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(54) **CONTROL OF AN ULTRASONIC HANDPIECE**

STEUERUNG EINES ULTRASCHALLHANDSTÜCKS

COMMANDE D'UNE PIÈCE À MAIN ULTRASONORE

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Description

BACKGROUND

[0001] Ultrasonic handpieces for performing surgical procedures are typically capable of cutting a variety of different types of tissue. In many surgical procedures, however, a practitioner desires to cut only some types of tissue while keeping other types of tissue intact.

[0002] An ultrasonic surgical apparatus with power reduction according to US 2015/0094723 A1 includes a probe with an operative edge or surface at a distal end, an electromechanical transducer connected to the probe, and an activation circuit connected to the transducer for supplying thereto an electrical waveform having an ultrasonic frequency and an amplitude. The activation circuit includes a signal generator and further includes a power reduction circuit operatively connected to the signal generator for inducing the signal generator to automatically reduce the amplitude of the waveform upon a sensing by the power reduction circuit of reduced load on the probe.

[0003] A system for actuating an ultrasonic handpiece with a tip is known from WO 2015/021216 A1. According to one example, the voltage and frequency of the drive signal applied to the handpiece drivers is a function of the equivalent of current through the mechanical components of the handpiece and tip and the frequency responsiveness of these components.

SUMMARY

[0004] A system for controlling vibrations of a tip of an ultrasonic handpiece is defined in claim 1. Optional features are defined in the dependent claims. No methods of surgery or treatment are claimed.

[0005] According to a first exemplary aspect, a control console for controlling vibrations of an ultrasonic handpiece is provided. The control console includes a signal generator for generating an AC drive signal applied to a transducer of the ultrasonic handpiece, which is coupled to and configured to vibrate a tip of the ultrasonic handpiece responsive to receiving the AC drive signal. Responsive to the signal generator sourcing the AC drive signal to the ultrasonic handpiece to vibrate the tip, the processor is configured to determine a property relating to a stiffness of tissue being contacted by the vibrating tip. The processor is then configured to adjust the AC drive signal output by the signal generator based on the determined property.

[0006] According to a second exemplary aspect, a method of operating the control console and/or performing the functions of the control console of the first aspect is provided.

[0007] Any of the above exemplary aspects can be implemented with any of the following implementations:
In one implementation, the ultrasonic handpiece is coupled to the control console and/or defines a lumen for providing suction at a surgical site.

[0008] In one implementation, the control console includes a sensor for measuring a voltage of the AC drive and a sensor for measuring a current of the AC drive signal. The processor is coupled to the sensors and configured to determine a tissue stiffness value for the tissue being contacted by the tip based on the measured current and voltage of the AC drive signal, and adjust the AC drive signal output by the signal generator based on the tissue stiffness value.

[0009] According to a third exemplary aspect, a control console for controlling vibrations of an ultrasonic handpiece is provided. The control console includes a signal generator for generating an AC drive signal applied to a transducer of the ultrasonic handpiece, which is coupled to and configured to vibrate a tip of the ultrasonic handpiece responsive to receiving the AC drive signal. The control console further includes a sensor for measuring a voltage of the AC drive signal, a sensor for measuring a current of the AC drive signal, and a processor coupled to the sensors and the signal generator. The processor is configured to determine a first displacement level for the tip that is a maximum displacement level for the tip and receive a tissue response model defining a stiffness threshold and second displacement levels for the tip that are each less than the first displacement level and associated within the tissue response model with a different potential tissue stiffness value greater than the stiffness threshold. The processor is further configured to determine a tissue stiffness value of tissue being contacted by the tip based on the measured voltage and current of the AC drive signal, and determine whether the determined stiffness value is less than or greater than the stiffness threshold. The processor is further configured to, responsive to determining that the determined stiffness value is less than the stiffness threshold, set a target displacement level for the tip of the ultrasonic handpiece to the first displacement level, and responsive to determining that the stiffness value is greater than the stiffness threshold, set the target displacement for the tip to the second displacement level associated with the potential tissue stiffness value corresponding to the determined tissue stiffness value. The processor is further configured to adjust the AC drive signal output by the signal generator to achieve the set target displacement level.

[0010] According to a fourth exemplary aspect, a method of operating the control console and/or performing the functions of the control console of the third aspect is provided.

[0011] Any of the above exemplary aspects can be combined in part, or in whole. Furthermore, any of the above

exemplary aspects above can be implemented with any of the following implementations:

In one implementation, the ultrasonic handpiece is coupled to the control console and/or defines a lumen for providing suction at a surgical site.

[0012] In one implementation, the processor is configured to determine, as the determined tissue stiffness value, a mechanical resistance of the ultrasonic handpiece based on the measured voltage and current of the AC drive signal, the stiffness threshold is defined by a mechanical resistance threshold, and the potential tissue stiffness values are defined by potential mechanical resistances of the ultrasonic handpiece.

[0013] In one implementation, the processor is configured to determine the mechanical resistance of the ultrasonic handpiece based on the measured voltage and current of the AC drive signal by being configured to determine a capacitance of the transducer of the ultrasonic handpiece, determine a resonant frequency of the ultrasonic handpiece, set a frequency of the AC drive signal to the determined resonant frequency of the ultrasonic handpiece, calculate a current through mechanical components of the ultrasonic handpiece based on the capacitance of the transducer, the frequency of the AC drive signal, the measured voltage of the AC drive signal, and the measured current of the AC drive signal, and calculate the mechanical resistance of the ultrasonic handpiece based on the current through the mechanical components of the ultrasonic handpiece and the measured voltage of the AC drive signal.

[0014] In one implementation, the tissue response model defines the second displacement levels such that the second displacement levels decrease as the potential tissue stiffness values increase.

[0015] In one implementation, the stiffness threshold is a first stiffness threshold, the tissue response model defines a third displacement level for the tip that is a non-zero minimum tip displacement level for the tip and is less than each second displacement level, and defines a second stiffness threshold that is greater than the potential tissue stiffness values. The processor is configured to, responsive to the determined tissue stiffness value being greater than the second stiffness threshold, set the target displacement level for the tip to the third displacement level, and responsive to the determined tissue stiffness value being greater than the first stiffness threshold and less than the second stiffness threshold, set the target displacement level for the tip to the second displacement level associated with the potential tissue stiffness value corresponding to the determined tissue stiffness value.

[0016] In one implementation, at least one of the first displacement level, the second displacement level, the third displacement level, the first stiffness threshold, the second stiffness threshold, or the relationship between the second displacement levels and the potential tissue stiffness values is based on a user-setting.

[0017] In one implementation, the relationship between the second displacement levels and the potential tissue stiffness values is defined by a negative linear function that maps the first stiffness threshold to the first displacement level and maps the second stiffness threshold to the third displacement level.

[0018] In one implementation, the relationship between the second displacement levels and the potential tissue stiffness values is defined by a decreasing curve function that maps the first stiffness threshold to the first displacement level and maps the second stiffness threshold to the third displacement level.

[0019] In one implementation, the tissue response model is configured for reducing ablation of a type of tissue during operation of the ultrasonic handpiece, and the relationship between the second displacement levels and the potential tissue stiffness values is defined by a curved decreasing function that is based on a voltage of the AC drive signal corresponding to puncture of the type of tissue.

[0020] In one implementation, the curved decreasing function is further based on a resistance offset corresponding to vibrating components of the ultrasonic handpiece.

[0021] In one implementation, the tissue response model is a first tissue response model, and control console further comprises a memory storing the first tissue response model and a second tissue response model configured for ablating stiffer tissue than the first tissue response model. The processor is configured to receive a user selection of the first tissue response model and the second tissue response model via a user interface. The processor is configured to, responsive to the user selection of the first tissue response model and to the tip being placed against a first type of tissue, set the target displacement level to the first displacement level, and responsive to the user selection of the first tissue response model and to the tip being placed against a second type of tissue stiffer than the first type of tissue, set the target displacement level to a displacement level less than the first displacement level. The processor is further configured to, responsive to the user selection of the second tissue response model and to the tip being placed against the first and second types of tissues, set the target displacement level to the first displacement level.

[0022] In one implementation, the stiffness threshold is a first stiffness threshold, the potential tissue stiffness values are first potential tissue stiffness values, the second tissue response model defines a second stiffness threshold that is greater than the first stiffness threshold and associates the second displacement levels each with a different second potential tissue stiffness value greater than the second stiffness threshold, and at least one of the first potential tissue stiffness values is less than each of the second potential tissue stiffness values.

[0023] In one implementation, the relationship between the second displacement levels and the second potential tissue stiffness values is defined by a function that is based on a voltage of the AC drive signal corresponding to puncture of a third type of tissue stiffer than the second type of tissue.

[0024] In one implementation, the target displacement level for the tip corresponds to a target current through mechanical components of the ultrasonic handpiece, and the processor is configured to adjust the AC drive signal output by the signal generator to achieve the set target displacement level by being configured to adjust the AC drive signal so that an actual current through the mechanical components of the ultrasonic handpiece substantially equals the target current through the mechanical components of the ultrasonic handpiece.

[0025] According to a fifth exemplary aspect, a control console for controlling vibrations of an ultrasonic handpiece is provided. The control console includes a signal generator for generating an AC drive signal applied to a transducer of the ultrasonic handpiece, which is coupled to and configured to vibrate a tip of the ultrasonic handpiece responsive to receiving the AC drive signal. The control console further includes a processor coupled to the signal generator. The processor is configured to activate a stall mode in which displacement of the tip of the ultrasonic handpiece caused by the ultrasonic handpiece is non-zero and insufficient to ablate a tissue being contacted by the tip, and maintain a resonant frequency of the ultrasonic handpiece while the stall mode is active.

[0026] According to a sixth exemplary aspect, a method of operating the control console and/or performing the functions of the control console of the fifth aspect is provided.

[0027] Any of the above exemplary aspects can be combined in part, or in whole. Furthermore, any of the above exemplary aspects above can be implemented with any of the following implementations:
In one implementation, the ultrasonic handpiece is coupled to the control console and/or defines a lumen for providing suction at a surgical site.

[0028] In one implementation, the processor is configured to receive user input indicating a type of tissue desired to remain intact, and responsive to the tip being placed against the type of tissue during vibration of the tip by the control console, activate the stall mode.

[0029] In one implementation, the control console further comprises a sensor for measuring a voltage of the AC drive signal and a sensor for measuring a current of the AC drive signal. The processor is configured to determine a tissue stiffness value based on the measured voltage and current of the AC drive signal, determine whether the tissue stiffness value is greater than a stiffness threshold, and activate the stall mode responsive to determining that the tissue stiffness value is greater than the stiffness threshold.

[0030] In one implementation, the stiffness threshold is defined by a mechanical resistance threshold, and the processor is configured to determine, as the tissue stiffness value, a mechanical resistance of the ultrasonic handpiece based on the measured voltage and current of the AC drive signal.

[0031] In one implementation, the processor is configured to determine a second mechanical resistance of the ultrasonic handpiece based on a second voltage and current of the AC drive signal measured by the sensors when the stall mode is active, determine whether the second mechanical resistance is less than the stiffness threshold, and responsive to determining that the second mechanical resistance is less than the stiffness threshold: deactivate the stall mode, and adjust the AC drive signal output by the signal generator such that the displacement of the tip caused by the adjusted AC drive signal is at the maintained resonant frequency and is capable of ablating the tissue being contacted by the tip.

[0032] According to a seventh exemplary aspect, a control console for controlling vibrations of an ultrasonic handpiece is provided. The control console includes a signal generator for generating an AC drive signal applied to a transducer of the ultrasonic handpiece, which is coupled to and configured to vibrate a tip of the ultrasonic handpiece responsive to receiving the AC drive signal. The control console further includes a sensor for measuring a voltage of the AC drive signal, a sensor for measuring a current of the AC drive signal, and a processor coupled to the sensors and the signal generator. The processor is configured to determine a property of the ultrasonic handpiece associated with a tissue being contacted by the tip based on the measured voltage and the measured current of the AC drive signal, determine a target displacement for the tip based on the determined property and a puncture voltage corresponding to the tissue being contacted by the tip, and adjust the AC drive signal output by the signal generator to achieve the determined target displacement for the tip.

[0033] According to an eighth exemplary aspect, a method of operating the control console and/or performing the functions of the control console of the seventh aspect is provided.

[0034] Any of the above exemplary aspects can be combined in part, or in whole. Furthermore, any of the above aspects above can be implemented with any of the following implementations:
In one implementation, the ultrasonic handpiece is coupled to the control console and/or defines a lumen for providing suction at a surgical site.

[0035] According to a ninth exemplary aspect, a control console for controlling vibrations of an ultrasonic handpiece is provided. The control console includes a signal generator for generating an AC drive signal applied to a transducer of the ultrasonic handpiece, which is coupled to and configured to vibrate a tip of the ultrasonic handpiece responsive to receiving the AC drive signal. The control console further includes a sensor for measuring a voltage of the AC drive signal, a sensor for measuring a current of the AC drive signal, a memory storing a first tissue response model and a second tissue response model configured for ablating stiffer tissue than the first tissue response model, and a processor coupled to the sensors, memory, and signal generator. The processor is configured to determine a first displacement

level for the tip that is a maximum displacement level for the tip and receive a user selection of the first tissue response model and the second tissue response model via a user interface. The processor is further configured to, responsive to the user selection of the first tissue response model and to the tip being placed against a first type of tissue, set a target displacement level for the tip to the first displacement level, and responsive to the user selection of the first tissue response model and to the tip being placed against a second type of tissue stiffer than the first type of tissue, set the target displacement level to a second displacement level that is less than the first displacement level. The processor is further configured to, responsive to the user selection of the second tissue response model and to the tip being placed against the first and second types of tissue, set the target displacement level to the first displacement level. The processor is further configured to adjust the AC drive signal output by the signal generator to achieve the set target displacement level for the tip.

[0036] According to a tenth exemplary aspect, a method of operating the control console and/or performing the functions of the control console of the ninth aspect is provided.

[0037] Any of the above exemplary aspects can be combined in part, or in whole. Furthermore, any of the above exemplary aspects above can be implemented with any of the following implementations:

In one implementation, the ultrasonic handpiece is coupled to the control console and/or defines a lumen for providing suction at a surgical site.

[0038] According to an eleventh exemplary aspect, a control console for controlling vibrations of an ultrasonic handpiece is provided. The control console includes a signal generator for generating an AC drive signal applied to a transducer of the ultrasonic handpiece, which is coupled to and configured to vibrate a tip of the ultrasonic handpiece responsive to receiving the AC drive signal. The control console further includes a sensor for measuring a voltage of the AC drive signal, a sensor for measuring a current of the AC drive signal, and a processor coupled to the sensors and the signal generator. The processor is configured to determine a mechanical resistance of the ultrasonic handpiece based on the measured voltage and the measured current of the AC drive signal, determine a target displacement for the tip based on the mechanical resistance, and adjust the AC drive signal output by the signal generator to achieve the determined target displacement for the tip.

[0039] According to a twelfth exemplary aspect, a method of operating the control console and/or performing the functions of the control console of the eleventh aspect is provided.

[0040] Any of the above exemplary aspects can be combined in part, or in whole. Furthermore, any of the above exemplary aspects above can be implemented with any of the following implementations:

In one implementation, the ultrasonic handpiece is coupled to the control console and/or defines a lumen for providing suction at a surgical site.

[0041] In one implementation, the processor is configured to determine the target displacement for the tip such that the target displacement represents a reduced displacement for the tip responsive to the determined mechanical resistance of the ultrasonic handpiece representing an increased mechanical resistance of the ultrasonic handpiece.

[0042] In one implementation, the processor is configured to determine the target displacement for the tip such that the target displacement represents the reduced displacement for the tip responsive to the determined mechanical resistance representing the increased mechanical resistance of the ultrasonic handpiece and the determined mechanical resistance being greater than a mechanical resistance threshold, and determine the target displacement for the tip such that the target displacement represents a maximum displacement level for the tip responsive to the determined mechanical resistance being less than the mechanical resistance threshold.

[0043] In one implementation, the processor is configured to determine a capacitance of the transducer of the ultrasonic handpiece; determine a resonant frequency of the ultrasonic handpiece; set a frequency of the AC drive signal to the determined resonant frequency of the ultrasonic handpiece; calculate a current through mechanical components of the ultrasonic handpiece based on the capacitance of the transducer, the measured voltage of the AC drive signal, and the measured current of the AC drive signal; and calculate the mechanical resistance of the ultrasonic handpiece based on the current through the mechanical components of the ultrasonic handpiece and the measured voltage of the AC drive signal

[0044] In one implementation, the processor is configured to receive a tissue response model that defines the target displacement for the tip as a function of the mechanical resistance; and determine the target displacement for the tip based on the tissue response model and the mechanical resistance.

