United States Patent	12390291
Kind Code	B2
Date of Patent	August 19, 2025
Inventor(s)	Suresh; Ashwinram et al.

Decoupling tool shaft from cable drive load

Abstract

A surgical tool is provided that includes a hollow shaft and a cable extending within the shaft such that the cable is isolated from external forces imparted to the shaft; the shaft and a carriage are included as links of a 4-bar linkage that also includes first and second side links that are rotatably mounted to the carriage at respective first and second distal pivot axes and that are rotatably mounted to the shaft at respective first and second proximal pivot axes; the segment of the cable extends between a distal pulley rotatably at the carriage and a proximal pulley rotatably mounted at the shaft and a segment of the cable extends within the shaft; a distance between the first distal and first proximal pivot axes matches a distance between an axis of the distal pulley axis and an axis of the proximal pulley such that a rocking motion of the 4-bar linkage due to external force upon the shaft exerts no force upon the cable.

Inventors:	**Suresh; Ashwinram (San Jose, CA), Kadokura; Grant M. (San Diego, CA)**
Applicant:	**Intuitive Surgical Operations, Inc.** (Sunnyvale, CA)
Family ID:	**1000008762541**
Assignee:	**Intuitive Surgical Operations, Inc. (Sunnyvale, CA)**
Appl. No.:	**17/293460**
Filed (or PCT Filed):	**November 15, 2019**
PCT No.:	**PCT/US2019/061883**
PCT Pub. No.:	**WO2020/102776**
PCT Pub. Date:	May 22, 2020

Prior Publication Data

Document Identifier	Publication Date

Related U.S. Application Data

us-provisional-application US 62767885 20181115

Publication Classification

Int. Cl.: **A61B34/00** (20160101); **A61B34/35** (20160101); **A61B34/37** (20160101); **A61B90/50** (20160101)

U.S. Cl.:

CPC **A61B34/71** (20160201); **A61B34/35** (20160201); **A61B34/37** (20160201); **A61B34/76** (20160201); **A61B34/77** (20160201); **A61B90/50** (20160201); A61B2034/715 (20160201); A61B2090/506 (20160201)

Field of Classification Search

CPC: A61B (34/71); A61B (34/35); A61B (34/37); A61B (34/76); A61B (34/77); A61B (90/50); A61B (2034/715); A61B (2090/506); A61B (34/70); A61B (2034/305); A61B (34/30)

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Primary Examiner: Ho; Tan-Uyen T

Assistant Examiner: Stein; David P

Background/Summary

CLAIM OF PRIORITY (1) This application is a U.S. national stage filing under 35 U.S.C. § 371 of International Application No. PCT/US2019/061883, entitled "DECOUPLING TOOL SHAFT FROM CABLE DRIVE LOAD," filed Nov. 15, 2019, which claims the benefit of priority to U.S. Provisional Patent Application Ser. No. 62/767,885, entitled "DECOUPLING TOOL SHAFT FROM CABLE DRIVE LOAD." filed Nov. 15, 2018, each of the disclosures of which is incorporated by reference herein in its entirety.

BACKGROUND
(1) Minimally invasive medical techniques are intended to reduce the amount of tissue that is damaged during diagnostic or surgical procedures, thereby reducing patient recovery time, discomfort, and deleterious side effects. Teleoperated surgical systems that use robot assisted technology may be used to overcome limitations of manual laparoscopic and open surgery. Advances in telepresence systems provide surgeons views inside a patient's body, an increased number of degrees of motion of surgical tools, and the ability for surgical collaboration over long distances. In manual minimally invasive surgery, surgeons feel the interaction of the tools with the patient via a long shaft, which eliminates tactile cues and masks force cues.
(2) In teleoperation surgery systems, natural force feedback is eliminated because the surgeon no longer manipulates the tool directly. Rather, an end effector at a distal end of a long shaft is actuated by control cables that extend within the shaft. A sensor at a proximal end portion of the shaft may be used to measure clinical forces imparted to patient tissue during a medical procedure due to contact between an end effector and patient tissue.
(3) Unfortunately, forces imparted by control cables extending within the shaft may be significantly larger than clinical forces that result from contact between an end effector and patient contact tissue. Thus, there is a need to isolate clinical forces from cable forces.

Description

BRIEF DESCRIPTION OF THE DRAWINGS
(1) Aspects of the present disclosure are best understood from the following detailed description when read with the accompanying figures. It is emphasized that, in accordance with the standard practice in the industry, various features are not drawn to scale. In fact, the dimensions of the

various features may be arbitrarily increased or reduced for clarity of discussion. In addition, the present disclosure may repeat reference numerals and/or letters in the various examples. This repetition is for the purpose of simplicity and clarity and does not in itself dictate a relationship between the various embodiments and/or configurations discussed.
(2) FIG. **1** is an illustrative plan view of a minimally invasive teleoperated surgical system for performing a minimally invasive diagnostic or surgical procedure on a patient who is lying on an operating table.
(3) FIG. **2** is a perspective view of a surgeon's console.
(4) FIG. **3** is a perspective view of a manipulator unit of a minimally invasive teleoperated surgical system.
(5) FIG. **4** is a diagrammatic side view of a surgical tool coupled to a tool carriage.
(6) FIGS. **5**A-**5**B are illustrative schematic diagrams representing a four-bar linkage operatively coupled to a proximal portion of a tool shaft and to a vertical sensor in a neutral position (FIG. **5**A) with no vertical force imparted to the shaft and in an axially displaced position (FIG. **5**B) with a vertical force imparted to the shaft.
(7) FIG. **5**C is an illustrative schematic diagram showing an alternative example four-bar linkage that includes a differential coaxial inductive displacement sensor and a spring force sensor.
(8) FIGS. **6**A-**6**C are illustrative side view of an embodiment of a four-bar linkage in example neutral (FIG. **6**A), lowered (FIG. **6**B), and raised (FIG. **6**C), in which a backend chassis and a shaft assembly are coupled to act as links.
(9) FIG. **7** is an illustrative schematic side cross-sectional view of an embodiment of a sensor of FIG. **6**.
(10) FIG. **8** is an illustrative simplified top view showing a layout of steering guide pulleys, waterfall guide pulleys and cable drive members mounted to the four-bar linkage embodiment of FIGS. **6**A-**6**C in accordance with some embodiments.
(11) FIG. **9** is an illustrative partial perspective view perspective of showing the arrangement of the first and second sets of steering guide pulleys and the first and second sets of waterfall guide pulleys of FIG. **8**.
(12) FIG. **10** is an illustrative perspective view of a first embodiment of the lower second side link and flexure beam and sensor assembly of FIGS. **6**A-**6**C.
(13) FIG. **11** an illustrative perspective partial view of a second embodiment of the lower second side link and flexure beam and sensor assembly of FIGS. **6**A-**6**C.
(14) FIG. **12** an illustrative perspective view of a third embodiment of the lower second side link and flexure beam and sensor assembly of FIGS. **6**A-**6**C.
DESCRIPTION OF EMBODIMENTS
Teleoperated Surgical System
(15) FIG. **1** is an illustrative plan view of a minimally invasive teleoperated surgical system **10** for performing a minimally invasive diagnostic or therapeutic surgical procedure on a patient **12** who is lying on an operating table **14**. The system includes a user control unit **16** for use by a surgeon **18** during the procedure. One or more assistants **20** also may participate in the procedure. The minimally invasive teleoperated surgical system **10** further includes one or more manipulator units **22** and an auxiliary unit **24**. The manipulator units **22** can manipulate at least one surgical instrument **26** through a minimally invasive incision in the body or a natural body orifice of the patient **12** while the surgeon **18** views the surgical site through the user console **16**. An image of the surgical site can be obtained by an endoscope **28**, such as a stereoscopic endoscope, which may be positioned using a manipulator unit **22**. Computer processors located on the auxiliary unit **24** may be used to process the images of the surgical site for subsequent display to the surgeon **18** through the user console **16**. The computer processor can include a logic unit and a memory that stores instructions carried out by the logic unit. In some embodiments, stereoscopic images may be captured, which allow the perception of depth during a surgical procedure. The number of surgical

