problems include i) undesirable and unpredictable torques and moment arms that are related to the primitive method currently used by surgeons, which involves manually banging the mallet on an impaction plate mated to the prosthesis and ii) non-standardized and essentially uncontrolled and unquantized amounts of force utilized in these processes.



Total hip replacement has been one of the most successful orthopedic operations. However, as has been previously described in the incorporated applications, it continues to be plagued with the problem of inconsistent acetabular cup placement. Cup mal-positioning is a significant cause of hip instability, a major factor in polyethylene wear, osteolysis, impingement, component loosening, and the need for hip revision surgery.

Solutions in the incorporated applications generally relate to particular solutions that may not, in every situation and implementation, achieve desired goal(s) of a surgeon.

What is needed is a system and method for allowing any surgeon, including those surgeons who perform a fewer number of a replacement procedure as compared to a more experienced surgeon who performs a greater number of procedures, to provide an improved likelihood of a favorable outcome approaching, if not exceeding, a likelihood of a favorable outcome as performed by a very experienced surgeon with the replacement procedure, such as by enabling hybrid solutions combining various selected features of the incorporated applications.

#### BRIEF SUMMARY OF THE INVENTION

Disclosed is a system and method for allowing any surgeon, including those surgeons who perform a fewer number of a replacement procedure as compared to a more experienced surgeon who performs a greater number of procedures, to provide an improved likelihood of a favorable outcome approaching, if not exceeding, a likelihood of a favorable outcome as performed by a very experienced surgeon with the replacement procedure, such as by enabling hybrid solutions combining various selected features of the incorporated applications.

The following summary of the invention is provided to facilitate an understanding of some of technical features related to total hip replacement, and is not intended to be a full description of the present invention. A full appreciation of the various aspects of the invention can be gained by taking the entire specification, claims, drawings, and abstract as a whole. The present invention is applicable to other surgical procedures, including replacement of other joints replaced by a prosthetic implant in addition to replacement of an acetabulum (hip socket) with an acetabular component (e.g., a cup). Use of pneumatic and electric motor implementations have both achieved a proof of concept development.

The disclosed concepts involve creation of a system/method/tool/gun that vibrates an attached prosthesis, e.g., an acetabular cup. The gun would be held in a surgeon's hands and deployed. It would use a vibratory energy to insert (not impact) and position the cup into desired alignment (using current intra-operation measurement systems, navigation, fluoroscopy, and the like).

In one embodiment, a first gun-like device is used for accurate impaction of the acetabular component at the desired location and orientation.

In another embodiment, a second gun-like device is used for fine-tuning of the orientation of the acetabular component, such as one installed by the first gun-like device, by traditional mallet and tamp, or by other methodology. However the second gun-like device may be used independently of the first gun-like device for adjusting an acetabular component installed using an alternate technique. Similarly the second gun-like device may be used independently of the first gun-like device, particularly when the initial installation is sufficiently close to the desired location and orientation.

These embodiments are not necessarily limited to fine-tuning as certain embodiments permit complete re-orientation. Some implementations allow for removal of an installed prosthesis.

Another embodiment includes a third gun-like device that combines the functions of the first gun-like device and the second gun-like device. This embodiment enables the surgeon to accurately locate, insert, orient, and otherwise position the acetabular component with the single tool.

Another embodiment includes a fourth device that installs the acetabular component without use of the mallet and the rod, or use of alternatives to strike the acetabular component for impacting it into the acetabulum. This embodiment imparts a vibratory motion to an installation rod coupled to the acetabular component that enables low-force, impactless installation and/or positioning.

An embodiment of the present invention may include axial alignment of force transference, such as, for example, an axially sliding hammer moving between stops to impart a non-torqueing installation force. There are various ways of motivating and controlling the sliding hammer, including a magnitude of transferred force. Optional enhancements may include pressure and/or sound sensors for gauging when a desired depth of implantation has occurred.

A novel system of inserting and aligning the acetabular cup in the human pelvic bone. This technique involves combining aspects of the BMD3 and BMD4 prototypes, initially utilizing BMD3 vibratory insertion to partially insert and perfectly align the acetabular cup into the pelvis. Subsequently switching to the BMD4 controlled impaction technique to apply specific quantifiable forces for full seating and insertion. In this manner we are combining the proven advantages of the vibratory insertion prototype with the advantages of the controlled impaction prototype.

Other embodiments include adaptation of various devices for accurate assembly of modular prostheses, such as those that include a head accurately impacted onto a trunion taper that is part of a stem or other element of the prosthesis.

Additional embodiments of the present invention may include a hybrid medical device that is capable of selectively using vibratory and/or axial-impacts at various phases of an installation as required, needed, and/or desired by the surgeon during a procedure. The single tool remains coupled to the prosthesis or prosthesis component as the surgeon operates the hybrid medical device in any of its phases, which include a pure vibratory mode, a pure axial mode, a blended vibratory and impactful mode. The axial impacts in this device may have sub-modes: a) unidirectional axial force-IN, b) unidirectional axial force-OUT, or c) bidirectional axial force.

A positioning device for an acetabular cup disposed in a bone, the acetabular cup including an outer shell having a sidewall defining an inner cavity and an opening with the sidewall having a periphery around the opening and with the acetabular cup having a desired abduction angle relative to the bone and a desired anteversion angle relative to the bone, including a controller including a trigger and a selector; a support having a proximal end and a distal end opposite of the proximal end, the support further having a longitudinal axis extending from the proximal end to the distal end with the proximal end coupled to the controller, the support further having an adapter coupled to the distal end with the adapter configured to secure the acetabular cup; and a number N, the number N, an integer greater than or equal to 2, of longitudinal actuators coupled to the controller and disposed around the support generally parallel to the longitudinal axis, each the actuator including an associated

impact head arranged to strike a portion of the periphery, each impact head providing an impact strike to a different portion of the periphery when the associated actuator is selected and triggered; wherein each the impact strike adjusts one of the angles relative to the bone.

An installation device for an acetabular cup disposed in a pelvic bone, the acetabular cup including an outer shell having a sidewall defining an inner cavity and an opening with the sidewall having a periphery around the opening and with the acetabular cup having a desired installation depth relative to the bone, a desired abduction angle relative to the bone, and a desired anteversion angle relative to the bone, including a controller including a trigger; a support having a proximal end and a distal end opposite of said proximal end, said support further having a longitudinal axis extending from said proximal end to said distal end with said proximal end coupled to said controller, said support further having an adapter coupled to said distal end with said adapter configured to secure the acetabular cup; and an oscillator coupled to said controller and to said support, said oscillator configured to control an oscillation frequency and an oscillation magnitude of said support with said oscillation frequency and said oscillation magnitude configured to install the acetabular cup at the installation depth with the desired abduction angle and the desired anteversion angle without use of an impact force applied to the acetabular cup.

An installation system for a prosthesis configured to be implanted into a portion of bone at a desired implantation depth, the prosthesis including an attachment system, including an oscillation engine including a controller coupled to a vibratory machine generating an original series of pulses having a generation pattern, said generation pattern defining a first duty cycle of said original series of pulses; and a pulse transfer assembly having a proximal end coupled to said oscillation engine and a distal end, spaced from said proximal end, coupled to the prosthesis with said pulse transfer assembly including a connector system at said proximal end, said connector system complementary to the attachment system and configured to secure and rigidly hold the prosthesis producing a secured prosthesis with said pulse transfer assembly communicating an installation series of pulses, responsive to said original series of pulses, to said secured prosthesis producing an applied series of pulses responsive to said installation series of pulses; wherein said applied series of pulses are configured to impart a vibratory motion to said secured prosthesis enabling an installation of said secured prosthesis into the portion of bone to within 95% of the desired implantation depth without a manual impact.

A method for installing an acetabular cup into a prepared socket in a pelvic bone, the acetabular cup including an outer shell having a sidewall defining an inner cavity and an opening with the sidewall having a periphery around the opening and with the acetabular cup having a desired installation depth relative to the bone, a desired abduction angle relative to the bone, and a desired anteversion angle relative to the bone, including (a) generating an original series of pulses from an oscillation engine; (b) communicating said original series of pulses to the acetabular cup producing a communicated series of pulses at said acetabular cup; (c) vibrating, responsive to said communicated series of pulses, the acetabular cup to produce a vibrating acetabular cup having a predetermined vibration pattern; and (d) inserting the vibrating acetabular cup into the prepared socket within a first predefined threshold of the installation

depth with the desired abduction angle and the desired anteversion angle without use of an impact force applied to the acetabular cup.

This method may further include (e) orienting the vibrating acetabular cup within the prepared socket within a second predetermined threshold of the desired abduction angle and within third predetermined threshold of the desired anteversion angle.

A method for inserting a prosthesis into a prepared location in a bone of a patient at a desired insertion depth wherein non-vibratory insertion forces for inserting the prosthesis to the desired insertion depth are in a first range, the method including (a) vibrating the prosthesis using a tool to produce a vibrating prosthesis having a predetermined vibration pattern; and (b) inserting the vibrating prosthesis into the prepared location to within a first predetermined threshold of the desired insertion depth using vibratory insertion forces in a second range, said second range including a set of values less than a lowest value of the first range.

Any of the embodiments described herein may be used alone or together with one another in any combination. Inventions encompassed within this specification may also include embodiments that are only partially mentioned or alluded to or are not mentioned or alluded to at all in this brief summary or in the abstract. Although various embodiments of the invention may have been motivated by various deficiencies with the prior art, which may be discussed or alluded to in one or more places in the specification, the embodiments of the invention do not necessarily address any of these deficiencies. In other words, different embodiments of the invention may address different deficiencies that may be discussed in the specification. Some embodiments may only partially address some deficiencies or just one deficiency that may be discussed in the specification, and some embodiments may not address any of these deficiencies.

Other features, benefits, and advantages of the present invention will be apparent upon a review of the present disclosure, including the specification, drawings, and claims.

#### BRIEF DESCRIPTION OF THE DRAWINGS

The accompanying figures, in which like reference numerals refer to identical or functionally-similar elements throughout the separate views and which are incorporated in and form a part of the specification, further illustrate the present invention and, together with the detailed description of the invention, serve to explain the principles of the present invention.