[0045] In one implementation, the tissue response model defines tip displacement levels decreasing over increasing mechanical resistance values.

[0046] In one implementation, the tissue response model defines a maximum tip displacement level associated with a first mechanical resistance threshold, a minimum tip displacement level associated with a second mechanical resistance threshold greater than the first mechanical resistance threshold, and intermediate tip displacement levels between the maximum and minimum tip displacement levels and associated with intermediate mechanical resistance values between the first and second mechanical resistance thresholds, the intermediate tip displacement levels decreasing over the intermediate mechanical resistance values.

[0047] In one implementation, the processor is configured to select the maximum tip displacement level as the target displacement for the tip responsive to the determined mechanical resistance being less than the first mechanical resistance threshold, select the minimum tip displacement level as the target displacement for the tip responsive to the determined mechanical resistance being greater than the second mechanical resistance threshold; and select one of the intermediate tip displacement levels associated with the determined mechanical resistance responsive to the determined mechanical resistance being between the first and second mechanical resistance thresholds.

[0048] In one implementation, at least one of the maximum tip displacement level, the minimum tip displacement level, the first mechanical resistance threshold, the second mechanical resistance threshold, or a relationship between the intermediate tip displacement levels is based on a user-setting.

[0049] In one implementation, the intermediate tip displacement levels are defined by a decreasing curve function that maps the first mechanical resistance threshold to the maximum tip displacement level and maps the second mechanical resistance threshold to the minimum tip displacement level.

[0050] In one implementation, the intermediate tip displacement levels are defined according to a curved decreasing function that is based on a voltage corresponding to puncture of a tissue being contacted by the tip of the ultrasonic handpiece.

[0051] In one implementation, the curved decreasing function is further based on a resistance offset corresponding to vibrating components of the ultrasonic handpiece.

[0052] In one implementation, the control console includes a memory storing a plurality of tissue response models, each of the tissue response models being defined based on a voltage corresponding to puncture of a different type of tissue. The processor is configured to receive the tissue response model by being configured to receive a user selection of one of the types of tissue; and retrieve the tissue response model from the memory corresponding to the selected type of tissue.

[0053] In one implementation, the intermediate tip displacement levels are defined by a negative linear function that maps the first mechanical resistance threshold to the maximum tip displacement level and maps the second mechanical resistance threshold to the minimum tip displacement level.

[0054] In one implementation, the target displacement for the tip corresponds to a target current through mechanical components of the ultrasonic handpiece, and the processor is configured to adjust the AC drive signal output by the signal generator to achieve the determined target displacement by being configured to adjust the AC drive signal so that an actual current through the mechanical components of the ultrasonic handpiece substantially equals the target current through the mechanical components of the ultrasonic handpiece.

[0055] According to a thirteenth exemplary aspect, a control console for controlling vibrations of an ultrasonic handpiece is provided. The control console includes a signal generator for generating an AC drive signal applied to a transducer of the ultrasonic handpiece, which is coupled to and configured to vibrate a tip of the ultrasonic handpiece responsive to receiving the AC drive signal. The control console further includes a sensor for measuring a voltage of the AC drive signal, a sensor for measuring a current of the AC drive signal, and a processor coupled to the sensors and the signal generator. The processor is configured to receive a tissue response model defining a maximum tip displacement level for the tip of the ultrasonic handpiece associated with a first tissue stiffness value, a minimum tip displacement level for the tip of the ultrasonic handpiece associated with a second tissue stiffness value greater than the first tissue stiffness value, and intermediate tip displacement levels for the tip of the ultrasonic handpiece ranging between the maximum and minimum tip displacement levels, where the intermediate tip displacement levels are associated with and decreasing as a function of increasing intermediate tissue stiffness values ranging between the first and second tissue stiffness values. The processor is further configured to determine a stiffness value for a tissue being contacted by the tip of the ultrasonic handpiece based on the measured current and the measured voltage, determine a target displacement level for the tip based on the determined stiffness value and the tissue response model, and adjust the AC drive signal output by the signal generator to achieve the determined target displacement for the tip.

[0056] According to a fourteenth exemplary aspect, a method of operating the control console and/or performing the functions of the control console of the thirteenth aspect is provided.

[0057] Any of the above exemplary aspects can be combined in part, or in whole. Furthermore, any of the above exemplary aspects above can be implemented with any of the following implementations:

In one implementation, the ultrasonic handpiece is coupled to the control console and/or defines a lumen for providing suction at a surgical site.

[0058] Any of the above implementations can be utilized for any of the aspects described above. Any of the above implementations can be combined in whole, or in part, for any one or more aspects described above.

BRIEF DESCRIPTION OF THE DRAWINGS

[0059] Advantages of the present disclosure will be readily appreciated, as the same becomes better understood by reference to the following detailed description, when considered in connection with the accompanying drawings. Non-

limiting and non-exhaustive instances of the present disclosure are described with reference to the following figures, wherein like numerals refer to like parts throughout the various views unless otherwise specified.

FIG. 1 is a perspective view of an ultrasonic tool system with tissue selection capability.
FIG. 2 is a schematic diagram of components of the system of FIG. 1.
FIG. 3 is a circuit diagram modeling components of an ultrasonic handpiece.
FIG. 4 is a flowchart of a method for implementing tissue selection during operation of an ultrasonic handpiece.
FIG. 5 is a flowchart illustrating additional details of the method of FIG. 4.
FIG. 6 is a graph of a tissue response model including a linear transition function.
FIG. 7 is a graph of a plurality of tissue response models each including a linear transition function.
FIG. 8 is a graph of a tissue response model including a curved transition function.
FIG. 9 is a circuit diagram of components that may contribute to mechanical resistance of an ultrasonic handpiece.

DETAILED DESCRIPTION

[0060] In the following description, numerous specific details are set forth in order to provide a thorough understanding of the present invention. It will be apparent to one having ordinary skill in the art, however, that the specific detail need not be employed to practice the present invention. In some instances, well-known materials or methods have not been described in detail in order to avoid obscuring the present invention.

[0061] Reference throughout this specification to "one instance," "an instance," "one example" or "an example" means that a particular feature, structure or characteristic described in connection with the instance or example is included in at least one instance or example of the present invention. Thus, appearances of the phrases "in one instance," "in an instance," "one example" or "an example" in various places throughout this specification are not necessarily all referring to the same instance or example. Furthermore, the particular features, structures or characteristics may be combined in any suitable combinations and/or sub-combinations in one or more instances or examples. In addition, it should be appreciated that the figures provided herewith are for explanation purposes to persons ordinarily skilled in the art and that the drawings are not necessarily drawn to scale.

[0062] Systems and methods for controlling an ultrasonic handpiece to implement tissue selection are disclosed herein. During a surgical procedure, a practitioner may use an ultrasonic handpiece to contact, cut, and ablate biological tissue. The practitioner often intends to cut and/or ablate some types of biological tissue, such as relatively soft tissue, while keeping other types of tissue, such as relatively stiffer tissue, intact. For instance, a practitioner may use the ultrasonic handpiece to cut and/or ablate portions of brain, intending to cut and/or ablate softer tissue, such as gray matter and white matter, without cutting and/or ablating higher stiffness tissue, such as blood vessels, dura mater, arachnoid mater, and pia mater.

[0063] The systems and methods may thus implement tissue selection to avoid cutting and/or ablating tissue that the practitioner desires to remain intact. Specifically, the systems and methods may control displacement of the tip of the ultrasonic handpiece based on a stiffness of the tissue in contact with the tip. Responsive to the tip contacting relatively stiffer tissue that the practitioner desires to remain intact, the systems and methods may reduce displacement of the tip so that the vibrations of the tip are insufficient to cut through and/or ablate the tissue without excessive force by the practitioner. By controlling vibrations of the tip in this manner, the practitioner is able to operate the ultrasonic handpiece with increased safety and avoid unintentional cutting and/or ablation. The systems and methods also provide improved tactile feel, allowing the practitioner to better appreciate contact with different types of tissue.

[0064] FIG. 1 illustrates a system 100 for controlling vibrations of a tip 102 of an ultrasonic handpiece 104 to implement tissue selection. The ultrasonic handpiece 104 may include a transducer 106 coupled to the tip 102. The transducer 106 may be a stack of piezoelectric drivers positioned at a proximate end of ultrasonic handpiece 104. The transducer 106 may be configured to vibrate the tip 102 in response to receiving an alternating current (AC) drive signal.

[0065] The ultrasonic handpiece 104 may define a lumen 108 extending from the proximate end of the ultrasonic handpiece 104 to the distal end of the tip 102. The lumen 108 may provide suction to a surgical site being treated by the ultrasonic handpiece 104. The ultrasonic handpiece 104 may also include a sleeve 109 disposed over the tip 102. The sleeve 109 may be spaced radially from the tip 102, and may be spaced longitudinally from the distal end of the tip 102. During treatment of tissue with the ultrasonic handpiece 104, irrigating fluid may be flowed through the gap between the tip 102 and the sleeve 109 to provide irrigation at the surgical site.

[0066] The ultrasonic handpiece 104 may be a surgical instrument that includes a cutting accessory (e.g., the tip 102) for treating biological tissue. For instance, the ultrasonic handpiece 104 may be the ultrasonic surgical handpiece disclosed in U.S. Patent Application No. 16/580,639. As disclosed in U.S. Patent Application No. 16/580,639, the tip 102 may include a cutting feature configured to cut, shape, and/or remove biological tissue. The tip 102 may have various other features, as described in U.S. Patent Nos. 6,497,715; 6,955,680; and 6,984,220.

[0067] The system 100 may include a control console 110 coupled to and driving the ultrasonic handpiece 104. The

control console 110 may be configured to source an AC drive signal to the transducer 106 of the ultrasonic handpiece 104. Specifically, referring to FIG. 2, the control console 110 may include a signal generator 112 for generating an AC drive signal 114 sourced to the transducer 106 of the ultrasonic handpiece 104. The control console 110 may source the AC drive signal 114 over a cable 119 (shown in FIG. 1) to which the ultrasonic handpiece 104 is connected. The AC drive signal 114 may include an alternating voltage component v_s and an alternating current component i_s. Responsive to receiving the AC drive signal 114, the transducer 106 may cause the tip 102 to vibrate in accordance with the voltage v_s and the current i_s of the AC drive signal 114.

[0068] Referring again to FIG. 1, the control console 110 may be configured to generate the AC drive signal 114 based on user input submitted to the control console 110 through a footswitch 121 or a remote 123 coupled to the control console 110. The control console 110 may also include a display 186 for presenting information to a practitioner. Non-limiting examples of presented information may include an identification of the ultrasonic handpiece 104 connected to the control console 110, and an operating state of the system 100. The display 186 may also be a touch screen display that enables a practitioner to provide user input to the control console 110, such as via on-screen controls.

[0069] Referring again to FIG. 2, the control console 110 may include a processor 122, memory 124, and a sensor 126. The processor 122 may include one or more devices selected from microprocessors, micro-controllers, digital signal processors, microcomputers, central processing units, field programmable gate arrays, programmable logic devices, state machines, logic circuits, analog circuits, digital circuits, and/or any other devices that manipulate signals (analog or digital) based on operational instructions stored in memory 124. Memory 124 may include a single memory device or a plurality of memory devices including, but not limited to, read-only memory (ROM), random access memory (RAM), volatile memory, non-volatile memory, static random access memory (SRAM), dynamic random access memory (DRAM), flash memory, cache memory, and/or any other device capable of storing information. Memory 124 may also include one or more persistent data storage devices such as non-volatile solid-state memory, EPROM, EEPROM, an RFID tag, and/or any other device capable of persistently storing information.

[0070] The processor 122 may be configured to implement the functions, features, processes, methods, and modules of the control console 110 described herein. In particular, the processor 122 may operate under the control of an operating system and/or one or more computer software applications residing in memory 124. The operating system may be configured, upon execution by the processor 122, to manage computer resources so each of the applications may be executed by the processor 122. Alternatively, the processor 122 may execute the applications directly, in which case the operating system may be omitted.

[0071] The applications and/or the operating system may each be configured upon execution to implement one or more of the functions, features, processes, methods and modules of the control console 110 described herein. Specifically, the applications and/or operating system may each be embodied by a set of computer-executable instructions residing in memory 124. Each set of computer-executable instructions may be configured, upon execution by the processor 122, to cause the processor 122 to implement one or more of the functions, features, processes, methods, and modules of the control console 110 described herein.

[0072] For example, the processor 122 may be configured, such as via execution of computer-executable instructions embodying one or more software applications residing in memory 124, to regulate the frequency and amplitude of the AC drive signal 114 generated by the signal generator 112, such as to implement tissue selection by the ultrasonic handpiece 104. In particular, the signal generator 112, shown as an alternating voltage source in FIG. 2, may include a power supply, an amplifier, and a transformer. The ultrasonic handpiece 104 may be coupled to a secondary winding of the transformer. During operation of the system 100, the power supply may output a constant voltage to the amplifier, which may be a variable gain amplifier. The processor 122 may be configured to also supply a control signal to the amplifier. The control signal may set a frequency and amplitude of a voltage generated by the amplifier from the constant voltage. The voltage generated by the amplifier may be applied across a primary winding of the transformer, which may cause the AC drive signal 114 to develop across the secondary winding. The voltage v_s of the AC drive signal 114 developed across the secondary winding of the transformer may be proportional to the voltage applied across the primary winding, and the frequency of the AC drive signal 114 may be equivalent to frequency of the applied voltage. Thus processor 122 may thus be configured set the frequency and voltage v_s of the AC drive signal 114 by being configured to set the frequency and voltage of the signal generated by the amplifier. An example signal generator of this type is disclosed in PCT Pub. WO 2016/183084 A1 and US Pat. Pub. No. 2018/0056328 A1.

[0073] One or more databases for collecting and organizing data used by processor 122 upon execution of the operating system and/or applications may also reside in memory 124. The databases may include data and supporting data structures that store and organize the data. The databases may be arranged with any database organization or structure including, but not limited to, a relational database, a hierarchical database, a network database, or combinations thereof. A database management system in the form of a computer software application executing as instructions on the processor 122 may be used to access the information or data stored in records of the databases in response to a query, where a query may be dynamically determined and executed by the processor 122.

[0074] For example, the one or more databases residing in memory 124 may organize tissue data 128. The tissue

data 128 may indicate one or more tissue response models that define target displacement levels for the tip 102 of the ultrasonic handpiece 104 as a function of tissue stiffness, or more particularly, as a function potential tissue stiffness values corresponding to tissues of different stiffnesses. As described in more detail below, the potential tissue stiffness values may be defined by potential mechanical resistances of the ultrasonic handpiece 104.

[0075] Each tissue response model may be associated with a different user setting, which may be submitted via a user interface of the control console 110 (e.g., display 168, remote 123, footswitch 121), and which may indicate one or more types of tissue desired to be cut and/or ablated, and/or may indicate one or more types of tissue for which ablation and/or cutting is desired to be reduced or avoided. Upon activation of the control console 110, the processor 122 may be configured to receive a user setting, and to retrieve the tissue response model corresponding to the user setting from the tissue data 128. The processor 122 may then be configured to control displacement of the tip 102 based on the retrieved tissue response model to only cut and/or ablate desired types of tissue and/or avoid or reduce cutting and/or ablating non-desired types of tissue indicated by the user setting.

[0076] The sensor 126 may be configured to measure the voltage v_s and current i_s of the AC drive signal 114, and to communicate these measurements to the processor 122. Although FIG. 2 illustrates the sensor 126 as a single sensor, the sensor 126 may include any suitable number of sensors for measuring the voltage v_s and current i_s of the AC drive signal 114. The sensor 126 may also include any suitable type of sensor for measuring the voltage v_s and the current i_s of the AC drive signal 114. For example, the sensor 126 may include a capacitive or resistive voltage sensor for measuring the voltage v_s, and may include an open-loop or closed-loop current sensor for measuring the current i_s.

[0077] The ultrasonic handpiece 104 may include handpiece (HP) memory 130, which may be disposed in the sleeve 109 of the ultrasonic handpiece 104. The HP memory 130 may store data specific to the ultrasonic handpiece 104 and/or tip 102, such as data identifying the ultrasonic handpiece 104 and/or tip 102, and data defining operational parameters specific to the ultrasonic handpiece 104 and/or tip 102. The HP memory 130 may include one or more of the memory devices described above in connection with the console memory 124, such as an EPROM, an EEPROM, or an RFID tag.