instruments **26** used at one time will generally depend on the diagnostic or therapeutic procedure and the space constraints within the operative site, among other factors. If it is necessary to change one or more of the surgical instruments **26** being used during a procedure, an assistant **20** may remove the surgical instrument **26** from a manipulator unit **22** and replace it with another surgical instrument **26** from a tray **30** in the operating room. An example computer processor at the auxiliary unit **24** can be configured process signals indicative of forces imparted at the surgical instrument. An example computer processor can produce haptic feedback corresponding to these imparted forces at the surgeon's console **16**.

(16) FIG. **2** is a perspective view of the user console **16**. The surgeon's console **16** includes a viewer display **31** that includes a left eye display **32** and a right eye display **34** for presenting the surgeon **18** with a coordinated stereoscopic view of the surgical site that enables depth perception. The user console **16** further includes one or more hand-operated control input devices **36**, **38** to receive larger-scale hand control movements. One or more slave surgical instruments **26** installed for use at on one or more corresponding manipulator units **22** move in relatively smaller-scale distances that match a surgeon **18**'s larger-scale manipulation of the one or more master control inputs **36**, **38**. The master control input devices **36**, **38** may provide the same mechanical degrees of freedom as their associated surgical instruments **26** to provide the surgeon **18** with telepresence, or the perception that the master control input devices **36** are integral with the slave surgical instruments **26** so that the surgeon has a keen sense of directly controlling the instruments **26**. To this end, position, force, and tactile feedback sensors (not shown) may be employed to transmit position, force, and tactile sensations from the surgical instruments **26** through the control input devices **36**,**38** to the surgeon's hands, subject to communication delay constraints. Signals (optionally optical or electronic) modulated based upon forces detected at force sensors (not shown) at the instrument **26** may be processed by the processors at the auxiliary unit cart **24** to produce haptic feedback at the control input devices **36** that is indicative of the detected forces.

(17) FIG. **3** is a perspective view of a manipulator unit **22** of the example minimally invasive teleoperated surgical system **10**, in accordance with some embodiments. The manipulator unit **22** includes four manipulator support structures **72**. Each manipulator support structure **72** includes articulated support structures **73** that are pivotally mounted end-to-end and a pivotally mounted support spar **74**. A respective surgical instrument carriage **75**, which includes motors to control instrument motion, is mounted at each support spar **74**. Additionally, each manipulator support structure **72** can optionally include one or more setup joints (e.g., unpowered and/or lockable) at the junctions of the articulated support structures **73** and at a junction with a spar **74**. A carriage **75** can be moved along a spar **74** to position the carriage **75** at different locations along the spar **74**. Thus, the spars **74** can be used to position the attached to surgical instrument carriage **75** in relation to a patient **12** for surgery. Each surgical instrument **26** is detachably connected to a carriage **75**. While the manipulator unit **22** is shown as including four manipulator support structures **72**, more or fewer manipulator support structures **72** can be used. In general, at least one of the surgical instruments will include a vision system that typically includes an endoscopic camera instrument for capturing video images and one or more video displays for displaying the captured video images that are coupled to one of the carriages **75**.

(18) In one aspect, a carriage **75** houses multiple teleoperated actuators such as motors (not shown) that impart motion to a tension member, such as a cable drive elements, that include one or more of drive shafts and capstans (not shown), that in turn, drive cable motions that the surgical instrument **26** translates into a variety of movements of an end effector portion of the surgical instrument **26**. In some embodiments, the teleoperated actuators in a carriage **75** impart motion to individual components of the surgical instrument **26** such as end effector wrist movement or jaw movement, for example.

(19) A surgeon manipulates the master control input devices **36**, **38** to control an instrument end effector. An input provided by a surgeon or other medical person to a control input device **36** or **38**

(a “master” command) is translated into a corresponding action by the surgical instrument **26** (a corresponding “slave” response) through actuation of one or more remote motors. A flexible wire cable-based force transmission mechanism or the like is used to transfer the motions of each of the remotely located teleoperated motors to a corresponding instrument-interfacing actuator output located at an instrument carriage **75**. In some embodiments, a mechanical adapter interface **76** mechanically couples an instrument **26** to actuators **443** within an instrument carriage to control motions inside the instrument **26**. The surgical instrument **26** may be mechanically coupled to a first actuator (not shown), which may control a first motion of the surgical instrument such as longitudinal (z-axis) rotation. The surgical instrument **26** may be mechanically coupled to a second actuator (not shown), which may control second motion of the surgical instrument such as planar two-dimensional (x, y) motion. The surgical instrument **26** may be mechanically coupled to a third actuator, which may control third motion of the surgical instrument such as opening and closing of jaws of an end effector, for example.

(20) FIG. **4** is a diagrammatic side view of a surgical tool **26**, coupled to a carriage **75**. The tool **26** includes an elongated hollow cylindrical tubular shaft **410** having a distal end portion **450** that includes an end effector **454** for insertion into a patient's body cavity and a proximal end portion **456** that is secured to a proximal tool controller **440**. An inner wall of the shaft defines a cylindrical hollow bore. The shaft **410** includes a longitudinal center axis **411** between the proximal and distal portions (a “shaft center axis”). As used herein the term “proximal” indicates a location at a surgical tool closer to a manipulator arm, and the term “distal'” indicates a location at a surgical tool more distant from the manipulator arm. The proximal tool controller **440** includes a housing **441** (shown transparent, indicated with dashed lines) that encloses a backend chassis **442** that mounts multiple cable drive elements **460**, which for example may include one or more capstans and drive shafts that are configured to couple drive forces imparted by one or more actuators **443** within carriage **75** to cables extending within the shaft **410** in parallel alignment with the shaft axis **411**. U.S. provisional patent application No. 62/767,895, filed on Nov. 15, 2018, which is expressly incorporated into this disclosure in its entirety, discloses drive members **460** in accordance with some embodiments. The cables **470** extend within the shaft between the drive members **460** and an end effector **454**.

(21) The end effector **454** can include a functional mechanical degree of freedom, such as jaws that open or close, or a knife that translates along a path or a wrist **452** that may move in x and y directions. U.S. Pat. No. 6,394,998 shows examples of end effectors with multiple degrees of mechanical freedom. The distal portion **450** of the tool **26** can provide any of a variety of different kinds of end effectors **454**, such as the forceps, a needle driver, a cautery device, a cutting tool, an imaging device (e.g., an endoscope or ultrasound probe), or the like.