FIG. 1-FIG. 9 relate to a vibratory Behzadi Medical Device (BMD3);

FIG. 1 illustrates a representative installation gun;

FIG. 2 illustrates a right-hand detail of the installation gun of FIG. 1;

FIG. 3 illustrates a left-hand detail of the installation gun of FIG. 1 and generally when combined with FIG. 2 produces the illustration of FIG. 1;

FIG. 4 illustrates a second representative installation system;

FIG. 5 illustrates a disassembly of the second representative installation system of FIG. 4;

FIG. 6 illustrates a first disassembly view of the pulse transfer assembly of the installation system of FIG. 4;

FIG. 7 illustrates a second disassembly view of the pulse transfer assembly of the installation system of FIG. 4;

FIG. 8 illustrates a third representative installation system; and

FIG. 9 illustrates a disassembly view of the third representative installation system of FIG. 8; and

FIG. 10-FIG. 15 relate to an axially-impactful Behzadi Medical Device (BMD4);

FIG. 10-FIG. 15 illustrate embodiments including installation of a prosthesis, including installation into living bone;

FIG. 10 illustrates an embodiment of the present invention for a sliding impact device;

FIG. 11 illustrates a lengthwise cross-section of the embodiment illustrated in FIG. 10 including an attachment of a navigation device;

FIG. 12 illustrates a cockup mechanical gun embodiment, an alternative embodiment to the sliding impact device illustrated in FIG. 10 and FIG. 11;

FIG. 13 illustrates an alternative embodiment to the devices of FIG. 10-12 including a robotic structure;

FIG. 14 illustrates an alternative embodiment to the devices of FIG. 10-13 including a pressure sensor to provide feedback; and

FIG. 15 illustrates an alternative embodiment to the feedback system of FIG. 14 including a sound sensor to provide feedback for the embodiments of FIG. 10-14; and

FIG. 16-FIG. 25 relate to a hybrid Behzadi Medical Device (BMD7) which may combine vibratory and axial impactful forces from BMD3 and BMD4;

FIG. 16-FIG. 25 illustrate a set of Force Resistance (FR) curves for various experimental configurations; and

FIG. 26-FIG. 30 relate to a particular implementation of a hybrid BMD7 which selectively provides vibratory and axial impactful forces;

FIG. 26 illustrates an exterior perspective view of a BMD7;

FIG. 27 illustrates a first interior perspective view of the BMD7 of FIG. 26;

FIG. 28 illustrates a second interior perspective view of the BMD7 of FIG. 27;

FIG. 29 illustrates a first actuator embodiment for use with the BMD7 of FIG. 26; and

FIG. 30 illustrates a second actuator embodiment for use with the BMD7 of FIG. 26.

#### DETAILED DESCRIPTION OF THE INVENTION

Embodiments of the present invention provide a system and method for allowing any surgeon, including those surgeons who perform a fewer number of a replacement procedure as compared to a more experienced surgeon who performs a greater number of procedures, to provide an improved likelihood of a favorable outcome approaching, if not exceeding, a likelihood of a favorable outcome as performed by a very experienced surgeon with the replacement procedure, such as by enabling hybrid solutions combining various selected features of the incorporated applications. The following description is presented to enable one of ordinary skill in the art to make and use the invention and is provided in the context of a patent application and its requirements.

Various modifications to the preferred embodiment and the generic principles and features described herein will be readily apparent to those skilled in the art. Thus, the present invention is not intended to be limited to the embodiment shown but is to be accorded the widest scope consistent with the principles and features described herein.

#### Definitions

Unless otherwise defined, all terms (including technical and scientific terms) used herein have the same meaning as

commonly understood by one of ordinary skill in the art to which this general inventive concept belongs. It will be further understood that terms, such as those defined in commonly used dictionaries, should be interpreted as having a meaning that is consistent with their meaning in the context of the relevant art and the present disclosure, and will not be interpreted in an idealized or overly formal sense unless expressly so defined herein.

The following definitions apply to some of the aspects described with respect to some embodiments of the invention. These definitions may likewise be expanded upon herein.

As used herein, the term “or” includes “and/or” and the term “and/or” includes any and all combinations of one or more of the associated listed items. Expressions such as “at least one of,” when preceding a list of elements, modify the entire list of elements and do not modify the individual elements of the list.

As used herein, the singular terms “a,” “an,” and “the” include plural referents unless the context clearly dictates otherwise. Thus, for example, reference to an object can include multiple objects unless the context clearly dictates otherwise.

Also, as used in the description herein and throughout the claims that follow, the meaning of “in” includes “in” and “on” unless the context clearly dictates otherwise. It will be understood that when an element is referred to as being “on” another element, it can be directly on the other element or intervening elements may be present therebetween. In contrast, when an element is referred to as being “directly on” another element, there are no intervening elements present.

As used herein, the term “set” refers to a collection of one or more objects. Thus, for example, a set of objects can include a single object or multiple objects. Objects of a set also can be referred to as members of the set. Objects of a set can be the same or different. In some instances, objects of a set can share one or more common properties.

As used herein, the term “adjacent” refers to being near or adjoining. Adjacent objects can be spaced apart from one another or can be in actual or direct contact with one another. In some instances, adjacent objects can be coupled to one another or can be formed integrally with one another.

As used herein, the terms “connect,” “connected,” and “connecting” refer to a direct attachment or link. Connected objects have no or no substantial intermediary object or set of objects, as the context indicates.

As used herein, the terms “couple,” “coupled,” and “coupling” refer to an operational connection or linking. Coupled objects can be directly connected to one another or can be indirectly connected to one another, such as via an intermediary set of objects.

As used herein, the terms “substantially” and “substantial” refer to a considerable degree or extent. When used in conjunction with an event or circumstance, the terms can refer to instances in which the event or circumstance occurs precisely as well as instances in which the event or circumstance occurs to a close approximation, such as accounting for typical tolerance levels or variability of the embodiments described herein.

As used herein, the terms “optional” and “optionally” mean that the subsequently described event or circumstance may or may not occur and that the description includes instances where the event or circumstance occurs and instances in which it does not.

As used herein, the term “bone” means rigid connective tissue that constitute part of a vertebral skeleton, including mineralized osseous tissue, particularly in the context of a

living patient undergoing a prosthesis implant into a portion of cortical bone. A living patient, and a surgeon for the patient, both have significant interests in reducing attendant risks of conventional implanting techniques including fracturing/shattering the bone and improper installation and positioning of the prosthesis within the framework of the patient's skeletal system and operation.

As used herein, the term "size" refers to a characteristic dimension of an object. Thus, for example, a size of an object that is spherical can refer to a diameter of the object. In the case of an object that is non-spherical, a size of the non-spherical object can refer to a diameter of a corresponding spherical object, where the corresponding spherical object exhibits or has a particular set of derivable or measurable properties that are substantially the same as those of the non-spherical object. Thus, for example, a size of a non-spherical object can refer to a diameter of a corresponding spherical object that exhibits light scattering or other properties that are substantially the same as those of the non-spherical object. Alternatively, or in conjunction, a size of a non-spherical object can refer to an average of various orthogonal dimensions of the object. Thus, for example, a size of an object that is a spheroidal can refer to an average of a major axis and a minor axis of the object. When referring to a set of objects as having a particular size, it is contemplated that the objects can have a distribution of sizes around the particular size. Thus, as used herein, a size of a set of objects can refer to a typical size of a distribution of sizes, such as an average size, a median size, or a peak size.

As used herein, mallet or hammer refers to an orthopedic device made of stainless steel or other dense material having a weight generally a carpenter's hammer and a stonemason's lump hammer.

As used herein, an impact force for impacting an acetabular component (e.g., an acetabular cup prosthesis) includes forces from striking an impact rod multiple times with the orthopedic device that are generally similar to the forces that may be used to drive a three inch nail into a piece of lumber using the carpenter's hammer by striking the nail approximately a half-dozen times to completely seat the nail. Without limiting the preceding definition, a representative value in some instances includes a force of approximately 10 lbs/square inch.

The following description relates to improvements in a wide-range of prostheses installations into live bones of patients of surgeons. The following discussion focuses primarily on total hip replacement (THR) in which an acetabular cup prosthesis is installed into the pelvis of the patient. This cup is complementary to a ball and stem (i.e., a femoral prosthesis) installed into an end of a femur engaging the acetabulum undergoing repair.

Embodiments of the present invention may include one of more solutions to the above problems. The incorporated U.S. Pat. No. 9,168,154 includes a description of several embodiments, sometimes referred to herein as a BMD3 device, some of which illustrate a principle for breaking down large forces associated with the discrete blows of a mallet into a series of small taps, which in turn perform similarly in a stepwise fashion while being more efficient and safer. The BMD3 device produces the same displacement of the implant without the need for the large forces from the repeated impacts from the mallet. The BMD3 device may allow modulation of force required for cup insertion based on bone density, cup geometry, and surface roughness. Further, a use of the BMD3 device may result in the acetabulum experiencing less stress and deformation and the implant may experience a significantly smoother sinking

pattern into the acetabulum during installation. Some embodiments of the BMD3 device may provide a superior approach to these problems, however, described herein are two problems that can be approached separately and with more basic methods as an alternative to, or in addition to, a BMD3 device. An issue of undesirable torques and moment arms is primarily related to the primitive method currently used by surgeons, which involves manually banging the mallet on the impaction plate. The amount of force utilized in this process is also non-standardized and somewhat out of control.

With respect to the impaction plate and undesirable torques, an embodiment of the present invention may include a simple mechanical solution as an alternative to some BMD3 devices, which can be utilized by the surgeon's hand or by a robotic machine. A direction of the impact may be directed or focused by any number of standard techniques (e.g., A-frame, C-arm or navigation system). Elsewhere described herein is a refinement of this process by considering directionality in the reaming process, in contrast to only considering it just prior to impaction. First, we propose to eliminate the undesirable torques by delivering the impacts by a sledgehammer device or a (hollow cylindrical mass) that travels over a stainless rod.

As noted in the background, the surgeon prepares the surface of the hipbone which includes attachment of the acetabular prosthesis to the pelvis. Conventionally, this attachment includes a manual implantation in which a mallet is used to strike a tamp that contacts some part of the acetabular prosthesis. Repeatedly striking the tamp drives the acetabular prosthesis into the acetabulum. Irrespective of whether current tools of computer navigation, fluoroscopy, robotics (and other intra-operative measuring tools) have been used, it is extremely unlikely that the acetabular prosthesis will be in the correct orientation once it has been seated to the proper depth by the series of hammer strikes. After manual implantation in this way, the surgeon then may apply a series of adjusting strikes around a perimeter of the acetabular prosthesis to attempt to adjust to the desired orientation. Currently such post-impaction result is accepted as many surgeons believe that post-impaction adjustment creates an unpredictable and unreliable change which does not therefore warrant any attempts for post-impaction adjustment.