[0078] Upon connection of the ultrasonic handpiece 104 with the control console 110, the HP memory 130 may become communicatively coupled with a memory reader 132 of the control console 110. The memory reader 132 may be coupled to the processor 122, and may be configured, such as at the direction of the processor 122, to read data from and write data to the HP memory 130 when coupled to the memory reader 132. The structure of memory reader 132 may complement the HP memory 130. Thus, as examples, the memory reader 132 may be an assembly capable of reading data on an EPROM or EEPROM, or may be an assembly capable of interrogating and reading data from an RFID tag.

[0079] For instance, the HP memory 130 may store HP tissue data 133 specific to the ultrasonic handpiece 104 and/or tip 102. The HP tissue data 133 may be analogous to the tissue data 128 residing in the memory 124 of the control console 110. Specifically, different ultrasonic handpieces 104 and/or tips 102 may affect various types of tissue differently responsive to receiving a same AC drive signal 114. As an example, one type of tip 102 may include a cutting feature effective to cut a type of a tissue responsive to the ultrasonic handpiece 104 receiving a given AC drive signal 114, while another type of tip 102 may include another cutting feature that is relatively less effective at cutting the type of tissue responsive to the ultrasonic handpiece 104 receiving the given AC drive signal 114. The HP tissue data 133 residing in the HP memory 130 of an ultrasonic handpiece 104 may thus define a tissue response model or a set of tissue response models that differ from those defined by the HP tissue data 133 residing in the HP memory 130 of another ultrasonic handpiece 104.

[0080] Hence, responsive to the ultrasonic handpiece 104 being connected to the control console 110, the processor 122 may be configured to read the HP tissue data 133 specific to the ultrasonic handpiece 104 and/or tip 102 residing in the HP memory 130 via the memory reader 132, and to control displacement of the tip 102 based on one of the tissue response models defined by the retrieved HP tissue data 133 as described above. Alternatively, the tissue data 128 residing in the memory 124 of the control console 110 may associate each of several different ultrasonic handpiece 104 and/or tip 102 identifiers with a different tissue response model or with a different set of tissue response models. In this case, responsive to the ultrasonic handpiece 104 being connected to the control console 110, the processor 122 may be configured to read identification data from the HP memory 130 indicating an identifier for the ultrasonic handpiece 104 and/or tip 102, and to use one of the tissue response models associated with the identifier within the tissue data 128 to regulate displacement of the tip 102.

[0081] FIG. 3 illustrates a circuit modeling components of the ultrasonic handpiece 104 during operation of the system 100. According to the model, the current i_s of the AC drive signal 114 sourced to the ultrasonic handpiece 104 may be separated into two components: a current i_{C_o} applied to the transducer 106 of the ultrasonic handpiece 32, and an equivalent of current i_m through the mechanical components of the ultrasonic handpiece 104 (also referred to herein as "mechanical current i_m"). The impedance provided by the transducer 106 may be primarily capacitive. Accordingly, the transducer 106 may be represented in the circuit by a capacitor with capacitance C_o. The mechanical components of the ultrasonic handpiece 104, which may include the tip 102, the transducer 106, and other elements of the ultrasonic handpiece 104 that vibrate to apply cutting and/or ablating force on contacted tissue, may include an inductive component, a resistive component, and a capacitive component. Accordingly, the mechanical components may be represented in

the circuit by an inductor with inductance L_m, a resistor with resistance R_m, and a capacitor with capacitance C_m. The equivalent of impedance Z_m of the mechanical components of the ultrasonic handpiece 104 (also referred to herein as "mechanical impedance Z_m") may be a function of the inductance L_m, the resistance R_m, and the capacitance C_m.

[0082] The resistance R_m of the ultrasonic handpiece 104 (also referred to herein as "mechanical resistance R_m") may be a function of both the vibrating components of the ultrasonic handpiece 104 and any substances, such as biological tissue, being contacted by vibrating components (*e.g.*, the tip 102) of the ultrasonic handpiece 104. Correspondingly, when the tip 102 contacts tissue, the resistance R_m may include a resistance of the tissue being contacted. The resistance of the tissue may indicate a stiffness of the tissue. As such, the mechanical resistance R_m of the ultrasonic handpiece 104 may correspond to a stiffness of tissue being contacted by the tip 102 of the ultrasonic handpiece 104. The stiffness of contacted tissue may be understood to correspond to the elastic modulus of the given tissue, and the mechanical resistance R_m of the ultrasonic handpiece 104 may vary as a function of the stiffness of the contacted tissue. Specifically, as the stiffness of tissue contacted by the tip 102 increases, the mechanical resistance R_m may increase. Similarly, as the stiffness of tissue being contacted by the tip 102 decreases, the mechanical resistance R_m may decrease.

[0083] The following relationships, relevant to the examples described below, can be derived from the circuit of FIG. 3 through various circuit analysis techniques:

$$i_{C_o} = j\omega C_o v_S \tag{1}$$

$$i_m = i_s - j\omega C_o v_S \tag{2}$$

$$Z_m = \frac{v_S}{i_m} \tag{3}$$

[0084] FIG. 4 illustrates a method 134 for regulating vibrations of the tip 102 of the ultrasonic handpiece 104 to implement tissue selection. In particular, the method 134 may regulate the vibrations of the tip 102 to cut desired tissue and avoid cutting tissue desired to remain intact. The method 134 may also provide an improved tactile feel that helps the practitioner differentiate between different types of tissues being contacted by the tip 102 of the ultrasonic handpiece 104. The processor 122 may be configured to perform the method 134, such as via a set of computer-executable instructions residing in memory 124 and configured, upon execution of the processor 122, to cause the processor 122 to perform the method 134. Each of the steps of the method 134 are discussed in more detail below.

[0085] In step 136, a property of the ultrasonic handpiece 104 associated with a tissue being contacted by the tip 102, such as stiffness value of the contacted tissue, may be determined based on the voltage v_s of the AC drive signal 114 and the current i_s of the AC drive signal 114, which may be measured by the sensor 126. As previously discussed, the mechanical resistance R_m of the ultrasonic handpiece 104 may correspond to a stiffness of the tissue being contacted by the tip 102. The mechanical resistance R_m may thus be determined and used as the determined stiffness value for the tissue being contacted by the tip 102.

[0086] In step 138, a target displacement for the tip 102 may be determined based on the determined property. The displacement of the tip 102 may correspond to an ability of the tip 102 to cut and/or ablate tissue. In particular, given a constant vibration frequency, increasing the displacement of the tip 102 per each vibratory cycle may increase the ability of the tip 102 to cut and/or ablate tissue. As such, if the mechanical resistance R_m determined in step 136 corresponds to the tip 102 being against tissue in which a practitioner desires to cut and/or ablate according to current tissue selection settings, then the processor 122 may be configured to select a relatively high target displacement for the tip 102 to facilitate cutting the tissue. Alternatively, if the mechanical resistance R_m determined in step 136 corresponds to the tip 102 being against tissue in which cutting and/or ablation is not desired according to current tissue selection settings, then the processor 122 may be configured to select a relatively low target displacement for the tip 102 so as to prevent the tip 102 from cutting and/or ablating the tissue.

[0087] For instance, the tissue selection settings may indicate to cut and/or ablate types of tissue having a stiffness less than a stiffness threshold (*i.e.*, relatively softer tissue), and to avoid cutting types of tissue having a stiffness greater than the stiffness threshold (*i.e.*, relatively stiffer tissue). As previously described, the mechanical resistance R_m of the ultrasonic handpiece 104 may indicate the stiffness of tissue in contact with the tip 102. The stiffness threshold may therefore be defined in terms of mechanical resistance R_m. In step 138, responsive to the determined mechanical resistance R_m of the ultrasonic handpiece 104 representing an increased mechanical resistance R_m of the ultrasonic handpiece 104 and/or being greater than the stiffness threshold, the processor 122 may be configured to select a decreased target displacement for the tip 102 to avoid cutting and/or ablating the currently contacted tissue.

[0088] In step 140, the AC drive signal 114 output by the signal generator 112 and sourced to the ultrasonic handpiece 104 may be adjusted to achieve the determined target displacement for the tip 102. In particular, the processor 122 may be configured to generate a control signal that causes the signal generator 112 to generate an AC drive signal 114 that results in the determined target displacement for the tip 102.

[0089] FIG. 5 also illustrates a method 142 for regulating vibrations of the tip 102 of the ultrasonic handpiece 104 to implement tissue selection. The steps of method 142 may be implemented in steps 136, 138, and 140 of the method 134 illustrated in FIG. 4. Thus, similar to the method 134, the method 142 may regulate the vibrations of the tip 102 to cut and/or ablate desired tissue and avoid cutting and/or ablating tissue desired to remain intact, and may also provide an improved tactile feel that helps the practitioner differentiate between different types of tissues being contacted by the tip 102 of the ultrasonic handpiece 104. The processor 122 may be configured to perform the method 142, such via a set of computer-executable instructions residing in the memory 124 and configured, upon execution of the processor 122, to cause the processor 122 to perform the method 142.

[0090] Steps 144 to 152 of the method 142 may be performed to determine the tissue stiffness value, or more particularly the mechanical resistance R_m of the ultrasonic handpiece 104, in step 136 of the method 134. In step 144, the capacitance C_o corresponding to the transducer 106 of the ultrasonic handpiece 104 may be determined. The capacitance C_o of the transducer 106 may be considered constant during operation of the ultrasonic handpiece 104. Accordingly, the capacitance C_o of the transducer 106 may be measured and stored in the HP memory 130 during production of the ultrasonic handpiece 104. Upon the ultrasonic handpiece 104 being connected to the control console 110 for a surgical operation, the processor 122 may be configured to read the capacitance C_o of the transducer 106 from the HP memory 130, such as via the memory reader 132.

[0091] In step 146, the resonant frequency of the ultrasonic handpiece 104 may be determined. The processor 122 may be configured to determine the resonant frequency using a variety of methods. For instance, the processor 122 may be configured to perform a frequency sweep and determine the frequency in which the mechanical current i_m, as calculated using Equation (2) above, is at a minimum. Alternatively, the processor 122 may determine the resonant frequency using an iterative process of calculating a ratio of i_{C_o} to i_m and adjusting the frequency of the AC drive signal 114, as disclosed in U.S. Patent No. 10,16,209. Thereafter, in step 148, the frequency of the AC drive signal 114 may be set to the determined resonant frequency. The processor 122 may be configured to generate and communicate a control signal corresponding to the resonant frequency to the signal generator 112, as described above.

[0092] In step 150, the mechanical current i_m of the ultrasonic handpiece 104 may be calculated. As illustrated in Equation (2), this calculation may be based on the capacitance C_o of the transducer 106, the measured voltage v_s of the AC drive signal 114, the measured current i_s of the AC drive signal 114, and the frequency of the AC drive signal 114 (*e.g.*, the resonant frequency of the ultrasonic handpiece 104).

[0093] In step 152, the mechanical resistance R_m of the ultrasonic handpiece 104 may be calculated based on the mechanical current i_m and the measured voltage v_s of the AC drive signal 114. In particular, the mechanical resistance R_m may be equal to the real part of the mechanical impedance Z_m, which may be calculated using Equation (3). When the ultrasonic handpiece 104 is operating at resonance (*i.e.*, when the frequency of the AC drive signal 114 is at a resonant frequency of the ultrasonic handpiece 104), the reactive components of the mechanical impedance Z_m of the ultrasonic handpiece 104, namely the inductance L_m and the capacitance C_m, may cancel each other out. As a result, the mechanical impedance Z_m of the ultrasonic handpiece 32 may equal the mechanical resistance R_m of the ultrasonic handpiece 32. In this case, the processor 122 may be configured to determine the mechanical resistance R_m of the ultrasonic handpiece 104 using the following equation:

$$R_m = \frac{v_s}{i_m} \tag{4}$$

where the voltage v_s of the AC drive signal 114 may be measured by the sensor 126 and the mechanical current i_m may be calculated using Equation (2). Alternatively, when the ultrasonic handpiece 104 is not operating at resonance (*e.g.*, steps 146 and 148 are omitted), the processor 122 may be configured to determine the mechanical resistance R_m of the ultrasonic handpiece 104 by calculating the real part of Z_m.

[0094] Steps 154 and 156 of the method 142 may be performed to determine the target displacement for the tip 102 in step 138 of the method 134. In step 154, a tissue response model (e.g., tissue response model 166A of FIG. 6) may be retrieved, such as by the processor 122. The tissue response model may define target displacements for the tip 102 as a function of potential tissue stiffness values, or more particularly potential mechanical resistances R_m, that may correspond to tissue in contact with the ultrasonic handpiece 104. In step 156, the target displacement for the tip 102 may be determined based on the tissue response model and the previous determined stiffness value corresponding to the stiffness of contacted tissue.

[0095] Step 158 of the method 142 may be performed to adjust the AC drive signal 114 to achieve the determined target displacement for the tip 102 in step 140 of the method 134. The displacement level of the tip 102 during a vibratory cycle may be proportional to the mechanical current i_m of the ultrasonic handpiece 104. As the mechanical current i_m increases, the displacement of the tip 102 may increase in proportion to the increase of the mechanical current i_m, and as the mechanical current i_m decreases, the displacement of the tip 102 may decrease in proportion to the decrease in the mechanical current i_m. The target displacement for the tip 102 may thus correspond to a target mechanical current i_{m_target} for the ultrasonic handpiece 104. Accordingly, in step 158, the AC drive signal 114 may be adjusted so that the actual mechanical current i_m of the ultrasonic handpiece 104 substantially equals a target mechanical current i_{m_target} corresponding to the target displacement (e.g., within twenty, ten, or two milliamps of the target mechanical current i_{m_target}, within one milliamp of the target mechanical current i_{m_target}, within 10%, 5%, or 1% of the of the target mechanical current i_{m_target}).

[0096] Specifically, responsive to determining the target displacement for the tip 102, the processor 122 may be configured to adjust the AC drive signal 114 so that the actual mechanical current i_m substantially equals the target mechanical current i_{m_Target} corresponding to the target displacement. For instance, the processor 122 may be configured to perform an iterative process, such as using a PID control loop, to generate a voltage v_s of the AC drive signal 114 that causes the actual mechanical current i_m, as calculated using Equation (2), to substantially equal the target mechanical current i_{m_Target}.

[0097] FIGS. 6-8 illustrate a variety of example tissue response models 166 that may be used by the processor 122 to determine the target displacement for the tip 102 based on the determined tissue stiffness value, or more particularly based on the mechanical resistance R_m of the ultrasonic handpiece 104. The illustrated tissue response models 166 are intended to be non-limiting, as other tissue response models that define target displacement for the tip 102 as a function of tissue stiffness value may be suitable.

[0098] Each tissue response model 166 may be represented by a graph in which the y-axis indicates target displacements and the x-axis indicates potential tissue stiffness values. The illustrated tissue response models 166 define tissue stiffness value in terms of mechanical resistance R_m of the ultrasonic handpiece 104, and define target displacement in terms of target mechanical current i_{m_Target}.

[0099] In other instances, a tissue response model may express target displacement in terms of an amplitude of displacement for the tip 102 during a vibratory cycle, and/or may express tissue stiffness value in terms of another characteristic derivable from the voltage v_s and current i_s of the AC drive signal 114. For example, a tissue response model may express target displacements in micrometers. In this case, the processor 122 may be configured to covert a determined target displacement for the tip 102 to a target mechanical current i_{m_Target} corresponding to the determined target displacement, such as via a lookup table. The processor 122 may then be configured to implement the target displacement by generating a control signal to the signal generator 112 that causes the mechanical current i_m of the ultrasonic handpiece 104 to equal the determined target mechanical current i_{m_Target}. As another example, the tissue response model may express tissue stiffness values in terms of the impedance of the ultrasonic handpiece 104, which may be determined by dividing the measured voltage v_s of the AC drive signal 114 by the measured current i_s of the AC drive signal 114.

[0100] Referring to FIG. 6 as an example, each tissue response model 166 may define a maximum tip displacement level 176, a minimum tip displacement level 178 less than the maximum tip displacement level 176, and a plurality of intermediate tip displacement levels extending between the maximum tip displacement level 176 and the minimum tip displacement level 178. The maximum tip displacement level 176 of each tissue response model 166 may be associated with potential tissue stiffness values less than or equal to a lower stiffness threshold 182, which may be represented by a lower mechanical resistance threshold, and the minimum tip displacement level 178 of each tissue response model 166 may be associated with potential tissue stiffness values greater than or equal to an upper stiffness threshold 184, which may be represented by an upper mechanical resistance threshold.

