State of the Art in Artificial Wrists: A Review of Prosthetic and Robotic Wrist Design

Neil M. Bajaj, *Student Member, IEEE*, Adam J. Spiers, *Member, IEEE*, and Aaron M. Dollar, *Senior Member, IEEE*

***Abstract*—The human wrist contributes greatly to the mobility of the arm/hand system, empowering dexterity and manipulation capabilities. However, both robotic and prosthetic research communities tend to favor the study and development of end-effectors/terminal devices (hands, grippers, etc.) over wrists. Wrists can improve manipulation capabilities, as they can orient the end-effector of a system without imparting significant translational motion. In this paper, we review the current state of the art of wrist devices, ranging from passive wrist prostheses to actuated robotic wrist devices. We focus on the mechanical design and kinematic arrangements of said devices and provide specifications when available.**

***Index Terms*—Amputee, commercial, design, mechanism, parallel, prosthetic, review, robot, serial, wrist.**

I. Introduction

THE spatial orientation of an end-effector such as a hand or a gripper is closely tied to its ability to perform a desired task, and nearly all robotic and prosthetic arms incorporate some type of wrist for this purpose. Yet both the academic and industrial research communities have tended to place more focus on hand/gripper development than that of wrist systems. Recent prosthetics investigations, however, have shown that increased dexterity in wrist prostheses may contribute more to manipulation capacity than a highly dexterous terminal device with limited wrist capability [1]. The role of the wrist becomes particularly significant when using a simple end-effector, or when an object fully constrains the fingers of the hand, such as during a cylindrical grasp.

The objective of this paper is to thoroughly review the design of artificial wrist devices in order to identify design strengths and trends, as well as suggest future directions for wrist development. We consider both prosthetic and robotic wrists in this review, as they share many of the same features. We characterize a prosthetic wrist as a unit that changes the orientation of a terminal device and is used by upper-limb amputees. In contrast, a robotic wrist is a device used in a nonhuman, robotic system to orient an end-effector. In many cases, the end-effector of a robot is a manipulation device, such as a robotic hand. However, orientation sensitive devices, such as tactile sensors or solar panels also feature often as end-effectors.

We focus on the mechanical design of the presented wrist devices, specifically: mobility in terms of degrees of freedom (DOF), kinematic architecture, actuation details, and physical design parameters when available. We examine both commercial devices and research prototypes.

In particular, we only consider devices that replace or create wrist function as opposed to those that augment it. Wrist exoskeletons fall into the latter category, as they support intact wrist capacity. As they are generally placed in parallel with the intact human wrist, these exoskeletons have different motion constraints and design requirements imparted on them that most standalone wrist designs do not. The design principles, requirements, and objectives within exoskeletons make them separate enough from standalone wrists to warrant their exclusion from this review.

Furthermore, we exclude works that only discuss the kinematic representation of a wrist from the review. While these representations are key for determining the workspace characteristics and singularities of (mostly parallel) mechanism, they do not fully address the physical implementation of the kinematic architecture into hardware. These kinematic representations generally do not address all the physical design issues, namely, size scale, weight, actuator selection, physical interference/collision of components, or passive joint limitations. These issues may in turn limit the application of a design due to torque, speed, weight/size, or range of motion requirements.

Very few previous reviews of wrist devices have been published. A preliminary version of this paper was published by the authors, covering only wrist prostheses [2], in which design trends, strengths, and deficiencies were identified. Otherwise, the only other published review is [3], which reviews the major advancements in wrist technology up to 1989, focusing primarily on devices utilized in industrial settings as well as some additional designs by the author. The inclusion criteria for this review are the following.

1) The wrist devices discussed herein must have been physically implemented.
2) Details regarding the actuation and kinematic arrangement must have been published in a refereed journal or

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The authors are with the Department of Mechanical Engineering and Materials Science, Yale University, New Haven, CT 06511 USA (e-mail: neil.bajaj@yale.edu; adam.spiers@yale.edu; aaron.dollar@yale.edu).