In most cases, any and all surgeons including an inexperienced surgeon may not be able to achieve the desired orientation of the acetabular prosthesis in the pelvis by conventional solutions due to unpredictability of the orientation changes responsive to these adjusting strikes. As noted above, it is most common for any surgeon to avoid post-impaction adjustment as most surgeons understand that they do not have a reliable system or method for improving any particular orientation and could easily introduce more/greater error. The computer navigation systems, fluoroscopy, and other measuring tools are able to provide the surgeon with information about the current orientation of the prosthesis (in real time) during an operation and after the prosthesis has been installed and its deviation from the desired orientation, but the navigation systems (and others) do not protect against torsional forces created by the implanting/positioning strikes. The prosthesis will find its own position in the acetabulum based on the axial and torsional forces created by the blows of the mallet. Even those navigation systems used with robotic systems (e.g., MAKO) that attempt to secure an implant in the desired orientation prior to impaction are not guaranteed to result in the installation of the implant at the desired orientation

because the actual implanting forces are applied by a surgeon swinging a mallet to manually strike the tamp.

A Behzadi Medical Device (BMD) is herein described and enabled that eliminates this crude method (i.e., mallet, tamp, and surgeon-applied mechanical implanting force) of the prosthesis (e.g., the acetabular cup). A surgeon using the BMD is able to insert the prosthesis exactly where desired with proper force, finesse, and accuracy. Depending upon implementation details, the installation includes insertion of the prosthesis into patient bone, within a desired threshold of metrics for insertion depth and location) and may also include, when appropriate and/or desired, positioning at a desired orientation with the desired threshold further including metrics for insertion orientation). The use of the BMD reduces risks of fracturing and/or shattering the bone receiving the prosthesis and allows for rapid, efficient, and accurate (atraumatic) installation of the prosthesis. The BMD provides a viable interface for computer navigation assistance (also useable with all intraoperative measuring tools including fluoroscopy) during the installation as a lighter more responsive touch may be used.

The BMD encompasses many different embodiments for installation and/or positioning of a prosthesis and may be adapted for a wide range of prostheses in addition to installation and/or positioning of an acetabular prosthesis during THR.

FIG. 1 illustrates a representative installation gun 100; FIG. 2 illustrates a right-hand detail of the installation gun 100; and FIG. 3 illustrates a left-hand detail of installation gun of 100 and generally when combined with FIG. 2 produces the illustration of FIG. 1. Installation gun 100 is represented as operable using pneumatics, though other implementations may use other mechanisms for creating a desired vibratory motion of prosthesis to be installed.

Installation gun 100 is used to control precisely one or both of (i) insertion, and (ii) abduction and anteversion angles of a prosthetic component. Installation gun 100 preferably allows both installation of an acetabular cup into an acetabulum at a desired depth and orientation of the cup for both abduction and anteversion to desired values. The following reference numbers in Table I refer to elements identified in FIG. 1-FIG. 3:

TABLE I

Device 100 Elements	
102	Middle guide housing
104	Klip
106	Kuciste
108	CILINDAR
110	Cjev
112	Poklopac
114	54 mm acetabular cup
116	Body
118	Valve
120	Bottom cap
122	Upper guide housing
124	Handle cam
126	DIN 3771 6 x 1,8-N-NBR 70
128	Main Air Inlet - Input Tube
130	Trigger
132	Trigger pin
134	DIN 3771 6 x 1,8-N-NBR 70
136	MirrorAR15 - Hand Grip 1
138	Crossover Tube
140	9657K103 compression spring
142	Elongate tube

TABLE I-continued

Device 100 Elements	
144	Lower guide housing
146	Primary adapter
148	Housing

Installation gun 100 includes a controller with a handle supporting an elongate tube 142 that terminates in adapter 146 that engages cup 114. Operation of trigger 130 initiates a motion of elongate tube 142. This motion is referred to herein as an installation force and/or installation motion that is much less than the impact force used in a conventional replacement process. An exterior housing 148 allows the operator to hold and position prosthesis 114 while elongate tube 142 moves within. Some embodiments may include a handle or other grip in addition to or in lieu of housing 148 that allows the operator to hold and operate installation gun 100 without interfering with the mechanism that provides a direct transfer of installation motion to prosthesis 114. The illustrated embodiment includes prosthesis 114 held securely by adapter 146 allowing a tilting and/or rotation of gun 100 about any axis to be reflected in the position/orientation of the secured prosthesis.

The installation motion includes constant, cyclic, periodic, and/or random motion (amplitude and/or frequency) that allows the operator to install cup 114 into the desired position (depth and orientation) without application of an impact force. There may be continuous movement or oscillations in one or more of six degrees of freedom including translation(s) and/or rotation(s) of adapter 146 about the X, Y, Z axes (e.g., oscillating translation(s) and/or oscillating/continuous rotation(s) which could be different for different axes such as translating back and forth in the direction of the longitudinal axis of the central support while rotating continuously around the longitudinal axis). This installation motion may include continuous or intermittent very high frequency movements and oscillations of small amplitude that allow the operator to easily install the prosthetic component in the desired location, and preferably also to allow the operator to also set the desired angles for abduction and anteversion.

In some implementations, the controller includes a stored program processing system that includes a processing unit that executes instructions retrieved from memory. Those instructions could control the selection of the motion parameters autonomously to achieve desired values for depth, abduction and anteversion entered into by the surgeon or by a computer aided medical computing system such as the computer navigation system. Alternatively those instructions could be used to supplement manual operation to aid or suggest selection of the motion parameters.

For more automated systems, consistent and unvarying motion parameters are not required and it may be that a varying dynamic adjustment of the motion parameters better conform to an adjustment profile of the cup installed into the acetabulum and status of the installation. An adjustment profile is a characterization of the relative ease by which depth, abduction and anteversion angles may be adjusted in positive and negative directions. In some situations these values may not be the same and the installation gun could be enhanced to adjust for these differences. For example, a unit of force applied to pure positive anteversion may adjust anteversion in the positive direction by a first unit of distance while under the same conditions that unit of force applied to pure negative anteversion may adjust anteversion in the

negative direction by a second unit of distance different from the first unit. And these differences may vary as a function of the magnitude of the actual angle(s). For example, as the anteversion increases it may be that the same unit of force results in a different responsive change in the actual distance adjusted. The adjustment profile when used helps the operator when selecting the actuators and the impact force(s) to be applied. Using a feedback system of the current real-time depth and orientation enables the adjustment profile to dynamically select/modify the motion parameters appropriately during different phases of the installation. One set of motion parameters may be used when primarily setting the depth of the implant and then another set used when the desired depth is achieved so that fine tuning of the abduction and anteversion angles is accomplished more efficiently, all without use of impact forces in setting the depth and/or angle adjustment(s).

This device better enables computer navigation as the installation/adjustment forces are reduced as compared to the impacting method. This makes the required forces more compatible with computer navigation systems used in medical procedures which do not have the capabilities or control systems in place to actually provide impacting forces for seating the prosthetic component. And without that, the computer is at best relegated to a role of providing after-the-fact assessments of the consequences of the surgeon's manual strikes of the orthopedic mallet. (Also provides information before and during the impaction. It is a problem that the very act of impaction introduces variability and error in positioning and alignment of the prosthesis.

FIG. 4 illustrates a second representative installation system 400 including a pulse transfer assembly 405 and an oscillation engine 410; FIG. 5 illustrates a disassembly of second representative installation system 400; FIG. 6 illustrates a first disassembly view of pulse transfer assembly 405; and FIG. 7 illustrates a second disassembly view of pulse transfer assembly 405 of installation system 400.

Installation system 400 is designed for installing a prosthesis that, in turn, is configured to be implanted into a portion of bone at a desired implantation depth. The prosthesis includes some type of attachment system (e.g., one or more threaded inserts, mechanical coupler, link, or the like) allowing the prosthesis to be securely and rigidly held by an object such that a translation and/or a rotation of the object about any axis results in a direct corresponding translation and/or rotation of the secured prosthesis.

Oscillation engine 410 includes a controller coupled to a vibratory machine that generates an original series of pulses having a generation pattern. This generation pattern defines a first duty cycle of the original series of pulses including one or more of a first pulse amplitude, a first pulse direction, a first pulse duration, and a first pulse time window. This is not to suggest that the amplitude, direction, duration, or pulse time window for each pulse of the original pulse series are uniform with respect to each other. Pulse direction may include motion having any of six degrees of freedom—translation along one or more of any axis of three orthogonal axes and/or rotation about one or more of these three axes. Oscillation engine 410 includes an electric motor powered by energy from a battery, though other motors and energy sources may be used.

Pulse transfer assembly 405 includes a proximal end 415 coupled to oscillation engine 410 and a distal end 420, spaced from proximal end 420, coupled to the prosthesis using a connector system 425. Pulse transfer assembly 405 receives the original series of pulses from oscillation engine 410 and produces, responsive to the original series of pulses,

an installation series of pulses having an installation pattern. Similar to the generation pattern, the installation pattern defines a second duty cycle of the installation series of pulses including a second pulse amplitude, a second pulse direction, a second pulse duration, and a second pulse time window. Again, this is not to suggest that the amplitude, direction, duration, or pulse time window for each pulse of the installation pulse series are uniform with respect to each other. Pulse direction may include motion having any of six degrees of freedom—translation along one or more of any axis of three orthogonal axes and/or rotation about one or more of these three axes.

For some embodiments of pulse transfer assembly 405, the installation series of pulses will be strongly linked to the original series and there will be a close match, if not identical match, between the two series. Some embodiments may include a more complex pulse transfer assembly 405 that produces an installation series that is more different, or very different, from the original series.

Connector system 425 (e.g., one or more threaded studs complementary to the threaded inserts of the prosthesis, or other complementary mechanical coupling system) is disposed at proximal end 420. Connector system 425 is configured to secure and rigidly hold the prosthesis. In this way, the attached prosthesis becomes a secured prosthesis when engaged with connector system 425.

Pulse transfer assembly 405 communicates the installation series of pulses to the secured prosthesis and produces an applied series of pulses that are responsive to the installation series of pulses. Similar to the generation pattern and the installation pattern, the applied pattern defines a third duty cycle of the applied series of pulses including a third pulse amplitude, a third pulse direction, a third pulse duration, and a third pulse time window. Again, this is not to suggest that the amplitude, direction, duration, or pulse time window for each pulse of the applied pulse series are uniform with respect to each other. Pulse direction may include motion having any of six degrees of freedom—translation along one or more of any axis of three orthogonal axes and/or rotation about one or more of these three axes.