[0101] The intermediate tip displacement levels of each tissue response model 166 may be associated with intermediate potential tissue stiffness values, which may be represented by intermediate potential mechanical resistance R_m values, extending between the lower stiffness threshold 182 and the upper stiffness threshold 184 according to a transition function 167. In particular, each intermediate tip displacement level may be based on application of a different intermediate tissue stiffness value to the transition function 167, and may thus be associated with a different potential intermediate tissue stiffness value within the tissue response model 166. The relationship between the intermediate tip displacement levels and the intermediate potential stiffness values may thus be defined by a transition function 167. The transition function 167 may be a decreasing function that decreases from the maximum tip displacement level 176 to the minimum tip displacement level 178 over a range of increasing intermediate potential tissue stiffness values (*e.g.*, increasing mechanical resistance R_m values).

[0102] The processor 122 may be configured to determine a target displacement for the tip 102 based on a retrieved tissue response model 166 in step 156 of the method 142 by determining whether the mechanical resistance R_m of the ultrasonic handpiece 104 is less than or equal to the lower stiffness threshold 182, greater than or equal to the upper

stiffness threshold 184, or between the lower stiffness threshold 182 and the upper stiffness threshold 184. Responsive to the mechanical resistance R_m being less than the lower stiffness threshold 182, the processor 122 may select the maximum tip displacement level 176 as the target displacement level. Responsive to the mechanical resistance R_m being greater than or equal to the upper stiffness threshold 184, the processor 122 may select the minimum tip displacement level 176 as the target displacement level. Responsive to the mechanical resistance R_m being between the lower stiffness threshold 182 and the upper stiffness threshold 184, the processor 122 may set the target displacement level for the tip 102 as the intermediate tip displacement level associated with the mechanical resistance R_m according to the transition function 167.

[0103] For example, referring to the tissue response model 166A of FIG. 6, the processor 122 may set 50 milliamps (mA) as the target displacement in response to the determined mechanical resistance R_m being less than or equal to 1,000 Ohms. The processor 122 may set 5 mA as the target displacement in response to the determined mechanical resistance R_m being greater than or equal to 10,000 Ohms. The processor 122 may set a target displacement between 50 mA and 5 mA in response to the determined mechanical resistance R_m being between 1,000 Ohms and 10,000 Ohms. For instance, the processor 122 may set a target displacement of 30 mA in response to the determined mechanical resistance R_m being 5,000 Ohms.

[0104] The maximum tip displacement level 176 of each tissue response model 166 may correspond to the maximum allowed displacement level for the tip 102 of the ultrasonic handpiece 104 during an operation. This level may be set by a user, such as using the display 186 of the control console 110. In particular, the memory 124 and/or the HP memory 130 may include data defining a global maximum displacement level for the ultrasonic handpiece 104. Prior to operation of the ultrasonic handpiece 104, a user may enter input to the control console 110 defining a percentage of the global maximum displacement level to use as the maximum tip displacement level 176. Such user input may be referred to as a "power level." Based on the power level submitted by the user, the processor 122 may be configured to set the maximum tip displacement level 176 to a percentage of the global maximum displacement level that corresponds to the power level. Referring to FIG. 6, for example, the global maximum displacement level of the ultrasonic handpiece 104 may be 100 mA, and the user-submitted power level may have been fifty percent, resulting in the processor 122 setting the maximum tip displacement level 176 to 50 mA.

[0105] The processor 122 may be configured operate the tip 102 at the maximum tip displacement level 176 when the stiffness of tissue being contacted by the tip 102 is such that the tissue stiffness value, or more particularly the mechanical resistance R_m of the ultrasonic handpiece 104, is less than or equal to the lower stiffness threshold 182. The maximum tip displacement level 176 may be sufficient to cut and/or ablate types of tissue that, when contacted by the tip 102 of the ultrasonic handpiece 104, result in the mechanical resistance R_m of the ultrasonic handpiece 104 being less than or equal to the lower stiffness threshold 182. In other words, the processor 122 may be configured to vibrate the tip 102 at a same tip displacement level, namely, at the maximum tip displacement level 176, for each contacted type of tissue with a stiffness that causes the mechanical resistance R_m of the ultrasonic handpiece 104 to be less than or equal to the lower stiffness threshold 182.

[0106] Responsive to the tip 102 of the ultrasonic handpiece 104 contacting tissue having a stiffness that causes the determined tissue stiffness value, or more particularly the mechanical resistance R_m, to be greater than the lower stiffness threshold 182, the processor 122 may be configured to reduce displacement of the tip 102 according to the transition function 167, and thereby reduce the tip's 102 effectiveness at cutting and/or ablating the contacted tissue. The practitioner may feel the reduced vibrations and effectiveness of the tip 102 and interpret this event as an indication that the tip 102 is contacting or approaching tissue that is not desired to be cut and/or ablated. In response, the practitioner may back off the ultrasonic handpiece 104 from the tissue. The lower stiffness threshold 182 of each tissue response model 166 may thus define types of tissues desired to cut and/or ablated (e.g., tissues with stiffness values less than or equal to the lower stiffness threshold 182), and may define types of tissues to keep intact (e.g., tissues with stiffness values greater than the lower stiffness threshold 182).

[0107] In some instances, the processor 122 may be configured to determine the lower stiffness threshold 182 for each tissue response model 166 based on user input, such as the user input power level described above. For instance, for each tissue response model 166 usable by the processor 122 to control displacement of the tip 102, the tissue data 128 and/or HP tissue data 133 may define the transition function 167, the minimum tip displacement level 178, and the upper stiffness threshold 184, such that the transition function 167 intersects the minimum tip displacement level 178 at the upper stiffness threshold 184. Responsive to retrieving a tissue response model 166 from the tissue data 128 or the HP tissue data 133, the processor 122 may be configured to determine the intersection between the transition function 167 and the maximum tip displacement level 176 set by the user as the lower stiffness threshold 182 for the tissue response model 166.

[0108] The minimum tip displacement level 178 of each tissue response model 166 may correspond to a non-zero minimum tip displacement level for the tip 102, and may advantageously allow the ultrasonic handpiece 104 to enter a non-zero "stall mode" when the stiffness of contacted tissue indicates a relatively high stiffness value, namely, a mechanical resistance R_m greater than or equal to the upper stiffness threshold 184, which may also be referred to herein

as a stall threshold. This may occur when the tip 102 contacts tissue of a relatively high stiffness that is not desired to be cut and/or ablated, or when a practitioner continues pushing the tip 102 into tissue of a stiffness that is not desired to be cut and/or ablated. During the stall mode, the target displacement of the tip 102 may be set to the minimum tip displacement level 178 (e.g., 5 mA), which may be insufficient to cut and/or ablate the contacted tissue.

[0109] By setting the minimum tip displacement level 178 to a non-zero value, the processor 122 may continue tracking the resonant frequency of the ultrasonic handpiece 104 and correspondingly maintain operation of the ultrasonic handpiece 104 at resonance while in the stall mode. Such a configuration is advantageous in instances where the tip 102 transitions from contacting higher stiffness tissue not desired to be cut and/or ablated to contacting softer stiffness tissue desired to be cut and/or ablated. Maintaining operation of the ultrasonic handpiece 104 at resonance during the stall mode allows the processor 122 to continuously monitor the tissue being contacted by the tip 102 to determine when the tip 102 transitions to such softer tissue. Responsive to this transition, the processor 122 may be configured to adjust the AC drive signal 114 output by signal generator 112 such that the displacement of the tip 102 caused by the adjusted AC drive signal 114 is at the maintained resonant frequency of the ultrasonic handpiece 104 and is capable of cutting and/or ablating the tissue being contacted by the tip 102 (e.g., at the maximum tip displacement level 176). The processor 122 may perform this adjustment without having to first establish resonance, resulting in a relatively faster changeover back to a displacement level of the tip 102 sufficient to cut and/or ablate tissue.

[0110] Specifically, if the processor 122 stopped displacement of the tip 102 in the stall mode rather than placing the tip 102 at a non-zero displacement level, then the processor 122 may need to be configured to restart the ultrasonic handpiece 104 periodically or on demand to check for transition to softer stiffness tissue desired to be cut and/or ablated. Upon the ultrasonic handpiece 104 being restarted, the processor 122 may need to dedicate processing time to determine and set the frequency of the AC drive signal 114 to the resonant frequency, resulting in a relatively erratic and slower transition back to the maximum tip displacement level 176. The non-zero stall mode thus enables the processor 122 to relatively smoothly and quickly transition the tip 102 from the minimum tip displacement level 178 to the maximum tip displacement level 176.

[0111] The transition function 167 of each tissue response model 166 may be understood to define a sensitivity of the tissue response model 166. In particular, the transition function 167 may be a decreasing function that extends from the maximum tip displacement level 176 to the minimum tip displacement level 178. The faster the transition function 167 decreases from the maximum tip displacement level 176 to the minimum tip displacement level 178 over a range of stiffness values, the faster the processor 122 may be configured to place the ultrasonic handpiece 104 in the stall mode after the tip 102 contacts tissue to be avoided, and correspondingly, the more sensitive the tissue response model 166.

[0112] As illustrated in FIGS. 6 and 7, the transition function 167 of one or more of the stored tissue response models 166 may be a negative linear function having the form $y = mx + b$. For each of these tissue response models 166, m may be a negative slope indicative of the sensitivity of the tissue response model 166, and b may equal the difference between the minimum tip displacement level 178 of the tissue response model 166 and the product of m and the upper stiffness threshold 184 of the tissue response model 166. For instance, the transition function 167A of the tissue response model 166A illustrated in FIG. 6 may be defined by the above linear equation with m equal to $-\frac{1\ mA}{200\ Ohms}$ and b equal to 55 mA. As described in more detail below, the transition function 167 for one or more of the stored tissue response models 166 may also be a decreasing curve function.

[0113] The transition function 167 of each tissue response model 166 may provide advantages to a user of the ultrasonic handpiece 104 by providing gradually increasing tactile feedback to the user as the tip 102 contacts tissue of increasing stiffness. In particular, the force applied on the ultrasonic handpiece 104 when the tip 102 is vibrating against tissue increases with decreasing tip displacement and increasing tissue stiffness. According to the transition function 167, as the stiffness of tissue contacting the tip 102 increases from the lower stiffness threshold 182 to the upper stiffness threshold 184, the displacement of the tip 102 may decrease from the maximum tip displacement level 176 to the minimum tip displacement level 178. Correspondingly, as the tip 102 vibrates against increasingly stiffer tissue, the force applied on the ultrasonic handpiece 104 and felt by the user may gradually increase, which may function to provide feedback to the user that the tip 102 is contacting stiffer tissue not desired to be cut and/or ablated.

[0114] This configuration enables the user to appreciate by feel the stiffness of tissue being contacted by the tip 102, and indicates to the user when the tip 102 is in or near contact with tissue intended to be avoided prior to the ultrasonic handpiece 104 entering the stall mode. In particular, when the tip 102 initially contacts tissue having a stiffness corresponding to a mechanical resistance R_m near the lower stiffness threshold 182, the practitioner may proceed to push the tip 102 against this tissue. As the practitioner continues pushing the tip 102 against the tissue, the mechanical resistance R_m of the ultrasonic handpiece 104 may increase towards the upper stiffness threshold 184. The increased tactile feedback provided by reduced displacement of the tip 102 according to the transition function 167 may enable the practitioner to detect contact with the stiffer tissue prior to the mechanical resistance R_m of the ultrasonic handpiece 104 reaching the upper stiffness threshold 184, and to responsively backtrack the tip 102 from the tissue. As a result,

the practitioner may avoid entering the stall mode, and may avert damaging the tissue, which may occur if the practitioner continues applying excessive force onto the ultrasonic handpiece 104 that causes the tip 102 to penetrate the tissue.

[0115] As described above, the tissue data 128 and HP tissue data 133 may each define several tissue response models 166, each including different tissue selectivity settings (*e.g.*, different lower stiffness threshold 182) and/or different sensitivity settings (*e.g.*, different transition functions 167). The processor 122 may thus be configured to select one of these tissue response models 166 for regulating the ultrasonic handpiece 104 based on user input defining tissue selectivity and/or sensitivity. Specifically, prior to operation of the ultrasonic handpiece 104, a user may enter such input into the control console 110, such as via the display 186. Responsive to the control console 110 receiving the user input, the processor 122 may be configured to retrieve the tissue response model 166 that corresponds to the user input.

[0116] For instance, FIG. 7 illustrates tissue response models 166A-E that may be defined by the tissue data 128 or HP tissue data 133. Each tissue response model 166A-E may have a same tissue sensitivity, as indicated by the similar slope and length of their respective transition functions 167. However, the lower stiffness thresholds 182 of each tissue response model 166A-E differ, indicating that the tissue response models 166A-E have different tissue selectivity.

[0117] In particular, the tissue response model 166A may be configured to avoid cutting softer tissue than the tissue response model 166B, which may be configured to avoid cutting softer tissue than the tissue response model 166C, and so on. More specifically, the lower stiffness threshold 182A of the tissue response model 166A is less than the lower stiffness threshold 182B of the tissue response model 166B. Accordingly, if the tip 102 were to contact tissue of increasing stiffness, then the tissue response model 166A would cause the processor 122 to reduce displacement of the tip 102 before the tissue response model 166B would cause the processor 122 to reduce displacement of the tip 102. The tissue response model 166A may thus avoid cutting and/or ablating softer tissue than the tissue response model 166B. Hence, responsive to receiving user input indicating a tissue selectivity setting corresponding to avoidance of all but the softest tissue, the processor 122 may be configured to retrieve and implement the tissue response model 166A. Alternatively, responsive to receiving user input indicating a tissue selectivity setting corresponding to avoiding only the stiffest tissue, the processor 122 may be configured to retrieve and implement the tissue response model 167E.

[0118] As mentioned above, the relationship between the intermediate tip displacement levels and the intermediate potential stiffness values of one more of the tissue response models 166 may be defined by a decreasing curve function. The decreasing curve function of each of these tissue response models 166 may be configured to prevent puncturing of a different one or more types of tissue. Prior to operating the ultrasonic handpiece 32, a practitioner may provide a user selection of a type of tissue to avoid puncturing, ablating, and/or cutting. Responsive to receiving such input, the processor 122 may be configured to retrieve the tissue response model 166 corresponding to the selected type of tissue, and to regulate the displacement level of the tip 102 based thereon so as to avoid or reduce puncture of the indicated tissue type.

[0119] As an example, FIG. 8 illustrates a tissue response model 166F where the intermediate tip displacement levels are defined by a curved transition function 167F for preventing puncture of a specific type of tissue. In particular, FIG. 8 shows a tissue puncture curve 188 that corresponds to combinations of displacement levels and stiffness values at which puncturing the specific type tissue may occur. For instance, the tissue puncture curve 188 indicates the ultrasonic handpiece 104 may puncture the specific type of tissue when the mechanical current i_m is 20 mA and the mechanical resistance R_m of the of the ultrasonic handpiece 104 is 7500 Ohms. The tissue puncture curve 188 for a specific type of tissue may be determined empirically, as described in more detail below. The curved transition function 167F of the tissue response model 166F may be determined by subtracting a safety margin i_{safety} from the tissue puncture curve 188, and may thus prevent or reduce puncture of the specific type of tissue associated with the tissue response model 166F during operation of the ultrasonic handpiece 104 according to the tissue response model 166F.

[0120] As described above, the tissue puncture curve 188 for a specific a type of tissue may be determined empirically. In particular, the tissue puncture curve 188 may be determined by operating the ultrasonic handpiece 104 against the type of tissue, and determining the average force needed to puncture the tissue (referred to herein as "force limit"). The tissue puncture curve 188 may then be calculated using the following formula:

$$i_{m\_puncture} = \frac{Force\ Limit}{R_m - R_{offset}} \tag{5}$$

[0121] The force limit for a type of tissue may be represented by a puncture voltage v_{Tissue} corresponding to puncture of the type of tissue. Referring to FIG. 9, during normal operation of the ultrasonic handpiece 104, the mechanical resistance R_m of the ultrasonic handpiece 104 may be a function of several components, including the tissue in contact with the tip 102 and components of the ultrasonic handpiece 104 such as the tip 102, the sleeve 109 disposed over the tip 102, irrigation, suction, and interfaces between the tip 102 and the transducer 106. To determine a puncture voltage v_{Tissue} corresponding to puncturing a type of tissue, the ultrasonic handpiece 104 may be applied to the type of tissue

without one or more of these additional resistive components, such as the sleeve 109, irrigation, and suction, under various power level settings. The voltage v_s of the AC drive signal 114 supplied to the ultrasonic handpiece 104 immediately before puncture of the type of tissue at each power level setting may be measured, and the average these measured voltages v_s may be used as the force limit in Equation (5). R_{offset} in Equation (5) may be a resistive offset corresponding to components other than tissue that contribute to the mechanical resistance R_m of the ultrasonic handpiece 104, such as the vibrating components of the ultrasonic handpiece 104, and may be determined by calculating the mechanical resistance R_m of the ultrasonic handpiece 104 as described above when the tip 102 is vibrating in water or air and not being pressed against tissue.