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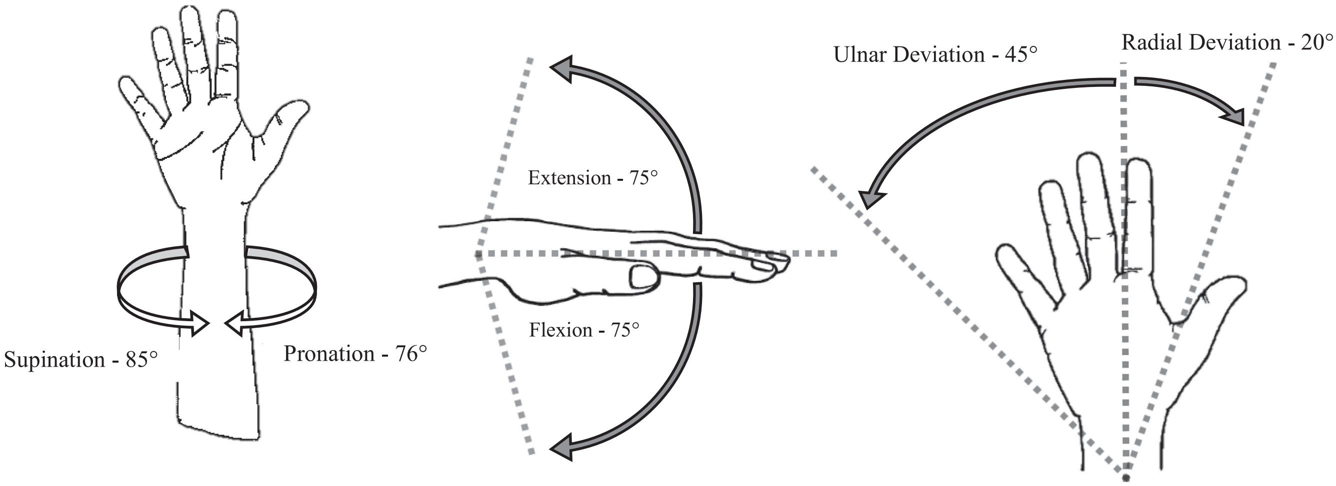


Fig. 1. DOFs of the human wrist and their ranges, shown from a neutral position. From left to right, pronation/supination, flexion/extension, and radial/ulnar deviation.

conference proceedings, patents, or within commercial product catalogs.

3) The devices must primarily impart rotational motion to the respective terminal devices or end-effectors.

We begin with an overview of human wrist biomechanics to provide a baseline of comparison for both prosthetic and robotic wrist devices. We subsequently introduce terminology relevant to the mechanical design of the devices regarding their topology and physical architecture. The following sections review wrist devices and their characteristics, organized by DOFs in the ascending order, then by mechanism type, and actuation method when appropriate. Physical specifications (such as weight, length, and torque) of the devices are provided when made available. Finally, we present the takeaways regarding wrist design as findings of the review.

II. Background

A. Human Wrist Capabilities

The healthy human wrist serves as an effective baseline toward which prosthetic wrists are designed, and a point of reference for which any orientation device may be considered. It is capable of motion in 3-DOFs, namely pronation/supination, flexion/extension, and radial/ulnar deviation. Each DOF is a paired set of motions, referring to positive and negative motion within each DOF. Henceforth, each DOF shall only be referred to by its positive direction of motion.

For an unaffected wrist, the maximal ranges of motion generally fall between 76°/85°, 75°/75°, and 20°/45° for pronation/supination, flexion/extension, and radial/ulnar deviation, respectively [4]–[6]. These DOF are coupled, meaning motion in one DOF may serve to limit the range of motion in the other two.

Healthy individuals only utilize a portion of each joint's full range of motion during activities of daily living (ADL). Investigations into these "functional" ranges of motion suggest that they fall between 65°/77°, 50°/70°, and 18°/40° for pronation/supination, flexion/extension, and radial/ulnar deviation, respectively [7]–[10]. The DOF and their ranges of motion can be seen in Fig. 1.

B. Wrist Terminology and Characteristics

In this section, we define relevant terminology for the review, which we use to both structure the review and discuss the individual devices.

1) Degrees of Freedom (DOFs): We primarily categorize the devices by the number of DOFs. Each DOF is defined (at least instantaneously) by rotation about an axis in space. An n-DOF wrist will typically have n linearly independent axes of rotation, except at any singular points in the workspace of the mechanism.

2) Mechanism Type: Depending on the kinematic arrangement of its joints and linkages, a mechanism may be classified as a serial, parallel, or hybrid mechanism.