For some embodiments of pulse transfer assembly 405, the applied series of pulses will be strongly linked to the original series and/or the installation series and there will be a close, if not identical, match between the series. Some embodiments may include a more complex pulse transfer assembly 405 that produces an applied series that is more different, or very different, from the original series and/or the installation series. In some embodiments, for example one or more components may be integrated together (for example, integrating oscillation engine 410 with pulse transfer assembly 405) so that the first series and the second series, if they exist independently are nearly identical if not identical).

The applied series of pulses are designed to impart a vibratory motion to the secured prosthesis that enable an installation of the secured prosthesis into the portion of bone to within 95% of the desired implantation depth without a manual impact. That is, in operation, the original pulses from oscillation engine 410 propagate through pulse transfer assembly 405 (with implementation-depending varying levels of fidelity) to produce the vibratory motion to the prosthesis secured to connector system 425. In a first implementation, the vibratory motion allows implanting without manual impacts on the prosthesis and in a second mode an orientation of the implanted secured prosthesis may be adjusted by rotations of installation system 400 while the vibratory motion is active, also without manual impact. In

some implementations, the pulse generation may produce different vibratory motions optimized for these different modes.

Installation system **400** includes an optional sensor **430** (e.g., a flex sensor or the like) to provide a measurement (e.g., quantitative and/or qualitative) of the installation pulse pattern communicated by pulse transfer assembly **405**. This measurement may be used as part of a manual or computerized feedback system to aid in installation of a prosthesis. For example, in some implementations, the desired applied pulse pattern of the applied series of pulses (e.g., the vibrational motion of the prosthesis) may be a function of a particular installation pulse pattern, which can be measured and set through sensor **430**. In addition to, or alternatively, other sensors may aid the surgeon or an automated installation system operating installation system **400**, such as a bone density sensor or other mechanism to characterize the bone receiving the prosthesis to establish a desired applied pulse pattern for optimal installation.

The disassembled views of FIG. **6** and FIG. **7** detail a particular implementation of pulse transfer assembly **405**, it being understood that there are many possible ways of creating and communicating an applied pulse pattern responsive to a series of generation pulses from an oscillation engine. The illustrated structure of FIG. **6** and FIG. **7** generate primarily longitudinal/axial pulses in response to primarily longitudinal/axial generation pulses from oscillation engine **410**.

Pulse transfer assembly **405** includes an outer housing **435** containing an upper transfer assembly **640**, a lower transfer assembly **645** and a central assembly **650**. Central assembly **650** includes a double anvil **655** that couples upper transfer assembly **640** to lower transfer assembly **645**. Outer housing **635** and central assembly **650** each include a port allowing sensor **630** to be inserted into central assembly **650** between an end of double anvil **655** and one of the upper/lower transfer assemblies.

Upper transfer assembly **640** and lower transfer assembly **645** each include a support **660** coupled to outer housing **435** by a pair of connectors. A transfer rod **665** is moveably disposed through an axial aperture in each support **660**, with each transfer rod **665** including a head at one end configured to strike an end of double anvil **655** and a coupling structure at a second end. A compression spring **670** is disposed on each transfer rod **665** between support **660** and the head. The coupling structure of upper transfer assembly **640** cooperates with oscillation engine **410** to receive the generated pulse series. The coupling structure of lower transfer assembly **645** includes connector system **425** for securing the prosthesis. Some embodiments may include an adapter, not shown, that adapts connector system **425** to a particular prosthesis, different adapters allowing use of pulse transfer assembly **405** with different prosthesis.

Central assembly **650** includes a support **675** coupled to outer housing **435** by a connector and receives double anvil **655** which moves freely within support **675**. The heads of the upper transfer assembly and the lower transfer assembly are disposed within support **675** and arranged to strike corresponding ends of double anvil **655** during pulse generation.

In operation, oscillation engine **410** generates pulses that are transferred via pulse transfer assembly **405** to the prosthesis secured by connector system **425**. The pulse transfer assembly **405**, via upper transfer assembly **640**, receives the generated pulses using transfer rod **665**. Transfer rod **665** of upper transfer assembly **640** moves within support **660** of upper transfer assembly **640** to communicate pulses to

double anvil **655** moving within support **675**. Double anvil **655**, in turn, communicates pulses to transfer rod **665** of lower transfer assembly **645** to produce vibratory motion of a prosthesis secured to connector system **425**. Transfer rods **665** move, in this illustrated embodiment, primarily longitudinally/axially within outer housing **435** (a longitudinal axis defined as extending between proximate end **415** and distal end **420**). In this way, the surgeon may use outer housing **435** as a hand hold when installing and/or positioning the vibrating prosthesis.

The use of discrete transfer portions (e.g., upper, central, and lower transfer assemblies) for pulse transfer assembly **405** allows a form of loose coupling between oscillation engine **410** and a secured prosthesis. In this way pulses from oscillation engine **410** are converted into a vibratory motion of the prosthesis as it is urged into the bone during operation. Some embodiments may provide a stronger coupling by directly securing one component to another, or substituting a single component for a pair of components.

FIG. **8** illustrates a third representative installation system **800**; and FIG. **9** illustrates a disassembly view of third representative installation system **800**.

The embodiments of FIG. **4**-FIG. **8** have demonstrated insertion of a prosthetic cup into a bone substitute substrate with ease and a greatly reduced force as compared to use of a mallet and tamp, especially as no impaction was required. While the insertion was taking place and vibrational motion was present at the prosthesis, the prosthesis could be positioned with relative ease by torqueing on a handle/outer housing to an exact desired alignment/position. The insertion force is variable and ranges between 20 to 800 pounds of force. Importantly the potential for use of significantly smaller forces in application of the prosthesis (in this case the acetabular prosthesis) in bone substrate with the present invention is demonstrated to be achievable.

Similarly to installation system **100** and installation system **400**, installation system **800** is used to control precisely one or both of (i) installation and (ii) abduction and anteversion angles of a prosthetic component. Installation system **800** preferably allows both installation of an acetabular cup into an acetabulum at a desired depth and orientation of the cup for both abduction and anteversion to desired values. The following reference numbers in Table II refer to elements identified in FIG. **8**-FIG. **9**:

TABLE II

Device 800 Elements	
802	Air Inlet
804	Trigger
806	Needle Valve
808	Valve Body
810	Throttle Cap
812	Piston
814	Cylinder
816	Driver
818	Needle Block
820	Needles
822	Suspension Springs
824	Anvil
826	Nozzle
828	Connector Rod
830	Prosthesis (e.g., acetabular cup)

Installation system **800** includes a controller with a handle supporting an elongate rod that terminates in a connector system that engages prosthesis **830**. Operation of trigger **804** initiates a motion of the elongate rod. This motion is referred to herein as an installation force and/or installation motion

that is much less than the impact force used in a conventional replacement process. An exterior housing allows the operator to hold and position prosthesis **830** while the elongate rod moves within. Some embodiments may include a handle or other grip in addition to or in lieu of the housing that allows the surgeon operator to hold and operate installation system **800** without interfering with the mechanism that provides a direct transfer of installation motion. The illustrated embodiment includes prosthesis **830** held securely allowing a tilting and/or rotation of installation system about any axis to be reflected in the position/orientation of the secured prosthesis.

The actuator is pneumatically operated oscillation device that provides the impact and vibration action this device uses to set the socket (it being understood that alternative motive systems may be used in addition to, or alternatively to, a pneumatic system). Alternatives including mechanical and/or electromechanical systems, motors, and/or engines. The actuator includes air inlet port **802**, trigger **804**, needle valve **806**, cylinder **814**, and piston **812**.

Air is introduced through inlet port **802** and as trigger **804** is squeezed needle valve **806** admits air into the cylinder **814** pushing piston **812** to an opposing end of cylinder **814**. At the opposite end piston **812** opens a port allowing the air to be admitted and pushing the piston **812** back to the original position.

This action provides the motive power for operation of the device and functions in this embodiment at up to 70 Hz. The frequency can be adjusted by trigger **804** and an available air pressure at air inlet port **802**.

As piston **812** impacts driver **816**, driver **816** impacts needles **820** of needle block **818**. Needles **820** strike anvil **824** which is directly connected to prosthesis **830** via connecting rod **828**.

Suspension springs **822** provide a flexibility to apply more or less total force. This flexibility allows force to be applied equally around prosthesis **830** or more force to one side of prosthesis **830** in order to locate prosthesis **830** at an optimum/desired orientation. Installation system **800** illustrates a BMD having a more strongly coupled pulse transfer system between an oscillation engine and prosthesis **830**.

The nature and type of coupling of pulse communications between the oscillation engine and the prosthesis may be varied in several different ways. For example, in some implementations, needles **820** of needle block **818** are independently moveable and respond differently to piston **812** motion. In other implementations, the needles may be fused together or otherwise integrated together, while in other implementations needles **820** and needle block **818** may be replaced by an alternative cylinder structure.

As illustrated, while both embodiments provide for a primarily longitudinal implementation, installation system **800** includes a design feature intended to allow the inserting/vibratory force to be "steered" by applying forces to be concentrated on one side or another of the prosthesis. Implementations that produce a randomized vibrational motion, including "lateral" motion components in addition to, or in lieu of, the primarily longitudinal vibrational motion of the disclosed embodiments may be helpful for installation of prosthesis in a wide range of applications including THR surgery.

Installation system **400** and installation system **800** included an oscillation engine producing pulses at approximately 60 Hz. System **400** operated at 60 Hz while system **800** was capable of operating at 48 to 68 Hz. In testing, approximately 4 seconds of operation resulted in a desired insertion and alignment of the prosthesis (meaning about

240 cycles of the oscillation engine). Conventional surgery using a mallet striking a tamp to impact the cup into place is generally complete after 10 blows of the mallet/hammer.

## EXPERIMENTAL

Both system **400** and system **800** were tested in a bone substitute substrate with a standard Zimmer acetabular cup using standard technique of under reaming a prepared surface by 1 mm and inserting a cup that was one millimeter larger. The substrate was chosen as the best option available to us to study this concept, namely a dense foam material. It was recognized that certain properties of bone would not be represented here (e.g. an ability of the substrate to stretch before failure).

Both versions demonstrated easy insertion and positioning of the prosthetic cup within the chosen substrate. We were able to move the cup in the substrate with relative ease. There was no requirement for a mallet or hammer for application of a large impact. These experiments demonstrated that the prosthetic cups could be inserted in bone substitute substrates with significantly less force and more control than what could be done with blows of a hammer or mallet. We surmise that the same phenomena can be reproduced in human bone. We envision the prosthetic cup being inserted with ease with very little force.