[0122] The above procedure may be used to generate the tissue puncture curve 188, and correspondingly the curved transition function 167F, so that displacement of the tip 102 is reduced to prevent or reduce puncture, cutting, and/or ablation of the type of tissue, but is not over-reduced, such as due to other components contributing to the mechanical resistance R_m. As shown in FIG. 8, the tissue puncture curve 188 and the curved transition function 167F are each curved decreasing functions. Because the force limit of Equation (5) is considered a constant value for each type of tissue, as the mechanical resistance R_m of the ultrasonic handpiece 104 increases, the output of Equation (5), and correspondingly the curve transition function 167F, which may equal the output of Equation (5) minus the safety margin i_{safety}, decreases.

[0123] Systems and methods are described herein for implementing tissue selection during operation of an ultrasonic handpiece to avoid cutting types of tissue desired to remain intact. Specifically, these systems and methods may control displacement of the tip of the ultrasonic handpiece based on a stiffness of tissue in contact with the tip to avoid undesired cutting of tissue. Controlling an ultrasonic handpiece in this manner enables the practitioner to operate the ultrasonic handpiece with increased safety and avoid unintentional cutting. These systems and methods also provide improved tactile feel, allowing the practitioner to better appreciate contact with different types of tissue.

[0124] Although specific features of various instances of the disclosure may be shown in some drawings and not in others, this is for convenience only. In accordance with the principles of the disclosure, any feature of a drawing or other instance may be referenced and/or claimed in combination with any feature of any other drawing or instance.

[0125] This written description uses examples to describe instances of the disclosure and also to enable any person skilled in the art to practice the instances, including making and using any devices or systems and performing any incorporated methods. The invention is defined by the appended claims.

Claims

1. A system (100) for controlling vibrations of a tip (102) of an ultrasonic handpiece (104), the system (100) comprising:

an ultrasonic handpiece (104) comprising:

a tip (102) defining a lumen (108) to provide suction at a surgical site, and
a transducer (106) coupled to the tip (102) and configured to vibrate the tip (102) responsive to receiving an AC drive signal; and

a control console (110) coupled to the ultrasonic handpiece (104), the control console (110) comprising:

a signal generator (112) for generating the AC drive signal applied to the transducer (106),
a sensor (126) for measuring a voltage of the AC drive signal,
a sensor (126) for measuring a current of the AC drive signal, and
a processor (122) coupled to the sensors (126) and the signal generator (112),

the system (100) **characterized in that** the processor (122) of the control console (110) is configured to:

determine a first displacement level for the tip (102) that is a maximum displacement level for the tip (102),
receive a tissue response model defining a stiffness threshold and second displacement levels for the tip (102) that are each less than the first displacement level and associated within the tissue response model with a different potential tissue stiffness value greater than the stiffness threshold,
determine a tissue stiffness value of tissue being contacted by the tip (102) based on the measured voltage and current of the AC drive signal,
determine whether the determined tissue stiffness value is less than the stiffness threshold,
responsive to determining that the determined tissue stiffness value is less than the stiffness threshold, set a target displacement level for the tip (102) to the first displacement level,

responsive to determining that the determined tissue stiffness value is greater than the stiffness threshold, set the target displacement level for the tip to the second displacement level associated with the potential tissue stiffness value corresponding to the determined tissue stiffness value, and
adjust the AC drive signal output by the signal generator (112) to the ultrasonic handpiece (104) to achieve the set target displacement level.

2. The system (100) of claim 1, wherein the processor (122) is configured to determine, as the determined tissue stiffness value, a mechanical resistance of the ultrasonic handpiece (104) based on the measured voltage and current of the AC drive signal, the stiffness threshold is defined by a mechanical resistance threshold, and the potential tissue stiffness values are defined by potential mechanical resistances of the ultrasonic handpiece (104).

3. The system (100) of claim 2, wherein the processor (122) is configured to determine the mechanical resistance of the ultrasonic handpiece based on the measured voltage and current of the AC drive signal by being configured to:

determine a capacitance of the transducer (106) of the ultrasonic handpiece (104);
determine a resonant frequency of the ultrasonic handpiece (104);
set a frequency of the AC drive signal to the determined resonant frequency of the ultrasonic handpiece (104);
calculate a current through mechanical components of the ultrasonic handpiece (104) based on the capacitance of the transducer (106), the frequency of the AC drive signal, the measured voltage of the AC drive signal, and the measured current of the AC drive signal; and
calculate the mechanical resistance of the ultrasonic handpiece (104) based on the current through the mechanical components of the ultrasonic handpiece (104) and the measured voltage of the AC drive signal.

4. The system (100) of any one of claims 1-3, wherein the tissue response model defines the second displacement levels such that the second displacement levels decrease as the potential tissue stiffness values increase.

5. The system (100) of any one of claims 1-4, wherein the stiffness threshold is a first stiffness threshold, the tissue response model defines a third displacement level for the tip (102) that is a non-zero minimum tip displacement level for the tip (102) and is less than each second displacement level, and defines a second stiffness threshold that is greater than the potential tissue stiffness values, and the processor (122) is configured to:

responsive to the determined tissue stiffness value being greater than the second stiffness threshold, set the target displacement level for the tip (102) to the third displacement level; and
responsive to the determined tissue stiffness value being greater than the first stiffness threshold and less than the second stiffness threshold, set the target displacement level for the tip (102) to the second displacement level associated with the potential tissue stiffness value corresponding to the determined tissue stiffness value.

6. The system (100) of claim 5, wherein at least one of the first displacement level, the third displacement level, the first stiffness threshold, the second stiffness threshold, or the relationship between the second displacement levels and the potential tissue stiffness values is based on a user-setting.

7. The system (100) of claims 5 or 6, wherein the relationship between the second displacement levels and the potential tissue stiffness values is defined by a negative linear function that maps the first stiffness threshold to the first displacement level and maps the second stiffness threshold to the third displacement level.

8. The system (100) of claims 5 or 6, wherein the relationship between the second displacement levels and the potential tissue stiffness values is defined by a decreasing curve function that maps the first stiffness threshold to the first displacement level and maps the second stiffness threshold to the third displacement level.

9. The system (100) of any one of claims 1-6 and 8, wherein the tissue response model is configured for reducing ablation of a type of tissue during operation of the ultrasonic handpiece (104), and the relationship between the second displacement levels and the potential tissue stiffness values is defined by a curved decreasing function that is based on a voltage of the AC drive signal corresponding to puncture of the type of tissue.

10. The system (100) of claim 9, wherein the curved decreasing function is further based on a resistance offset corresponding to vibrating components of the ultrasonic handpiece (104).

11. The system (100) of any one of claims 1-10, wherein the tissue response model is a first tissue response model,

and further comprising:

a memory (124) storing the first tissue response model and a second tissue response model configured for ablating stiffer tissue than the first tissue response model,
wherein the processor (122) is configured to:

receive a user selection of the first tissue response model and the second tissue response model via a user interface (128, 123, 121);
responsive to the user selection of the first tissue response model:

responsive to the tip (102) being placed against a first type of tissue, set the target displacement level to the first displacement level, and
responsive to the tip (102) being placed against a second type of tissue stiffer than the first type of tissue, set the target displacement level to a displacement level less than the first displacement level; and

responsive to the user selection of the second tissue response model and to the tip (102) being placed against the first and second types of tissues, set the target displacement level to the first displacement level.

12. The system (100) of claim 11, wherein the stiffness threshold is a first stiffness threshold, the potential tissue stiffness values are first potential tissue stiffness values, the second tissue response model defines a second stiffness threshold that is greater than the first stiffness threshold and associates the second displacement levels each with a different second potential tissue stiffness value greater than the second stiffness threshold, and at least one of the first potential tissue stiffness values is less than each of the second potential tissue stiffness values.

13. The system (100) of claim 12, wherein the relationship between the second displacement levels and the second potential tissue stiffness values is defined by a function that is based on a voltage of the AC drive signal corresponding to puncture of a third type of tissue stiffer than the second type of tissue.

14. The system (100) of any one of claims 1-13, wherein the target displacement level for the tip corresponds to a target current through mechanical components of the ultrasonic handpiece (104), and the processor (122) is configured to adjust the AC drive signal output by the signal generator (112) to achieve the set target displacement level by being configured to adjust the AC drive signal so that an actual current through the mechanical components of the ultrasonic handpiece (104) substantially equals the target current through the mechanical components of the ultrasonic handpiece (104).

Patentansprüche

1. System (100) zum Steuern von Schwingungen einer Spitze (102) eines Ultraschall-Handstücks (104), wobei das System (100) umfasst:

ein Ultraschallhandstück (104), umfassend:

eine Spitze (102), die ein Lumen (108) definiert, um eine Saugwirkung an einer chirurgischen Stelle bereitzustellen, und
einen Wandler (106), der mit der Spitze (102) gekoppelt und ausgebildet ist, um die Spitze (102) in Reaktion auf ein Empfangen eines Wechselstrom-Antriebssignals in Schwingung zu versetzen; und

eine Steuerkonsole (110), die mit dem Ultraschallhandstück (104) gekoppelt ist, wobei die Steuerkonsole (110) umfasst:

einen Signalerzeuger (112) zum Erzeugen des an den Wandler (106) angelegten Wechselstrom-Antriebssignals,
einen Sensor (126) zum Messen einer Spannung des Wechselstrom-Antriebssignals,
einen Sensor (126) zum Messen eines Stroms des Wechselstrom-Antriebssignals, und
einen Prozessor (122), der mit den Sensoren (126) und dem Signalerzeuger (112) verbunden ist,

wobei das System (100) **dadurch gekennzeichnet ist, dass** der Prozessor (122) der Steuerkonsole (110)

ausgebildet ist, zum:

Bestimmen eines ersten Verschiebungsausmaßes für die Spitze (102), das ein maximales Verschiebungsausmaß für die Spitze (102) ist,
Empfangen eines Gewebereaktionsmodells, das eine Steifigkeitsschwelle und zweite Verschiebungsausmaße für die Spitze (102) definiert, die jeweils kleiner als das erste Verschiebungsausmaß sind und innerhalb des Gewebereaktionsmodells mit einem unterschiedlichen potentiellen Gewebesteifigkeitswert, der größer als die Steifigkeitsschwelle ist, in Beziehung gebracht sind,
Bestimmen eines Gewebesteifigkeitswertes von Gewebe, das von der Spitze (102) kontaktiert wird, basierend auf der gemessenen Spannung und dem gemessenen Strom des Wechselstrom-Antriebssignals,
Bestimmen, ob der ermittelte Gewebesteifigkeitswert kleiner als der Steifigkeitsschwellenwert ist,
als Reaktion auf das Bestimmen, dass der ermittelte Gewebesteifigkeitswert kleiner als der Steifigkeitsschwellenwert ist, ein Zielverschiebungsausmaß für die Spitze (102) auf das erste Verschiebungsausmaß einzustellen,
als Reaktion auf die Feststellung, dass der ermittelte Gewebesteifigkeitswert größer als der Steifigkeitsschwellenwert ist, das Zielverschiebungsausmaß für die Spitze auf das zweite Verschiebungsausmaß einzustellen, das mit dem potentiellen Gewebesteifigkeitswert in Beziehung gebracht ist, der dem ermittelten Gewebesteifigkeitswert entspricht, und
Anpassen des Wechselstrom-Antriebssignals, das von dem Signalerzeuger (112) an das Ultraschallhandstück (104) ausgegeben wird, um das eingestellte Zielverschiebungsausmaß zu erreichen.

2. System (100) nach Anspruch 1, wobei der Prozessor (122) ausgebildet ist, um einen mechanischen Widerstand des Ultraschallhandstücks (104) auf der Grundlage der gemessenen Spannung und des gemessenen Stroms des Wechselstrom-Antriebssignals als den ermittelten Gewebesteifigkeitswert zu bestimmen, wobei der Steifigkeitsschwellenwert durch einen mechanischen Widerstandsschwellenwert definiert ist und die potentiellen Gewebesteifigkeitswerte durch potentielle mechanische Widerstände des Ultraschallhandstücks (104) definiert sind.

3. System (100) nach Anspruch 2, wobei der Prozessor (122) ausgebildet ist, um den mechanischen Widerstand des Ultraschallhandstücks basierend auf der gemessenen Spannung und dem gemessenen Strom des Wechselstrom-Antriebssignals zu bestimmen, indem er ausgebildet ist, zum:

Bestimmen einer Kapazität des Wandlers (106) des Ultraschallhandstücks (104);
Bestimmen einer Resonanzfrequenz des Ultraschallhandstücks (104);
Einstellen einer Frequenz des Wechselstrom-Antriebssignals auf die ermittelte Resonanzfrequenz des Ultraschallhandstücks (104);
Berechnen eines Stroms durch mechanische Komponenten des Ultraschallhandstücks (104) auf der Grundlage der Kapazität des Wandlers (106), der Frequenz des Wechselstrom-Antriebssignals, der gemessenen Spannung des Wechselstrom-Antriebssignals und des gemessenen Stroms des Wechselstrom-Antriebssignals; und
Berechnen des mechanischen Widerstands des Ultraschallhandstücks (104) auf der Grundlage des Stroms durch die mechanischen Komponenten des Ultraschallhandstücks (104) und der gemessenen Spannung des Wechselstrom-Antriebssignals.

4. System (100) nach einem der Ansprüche 1 bis 3, wobei das Gewebereaktionsmodell die zweiten Verschiebungsausmaße derart definiert, dass die zweiten Verschiebungsausmaße abnehmen, wenn die potenziellen Gewebesteifigkeitswerte zunehmen.

5. System (100) nach einem der Ansprüche 1 bis 4, wobei der Steifigkeitsschwellenwert ein erster Steifigkeitsschwellenwert ist, das Gewebereaktionsmodell ein drittes Verschiebungsausmaß für die Spitze (102) definiert, das ein von Null verschiedenes minimales Spitzenverschiebungsausmaß für die Spitze (102) ist und kleiner als jedes zweite Verschiebungsausmaß ist, und einen zweiten Steifigkeitsschwellenwert definiert, der größer als die potentiellen Gewebesteifigkeitswerte ist, und der Prozessor (122) ausgebildet ist, um:

als Reaktion darauf, dass der ermittelte Gewebesteifigkeitswert größer als der zweite Steifigkeitsschwellenwert ist, das Zielverschiebungsausmaß für die Spitze (102) auf das dritte Verschiebungsausmaß einzustellen; und
als Reaktion darauf, dass der ermittelte Gewebesteifigkeitswert größer als der erste Steifigkeitsschwellenwert und kleiner als der zweite Steifigkeitsschwellenwert ist, das Zielverschiebungsausmaß für die Spitze (102) auf das zweite Verschiebungsausmaß einzustellen, das mit dem potentiellen Gewebesteifigkeitswert verbunden ist, der dem ermittelten Gewebesteifigkeitswert entspricht.

6. System (100) nach Anspruch 5, wobei mindestens eines von dem ersten Verschiebungsausmaß, dem dritten Verschiebungsausmaß, dem ersten Steifigkeitsschwellenwert, dem zweiten Steifigkeitsschwellenwert oder der Beziehung zwischen den zweiten Verschiebungsausmaßen und den potentiellen Gewebesteifigkeitswerten auf einer Benutzereinstellung basiert.

7. System (100) nach Anspruch 5 oder 6, wobei die Beziehung zwischen den zweiten Verschiebungswerten und den potentiellen Gewebesteifigkeitswerten durch eine negative lineare Funktion definiert ist, die den ersten Steifigkeitsschwellenwert dem ersten Verschiebungswert zuordnet und den zweiten Steifigkeitsschwellenwert dem dritten Verschiebungswert zuordnet.

8. System (100) nach Anspruch 5 oder 6, wobei die Beziehung zwischen den zweiten Verschiebungsausmaßen und den potentiellen Gewebesteifigkeitswerten durch eine abnehmende Kurvenfunktion definiert ist, die den ersten Steifigkeitsschwellenwert dem ersten Verschiebungsausmaß zuordnet und den zweiten Steifigkeitsschwellenwert dem dritten Verschiebungsausmaß zuordnet.