(22) The cables **470** are operatively coupled so that movement of the cables may impart motion to end effector **454** such as to open or close of jaws, drive wrist motion, or operate other distal end effector components, for example. Thus, actuators **443** (such as motors) located at the carriage **75** near the proximal end portion **456** of the shaft **410** control movement of the end effector **454** at the distal end portion **450** of the shaft **410** by causing drive members **460** within the housing **441** of the proximal tool controller **440** to exert control forces upon cables **470** extending within the shaft **410** parallel to the shaft axis **411** between the drive members **460** and the end effector **454**.

Decoupling Vertical Clinical Force from Lateral Cable Actuation Force

(23) FIGS. **5**A-**5**B are illustrative schematic diagrams representing a four-bar linkage **502** operatively coupled to a proximal portion of a carriage **75** and to a sensor **562**. As shown in FIG. **5**A, linkage **502** is in a neutral position with no axial force imparted to the shaft **410**. As shown in FIG. **5**B, linkage **502** is displaced because shaft **410** is in an axially displaced position with an axial force F.sub.H imparted to end effector **454**. It can be seen that the axial force F.sub.H transmitted via shaft **410** and via linkage **502** to sensor **562**, which is coupled to chassis **442**. In this way axially-oriented force on end effector **454** is sensed by sensor **562**.

(24) The sensor **562** can be configured as a deflection sensor to measure an amount of deflection of a diaphragm region **702** (described below) of the sensor **562** due to the axial force F.sub.H. The amount of deflection is indicative of magnitude of the force F.sub.H. In some embodiments, the sensor **562** includes a force sensor configured to sense force bounded as approximately ±20 N. With no axial force imparted to the housing **440** as shown in FIG. **5**A, actuators **443** within the carriage **75** impart forces to cables **550**, **552** to maintain the links of the four-bar linkage **502** are in neutral positions so that no force is imparted to the sensor **562**. With an axial force F.sub.H imparted to the end effector **454** as shown in FIG. **5**B, links of the four-bar linkage are displaced to impart a linkage force F.sub.L to the sensor **562**. In some embodiments, the linkage force F.sub.L is proportional in magnitude to a magnitude of the housing force F.sub.H.
(25) More specifically, the four-bar linkage **502** includes an upper first side link **504**, a lower second side link **506**, an end third frame link **508**, and an end fourth coupler link **510** that are all coupled together in a double-rocker configuration. A portion of tool carriage **75**, or optionally another component coupled to carriage **75**, may form frame link **508**. And, a portion of shaft **410**, or optionally another component coupled to shaft **410**, may form coupler link **510**. In some embodiments, the four-bar linkage **502** is formed of a rigid material such as plastic, aluminum, titanium, stainless steel, or composites such as carbon filled plastic. A first pivot joint **512** having a first pivot joint axis **513** pivotally couples a proximal first end portion **504***p* of the first side link **504** to a proximal portion of the frame link **508**. A second pivot joint **514** having a second pivot joint axis **515** pivotally couples a proximal first end portion **506***p* of the second side link **506** to a distal portion of the frame link **508**. A third pivot joint **516** having a third pivot joint axis **517** pivotally couples a distal second end portion **504***d* of the first side link **504** to a proximal portion of the coupler link **510**. A fourth pivot joint **518** having a fourth pivot joint axis **519** pivotally couples a distal second end portion **506***d* of the second side link **506** to a distal portion of the coupler link **510**. The frame link has a fixed position in space with reference to the first, second, and fourth links, which move with reference to the frame link as shaft **410** translates laterally along shaft center axis **411**. The first, second, third, and fourth pivot axes are parallel to each other.
(26) A first side link length (the “side lateral length” or “S.sub.LL”) of the first side link **504** between the first pivot joint axis **513** and the third pivot joint axis **517** equals a second side link length of the second side link **506** between the second pivot joint axis **515** and the fourth pivot joint axis **519**. In other words, the first and second side links **504**, **506** have matching side lateral lengths between their respective pivot joints. The first and second side links **504**, **506** each have a respective longitudinal axis **504**A, **506**A. The respective longitudinal axis **504**A, **506**A are askew from the shaft axis **411** in that they are not aligned parallel with the shaft axis **411**. An end lateral length (“E.sub.LL”) of the frame link **508** between the first pivot joint axis **513** and the second pivot joint axis **515** equals an end lateral length of the coupler link **510** between the third pivot joint axis **517** and the fourth pivot joint axis **519**. The frame and coupler links **508**, **510** each have a respective longitudinal axis **508**A, **510**A. As used herein, the term lateral refers to directions parallel to longitudinal axes **504**A, **506**A of the first and second side links **504**, **506**, and the term vertical refers to directions parallel to the longitudinal axes **508**A, **510**A of the frame link and the coupler links **508**, **510**.
(27) A proximal end portion of a hollow shaft **410** is secured at a distal portion of the coupler link **510**. Thus, axial movement, vertically up and down, of the hollow shaft **410** parallel to the shaft axis **411** causes rotational motion of the four links **504**, **506**, **508**, **510** of the four-bar linkage **502** about the four pivot joints **512**, **514**, **516**, **518**, which results in rocking motions of the of the first and second side links **504**, **506**. More particularly, motion imparted to the coupler link **510** by axial movement of the shaft **410** causes the first and third pivot joints **512**, **516** to direct corresponding motion of the distal second end portion **504***d* of the first side link **504** to follow the axial motion of the shaft **440**. Likewise, motion imparted to the coupler link **510** by axial movement of the shaft **440** causes the second and fourth pivot **514**, **518** joints to direct corresponding motion of the distal

second end portion **506***d* of the second side link **506** to follow the axial motion of the shaft **440**. Throughout such motion of the coupler link **510** and the corresponding rocking movement of the first and second side links **504**, **506**, the longitudinal axes **504**A, **506**A of the first and second side links **504**, **506** continuously extend parallel to each other, and the longitudinal axes **508**A, **510**A of the frame link **508** and the coupler link **510** continuously extend parallel to each other.

(28) First and second sets of distal waterfall guide pulleys **520**W, **522**W are rotatably mounted to the coupler link **510**. Corresponding first and second sets of proximal backend steering guide pulleys **530**S, **532**S are rotatably mounted to the frame link **508**. In an example four-bar linkage assembly **502**, the waterfall guide pulleys **520**W, **522**W and the steering pulleys **530**S **532**S are arranged to rotate perpendicular to one another. Each waterfall pulley **520**W, **522**W has a waterfall pulley rotation axis **521**, **523** that extends parallel to the axes of the four-bar linkage pivot joints. Each steering guide pulley **530**S **532**S has a steering guide pulley rotation axis **531**, **533** that extends perpendicular to the waterfall pulley axes and parallel to axis **508**A of the **508** frame. Corresponding first and second sets of cable drive members **540**D, **542**D are rotatably mounted to the frame link **508** with respective rotation axes **541**, **543** that extend perpendicular to the waterfall pulley axes **521**, **523**. It will be understood that once the cables depart the four-bar linkage, they can be driven in different directions (not shown) using other actuators. To simplify the drawings and the explanation, only one waterfall guide pulley, one steering guide pulley, and one drive member of each set is shown. It will be appreciated that the term “waterfall” is used for convenience in denoting location of the distal guide pulleys located at the coupler link **510** and how the cables are routed around the distal guide pulleys and into the shaft. Moreover, it will be appreciated that the term “steering” is used for convenience in denoting location of the proximal guide pulleys located at the frame link **508**, and cables over these proximal guide pulleys can be used for end effector actuation as described above.