Additionally we believe that simultaneously, while the cup is being inserted, the position of the cup can be adjusted under direct visualization with any intra-operative measurement system (navigation, fluoroscopy, etc.). This invention provides a system that allows insertion of a prosthetic component with NON-traumatic force (insertion) as opposed to traumatic force (impaction).

### Experimental Configuration—System **400**

Oscillation engine **410** included a Craftsman G2 Hammerhead nailer used to drive fairly large framing nails into wood in confined spaces by applying a series of small impacts very rapidly in contrast to application of few large impacts.

The bone substitute was 15 pound density urethane foam to represent the pelvic acetabulum. It was shaped with a standard cutting tool commonly used to clean up a patient's damaged acetabulum. A 54 mm cup and a 53 mm cutter were used in testing.

In one test, the cup was inserted using a mallet and tamp, with impaction complete after 7 strikes. Re-orientation of the cup was required by further strikes on an periphery of the cup after impaction to achieve a desired orientation. It was qualitatively determined that the feel and insertion were consistent with impaction into bone.

An embodiment of system **400** was used in lieu of the mallet and tamp method. Several insertions were performed, with the insertions found to be much more gradual; allowing the cup to be guided into position (depth and orientation during insertion). Final corrective positioning is easily achievable using lateral hand pressure to rotate the cup within the substrate while power was applied to the oscillation engine.

Further testing using the sensor included general static load detection done to determine the static (non-impact) load to push the cup into the prepared socket model. This provided a baseline for comparison to the impact load testing. The prosthesis was provided above a prepared socket with a screw mounted to the cup to transmit a force applied from a bench vise. The handle of the vice was turned



to apply an even force to compress the cup into the socket until the cup was fully seated. The cup began to move into the socket at about an insertion force of ~200 pounds and gradually increased as diameter of cup inserted into socket increased to a maximum of 375 pounds which remained constant until the cup was fully seated.

Installation system **400** was next used to install the cup into a similarly prepared socket. Five tests were done, using different frame rates and setup procedures, to determine how to get the most meaningful results. All tests used a 54 mm acetabular Cup. The oscillation engine ran at an indicated 60 impacts/second. The first two tests were done at 2,000 frames/second, which wasn't fast enough to capture all the impact events, but helped with designing the proper setup. Test 3 used the oscillation engine in an already used socket, 4,000 frames per second. Test 4 used the oscillation engine in an unused foam socket at 53 mm, 4,000 frames per second.

Test 3: In already compacted socket, the cup was pulsed using the oscillation engine and the pulse transfer assembly. Recorded strikes between 500 and 800 lbs, with an average recorded pulse duration 0.8 ms.

Test 4: Into an unused 53 mm socket, the cup was pulsed using the oscillation engine and the pulse transfer assembly. Recorded impacts between 250 and 800 lbs, and an average recorded pulse duration 0.8 ms. Insertion completed in 3.37 seconds, 202 impact hits.

Test 5: Into an unused 53 mm socket, the cup was inserted with standard hammer (for reference). Recorded impacts between 500 and 800 lbs, and an average recorded pulse duration 22.0 ms. Insertion completed in 4 seconds using 10 impact hits for a total pressure time of 220 ms. This test was performed rapidly to complete it in 5 seconds for good comparability with tests 3 and 4 used 240 hits in 4 seconds, with a single hit duration of 0.8 ms, for a total pressure time of 192 ms.

In non-rigorous comparison testing without a direct comparison between system **400** and system **800**, generally it appears that the forces used for installation using system **800** were lower than system **400** by a factor of 10. This suggests that there are certain optimizing characteristics for operation of an installation system. There are questions such as to how low these forces can be modulated and still allow easy insertion of the prosthetic cup in this model and in bone. What is the lowest force required for insertion of a prosthetic cup in to this substrate using the disclosed concepts? What is the lowest force required for insertion of a prosthetic cup into hard bone using the these concepts? And what is the lowest force required for insertion of a prosthetic cup into soft and osteoporotic bone using these concepts? These are the questions that can be addressed in future phase of implementations of the present invention.

Additionally, basic studies can further be conducted to correlate a density and a porosity of bone at various ages (e.g., through a cadaver study) with an appropriate force range and vibratory motion pattern required to insert a cup using the present invention. For example a surgeon will be able to insert sensing equipment in patient bone, or use other evaluative procedures, (preoperative planning or while performing the procedure for example) to assess porosity and density of bone. Once known, the density or other bone characteristic is used to set an appropriate vibratory pattern including a force range on an installation system, and thus use a minimal required force to insert and/or position the prosthesis.

BMD is a "must have" device for all medical device companies and surgeons. Without BMD the Implantation

problem is not addressed, regardless of the recent advances in technologies in hip replacement surgery (i.e.; Navigation, Fluoroscopy, MAKO/robotics, accelerometers/gyro meters, etc.). Acetabular component (cup) positioning remains the biggest problem in hip replacement surgery. Implantation is the final step where error is introduced into the system and heretofore no attention has been brought to this problem. Current technologies have brought significant awareness to the position of the implants within the pelvis during surgery, prior to impaction. However, these techniques do not assist in the final step of implantation.

BMD allows all real time information technologies to utilize (a tool) to precisely and accurately implant the acetabular component (cup) within the pelvic acetabulum. BMD device coupled with use of navigation technology and fluoroscopy and (other novel measuring devices) is the only device that will allow surgeons from all walks of life, (low volume/high volume) to perform a perfect hip replacement with respect to acetabular component (cup) placement. With the use of BMD, surgeons can feel confident that they are doing a good job with acetabular component positioning, achieving the "perfect cup" every time. Hence the BMD concept eliminates the most common cause of complications in hip replacement surgery which has forever plagued the surgeon, the patients and the society in general.

It is known to use ultra sound devices in connection with some aspects of THR, primarily for implant removal (as some components may be installed using a cement that may be softened using ultrasound energy). There may be some suggestion that some ultrasonic devices that employ "ultrasound" energy could be used to insert a prosthesis for final fit, but it is in the context of a femoral component and it is believed that these devices are not presently actually used in the process). Some embodiments of BMD, in contrast, can simply be a vibratory device (non ultrasonic, others ultrasonic, and some hybrid impactful and vibratory), and is more profound than simply an implantation device as it is most preferably a positioning device for the acetabular component in THR. Further, there is a discussion that ultrasound devices may be used to prepare bones for implanting a prosthesis. BMD does not address preparation of the bone as this is not a primary thrust of this aspect of the present invention. Some implementations of BMD may include a similar or related feature.

Some embodiments BMD include devices that concern themselves with proper installation and positioning of the prosthesis (e.g., an acetabular component) at the time of implanting of the prosthesis. Very specifically, it uses some form of vibratory energy coupled with a variety of "real time measurement systems" to POSITION the cup in a perfect alignment with minimal use of force. A prosthesis, such as for example, an acetabular cup, resists insertion. Once inserted, the cup resists changes to the inserted orientation. The BMDs of the present invention produce an insertion vibratory motion of a secured prosthesis that reduces the forces resisting insertion. In some implementations, the BMD may produce a positioning vibratory motion that reduces the forces resisting changes to the orientation. There are some implementations that produce both types of motion, either as a single vibratory profile or alternative profiles. In the present context for purposes of the present invention, the vibratory motion is characterized as "floating" the prosthesis as the prosthesis can become much simpler to insert and/or re-orient while the desired vibratory motion is available to the prosthesis. Some embodiments are described as producing vibrating prosthesis with a predetermined vibration pattern. In some implementations, the predeter-

mined vibration pattern is predictable and largely completely defined in advance. In other implementations, the predetermined vibration pattern includes randomized vibratory motion in one or more motion freedoms of the available degrees of freedom (up to six degrees of freedom). That is, whichever translation or rotational freedom of motion is defined for the vibrating prosthesis, any of them may have an intentional randomness component, varying from large to small. In some cases the randomness component in any particular motion may be large and in some cases predominate the motion. In other cases the randomness component may be relatively small as to be barely detectable.

FIG. 10-FIG. 15 relate to an axially-impactful Behzadi Medical Device (BMD4). FIG. 10-FIG. 15 illustrate embodiments including installation of a prosthesis, including installation into living bone. FIG. 10 illustrates an embodiment of the present invention for a sliding impact device 1000, and FIG. 11 illustrates a lengthwise cross-section of sliding impact device 1000 including an attachment of a navigation device 1105.

Device 1000 includes a moveable hammer 1005 sliding axially and freely along a rod 1010. Rod 1010 includes a proximal stop 1015 and distal stop 1020. These stops that may be integrated into rod 1010 to allow transference of force to rod 1010 when hammer 1005 strikes distal stop 1020. At a distal end 1110 of rod 1010, device 1000 includes an attachment system 1115 for a prosthesis 1120. For example, when prosthesis 1120 includes an acetabular cup having a threaded cavity 1125, attachment system 1115 may include a complementary threaded structure that screws into threaded cavity 1125. The illustrated design of device 1000 allows only a perfect axial force to be imparted. The surgeon cannot deliver a blow to the edge of an impaction plate. Therefore the design of this instrument is in and of itself protective, eliminating a problem of "surgeon's mallet hitting on the edge of the impaction plate" or other mis-aligned force transference, and creating undesirable torques, and hence unintentional mal-alignment of prosthesis 1120 from an intended position/orientation. This embodiment may be modified to include a vibratory engine as described herein and illustrated in FIG. 1-9 to have hybrid features as further described herein.

FIG. 12 illustrates a cockup mechanical gun 1200 embodiment, an alternative embodiment to the sliding impact device illustrated in FIG. 10 and FIG. 11. An alternate embodiment includes cockup mechanical gun 1200 that uses the potential energy of a cocked up spring 1205 to create an axially aligned impaction force. Hammer 1005 is drawn back and spring 1205 is locked until an operator actuates a trigger 1210 to release spring 1205 and drive hammer 1005 along rod 1010 to strike distal stop 1020 and transfer an axially aligned impacting force to prosthesis 1120.

Each pull of trigger 1210 creates the same predetermined fixed unit of force (some alternatives may provide a variably predetermined force). The surgeon cannot deliver a mis-aligning impact to an impaction plate with this design. Features of the mechanical cockup may be combined with a vibratory engine/system to produce a hybrid vibratory/axial-impactful system.

FIG. 13 illustrates an alternative robotic device 1300 embodiment to the devices of FIG. 10-12 including a robotic control structure 1305. For example, device 1000 and/or device 1200 may be mounted with robot control structure 1305 and the co-axial impacts may be delivered mechani-

cally by a robotic tool using pneumatic or electric energy to apply, as desired, one or both of vibratory and/or axial impacts.