9. System (100) nach einem der Ansprüche 1 bis 6 und 8, wobei das Gewebereaktionsmodell ausgebildet ist, um die Ablation einer Gewebeart während des Betriebs des Ultraschallhandstücks (104) zu verringern, und die Beziehung zwischen den zweiten Verschiebungsausmaßen und den potentiellen Gewebesteifigkeitswerten durch eine gekrümmte abnehmende Funktion definiert ist, die auf einer Spannung des Wechselstrom-Antriebssignals basiert, die der Punktion der Gewebeart entspricht.

10. System (100) nach Anspruch 9, wobei die gekrümmt abfallende Funktion ferner auf einem Widerstandsversatz basiert, der schwingenden Komponenten des Ultraschallhandstücks (104) entspricht.

11. System (100) nach einem der Ansprüche 1-10, wobei das Gewebereaktionsmodell ein erstes Gewebereaktionsmodell ist, und ferner umfassend:

einen Speicher (124), der das erste Gewebereaktionsmodell und ein zweites Gewebereaktionsmodell speichert, das zum Abtragen von steiferem Gewebe als das erste Gewebereaktionsmodell ausgebildet ist,
wobei der Prozessor (122) ausgebildet ist zum:

Empfangen einer Benutzerauswahl des ersten Gewebereaktionsmodells und des zweiten Gewebereaktionsmodells über eine Benutzerschnittstelle (128, 123, 121);
als Reaktion auf die Benutzerauswahl des ersten Gewebereaktionsmodells:

als Reaktion darauf, dass die Spitze (102) gegen einen ersten Gewebetyp platziert wird, das Zielverschiebungsausmaß auf das erste Verschiebungsausmaß einzustellen, und
als Reaktion darauf, dass die Spitze (102) gegen einen zweiten Gewebetyp platziert wird, der steifer als der erste Gewebetyp ist, das Zielverschiebungsausmaß auf ein Verschiebungsausmaß einzustellen, das geringer als das erste Verschiebungsausmaß ist; und
als Reaktion auf die Benutzerauswahl des zweiten Gewebereaktionsmodells und darauf, dass die Spitze (102) gegen den ersten und den zweiten Gewebetyp platziert wird, das Zielverschiebungsausmaß auf das erste Verschiebungsausmaß einzustellen.

12. System (100) nach Anspruch 11, wobei der Steifigkeitsschwellenwert ein erster Steifigkeitsschwellenwert ist, die potentiellen Gewebesteifigkeitswerte erste potentielle Gewebesteifigkeitswerte sind, das zweite Gewebereaktionsmodell einen zweiten Steifigkeitsschwellenwert definiert, der größer ist als der erste Steifigkeitsschwellenwert, und die zweiten Verschiebungsausmaße jeweils mit einem unterschiedlichen zweiten potentiellen Gewebesteifigkeitswert in Beziehung setzt, der größer ist als der zweite Steifigkeitsschwellenwert, und mindestens einer der ersten potentiellen Gewebesteifigkeitswerte kleiner ist als jeder der zweiten potentiellen Gewebesteifigkeitswerte.

13. System (100) nach Anspruch 12, wobei die Beziehung zwischen den zweiten Verschiebungsstufen und den zweiten potentiellen Gewebesteifigkeitswerten durch eine Funktion definiert ist, die auf einer Spannung des Wechselstrom-Antriebssignals basiert, die der Punktion eines dritten Gewebetyps entspricht, der steifer ist als der zweite Gewebetyp.

14. System (100) nach einem der Ansprüche 1 bis 13, wobei das Zielverschiebungsausmaß für die Spitze einem Zielstrom durch mechanische Komponenten des Ultraschallhandstücks (104) entspricht und der Prozessor (122)

ausgebildet ist, um das Wechselstrom-Antriebssignal, das von dem Signalerzeuger (112) ausgegeben wird, anzupassen, um das eingestellte Zielverschiebungsausmaß zu erreichen, indem er ausgebildet ist, um das Wechselstrom-Antriebssignal derart anzupassen, dass ein tatsächlicher Strom durch die mechanischen Komponenten des Ultraschallhandstücks (104) im Wesentlichen gleich dem Zielstrom durch die mechanischen Komponenten des Ultraschallhandstücks (104) ist.

Revendications

1. Système (100) de réglage des vibrations d'un embout (102) d'une pièce à main ultrasonique (104), le système (100) comprenant:

une pièce à main ultrasonique (104) comprenant:

un embout (102) définissant une lumière (108) pour fournir une aspiration à un champ opératoire, et
un transducteur (106) couplé à l'embout (102) et conçu pour faire vibrer l'embout (102) en réponse à la réception d'un signal de commande CA; et

une console de commande (110) couplée à la pièce à main ultrasonique (104), la console de commande (110) comprenant:

un générateur de signaux (112) pour générer le signal de commande CA appliqué au transducteur (106),
un capteur (126) pour mesurer une tension du signal de commande CA,
un capteur (126) pour mesurer un courant du signal de commande CA, et
un processeur (122) couplé aux capteurs (126) et au générateur de signaux (112),

le système (100) étant **caractérisé en ce que** le processeur (122) de la console de commande (110) est configuré pour:

déterminer un premier niveau de déplacement pour l'embout (102) qui est un niveau de déplacement maximal pour l'embout (102),
recevoir un modèle de réponse de tissu définissant un seuil de rigidité et des seconds niveaux de déplacement pour l'embout (102) qui sont chacun inférieurs au premier niveau de déplacement et associés dans le modèle de réponse de tissu à une valeur de rigidité tissulaire potentielle différente supérieure au seuil de rigidité,
déterminer une valeur de rigidité du tissu en contact avec l'embout (102) sur la base de la tension et du courant mesurés du signal de commande CA,
déterminer si la valeur de rigidité tissulaire déterminée est inférieure au seuil de rigidité,
après avoir déterminé que la valeur de rigidité tissulaire déterminée est inférieure au seuil de rigidité, fixer un niveau de déplacement cible pour l'embout (102) au premier niveau de déplacement,
après avoir déterminé que la valeur de rigidité tissulaire déterminée est supérieure au seuil de rigidité, fixer le niveau de déplacement cible pour l'embout au deuxième niveau de déplacement associé à la valeur de rigidité tissulaire potentielle correspondant à la valeur de rigidité tissulaire déterminée, et
ajuster le signal de commande CA émis par le générateur de signaux (112) vers la pièce à main ultrasonique (104) afin d'atteindre le niveau de déplacement cible défini.

2. Système (100) selon la revendication 1, dans lequel le processeur (122) est configuré pour déterminer, en tant que valeur de rigidité tissulaire déterminée, une résistance mécanique de la pièce à main ultrasonique (104) sur la base de la tension et du courant mesurés du signal de commande CA, le seuil de rigidité est défini par un seuil de résistance mécanique, et les valeurs potentielles de rigidité tissulaire sont définies par les résistances mécaniques potentielles de la pièce à main ultrasonique (104).

3. Système (100) de la revendication 2, dans lequel le processeur (122) est configuré pour déterminer la résistance mécanique de la pièce à main ultrasonique sur la base de la tension et du courant mesurés du signal de commande CA en ce qu'il est configuré pour:

déterminer la capacité du transducteur (106) de la pièce à main ultrasonique (104);
déterminer une fréquence de résonance de la pièce à main ultrasonique (104);
régler une fréquence du signal de commande CA sur la fréquence de résonance déterminée de la pièce à main

ultrasonique (104);
calculer un courant circulant dans les composants mécaniques de la pièce à main ultrasonique (104) sur la base de la capacité du transducteur (106), de la fréquence du signal de commande CA, de la tension mesurée du signal de commande CA et du courant mesuré du signal de commande CA; et
calculer la résistance mécanique de la pièce à main ultrasonique (104) sur la base du courant circulant dans les composants mécaniques de la pièce à main ultrasonique (104) et de la tension mesurée du signal de commande CA.

4. Système (100) de l'une des revendications 1 à 3, dans lequel le modèle de réponse de tissu définit les seconds niveaux de déplacement de telle sorte que les seconds niveaux de déplacement diminuent au fur et à mesure que les valeurs de rigidité tissulaire potentielle augmentent.

5. Système (100) selon l'une quelconque des revendications 1 à 4, dans lequel le seuil de rigidité est un premier seuil de rigidité, le modèle de réponse tissulaire définit un troisième niveau de déplacement pour l'embout (102) qui est un niveau de déplacement minimum non nul pour l'embout (102) et qui est inférieur à chaque deuxième niveau de déplacement, et définit un deuxième seuil de rigidité qui est supérieur aux valeurs potentielles de rigidité tissulaire, et le processeur (122) est configuré pour:

en réponse à la valeur de rigidité tissulaire déterminée qui est supérieure au deuxième seuil de rigidité, fixer le niveau de déplacement cible pour l'embout (102) au troisième niveau de déplacement; et
lorsque la valeur de rigidité tissulaire déterminée est supérieure au premier seuil de rigidité et inférieure au second seuil de rigidité, régler le niveau de déplacement cible pour l'embout (102) au deuxième niveau de déplacement associé à la valeur de rigidité tissulaire potentielle correspondant à la valeur de rigidité tissulaire déterminée.

6. Système (100) de la revendication 5, dans lequel au moins l'un parmi le premier niveau de déplacement, le troisième niveau de déplacement, le premier seuil de rigidité, le deuxième seuil de rigidité ou la relation entre les deuxièmes niveaux de déplacement et les valeurs potentielles de rigidité tissulaire est basé sur un réglage de l'utilisateur.

7. Système (100) des revendications 5 ou 6, dans lequel la relation entre les deuxièmes niveaux de déplacement et les valeurs potentielles de rigidité tissulaire est définie par une fonction linéaire négative qui associe le premier seuil de rigidité au premier niveau de déplacement et associe le deuxième seuil de rigidité au troisième niveau de déplacement.

8. Système (100) des revendications 5 ou 6, dans lequel la relation entre les deuxièmes niveaux de déplacement et les valeurs potentielles de rigidité tissulaire est définie par une fonction de courbe décroissante qui associe le premier seuil de rigidité au premier niveau de déplacement et associe le deuxième seuil de rigidité au troisième niveau de déplacement.

9. Système (100) de l'une des revendications 1 à 6 et 8, dans lequel le modèle de réponse tissulaire est configuré pour réduire l'ablation d'un type de tissu pendant le fonctionnement de la pièce à main ultrasonique (104), et la relation entre les deuxièmes niveaux de déplacement et les valeurs potentielles de rigidité tissulaire est définie par une fonction décroissante incurvée qui est basée sur une tension du signal de commande CA correspondant à la perforation du type de tissu.

10. Système (100) de la revendication 9, dans lequel la fonction de diminution incurvée est en outre basée sur un décalage de résistance correspondant aux composants vibrants de la pièce à main ultrasonique (104).

11. Système (100) de l'une des revendications 1 à 10, dans lequel le modèle de réponse tissulaire est un premier modèle de réponse tissulaire, et comprenant en outre:

une mémoire (124) stockant le premier modèle de réponse tissulaire et un second modèle de réponse tissulaire conçu pour l'ablation d'un tissu plus rigide que le premier modèle de réponse tissulaire
dans lequel le processeur (122) est configuré pour:

recevoir une sélection par l'utilisateur du premier modèle de réponse tissulaire et du second modèle de réponse tissulaire par l'intermédiaire d'une interface utilisateur (128, 123, 121);
en réponse à la sélection par l'utilisateur du premier modèle de réponse tissulaire:

lorsque l'embout (102) est placée contre un premier type de tissu, régler le niveau de déplacement cible sur le premier niveau de déplacement, et
lorsque l'embout (102) est placée contre un second type de tissu plus rigide que le premier type de tissu, régler le niveau de déplacement cible à un niveau de déplacement inférieur au premier niveau de déplacement; et

en réponse à la sélection par l'utilisateur du second modèle de réponse tissulaire et à la mise en place de l'embout (102) contre le premier et le second type de tissus, régler le niveau de déplacement cible sur le premier niveau de déplacement.

12. Système (100) de la revendication 11, dans lequel le seuil de rigidité est un premier seuil de rigidité, les valeurs de rigidité tissulaire potentielle sont des premières valeurs de rigidité tissulaire potentielle, le deuxième modèle de réponse tissulaire définit un deuxième seuil de rigidité qui est supérieur au premier seuil de rigidité et associe chacun des deuxièmes niveaux de déplacement à une deuxième valeur de rigidité tissulaire potentielle différente supérieure au deuxième seuil de rigidité, et au moins une des premières valeurs de rigidité tissulaire potentielle est inférieure à chacune des deuxièmes valeurs de rigidité tissulaire potentielle.

13. Système (100) de la revendication 12, dans lequel la relation entre les deuxièmes niveaux de déplacement et les deuxièmes valeurs potentielles de rigidité tissulaire est définie par une fonction qui est basée sur une tension du signal de commande CA correspondant à la perforation d'un troisième type de tissu plus rigide que le deuxième type de tissu.

14. Système (100) de l'une des revendications 1 à 13, dans lequel le niveau de déplacement cible pour l'embout correspond à un courant cible circulant dans les composants mécaniques de la pièce à main ultrasonique (104), et le processeur (122) est configuré pour ajuster le signal de commande CA émis par le générateur de signaux (112) pour atteindre le niveau de déplacement cible défini en étant configuré pour ajuster le signal de commande CA de sorte qu'un courant réel circulant dans les composants mécaniques de la pièce à main ultrasonique (104) soit sensiblement égal au courant cible circulant dans les composants mécaniques de la pièce à main ultrasonique (104).