(29) As shown, center axes of rotation **521**, **523** of the first and second sets of waterfall guide pulleys **520**W, **522**W are at the coupler link **510** between the third and fourth pivot joints **516**, **518**. Center axes of rotation **521**, **523** of the first and second sets of waterfall pulleys **520**W, **522**W are vertically offset from one another by a pulley vertical offset amount P.sub.VO. The center axes **521** of the first set of waterfall pulleys **520**W are vertically closer to the first side linkage **504** than are the center axes **523** of the second set of waterfall pulleys **522**W. Likewise, the center axes **523** of the second set of waterfall pulleys **522**W are vertically closer to the second side linkage **506** than are the center axes **521** of the first set of waterfall pulleys **520**W.

(30) Also as shown, center axes of rotation **521**, **523** of the first and second sets of waterfall pulleys **520**W, **522**W are laterally offset from one another by a pulley lateral offset amount P.sub.LO. This offset amount P.sub.LO also represents that the center axes of rotation **521** of the first set of waterfall pulleys **520**W are laterally farther from the center axes **513**, **515** of the first and second pivot joints **512**, **514** than are the center axes of rotation **523** of the second set of waterfall pulleys **522**W. The center axes **523** of the second set of waterfall pulleys **522**W are disposed laterally closer to the center axes **513**, **515** of the first and second pivot joints **512**, **514** than are the center axes **521** of the first set of waterfall pulleys **520**, by the pulley lateral offset amount P.sub.LO. It will be appreciated that the offset amount P.sub.LO of cables guided about the first and second sets of waterfall pulleys **520**W, **522**W permits cables **550**, **552** guided by these pulleys across to be positioned to extend within the shaft **410**, laterally spaced apart from one another, parallel to the shaft center axis **411**.

(31) The first and second sets of backend steering guide pulleys **530**S, **532**S are mounted to the frame link **508** at locations vertically offset from one another by the pulley vertical offset amount P.sub.VO. The center axes **531** of the first set of steering pulleys **530**S are the frame link **508** vertically closer to the first side linkage **504** than are the center axes **533** of the second set of steering pulleys **532**S. The center axes **533** of the second set of steering pulleys **532**S are disposed at the frame link **508** vertically closer to the second side linkage **506** than are the center axes **531** of

the first set of steering pulleys **530**S. Center axes **531**, **533** of the first and second sets of steering pulleys **530**S, **532**S are laterally offset from one another at the frame link **508** by the pulley lateral offset amount P.sub.LO. The center axes **531** of the first set of steering pulleys **530**S are disposed laterally closer to the center axes **517**, **519** of the third and fourth pivot joints **516**, **518** than are the center axes **533** of the second set of steering pulleys **532**S. The center axes **533** of the second set of steering pulleys **532**S are disposed laterally farther from the center axes **517**, **519** third and fourth pivot joints **516**, **518** than are the center axes **531** of the first set of steering pulleys **530**S.
(32) Multiple cables **550**, **552** extend within the hollow shaft **410** parallel to the shaft axis **411**. Each of the cables **550**, **552** is anchored at a proximal end to a corresponding cable drive member **540**D, **542**D and is anchored at a distal end to the end effector **454**. Each of the cables **550**, **552** engages a corresponding steering pulley **530**S, **532**S and a corresponding waterfall pulley **520**W, **522**W. In some embodiments, the cables are formed of a material such as stainless steel, titanium, or tungsten, or synthetic materials such as polyethylene, or polybenzoxazole (PBO), for example. More particularly, each cable **550**S, **552**S includes a cable portion that wraps about a perimeter engagement surface of its associated steering pulley **530**S, **532**S, and each cable wraps about a perimeter engagement surfaces of its associated waterfall pulley **520**W, **522**W at the coupling link **510**. Thus, each respective cable **550**S, **552**S extends between the corresponding axes **531**, **533** of the cable's associated steering pulley **530**S, **532**S and corresponding axes **521**, **523** of the cable's associated waterfall pulley **520**W, **522**W. To simplify the drawings and the explanation, only two cables **550**, **552** are shown, although in some embodiments, four, or more than six cables may be used.
(33) The first and second sets of waterfall pulleys **520**W, **522**W and the first and second sets of steering pulleys **530**S, **532**S are configured to maintain each of the multiple cables **550**, **552** aligned parallel to the first and second side links **504**, **506** both when the four-bar linkage is at rest in the neutral position and when the four-bar linkage is displaced in its rocking motion. In accordance with some embodiments, the first and second cables **550**, **552** are pre-tensioned with a force of 0.5-5 lbf. An intermediate cable segment of the first cable **550** has a length between the center axes **521** of the first set of waterfall pulleys **520**W and the center axes **531** of the first set of steering pulleys **530**S that matches the side lateral length. Likewise, an intermediate cable segment of the second cable **552** has a length between the center axes **523** of the second set of waterfall pulleys **522**W and the center axes **533** of the second set of steering pulleys **532**S that matches the side lateral length. The first and second sets of steering pulleys **530**S, **532**S are rotatably mounted at locations at the frame link **508** and the first and second sets of waterfall pulleys **520**W, **522**W are rotatably mounted at locations at the coupling link **510** so that these steering pulleys and waterfall pulleys guide the intermediate cable segments of the first and second cables **550**, **552** to extend parallel to the first and second side links **504**, **506** while the four-bar linkage **502** is at rest and while the 4-bar linkage **502** experiences the rocking motion as shaft **410** moves vertically. Thus, even during rocking of the first and second side links **504**, **506** in response to vertical motion of the shaft **440**, for example, the intermediate cable segments of the first and second cables **550**, **552** continuously extend parallel to the first and second side links **504**, **506**.
(34) A flexure beam **560** includes a distal first end portion **560***d* and a proximal second end portion **560***p*. The distal first end portion **560***d* of the flexure beam is coupled to the proximal first end portion **506***p* of the second side link **506**. The proximal second end portion **560***p* of the flexure beam is operatively coupled to the sensor **562**. More particularly, the flexure beam **560** is operatively coupled to impart the link force F.sub.L force to the sensor **562** that that has a magnitude proportional to the axial force F.sub.H imparted by the shaft housing **440** to the coupler link **510** during axial motion of the shaft **440**. In particular, for example, F.sub.H and its associated vertical displacement is transmitted from the end effector via the shaft to the coupler link. The magnitude of the link force imparted to the sensor **562** due to a corresponding force imparted by the shaft to the coupler link **510** is determined based upon the length of the flexure beam **560**.