FIG. 14 illustrates an alternative embodiment 1400 to the devices of FIG. 10-13 including a pressure sensor 1305 to provide feedback during installation. With respect to management of the vibration/force required for some of these tasks, it is noted that with current techniques (the use of the mallet) the surgeon has no indication of how much force is being imparted onto the implant and/or the implant site (e.g., the pelvis). Laboratory tests may be done to estimate what range of force should be utilized in certain age groups (as a rough guide) and then fashioning a device 1400, for example a modified sledgehammer 1000 or cockup gun 1200 to produce just the right amount of force. Typically the surgeon may use up to 2000 N to 3000 N of force to impact a cup into the acetabular cavity. Also, since some embodiments cannot deliver the force in an incremental fashion as described in association with the BMD3 device, device 1400 includes a stopgap mechanism. Some embodiments of the BMD3 device have already described the application of a sensor in the body of the impaction rod. Device 500 includes sensing system/assembly 1405 embedded in device 1400, for example proximate rod 1010 near distal end 1110, and used to provide valuable feedback information to the surgeon. Pressure sensor 1405 can let the surgeon know when the pressures seem to have maximized, whether used for the insertion of an acetabular cup, or any other implant including knee and shoulder implants and rods used to fix tibia and femur fractures. When pressure sensor 1405 is not showing an advance or increase in pressure readings and has plateaued, the surgeon may determine it is time to stop operation/impacting. An indicator, for example an alarm can go off or a red signal can show when maximal peak forces are repeatedly achieved. As noted above, the incorporated patents describe a presence of a pressure sensor in an installation device, the presence of which was designed as part of a system to characterize an installation pulse pattern communicated by a pulse transfer assembly. The disclosure here relates to a pressure sensor provided not to characterize the installation vibration/pulse pattern but to provide an in situ feedback mechanism to the surgeon as to a status of the installation, such as to reduce a risk of fracturing the installation site. Some embodiments may also employ this pressure sensor for multiple purposes including characterization of an applied pulse pattern such as, for example, when the device includes automated control of an impacting engine coupled to the hammer. Other embodiments of this invention may dispose the sensor or sensor reading system within a handle or housing of the device rather than in the central rod or shaft.

FIG. 15 illustrates an alternative device 1500 embodiment to the feedback system of FIG. 14 including a sound sensor 1405 to provide feedback for the embodiments of FIG. 10-14. Surgeons frequently use a change in pitch (sound) to gauge whether an implant (e.g., the cup) has "bottomed out" and device 1500 includes sound sensor 1505 either attached or coupled to rod 1010 or otherwise disposed separately in the operating room. Sound sensor system/assembly 1505 may be used in lieu of, or in addition to, pressure sensor system/assembly 1505 illustrated in FIG. 14.

Previous work have sought to address the two problems noted above culminating in a series of devices identified as BMD2, BMD3, and BMD4. Each of these systems attempts to address the two problems noted above with different and novel methods.

The BMD2 concept proposed a system of correcting a cup (acetabular implant) that had already been implanted in a mis-aligned position. It basically involves a gun like tool with a central shaft and peripheral actuators, which attaches to an already implanted cup with the use of an adaptor. Using computer navigation, through a series of calculations, pure points (specifically defined) and secondary points on the edge of the cup are determined. This process confers positional information to the edge of the cup. The BMD2 tool has actuators that correspond to these points on the cup, and through a computer program, the appropriate actuators impact on specific points on the edge of the cup to adjust the position of the implanted cup. The surgeon dials in the desired alignment and the BMD2 tool fires the appropriate actuators to realign the cup to the perfect position.

In BMD3, we considered that vibratory forces may be applied in a manner to disarm frictional forces in insertion of the acetabular cup into the pelvis. We asked the following questions: Is it possible to insert and position the cup into the pelvis without high energy impacts? Is it possible to insert the cup using vibratory energy? Is insertion and simultaneous alignment and positioning of the cup into the pelvis possible? BMD3 prototypes were designed and the concept of vibratory insertion was proven. It was possible to insert the cup with vibratory energy. The BMD3 principle involved the breaking down of the large momentum associated with the discrete blows of the mallet into a series of small taps, which in turn did much of the same work incrementally, and in a stepwise fashion. We considered that this method allowed modulation of force required for cup insertion. In determining the amount of force to be applied, we studied the resistive forces involved in a cup/cavity interaction. We determined that there are several factors that produce the resistive force to cup insertion. These include bone density (hard or soft), cup geometry (spherical or elliptical), and surface roughness of the cup. With the use of BMD3 vibratory insertion, we demonstrated through FEM studies, that the acetabulum experiences less stress and deformation and the cup experiences a significantly smoother sinking pattern. We discovered the added benefit of ease of movement and the ability to align the cup with the BMD3 vibratory tool. During high frequency vibration the frictional forces are disarmed in both effective and realistic ways, (see previous papers—periodic static friction regime, kinetic friction regime). We have also theorized that certain “mode shapes” (preferred directions of deformation) can be elicited with high frequency vibration to allow easy insertion and alignment of the cup. The pelvis has a resonant frequency and is a viscoelastic structure. Theoretically, vibrations can exploit the elastic nature of bone and it’s dynamic response. This aspect of vibratory insertion can be used to our advantage in cup insertion and deserves further study. Empirically, the high frequency aspect of BMD3 allows easy and effortless movement and insertion of the cup into the pelvis. This aspect BMD3 is clinically significant allowing the surgeon to align the cup in perfect position while the vibrations are occurring.

The BMD4 idea was described to address the two initial problems (uncontrolled force and undesirable torques) in a simpler manner. The undesirable torque and mis-alignment problem from mallet blows were neutralized with the concept of the “slide-hammer” which only allows axial exertion of force. With respect to the amount of force, BMD4 allowed the breaking down of the large impaction forces (associated with the use of the mallet) into quantifiable and smaller packets of force. The delivery of this force occurs through a simple slide-hammer, cockup gun, robotic tool, electric or

pneumatic gun (all of which deliver a sliding mass over a central coaxial shaft attached to the impaction rod and cup. In the BMD4 paper we described two “stop gap” mechanisms to protect the pelvis from over exertion of force. We described a pressure sensor in the shaft of the BMD4 tool that monitors the force pressure in the (tool/cup system). This force sensor would determine when the pressure had plateaued indicating the appropriate time to stop the manual impacts. We also described a pitch/sound sensor in the room, attached to the gun or attached to the pelvis that would assess when the pitch is not advancing, alerting the surgeon to stop applying force. These four aspects of BMD4 (coaxially of the gun, quantification and control of the force, a force sensor, a sound sensor) are separated and independent functions which can could be used alone or in conjunction with each other.

We also recommended that BMD4’s (coaxiality and force control function) and BMD3’s (vibratory insertion) be utilized for application of femoral and humeral heads to trunions, to solve the trunionosis problem.

Materials and Methods: During our development, we evaluated different aspects of the BMD3 and BMD4 prototypes. With BMD3 concept we sought to study several aspects of vibratory insertion:

1. The ultimate effect of frequency on cup insertion
2. The range of impact forces achievable with vibratory insertion.
3. The effect of frequency and vibratory impaction forces on cup insertion and (extraction forces measured to assess the quality of insertion).

With Respect to BMD4 we studied the various aspects of “controlled impaction” utilizing Drop Tests (dynamic testing) and Instron Machine (static testing) to determine the behavior of cup/cavity interaction.

Results:

BMD3

Preliminary results suggest that vibratory insertion of the cup into a bone substitute is possible. It is clear that vibratory insertion at higher frequencies allow easy insertion and alignment of the cup in bone.

It is unclear as to how much higher frequencies contribute to the depth and quality of insertion, as measured by the extraction force, particularly as the cup is inserted deeper into the substrate.

We determined that with vibrational insertion, the magnitude of impaction force is limited and dependent on other mechanical factors such as frequency of vibration and the dwell time. So far 400 lbs of force has been achieved with the BMD/BE prototype, 250 lbs of force have been achieved with the auto hammer prototype, and 150 lbs of force have been achieved by the pneumatic prototype. Further work is underway to determine the upper limit of achievable forces with the Vibrational tools.

During our study of Vibrational insertion we also discovered that vibrational insertion can be unidirectional or bidirectional. For insertion of the cup into a substrate it was felt that unidirectional vibratory insertion (in a positive direction) is ideal. We discovered that unidirectional vibratory withdrawal and bidirectional vibration have other applications such as in revision surgery, preparation of bone, and for insertion of bidirectional prosthetic cups. The directionality of the BMD3 vibratory prototype and its applications will be further discussed in additional applications.

BMD4

With respect to controlled impacts we sought to understand the cup/cavity interaction in a more comprehensive way. We wanted to discover the nature of the resistive forces

involved in a cup/cavity interaction. We felt it was necessary for us to know this information in order to be able to produce the appropriate amount of force for both BMD3 “vibratory insertion” and BMD4 “controlled impaction”. We proposed and conducted dynamic Drop tests and static Instron tests to evaluate the relationship between the cup and the cavity. Instron testing is underway and soon to be completed. The drop tests were conducted using a Zimmer continuum 62 mm cup and 20 lbs urethane foam. Multiple drop tests were conducted at various impaction forces to evaluate the relationship between applied force (TMIF) and displacement of the cup, and the quality of insertion (Extraction Force). We discovered that for insertion of a cup into a cavity the total resistive force can be generally represented by an exponential curve. We have termed this resistive force the FR, which is determined by measuring the relationship of applied force (TMIF) and cup insertion for any particular (cup/cavity) system. FR is a function of several factors including the spring like quality of bone which applies a compressive resistive force (Hooke’s law  $F=kx$ ) to the cup, the surface roughness’s of the cup, and the geometry of the cup (elliptical v spherical).

Definitions

FR=Force Resistance (total resistive force to cup insertion over full insertion of the cup into bone substitute); TMIF=Theoretical Maximum Impact Force (external force applied to the system) to accomplish cup insertion; and mIF=measured Impact Force (force measured within the system) (as measured on the BMD3 and BMD4) tools.

BMD/BE	vibratory prototype
Auto hammer	vibratory prototype
Pneumatic	vibratory prototype

Evaluation of the drop test data reveals a nonlinear (exponential) curve that represents FR. We contemplated that the cup/cavity system we used (62 m Continuum cup and 20 lb urethane foam) has a specific profile or “cup print”, and that this profile was important to know in advance so that application of force can be done intelligently.