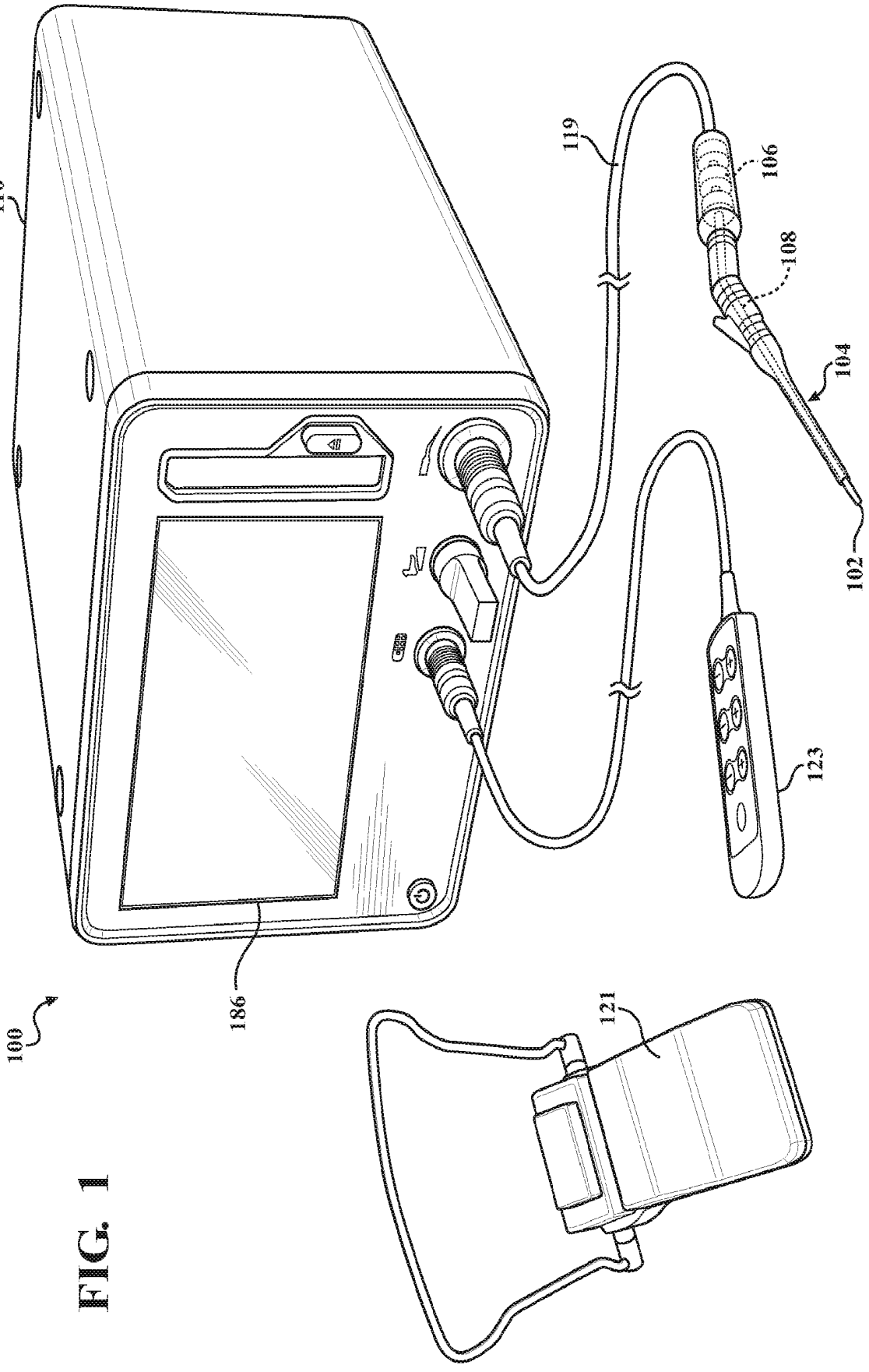


FIG. 1

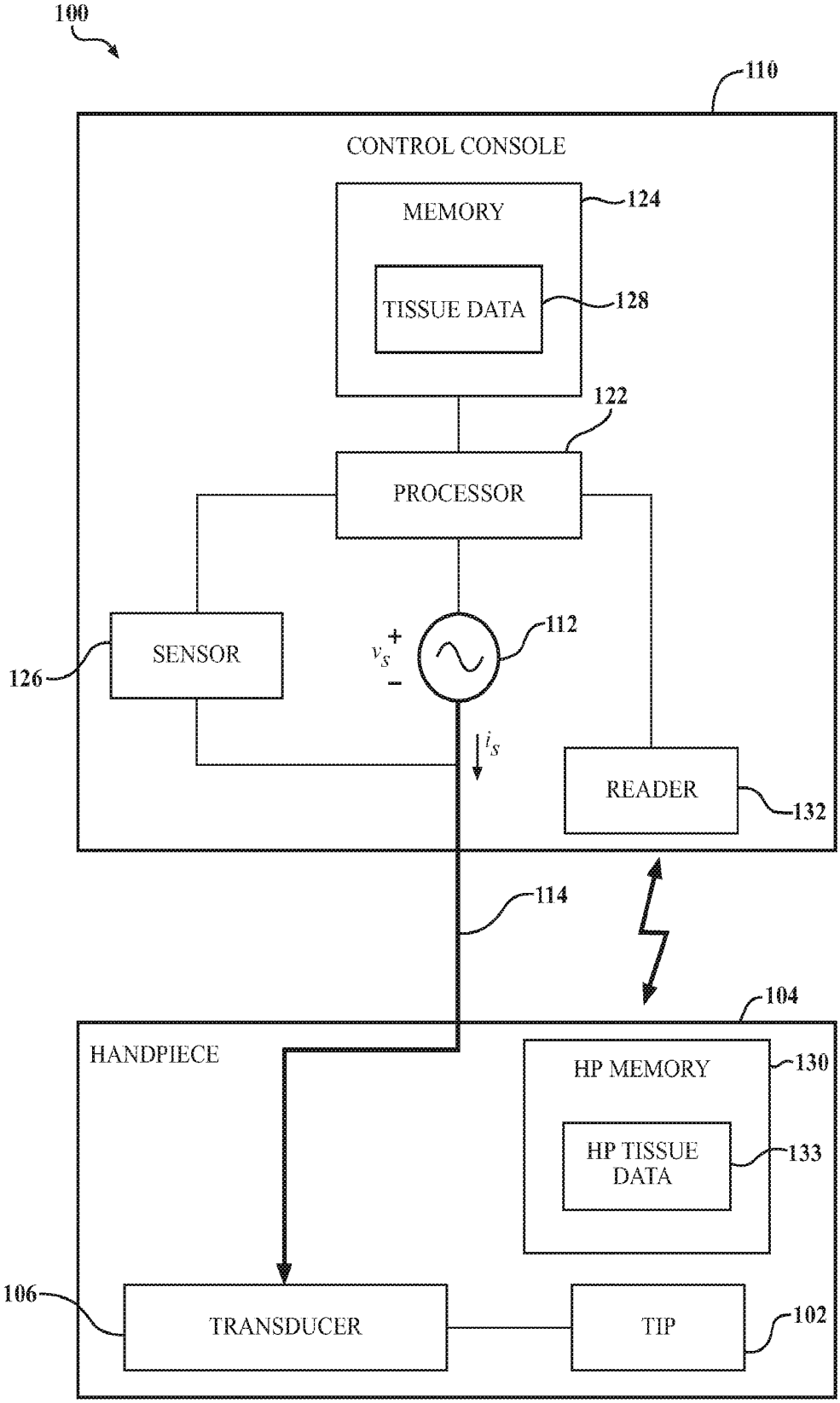

100
110
CONTROL CONSOLE
MEMORY
124
TISSUE DATA
128
122
PROCESSOR
SENSOR
126
v_s
+
−
112
i_s
READER
132
114
104
HANDPIECE
HP MEMORY
130
HP TISSUE DATA
133
106
TRANSDUCER
TIP
102

FIG. 2

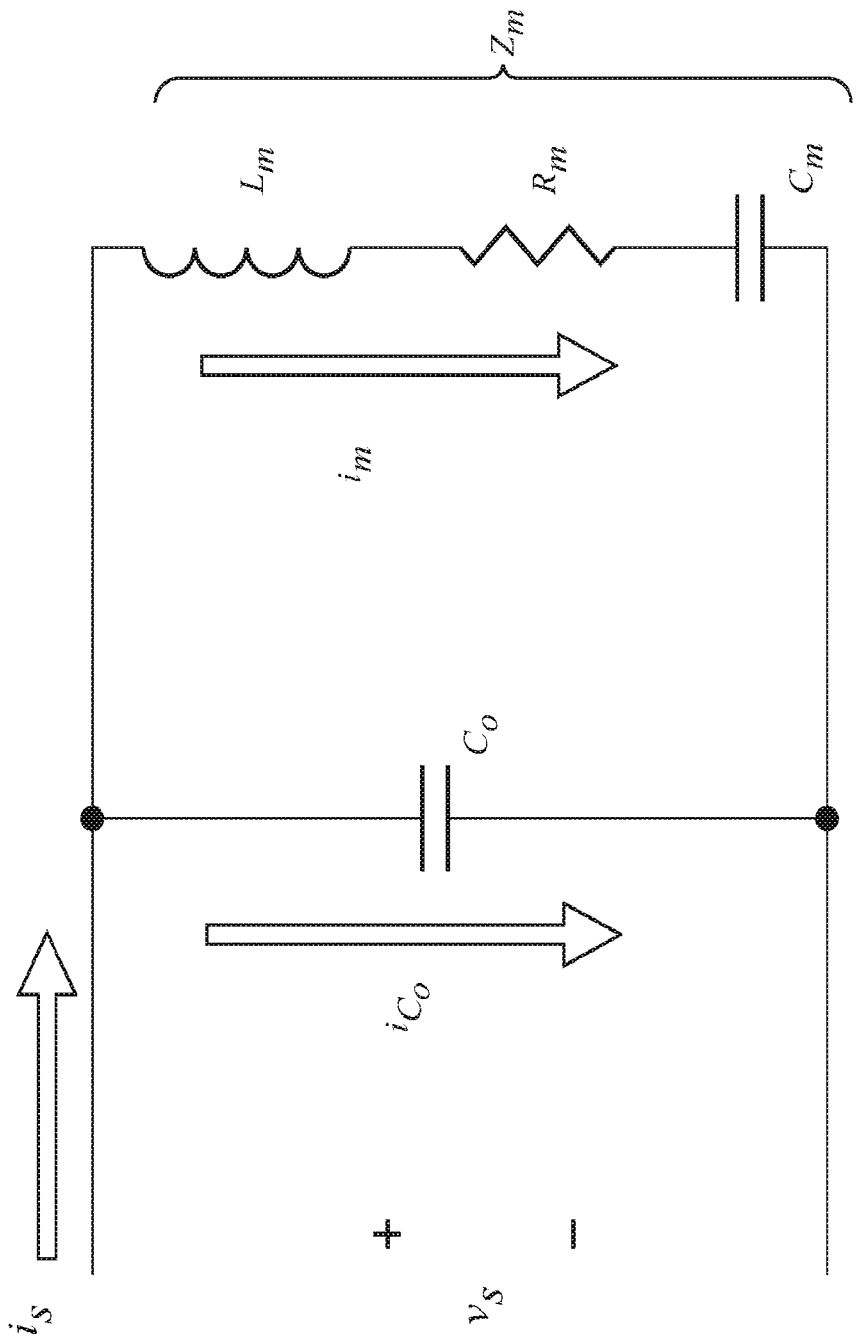


FIG. 3

FIG. 4

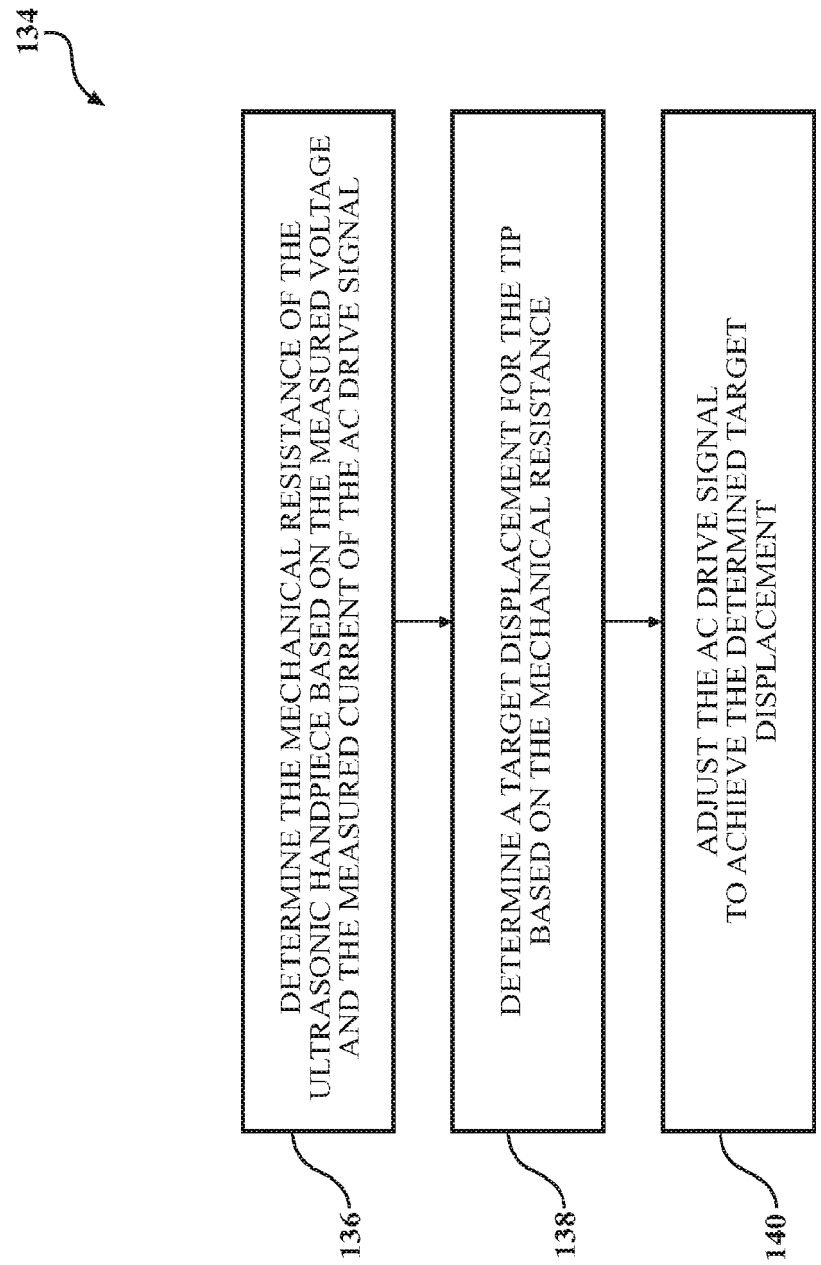
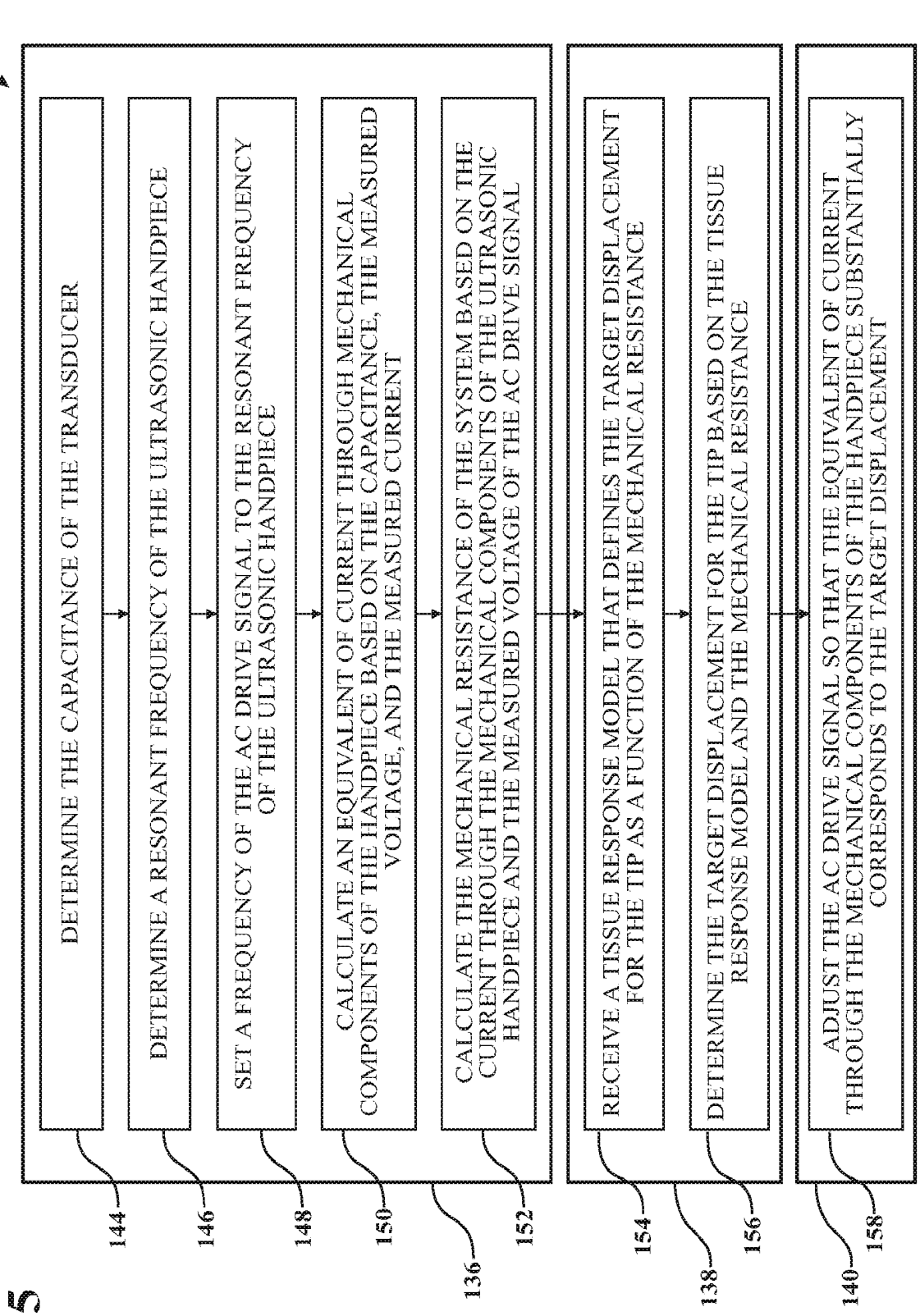

134
DETERMINE THE MECHANICAL RESISTANCE OF THE ULTRASONIC HANDPIECE BASED ON THE MEASURED VOLTAGE AND THE MEASURED CURRENT OF THE AC DRIVE SIGNAL
136
DETERMINE A TARGET DISPLACEMENT FOR THE TIP BASED ON THE MECHANICAL RESISTANCE
138
ADJUST THE AC DRIVE SIGNAL TO ACHIEVE THE DETERMINED TARGET DISPLACEMENT
140