Rotation of the distal first end portion **506***d* of the second side link **506** about the second pivot joint axis **515** during rocking motion of the four-bar linkage **502**, caused by a force imparted to the coupler link **510** due to axial motion of the shaft **440**, causes corresponding motion of the flexure beam **560**, which in turn, imparts a corresponding link force F.sub.L to the sensor, which is proportional to the axial force F.sub.H imparted by the shaft **440** to the coupler link **410**.
(35) In some embodiments, the flexure, beam **560** is optionally formed of a material such as aluminum, stainless steel, or titanium, or it may optionally be formed of a composite material such as carbon filled plastic. Flexure beam **560** is configured to have a bending stiffness in a direction parallel to the shaft center axis **411** of the shaft **410** that is less than a bending stiffness of the linkages of the four-bar linkage **502**. The linkages of the four-bar linkage **502** have a high enough bending stiffness such that they do not bend in response to cable forces exerted by the cable drive members **540**D, **542**D. Likewise, the links of the four-bar linkage **502** have a high enough bending stiffness such that they do not bend during normal rocking motion m response to axial motion of the shaft **410**. The instrument shaft **410** has an insertion stiffness in a range of 5-50 N/mm. In some embodiments, total cable forces may be in a range of about 100 lbf. By comparison, a bending stiffness of the flexure beam **560** is small enough to flex during normal rocking motion of the four-bar linkage **502** in response to axial motion of the shaft **410**. More particularly, in some embodiments, the flexure beam **560** has a bending stiffness that is low enough to flexibly bend, without sustaining damage such as breakage, in response to certain shaft forces imparted to the coupler link **510** during axial motion of the shaft **410**. In some embodiments, the shaft force is caused by axial clinical force imparted to an end effector **454** at a distal end portion of the shaft **410** due to the end effector contacting anatomical tissue, for example. In some embodiments, such clinical forces may be in a range of about 20 N.
(36) The configuring of the waterfall pulleys **520**W, **522**W and the steering pulleys **530**S, **532**S to maintain the intermediate cable segments in parallel alignment with the longitudinal axes **504**A, **506**A of the first and second side linkages **504**, **506** at all times, including throughout rocking motion four-bar linkage **502**, decouples cable forces at the four-bar linkage **502** from forces imparted at the four-bar linkage **502** due to motion of the shaft **410**. The larger cable forces are imparted to the intermediate cable segments in a direction parallel to the longitudinal axis **504**A, **506**A of the first and second side links **504**, **506**. Much smaller clinical forces imparted to shaft can be imparted to the coupler linkage **510** in a direction perpendicular to the longitudinal axis **504**A, **506**A of the first and second side links **504**, **506**. Thus, cable forces F.sub.C1, F.sub.C2 on cables **550**,**552** that drive end effector **454** and that are imparted to the four-bar is linkage **502** are isolated from the axial forces F.sub.H imparted to the four-bar linkage **502** due to axial motion of the shaft **410**. Therefore, a smaller contact force at an end effector **454** imparts a corresponding vertical force F.sub.H to the shaft **410** and to the coupler link **510**, and this vertical force is isolated from larger lateral cable forces F.sub.C1, F.sub.C2 imparted to the cables **550**, **552**. The vertical (axial) force F.sub.H causes a rocking motion of the four-bar linkage **502** and of the flexure beam **560** coupled thereto, which in turn, imparts a link force F.sub.L force to the sensor **560** that has a magnitude proportional to the smaller vertical (axial) force F.sub.H.
(37) FIG. **5**C is an illustrative schematic diagram showing an alternative example four-bar linkage that includes a differential coaxial coil inductive displacement sensor **552** and a spring force sensor **554**. In various embodiments, a dual-coil distance displacement force sensor **552** can be used in conjunction flexure **554** to measure axial force upon the instrument shaft **410**. The axial direction is taken as a direction parallel to the center axis **411**. An example displacement sensor **552** includes a sensor shaft **558**, a proximal annular coil **560**, and a distal annular coil **562**. The proximal and distal coils are at a fixed location and coaxially aligned with the sensor shaft **558**. The sensor shaft **558** and the proximal and distal coils **560**, **562** are arranged to permit the sensor shaft **558** to move axially while inserted within the coils **560**, **562**. A magnetic material structure **566** is located on the sensor shaft **558**, which is fixed to the tool shaft **410** so that the tool shaft **410** and the sensor shaft

558 move in unison, axially. An axial direction force imparted to an end effector **454** at a distal end of the tool shaft **410** that axially displaces the tool shaft **410** results in corresponding axial force upon and displacement of the sensor shaft **558**.
(38) When ‘at rest,’ with no axial direction force exerted upon the tool shaft **410**, the sensor shaft **558** can be axially positioned such that the magnetic material structure **566** is in part within each of the annular proximal and annular distal coils **560**, **562**. With no axial direction force excited upon the tool shaft **410**, equal portions of the magnetic material structure **566** can be located within each of the coils **560**, **562**. Each coil can be coupled into a separate LC circuit (not shown) in which the coil acts as an inductor (L) and in which the inductance varies with the amount of the magnetic material contained within the respective coil. The resonant frequency of each circuit varies with changes in inductance of the respective circuit.
(39) When an axial force causes axial movement of the tool shaft **410** and the sensor shaft **558**, the proportion of the magnetic material structure **566** within each of the proximal and distal coils **560**, **562** changes. The inductance of one of the coils increase while the inductance of the other decreases. As a result, the proximal and distal coils **560**,**562** have inductance values that do not match. The separate LC circuits are used to measure the difference in inductances of the coils, which provides an indication of axial displacement distance of the sensor shaft **558**.
(40) The flexure **554** has one portion secured to a proximal end portion of a lower second side link **506** and has an opposite end secured to the frame link **508**. The flexure **554** has known stiffness that can be used to force based upon displacement of the flexure. A measure of displacement of the sensor shaft **558** based upon measurement of inductance values of the proximal and distal coils **560**, **562** is used to determine sensor shaft displacement distance. The inductive coils **560**, **562** can be used to measure shaft displacement. The flexure **554** can be used to measure corresponding axial force; the flexure has a known stiffness and the amount of flexure displacement is indicative of magnitude of axial force imparted the end effector and transmitted by side link **506** to the flexure **554**. Thus, shaft displacement can be calibrated to flexure displacement and flexure stiffness can be used to determine axial force corresponding to shaft displacement. An example of force measurement using a differential coaxial inductive displacement sensor used with spring force sensor is provided in U.S. Patent Application No. 62/901,729, filed Sep. 17, 2019, which is expressly incorporated herein in its entirety.
(41) FIGS. **6**A-**6**C are illustrative side view of an embodiment of a four-bar linkage **602** in which the backend chassis **442** and a shaft assembly **601** are coupled to act as a frame link and coupler link, respectively. As explained above, the proximal tool controller **440** includes the backend chassis **442**. FIG. **6**A shows the four-bar linkage **602** in a neutral position in which upper and lower sidebars **604**, **606** are aligned horizontal. FIG. **6**B shows the upper and lower sidebars **604**, **606** rotated slightly downward when the shaft **410** is disposed in an axially lower position. FIG. **6**C shows the upper and lower sidebars **604**, **606** rotated slightly upward when the shaft **3***s* disposed in an axially vertically higher position.
(42) The four-bar linkage includes an upper first link **604** and a lower second side link **606** frame link **608**, a coupler link **610**. The backend chassis **442** acts as the frame link **608**. The shaft assembly **601** acts as the coupler link **610**. The waterfall pulleys and steering pulleys are omitted to simplify the drawing and to avoid hiding details of the four-bar linkage **602**.
(43) A proximal end portion of the upper first side link **604** is rotatably coupled at a first pivot joint **612** to the frame link **608**. A proximal end portion of the lower second side link **506** is rotatably coupled at a second pivot joint **614** to the frame link **608**. A distal end portion of the upper first side link **604** is rotatably coupled at a third pivot joint **616** to the frame link **610**. A distal end portion of the lower second side link **606** is rotatably coupled at a fourth pivot joint **616** to the frame link **610**. A side lateral length (S.sub.LL) along the upper first side link between the first and third pivot joints equals a side lateral length along the lower second side link between the second and fourth pivot joints. An end lateral length (E.sub.LL) of the frame link **608** between the first and second

pivot joints **612**, **614** equals an end lateral length (E.sub.LL) of the coupler link **610** between the third and fourth pivot joints **616**, **618**.