We observed the general shape of FR to be non-linear with three distinct segments to the curve, which we have termed A, B, and C. In section A the resistive force is low (from 100 to 350 lbs) with a smaller slope. In section A, if an applied force (TMIF) greater than this FR is applied, it can produce up to 55% cup insertion and 30% extraction force. A TMIF that is tuned to cross FR at the A range is at risk for poor seating and pull out. In section B the resistive forces range from 500 lbs to 900 lbs. The slope rises rapidly and is significantly larger than in section A (as expected in an exponential curve). In section B, if a TMIF greater than this FR is applied, it can produce between 74% to 90% cup insertion and between 51% to 88% extraction force. We name this section the “B cloud”, to signify that the applied force (TMIF) should generally be tuned to this level to obtain appropriate insertion with less risk for fracture and or pull out, regardless of whether the TMIF is applied by a BMD3 or BMD4 tool. In section C the curve asymptotes, with small incremental increase in cup insertion and large increases in extraction force. The clinical value of the higher extraction force is uncertain with increased risk of fracture. A TMIF that is tuned to cross the FR at the C range is high risk for fracture and injury to the pelvis.

FIG. 16-FIG. 25 relate to a hybrid Behzadi Medical Device (BMD7) which may combine vibratory and axial impactful forces from BMD3 and BMD4; and FIG. 16-FIG. 25 illustrate a set of Force Resistance (FR) curves for various experimental configurations.

Discussion:

The FR curve represents a very important piece of information. To the surgeon the FR curve should have the same significance that a topographical map has to a mountaineer. Knowing the resistive forces involved in any particular cup/cavity interaction is necessary in order to know how much force is necessary for insertion of the cup. We believe that in vitro, all cup/cavity interactions have to be studied and qualified. For example it is important to know if the same 62 mm Continuum cup we used in this experiment is going to be used in a 40 year old or 70 year old person. The variables that will determine FR include bone density which determines the spring like quality of bone that provides compression to the cup, the geometry of the cup, and the surface roughness of the cup. Once the FR for a particular cup and bone density is known, the surgeon is now armed with information he/she can use to reliably insert the cup. This would seem to be a much better way to approach cup insertion than banging clueless on a an impaction rod with a 4 lbs mallet. Approaching FR with an eye for the B range will assure that the cup is not going to be poorly seated with risk of pullout or too deeply seated with a risk of fracture.

We have contemplated approaching FR with both vibratory (BMD3) insertion and controlled (BMD4 impaction). Each of these systems has advantages and disadvantages that continue to be studied and further developed.

For example we believe that vibratory insertion with the current BMD3 prototypes have the clear advantage of allowing the surgeon ease of movement and insertion. The surgeon appears to be able to move the cup within the cavity by simple hand pressure to the desired alignment. This provides the appearance of a frictionless state. However, to date we have not quite been able to achieve higher forces with the BMD3 tools. So far we have been able to achieve up to 150 lb (pneumatic), 250 (auto hammer), and 400 lb (BMD/BE) in our vibratory prototypes. This level of applied force provides submaximal level of insertion and pull out force. We believe that ultimately, higher forces can be achieved with the vibratory BMD3 tools (500 to 900 lbs) which will provide for deep and secure seating.

With regards to this concern, we have contemplated a novel approach to address the current technological deficits. We propose a combination of BMD3 vibratory insertion with controlled BMD4 impaction. The BMD3 vibratory tool (currently at 100 lbs to 400 lbs) is used to initiate the first phase of insertion allowing the surgeon to easily align and partially insert the prosthesis with hand pressure, while monitoring the alignment with the method of choice (A-frame, navigation, C-arm, IMU). The BMD4 controlled impaction is then utilized to apply quantifiable packets of force (100 lbs to 900 lbs) to the cup to finish the seating of the prosthesis in the B range of the FR curve. This can be done either as a single step fashion or “walking up the FR curve” fashion.

Alternatively, BMD4 controlled impaction can be utilized to insert the cup without the advantage of BMD3 tool. The BMD4 technique provides the ability to quantify and control the amount of applied force (TMIF) and provides coaxiality to avoid undesirable torques during the impaction. It is particularly appealing for robotic insertion where the position of the impaction rod is rigidly secured by the robot.

We have contemplated that the BMD4 controlled impaction can be utilized in two separate techniques.

The first technique involves setting the impaction force within the middle of the B Cloud where 74% to 90% insertion and 51% to 88% extraction forces could be expected, and then impacting the cup. The BMD4 tool acts through the slide hammer mechanism to produce a specific amount of force (for example 600 lbs) and deliver it axially. This can be considered a single step mechanism for use of BMD4 technique.

The second method involves “walking the forces” up the FR curve. In this system the applied force (TMIF) is provided in “packets of energy”. For example, the BMD4 gun may create 100 lbs packets of force. It has an internal pressure sensing mechanism that allows the tool to know if insertion is occurring or not. A force sensor and a corresponding algorithm within the BMD4 tool is described herein. The force sensor monitors the measured impact force (mIF) and the corresponding change in mIF within the system. As we have described before, when impacts are applied to an “inelastic” system, energy is lost at the interface as insertion occurs and heat is produced. This loss of energy is measured and calculated in the (change) or slope of mIF. Consecutive mIF s have to be measured and compared to previous mIFs to determine if insertion is occurring. As long as insertion is occurring impactions will continue. When the change in mIF approaches zero, insertion is not occurring, there is no dissipation of energy within the system. The slope or (change) in mIF has approached zero. At this point the cup and cavity move together as a rigid system (elastic), and all the kinetic energy of TMIF is experienced by the cup/cavity system and mIF is measured to be the same as TMIF. When insertion is not occurring mIF has approached TMIF and change in mIF has approached zero.

At this point the next step is taken and TMIF is increased, for example by a packet of 100 lbs. The subsequent mIF measurements are taken and if the slope (change) in mIF is high, insertion is occurring with the new TMIF, therefore impacts should continue until the change in mIF approaches zero again.

Conversely, if an increase in TMIF results in an increase in mIF but not the change (slope) in mIF, we know the cup is no longer inserting and has reached its maximum insertion point. We should point out that when the cup stops inserting, this also the point where FR exceeds TMIF. In this manner, we have contemplated an algorithm that allows for monitoring of the forces experienced in the system. Based on this algorithm, a system is created in which the surgeon can walk the TMIF up the FR curve while being given real time feedback information as to when to stop impaction.

The general idea is that at some point in time the cup will no longer insert (even though not fully seated). This algorithm determines when no further insertion is occurring. The surgeon will be content to stop impaction in the B cloud range of the FR curve.

We have also discovered that  $mIF = TMIF + FR$ . The value of TMIF is known. The value of mIF is measured. The FR can be calculated live during insertion by the BMD3 and BMD4 tools and shown to the surgeon as a % or (probability of fracture). This calculation and algorithm could be very significant.

A few words on Alignment:

We have so far proposed that the BMD3 vibratory tool be used to insert the cup under monitoring by current alignment techniques (navigation,

Fluoroscopy, A-frame). We have now devised a novel system, which we believe will be the most efficacious

method of monitoring and assuring alignment. This system relies of Radlink (Xrays) and PSI (patient specific models) to set and calibrate the OR space as the first step.

As a second step, it utilizes a novel technique with use of IMU technology to monitor the movement of the reamers, tools (BMDs) and impaction rods. This is discussed in a separate paper. Needs to be written up.

Summary and Recommendations for BMD/BE project.

1. We propose a novel system of inserting and aligning the acetabular cup in the human pelvic bone. This technique involves combining aspects of the BMD3 and BMD4 prototypes, initially utilizing BMD3 vibratory insertion to partially insert and perfectly align the acetabular cup into the pelvis. Subsequently switching to the BMD4 controlled impaction technique to apply specific quantifiable forces for full seating and insertion. In this manner we are combining the proven advantages of the vibratory insertion prototype with the advantages of the controlled impaction prototype.

2. We have described a force sensing system within the BMD tool with capacity to measure the force experienced by the system (mIF) and calculate the change in mIF with respect to time or number of impacts. This system provides a feedback mechanism for the BMD tools as to when impaction should stop.

3. We have described the FR curve which is a profile (cup print) of any cup/cavity interaction. And have recommended that this “cup print” for most cup/cavity interactions be determined in vitro to arm the surgeon with information necessary for cup insertion. We feel that every cup/cavity interaction deserves study to determine its FR profile. Once the FR is known, BMD3 and BMD4 tools can be used to intelligently and confidently apply force for insertion of the acetabular prosthesis.

4. We have described two methods for use of BMD4 controlled cup impaction

a. Setting the TMIF to the middle of the B cloud (somewhere between 500 to 900 range for our FR) and producing a single stage impaction.

b. Producing sequential packets of increasing TMIF in order to walk TMIF up the FR curve. (Increasing packets of 100 lbs or 200 lbs)

5. We have also discovered that  $mIF = TMIF + FR$ . The value of TMIF is known. The value of mIF is measured. The FR can be calculated live during insertion by the BMD3 and BMD4 tools and shown to the surgeon as a % or (probability of fracture). This calculation and algorithm could be very significant in help the surgeon to insert the cup deeply without fracture.

Concept 5W and 1H: 1. Who: The surgeon; 2. What: Cup insertion; 3. When: When to increase the force and when to stop; 4. Where: PSI and Radlink to set. IMU to monitor alignment and position; 5. Why: Consistency for the surgeon and the patient; and 6. How: FR for every cup/cavity interaction, BMD3 and BMD4 tools.

In FIG. 17-FIG. 24, a series of FR Curves are presented in which a value of TMIF is applied and a number of impacts is measured in which MIF approaches TMIF (delta mIF approaches zero, and FR to overtake TMIF, along with values for impacts, displacement, and extractive force. Table III summarizes these values for each of these Figures.

TABLE III

FR Curve Values				
FIG.	TMI (lbf)	Impacts (No)	Displacement (mm)	Extraction Force (lbf)
17	173	47	1.4	16
18	368	52	3.5	58
19	547	27	4.7	105
20	698	23	6	152
21	892	16	5.6	172
22	1092	9	6.1	186
23	1531	6	6.2	191
24	1774	4	6.3	195

FIG. 25 identifies the Bcloud, a fracture zone, and a region that may include an undesirable risk of too little installation and too low extractive force resisting removal of a prosthesis after installation.