FIG. 5


142
DETERMINE THE CAPACITANCE OF THE TRANSDUCER
DETERMINE A RESONANT FREQUENCY OF THE ULTRASONIC HANDPIECE
SET A FREQUENCY OF THE AC DRIVE SIGNAL TO THE RESONANT FREQUENCY OF THE ULTRASONIC HANDPIECE
CALCULATE AN EQUIVALENT OF CURRENT THROUGH MECHANICAL COMPONENTS OF THE HANDPIECE BASED ON THE CAPACITANCE, THE MEASURED VOLTAGE, AND THE MEASURED CURRENT
CALCULATE THE MECHANICAL RESISTANCE OF THE SYSTEM BASED ON THE CURRENT THROUGH THE MECHANICAL COMPONENTS OF THE ULTRASONIC HANDPIECE AND THE MEASURED VOLTAGE OF THE AC DRIVE SIGNAL
RECEIVE A TISSUE RESPONSE MODEL THAT DEFINES THE TARGET DISPLACEMENT FOR THE TIP AS A FUNCTION OF THE MECHANICAL RESISTANCE
DETERMINE THE TARGET DISPLACEMENT FOR THE TIP BASED ON THE TISSUE RESPONSE MODEL AND THE MECHANICAL RESISTANCE
ADJUST THE AC DRIVE SIGNAL SO THAT THE EQUIVALENT OF CURRENT THROUGH THE MECHANICAL COMPONENTS OF THE HANDPIECE SUBSTANTIALLY CORRESPONDS TO THE TARGET DISPLACEMENT
144
146
148
150
136
152
154
138
156
140
158

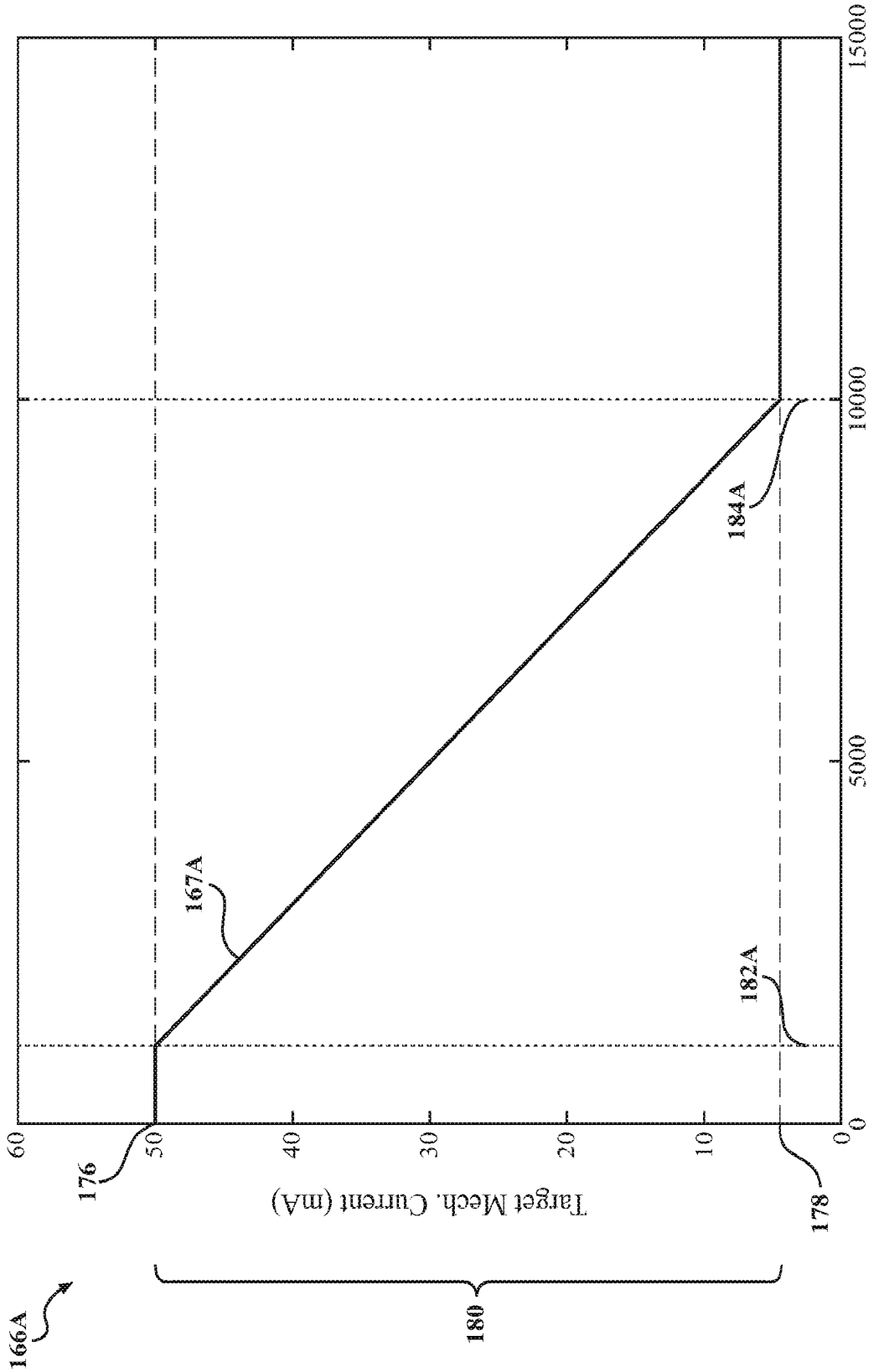

166A
180
Target Mech. Current (mA)
60
50
40
30
20
10
0
176
178
167A
182A
184A
0
5000
10000
15000
Mech. Resistance (Ohms)

FIG. 6

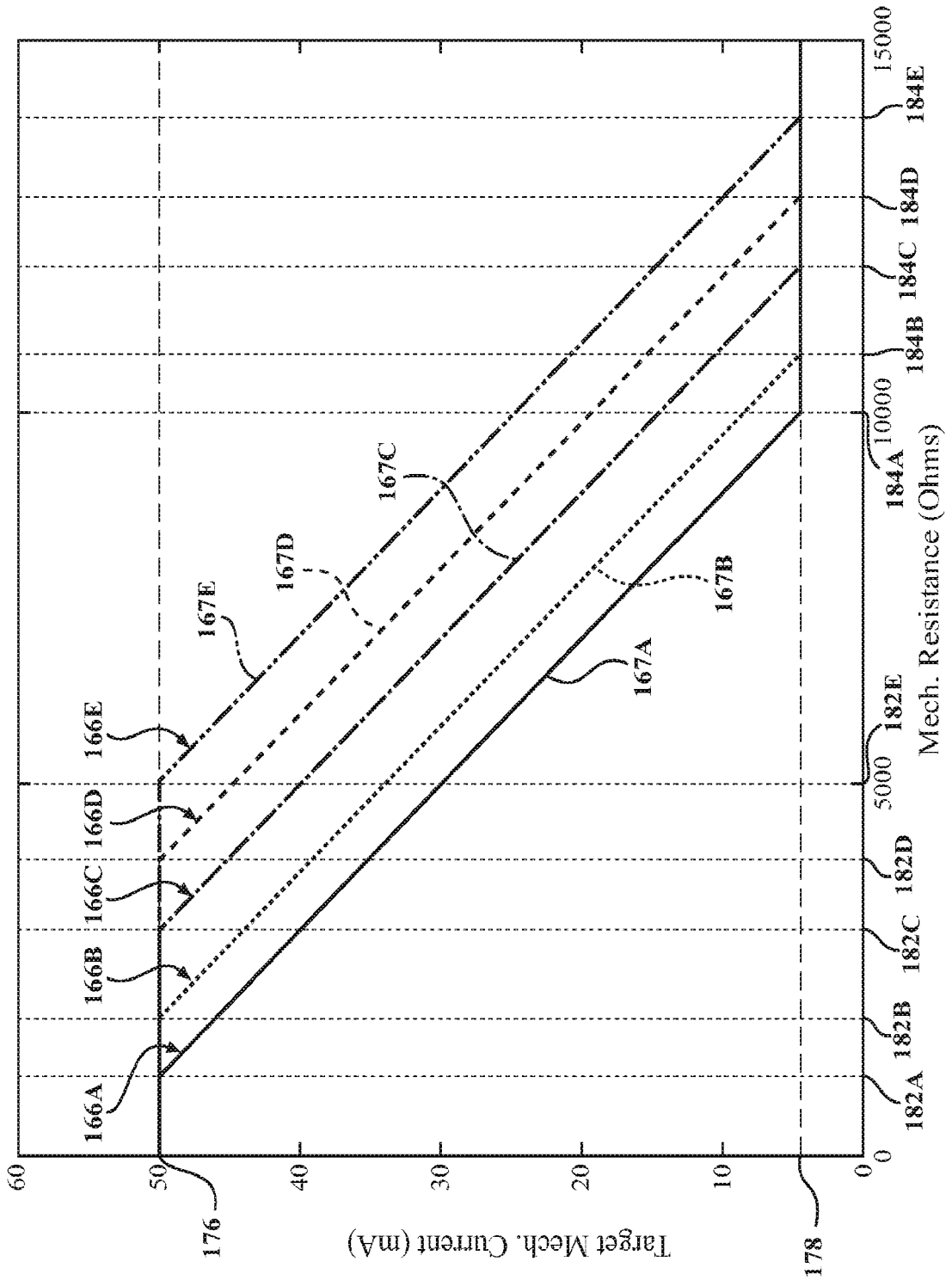

Target Mech. Current (mA)
60
50
40
30
20
10
0
176
178
Mech. Resistance (Ohms)
0
5000
10000
15000
182A
182B
182C
182D
182E
184A
184B
184C
184D
184E
166A
166B
166C
166D
166E
167A
167B
167C
167D
167E

FIG. 7

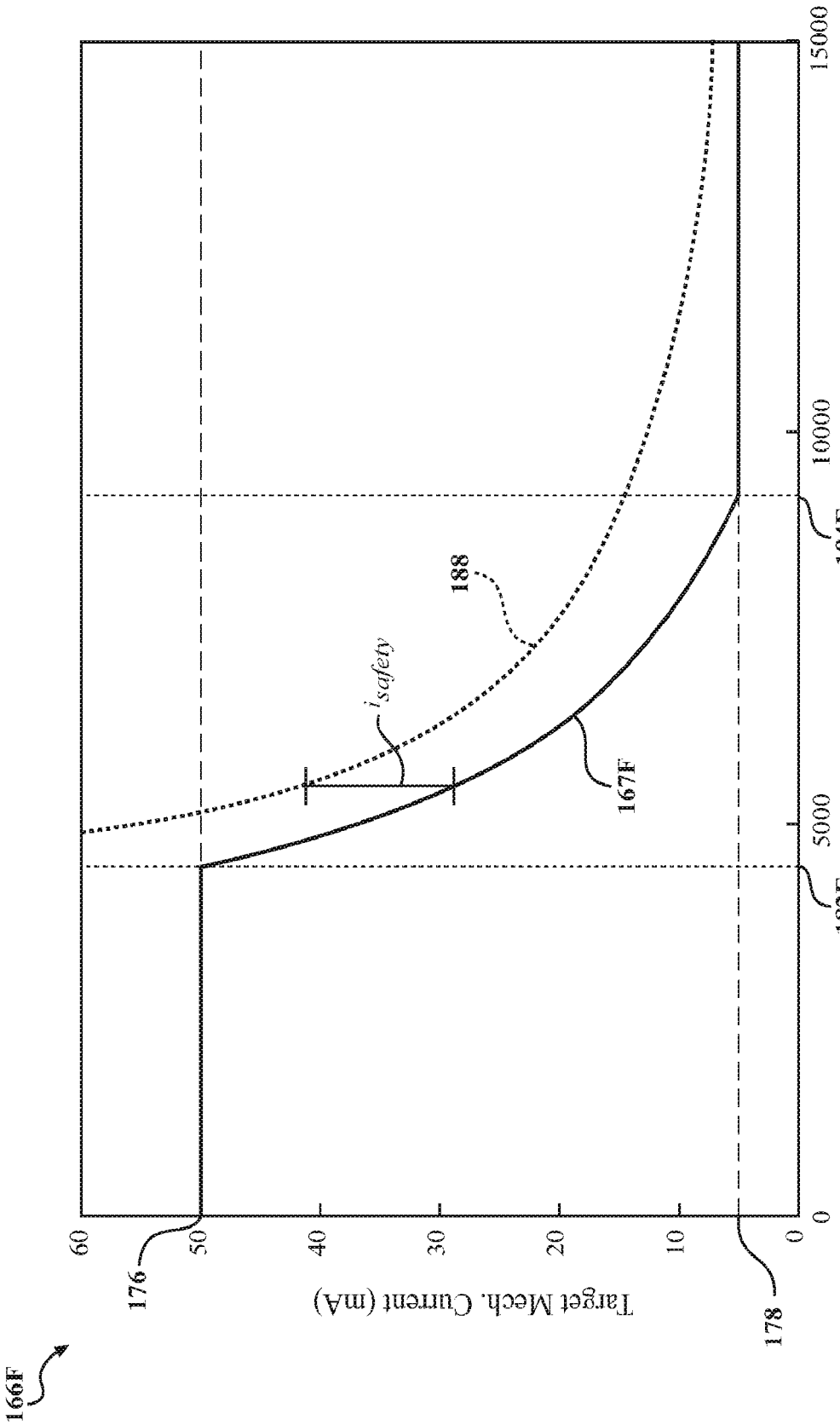

166F
Target Mech. Current (mA)
60
50
40
30
20
10
0
176
178
0
5000
10000
15000
Mech. Resistance (Ohms)
182F
184F
188
I_{safety}
167F

FIG. 8

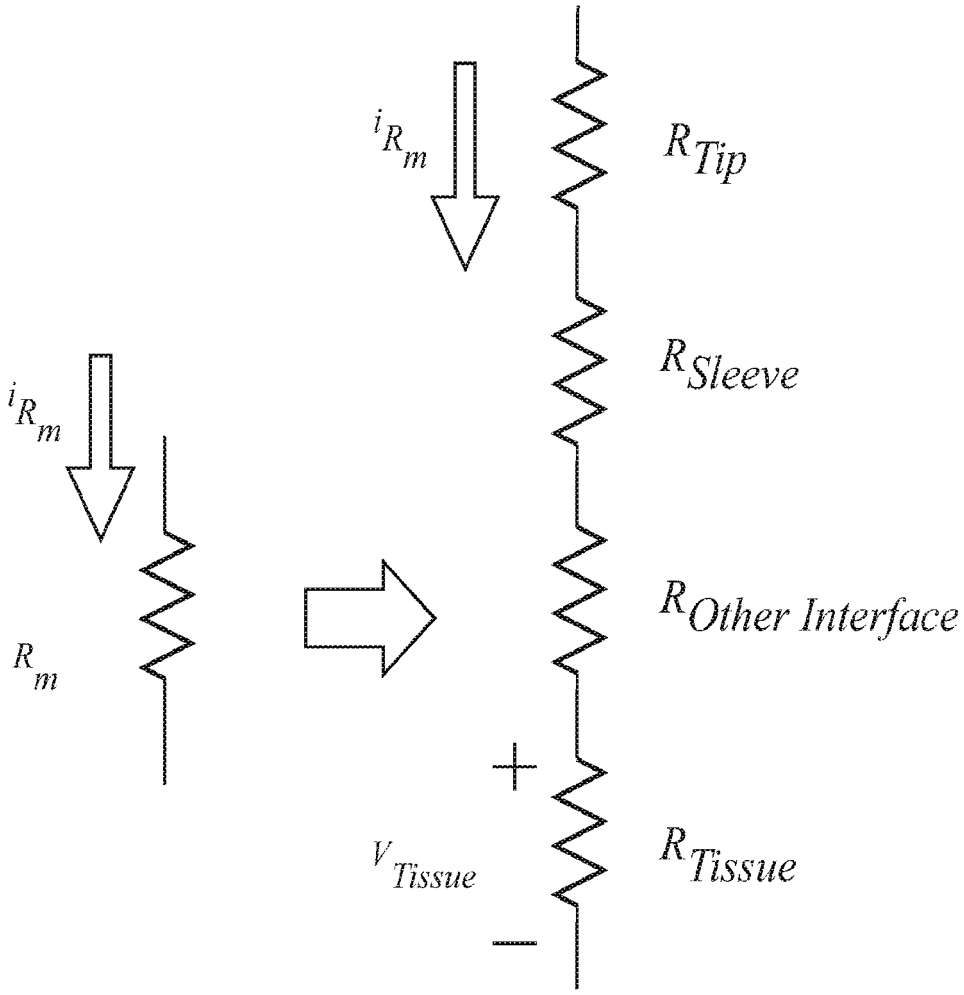


FIG. 9

REFERENCES CITED IN THE DESCRIPTION

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