(44) A first waterfall pulley mount **626** and a second waterfall pulley mount **628** are disposed at the coupler link **610** to mount first and second sets of waterfall pulleys (not shown) about first and second waterfall pulley axes that extend parallel to rotation axes of the first through fourth pivot joints **612-618**. The first and second waterfall pulley mounts **626**, **628** are laterally offset from one another by a pulley lateral offset amount P.sub.LO. The first and second waterfall pulley mounts **626**, **628** are vertically offset from one another by a pulley vertical offset amount P.sub.VO.

(45) A flexure beam **660** is fixedly secured to rotate in unison with the second side link **606** about the second pivot joint **614**. More particularly, a distal end portion **660***d* of the flexure beam is coupled to a distal end portion of the lower second side link **606**, and a proximal end portion is operatively couple to a sensor **662**. Upward motion of the shaft assembly in direction of arrow “U” causes downward motion of the proximal end portion **660***p* of the flexure bean **660** in direction of arrow “D”. To simplify the drawings, the beam flexure and sensor are not shown in FIGS. **6**B-**6**C.

(46) FIG. **7** is an illustrative schematic side cross-sectional view of an embodiment of the sensor **662** of FIGS. **6**A-**6**C. In some embodiments, the sensor is a diaphragm force sensor that includes a thin annular substantially planar diaphragm **702** and upstanding sensor beam **704** disposed to impart a perpendicular force to the diaphragm **702**. The diaphragm **702** includes reverse facing planar first and second surfaces **706**,**708**. Strain gauges **710** are disposed upon the second surface **708**. The proximal end portion **660***p* of the flexure beam **660** is operatively coupled to impart a perpendicular link force F.sub.L to the upstanding sensor beam **704** in response to rotation of the lower second side link **606** about the second pivot joint **614**. In some embodiments, the first surface **706** of the diaphragm **702** may be contoured to increase force measurement sensitivity. U.S. Patent Application No. 62/767,891, filed Nov. 15, 2018, which is expressly incorporated herein in its entirety by this reference, discloses a diaphragm sensor with a contoured diaphragm surface.

(47) FIG. **8** is an illustrative simplified top view showing a layout of steering guide pulleys **730**S, **732**S, waterfall guide pulleys **720**W, **7222**W and cable drive elements **850** mounted to the four-bar linkage embodiment of FIGS. **6**A-**6**C in accordance with some embodiments. Various details are omitted or simplified to not obscure the layout of the pulleys. A first set of steering pulleys **730**S and a second set of steer steering **732**S are rotatably mounted to the chassis **442**, which acts as the frame link **608**. A first set of waterfall pulleys **720**W and a second set of waterfall pulleys **722**W are mounted to the shaft assembly (not shown), which acts as the coupler link **610**. In some embodiments, the cable drive elements **850** may include capstans mounted to the chassis **442** act as cable drive elements **850**. Rotation axes of the first and second sets of steering pulleys **730**S, **732**S are laterally offset from and are perpendicular to rotation axes of the first and second sets of waterfall pulleys **720**W, **722**W. The lateral offset between the rotation axes of the first set of steering pulleys **730**S and the rotation axes of the first set of waterfall pulleys **720**W is the side lateral length (S.sub.LL) between the first and third pivot joints **612**, **616**. The lateral offset between the rotation axes of the second set of steering pulleys **732**S and the rotation axes of the second set of waterfall pulleys **722**W is the side lateral length (S.sub.LL) between the second and fourth pivot joints **614**, **618**. Thus, the rotational axes offsets, S.sub.LL, match. The illustrative first and second sets of steering pulleys **730**S, **732**S each have some pulleys with different diameters, although each steering pulley is offset from its corresponding set of waterfall pulleys by the side lateral length (S.sub.LL). It will be understood that the first and second sets of waterfall pulleys **720**W, **722**W also each have some pulleys with different diameters. Smaller diameter steering pulleys are paired with larger diameter waterfall pulleys and vice versa so that cable lengths are the same for all steering/waterfall pulley pairs. It will be appreciated that use of pulleys having different diameters more readily permits distribution of cables **852** at different locations within the shaft **410**. The different diameter pulleys also allow cables to be routed to the correct capstan while keeping the cable parallel to linkages **504** and **506**. Individual cables **852** are secured to an

associated capstan, are guided by individual steering pulleys and associated individual waterfall pulleys, which guide the individual cables **852** into alignment with the longitudinal axis **411** of the shaft **410**.
(48) FIG. **9** is an illustrative partial perspective view of showing the arrangement of the first and second sets of steering guide pulleys **730**S, **732**S and the first and second sets of waterfall guide pulleys **720**W, **722**W of FIG. **8**. Rotational axes of the steering, pulleys **730**S, **732**S are perpendicular to rotational axes of the waterfall pulleys **720**W, **722**W. The steering pulleys **730**S, **732**S act to guide cables **852** operably coupled to drive elements (not shown) to associated waterfall pulleys **720**W, **722**W which guide the cables **852** into alignment axial alignment with the shaft (not shown).
(49) FIG. **10** is an illustrative perspective view of a first embodiment of the lower second side link **606** and flexure beam **660** and sensor **662** assembly of FIGS. **6**A-**6**C. A distal end portion **606***d* of the side link **606** includes a distal clevis **1010** with inward facing pivot joint pins **1011** for pivotally mounting the shaft (not shown). A proximal end portion **606***p* of the side link **606** includes a proximal clevis **1012** with outward facing pivot joint pins **1013** for rotatable mounting at the second pivot joint **614** described above. The flexure beam **660** includes first and second rigid arms **1020**, **1022** each coupled having a respective distal end coupled to a different one of the arms of the distal clevis **1012**. The flexure beam **660** includes a cross member **1024** integrally secured to respective proximal ends of the first and second arms **1020**, **1022**. The first and second arms **1020** **1022** have rectangular cross-section. The cross member **1024** is operatively coupled to the secured upstanding sensor beam **704**. In some embodiments, axial stiffness along an axis of the upstanding sensor beam **704** stiffness is determined based upon bending stiffness of the flexure beam **660**, stiffness of the sensor diaphragm **702** and length of the flexure beam **660**. In some embodiments, the flexure beam **660** and the diaphragm **702** may be configured to provide an axial stiffness along an axis of the upstanding beam **704** such that the effective stiffness of the instrument along the axis **411** is tuned in such a way that it improves the stability of the teleoperation of the instrument in the presence of force feedback. For those skilled in the art of designing system teleoperation with force feedback and controls will be readily apparent the impact of effective stiffness of the end effector on the stability of the system when interacting with the environment. This configuration provides the ability to tune the stiffness along the axis **411** without compromising the ability to decouple cable forces from the forces F.sub.H applied on the end effector **454**.
(50) FIG. **11** an illustrative perspective partial view of a second embodiment of the lower second side link **606** and flexure beam **660** and sensor **662** assembly of FIGS. **6**A-**6**C. The flexure beam has a planar contour and is mounted such that a plane of the flexure beam passes through the second pivot joint axis **515**. The flexure beam has a lateral axis **1015** that is colinear with the second pivot joint axis and has a longitudinal axis (not shown) that is aligned with the second side link longitudinal axis **506**A when in rest position, so that when vertical motion of the proximal tool controller **440** causes minimal side to side deflection of the post **704**. The diaphragm sensor **662** is designed to measure deflection of **704** in the vertical direction, so minimizing the side to side deflection of **704** is beneficial in terms of the magnitude of the side deflection/load the diaphragm sensor has to reject. This embodiment shows an alternative way to achieve this alignment and reduces the complexity of the parts and manufacturability.
(51) FIG. **12** an illustrative perspective view of a third embodiment of the lower second side link **606** and flexure beam **660** and sensor **662** assembly of FIGS. **6**A-**6**C. The first and second rigid arms **1020** **1022** have circular cross-section. The third embodiment has advantages like those described above for the second embodiment.
(52) The above description is presented to enable any person skilled in the art to create and use a surgical tool having a shaft having a proximal end portion suspended from a tool controller and having an end effector secured to a distal end portion thereof. The shaft is pivotally secured to a four-bar linkage structure at the tool controller to direct cable forces imparted to cables extending