FIG. 26-FIG. 30 relate to a particular implementation of a hybrid BMD 2600 which selectively provides vibratory and axial impactful forces; FIG. 26 illustrates an exterior perspective view of BMD 2600; FIG. 27 illustrates a first interior perspective view of BMD 2600; FIG. 28 illustrates a second interior perspective view of BMD 2600 of FIG. 27; FIG. 29 illustrates a first actuator embodiment for use with BMD 2600 of FIG. 26; and FIG. 30 illustrates a second actuator embodiment for use with BMD 2600 of FIG. 26.

BMD3 (e.g., vibratory system) and BMD4 (e.g., discrete axial impacts) utilize different actuator designs to generate different benefits when inserting the acetabular cup. While vibratory insertion has shown benefit with cup realignment, the added signal noise of rapid impacts in succession can, in some cases, pose a significant challenge to inferring the resistance curve of the cup. Conversely, discrete impacts may allow easier control of cup insertion at a detriment to the ease of insertion and realignment.

While two separate devices may be used in conjunction, it has been proposed to develop a single device that would allow the user to easily switch between insertion modes, allowing vibratory actuation at the beginning of the insertion process, and discrete impacts once cup alignment is established. As illustrated, a common motor selectively drives different gear trains depending upon a gear selector switch to set a BMD 2600 into either a BMD3 mode or a BMD4 mode. The discrete mode would switch to a gearing sufficiently low enough that the time between impacts could be treated as discrete events, while the vibratory mode would switch to a gearing high enough to generate impacts of sufficiently high frequency. This would allow the same instrument shaft spring to be used to generate all impacts. A rotary encoder or hall sensor placed on the cam shaft could be used in order to allow the system to know when an impact will take place. Using this information in discrete mode, the system could compress the spring to its full displacement and then stop, allowing the user to subsequently generate an impact with a pull of the trigger. The system would then compress the spring again, and would not allow release until the trigger is cycled. That is, in the BMD3 mode, the system continues to vibrate when the trigger is actuated. In the BMD4 mode, each trigger pull results in an initiation of a discrete axial impact set of pulses (e.g., number of discrete pulses in the train is 1 but some systems may initiate a limited number of pulses in discrete fashion). Additionally, it is possible some embodiments may provide that the axial forces applied in the BMD4 mode be greater magnitude than the vibratory impacts in BMD3 mode.

There are many different ways to implement BMD3 and BMD4 modes separately, some of which are detailed in the incorporated patent applications. Additionally, US patent application Ser. No. 15/235,032 details additional embodiments of BMD4 devices and US patent application Ser. No. 15/235,078 details additional embodiments of BMD3 insertion/alignment devices, these applications are hereby expressly incorporated by reference herein in their entireties for all purposes.

BMD 2600 includes selector, a cam, responsive to different gear trains (high and low), to operate on an actuator and controlled by an encoder. The actuator includes a spring mechanism, alternatives illustrated in FIG. 29 and FIG. 30. The motor drives the cam to compress the spring of the actuator until sufficiently compressed and then, in response to a trigger actuation, the energy of the actuator is delivered axially along a shaft coupled to the cup. Preferably one force application per trigger actuation, once sufficient energy is stored in the actuator. In a BMD3 operation, this actuator is driven faster to impart a vibratory motion to the cup.

The proposed solution will have the actuator control the amount of energy being transmitted during each impact. This could be done in a number of ways, with two examples explained below.

Impact Energy Control Mechanism, Spring Preload

The first approach (FIG. 29) would have the device compress a spring of known spring constant by retracting the instrument shaft by a fixed distance. This shaft displacement is performed via a rotating cam which in turn uses a rocker to convert the rotational motion to linear movement. The device would be able to vary the energy stored within the shaft spring for each impact by varying the amount of spring preload (i.e. the amount of spring compression immediately after an impact has occurred).

The preload is varied using a spring compression insert. The spring compression insert includes external threads which mates to the housing of the tool. A gear head is attached to the top face of the spring compression insert, which mates to a motor via a worm gear or other appropriate mechanism (e.g. chain drive, belt drive, gear train, etc.). The vertical position of the insert relative to the shaft spring can be increased or decreased by incrementing the motor either clockwise or counterclockwise. This in turn will rotate the compression insert, which will raise or lower via its external threading.

Motor design can use a stepper motor, brushed DC, or brushless DC. Depending on the accuracy required a rotary encoder can be incorporated, being placed either on the output shaft of the spring preload motor or on the spring compression gear face.

The second example (FIG. 30) would have a static spring preload, and would instead use friction to control the amount of energy transferred for each impact. The shaft spring would strike a hollow tube, which would fit over a distal instrument shaft. One or more ball plungers would be threaded through the wall of the tube, pressing onto the side of the instrument shaft. The insertion depth of the ball plungers could be controlled via a motor and ball detent control gear, which in turn would determine the friction forces between the tube and the instrument shaft. The ball detent control gear would have a cam inner profile, allowing the depth of the ball plungers to be varied depending on the rotational position of the gear. The friction force generated by the ball plungers would determine the amount of energy that would be transmitted to the instrument shaft, with any excess spring forces resulting in slip between the tube and shaft.

The system and methods above has been described in general terms as an aid to understanding details of preferred embodiments of the present invention. In the description herein, numerous specific details are provided, such as examples of components and/or methods, to provide a thorough understanding of embodiments of the present invention. Some features and benefits of the present invention are realized in such modes and are not required in every case. One skilled in the relevant art will recognize, however, that an embodiment of the invention can be practiced without one or more of the specific details, or with other apparatus, systems, assemblies, methods, components, materials, parts, and/or the like. In other instances, well-known structures, materials, or operations are not specifically shown or described in detail to avoid obscuring aspects of embodiments of the present invention.

Reference throughout this specification to “one embodiment”, “an embodiment”, or “a specific embodiment” means that a particular feature, structure, or characteristic described in connection with the embodiment is included in at least one embodiment of the present invention and not necessarily in all embodiments. Thus, respective appearances of the phrases “in one embodiment”, “in an embodiment”, or “in a specific embodiment” in various places throughout this specification are not necessarily referring to the same embodiment. Furthermore, the particular features, structures, or characteristics of any specific embodiment of the present invention may be combined in any suitable manner with one or more other embodiments. It is to be understood that other variations and modifications of the embodiments of the present invention described and illustrated herein are possible in light of the teachings herein and are to be considered as part of the spirit and scope of the present invention.

It will also be appreciated that one or more of the elements depicted in the drawings/figures can also be implemented in a more separated or integrated manner, or even removed or rendered as inoperable in certain cases, as is useful in accordance with a particular application.

Additionally, any signal arrows in the drawings/Figures should be considered only as exemplary, and not limiting, unless otherwise specifically noted. Combinations of components or steps will also be considered as being noted, where terminology is foreseen as rendering the ability to separate or combine is unclear.

The foregoing description of illustrated embodiments of the present invention, including what is described in the Abstract, is not intended to be exhaustive or to limit the invention to the precise forms disclosed herein. While specific embodiments of, and examples for, the invention are described herein for illustrative purposes only, various equivalent modifications are possible within the spirit and scope of the present invention, as those skilled in the relevant art will recognize and appreciate. As indicated, these modifications may be made to the present invention in light of the foregoing description of illustrated embodiments of the present invention and are to be included within the spirit and scope of the present invention.

Thus, while the present invention has been described herein with reference to particular embodiments thereof, a latitude of modification, various changes and substitutions are intended in the foregoing disclosures, and it will be appreciated that in some instances some features of embodiments of the invention will be employed without a corresponding use of other features without departing from the scope and spirit of the invention as set forth. Therefore, many modifications may be made to adapt a particular

situation or material to the essential scope and spirit of the present invention. It is intended that the invention not be limited to the particular terms used in following claims and/or to the particular embodiment disclosed as the best mode contemplated for carrying out this invention, but that the invention will include any and all embodiments and equivalents falling within the scope of the appended claims. Thus, the scope of the invention is to be determined solely by the appended claims.

What is claimed as new and desired to be protected by Letters Patent of the United States is:

1. A system of inserting and aligning an acetabular cup in the human pelvic bone, including selectively combining aspects of a vibratory BMD3 including a set of vibratory aspects and an axially-impacting BMD4 including a set of impacting aspects, including initially utilizing BMD3 vibratory insertion to partially insert and align the acetabular cup into the pelvis, and subsequently switching to a BMD4 controlled impaction technique to apply specific quantifiable forces for seating and insertion, wherein said set of vibratory aspects and said set of impacting aspects are combined in a single device configured for non-overlapping applications of said sets of aspects to seat and insert the acetabular cup.

2. A hybrid tool for installing a prosthesis into a prepared cavity in a portion of a bone, comprising:

- a motor producing a motive force;
- a shaft for coupling to the prosthesis; and
- a force transfer mechanism, coupled to said motor and to shaft, including a first set of components configured to produce a vibration of the prosthesis responsive to said motive force, a second set of components configured to produce a set of one or more discrete impact forces and transfer said set of one or more impact forces to the prosthesis, and a selector coupled to said sets of components, said selector activating no more than one of said sets of components at any given moment wherein said activated sets of components are configured to install the prosthesis into the prepared cavity.

3. The hybrid tool of claim 2 wherein said motive force includes a rotational motion, wherein said vibration includes a linear vibratory motion mechanically derived from said rotational motion, and wherein said each said impact force includes a discrete linear impacting force mechanically derived from said rotational motion.

4. A method for installing a prosthesis into a portion of a bone using a single device, comprising:

- producing a motive force using the single device;
- engaging the prosthesis with a shaft of the single device;
- selecting, using a mode selector, one of an impact mode or a vibrate mode for the single device;
- applying, using an impactor coupled to said shaft and responsive to said mode selector and to said motive force, a set of one or more discrete impacts to the prosthesis when the single device is operated in said impact mode;
- applying, using a pulse generator coupled to said shaft and responsive to said mode selector and to said motive force, a series of vibrations to the prosthesis when the single device is operated in said vibrate mode; and
- switching, using said mode selector, said mode of the single device wherein the single device operates in at most one of said modes at any moment.

5. The hybrid tool of claim 2 wherein said motor includes a single motor producing said motive force for both said sets of components wherein no more than one set of components are activated by said motive force at any particular time.

6. The hybrid tool of claim 2 wherein the prepared bone includes a prepared cavity, wherein the prosthesis includes an implant configured for a pressfit fixation into said prepared cavity, wherein said vibration is configured for implantation at a first depth within 95% of predetermined depth into said prepared cavity and a predetermined orientation with respect to said prepared cavity, and wherein said impact force is configured to advance said pressfit fixation to a second depth deeper than said first depth.

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