within the shaft between the tool controller and the end effector, while decoupling the cable forces from clinical axial forces imparted to the shaft due to contact between the shaft and anatomical tissue. Various modifications to the embodiments will be readily apparent to those skilled in the art, and the generic principles defined herein may be applied to other embodiments and applications without departing from the scope of the invention.
(53) In view of the description herein it can be seen that any mechanical device that performs the function of the 4-bar linkage can be substituted for the 4-bar linkage. For example, a single rocking link between the chassis and the shaft that resists the cable forces might be used, as long as the shaft is constrained to movement along the shaft center axis, and as long cable length is not changed as the shaft moves with reference to the tool chassis.
(54) And in view of the description herein it can be seen that other optional spring arrangements can be used to provide the necessary vertical resilient forces on shaft **410** along shaft center axis **411** in the proximal direction, the distal direction, or in both the proximal and distal directions. For example, one or more springs could be coupled directly to the shaft so that the shaft is held in a neutral position and the desired proximal, distal, or both proximal and distal resilient forces are imparted to the shaft.
(55) And further in view of the description herein it can be seen that the force sensor may be in various positions with reference to the side links of the 4-bar linkage (or its equivalent). For example, as described herein the bottom side link and force sensor beam act together as a class 1 lever, but in optional embodiments they may be positioned as a class 2 lever. And, in other optional embodiments the force sensor beam may be coupled to the top side link of the 4-bar linkage.
(56) And still further in view of the description herein it can be seen that cables may optionally be driven by drive inputs other than capstans. For example, optional linear drive members may be coupled to the proximal ends of the cables, and such linear drive members may be driven by lead screws or direct engagement with counterpart linear actuators.
(57) In the preceding description, numerous details are set forth for the purpose of explanation. However, one of ordinary skill in the art will realize that the embodiments in the disclosure might be practiced without the use of these specific details. In other instances, well-known processes are shown in block diagram form in order not to obscure the description of the invention with unnecessary detail. Identical reference numerals may be used to represent different views of the same or similar item in different drawings. Thus, the foregoing description and drawings of embodiments in accordance with the present invention are merely illustrative of the principles of the invention. Therefore, it will be understood that various modifications can be made to the embodiments by those skilled in the art without departing from the scope of the invention, which is defined in the appended claims.

Claims

1. A surgical tool comprising: a chassis; a shaft including a proximal end portion and a distal end portion, the shaft having a longitudinal shaft center axis extending between the proximal end portion and the distal end portion; an end effector coupled to the distal end portion of the shaft; a linkage including a frame link coupled to the chassis, a coupler link coupled to the proximal end portion of the shaft, a first side link pivotally coupled to the frame link and pivotally coupled to the coupler link at a first pivot joint to rotate about a first pivot axis, and a second side link pivotally coupled to the frame link and pivotally coupled to the coupler link at a second pivot joint to rotate about a second pivot axis, the second pivot joint being different than the first pivot joint, and first pivot axis being different than the second pivot axis; a first cable drive member coupled to the chassis; a first distal pulley coupled to the coupler link; a first proximal pulley coupled to the chassis; and a first cable including a proximal end portion secured to the first cable drive member, a distal end portion extending within the shaft parallel to the longitudinal shaft center axis, and an

intermediate segment engaging the first distal pulley and the first proximal pulley; wherein the first distal pulley and the first proximal pulley are positioned to route the first cable between the first cable drive member and the proximal end portion of the shaft and to isolate a cable force imparted to the first cable by the first cable drive member from an axial force imparted to the end effector in a direction parallel to the longitudinal shaft center axis.

2. The surgical tool of claim 1, wherein: the surgical tool further comprises a second cable drive member, a second distal pulley, a second proximal pulley, and a second cable; the second cable drive member is coupled to the chassis; the second distal pulley is coupled to the coupler link; the second proximal pulley is coupled to the chassis; the second cable includes a proximal end portion operably coupled to the second cable drive member, a distal end portion extending within the shaft parallel to the longitudinal shaft center axis, and an intermediate segment engaging the second distal pulley and the second proximal pulley; and the second distal pulley and the second proximal pulley are positioned to route the second cable between the second cable drive member and the proximal end portion of the shaft to isolate a cable force imparted to the second cable by the second cable drive member from the axial force imparted to the end effector in a direction parallel to the longitudinal shaft center axis.

3. The surgical tool of claim 1, wherein: the first distal pulley rotates about a first distal pulley rotation axis; the first proximal pulley rotates about a first proximal pulley rotation axis; and the first distal pulley rotation axis is nonparallel to the first proximal pulley rotation axis.

4. The surgical tool of claim 1, wherein: the first side link includes a proximal portion and a distal portion; the proximal portion of the first side link is rotatably coupled to the frame link at a third pivot axis; the distal portion of the first side link is rotatably coupled to the coupler link at the first pivot axis; the first proximal pulley rotates about a first proximal pulley rotation axis; the first distal pulley rotates about a first distal pulley rotation axis; and a distance between the third pivot axis and the first pivot axis matches a distance between the first distal pulley rotation axis and the first proximal pulley rotation axis.

5. The surgical tool of claim 4, wherein: the surgical tool further comprises a second cable drive member, a second distal pulley, a second proximal pulley, and a second cable; the second cable drive member is coupled to the chassis; the second distal pulley is coupled to the coupler link and rotates about a second distal pulley rotation axis; the second proximal pulley is coupled to the chassis and rotates about a second proximal pulley rotation axis; the second cable includes a proximal end portion secured to the second cable drive member, a distal end portion extending within the shaft parallel to the longitudinal shaft center axis, and an intermediate segment engaging the second distal pulley and engaging the second proximal pulley; the second side link includes a proximal portion and a distal portion; the proximal portion of the second side link is rotatably coupled to the frame link at a fourth pivot axis; the distal portion of the second side link is rotatably coupled to the coupler link at the second pivot axis; and a distance between the fourth pivot axis and the second pivot axis matches a distance between the second distal pulley rotation axis and the second proximal pulley rotation axis.

6. The surgical tool of claim 1, wherein: the surgical tool further comprises a force sensor operatively coupled to the linkage; and an axial force imparted on the shaft causes the shaft to be displaced axially a first distance and a portion of the force sensor to be displaced axially a second distance corresponding to the first distance.

7. A surgical tool comprising: a linkage including a frame link, a coupler link, a first side link rotatably coupled to the frame link at a first pivot joint and to the coupler link at a third pivot joint to rotate about a first pivot axis, and a second side link rotatably coupled to the frame link at a second pivot joint and to the coupler link at a fourth pivot joint to rotate about a second pivot axis, the second pivot axis being different than the first pivot axis, the third pivot joint being different than the fourth pivot joint; a shaft including a proximal end portion and a distal end portion, with an axial direction of the shaft defined by a length between the proximal and distal end portions of

the shaft; an end effector coupled to the distal end portion of the shaft; and a sensor operatively coupled to the linkage or to the shaft; wherein the proximal end portion of the shaft includes the coupler link; and wherein an axial force imparted on the shaft causes the shaft to be displaced axially a first distance and a portion of the sensor to be displaced axially a second distance corresponding to the first distance.

8. The surgical tool of claim 7, wherein: the surgical tool further comprises a first proximal pulley, a first distal pulley, a first cable drive member, and a first cable; the first proximal pulley is coupled to the frame link to rotate about a rotation axis of the first proximal pulley; the first distal pulley is coupled to the coupler link to rotate about a rotation axis of the first distal pulley; the first cable drive member is coupled to the frame link; and the first cable includes a proximal end portion secured to the first cable drive member, a distal end portion secured to the end effector, and an intermediate segment engaging the first proximal pulley and the first distal pulley; the first proximal pulley and the first distal pulley are arranged to cooperatively guide the intermediate segment of the first cable parallel to the first and second side links during rocking motion of the linkage.

9. The surgical tool of claim 8, wherein: the surgical tool further comprises a second proximal pulley, a second distal pulley, and a second cable; the second proximal pulley is rotatably coupled to the frame link between the first and second side links and rotates about a rotation axis of the second proximal pulley; the second distal pulley is rotatably coupled to the coupler link between the first and second side links and rotates about a rotation axis of the second distal pulley; the second cable engages the second proximal pulley, engages the second distal pulley, and extends within the shaft parallel to a shaft longitudinal axis; the rotation axis of the first proximal pulley and the rotation axis of the second proximal pulley are offset from one another by a pulley lateral offset amount; the rotation axis of the first proximal pulley and the rotation axis of the second proximal pulley are offset from one another by a pulley vertical offset amount; the rotation axis of the first distal pulley and a rotation axis of the second distal pulley are offset from one another by the pulley lateral offset amount; the rotation axis of the first distal pulley and a rotation axis of the second distal pulley are offset from one another by the pulley vertical offset amount; the rotation axis of the first distal pulley is laterally offset from the rotation axis of the first proximal pulley by the lateral offset length; the rotation axis of the second distal pulley is laterally offset from the rotation axis of the second proximal pulley by the lateral offset length; and the second proximal pulley and the second distal pulley are positioned to cooperatively guide the intermediate segment of the second cable parallel to the first and second side links during the rocking motion of the linkage.

10. The surgical tool of claim 8, wherein: the surgical tool further comprises a second proximal pulley, a second distal pulley, a second cable drive member, and a second cable; the second proximal pulley is rotatably coupled to the frame link to rotate about a rotation axis of the second proximal pulley between the first side link and the second side link and offset from the first proximal pulley; the first proximal pulley has a diameter, and the second proximal pulley has a diameter different from the diameter of the first proximal pulley; the second distal pulley is rotatably coupled to the coupler link to rotate about a rotation axis of the second distal pulley between the first side link and the second side link and coaxial with the rotation axis of the first distal pulley; the rotation axis of the first distal pulley is laterally offset from the rotation axis of the first proximal pulley; the rotation axis of the second distal pulley is laterally offset from the rotation axis of the second proximal pulley; the second cable includes a proximal end portion secured to the second cable drive member, a distal end portion secured to the end effector, and an intermediate segment engaging the second proximal pulley and the second distal pulley; and the second proximal pulley and the second distal pulley are arranged to cooperatively guide the intermediate segment of the second cable parallel to the first and second side links during the rocking motion of the linkage.

11. The surgical tool of claim 10, wherein: the first distal pulley has a diameter, and the second distal pulley has a diameter different from the diameter of the first distal pulley.
12. The surgical tool of claim 7, wherein: an insertion axis stiffness for the shaft along the axial direction of the shaft is in a range of 5-50 N/mm; and the sensor includes a force sensor configured to sense force within a range of approximately ±20 N.
13. The surgical tool of claim 7, wherein: the sensor includes a flexure and a flexible diaphragm; and the flexure is operatively coupled to impart a force to the flexible diaphragm indicative of the axial force imparted to the shaft.
14. The surgical tool of claim 7, further comprising: a first proximal pulley coupled to the frame link; and a first distal pulley coupled to the coupler link; wherein the first distal pulley rotates about a first distal pulley rotation axis, wherein the first proximal pulley rotates about a first proximal pulley rotation axis, and wherein the first distal pulley rotation is nonparallel to the first proximal pulley rotation axis.
15. The surgical tool of claim 7, wherein: the sensor is a coil inductive displacement sensor.
16. The surgical tool of claim 7, wherein: the sensor includes an inductive coil, a sensor shaft moveably coupled to the inductive coil, and a magnet coupled the sensor shaft; an axial force imparted on the shaft causes the shaft to be displaced axially a first distance; and the axial force imparted on the shaft causes the sensor shaft and magnet to be displaced axially a second distance within the inductive coil corresponding to the first distance.
17. A surgical tool comprising: a chassis; a cable drive element mounted in the chassis; a shaft; a linkage comprising a first pair of opposite links and a second pair of opposite links, a first link of the first pair of opposite links being coupled to the chassis, and a second link of the first pair of opposite links being coupled to the shaft, a first link of the second pair of opposite links being coupled between the first and second links of the first pair of opposite links and pivotally coupled to the shaft at a first pivot joint to rotate about a first pivot axis, and a second link of the second pair of opposite links being coupled between the first and second links of the first pair of opposite links and pivotally coupled to the shaft at a second pivot joint to rotate about a second pivot axis, the first pivot joint being different than the second pivot joint and the first pivot axis being different than the second pivot axis; a cable routed from the cable drive element via a path parallel to the second pair of opposite links of the linkage and through the shaft; and a sensor operatively coupled to the linkage; wherein an axial force imparted on the shaft causes the shaft to be displaced axially a first distance and a portion of the sensor to be displaced axially a second distance corresponding to the first distance.
18. The surgical tool of claim 17, further comprising: a beam coupled between the first link of the second pair of opposite links of the linkage and the sensor.
19. The surgical tool of claim 18, wherein: the beam is a resilient, flexible beam.
20. The surgical tool of claim 17, wherein: the sensor is a coil inductive displacement sensor.
21. The surgical tool of claim 17, wherein: the sensor includes an inductive coil, a sensor shaft moveably coupled to the inductive coil, and a magnet coupled the sensor shaft; and an axial force imparted on the shaft, causes the shaft to be displaced axially a first distance, and the sensor shaft and magnet to be displaced axially a second distance within the inductive coil corresponding to the first distance.