A serial mechanism, or serial chain, consists of a sequential connection of joints and links, resulting in motion of the end-effector relative to the static base. The types of joints that comprise a serial chain are Revolute (R), Prismatic (P), Universal (U), and Spherical (S) joints. Each type of joint and their DOF are shown in Fig. 2. The human wrist may effectively be considered a serial RU chain, indicating it is kinematically equivalent to a universal joint (located at the carpal bones) in series with a revolute joint (within the forearm).

A parallel mechanism consists of two or more serial chains that connect a (generally fixed) common base to a mobile common platform. With respect to wrist deceives, the platform is usually the end-effector or terminal device. An example parallel mechanism, the S, 3SPS is shown in Fig. 3. The "3SPS" portion of the name indicates that there are three serial chains, all of which have a spherical, prismatic, and another spherical joint in series. The preceding "S" indicates there is another serial chain comprising solely of one spherical joint, though it is still in parallel with the other three SPS chains.

A hybrid mechanism is simply a chain of serial and parallel mechanisms. An example hybrid mechanism could be a 2DOF

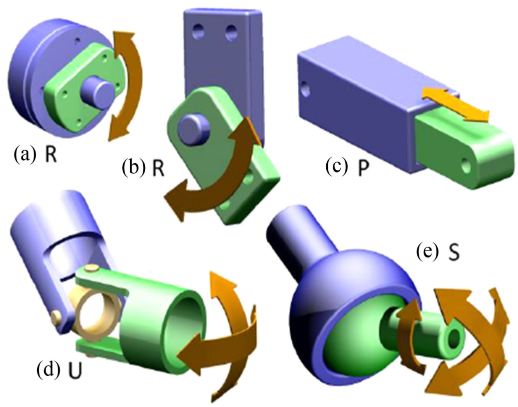


Fig. 2. Mechanical joint types and corresponding DOFs. (a) Revolute rotator (R). (b) Revolute flexor (R). (c) Prismatic (P). (d) Universal (U). (e) Spherical (S).

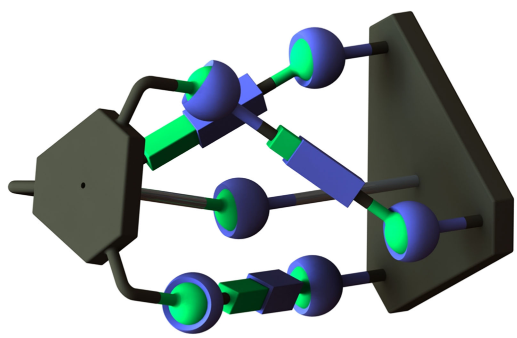


Fig. 3. S, 3-SPS parallel mechanism.

parallel mechanism that has a single revolute joint on the platform, allowing for "roll" motion of the end-effector.

3) Actuation Method: In the context of this review, a wrist may be passively, body powered, or actively actuated. This classification is useful mainly for prosthetic wrists, as neither passive nor body-powered wrists are used outside of prosthetics to our knowledge.

With passively actuated wrists, external forces and torques are used to reorient the end-effector. In prosthetics, such devices are usually manually articulated by the amputee user. They often use the opposite hand to twist or adjust their wrist device, but forces that arise due to manipulation may also reorient the wrist, though purposefully or unintentionally.

Body-powered prosthetic devices affect articulation by using motion and forces generated elsewhere on the body of the user. A typical arrangement involves a Bowden cable that connects a wrist or end-effector to a shoulder harness (or, more recently dermal anchor patches). As the user moves their shoulder relative to their arm, force is transmitted along the cable and results in prosthetic device articulation.

Actively actuated wrists utilize powered actuators to generate motion of the end-effector. These systems often feature electric motors, but may also be pneumatic or hydraulic systems. We consider a device to be actively actuated only if the actuator causes motion of the end-effector or terminal device. Thus, an active hand with a passive wrist would not be considered to be an active wrist.

C. Wrist Design Objectives

Though varied in design and appearance, most wrist devices seek to achieve similar objectives. Namely, devices should be designed to provide spherical rotational motion, meaning that the axes of rotation of a multi-DOF wrist should intersect, or the distance between axes should be minimized. Linear movements of the end-effector are generally accomplished via proximal joints in the arm system. Generally, weight and rotational inertia should be minimized as well, as wrists are often located near the distal end of the arm. Minimizing mass and inertia often involves minimization of the total size of the wrist (especially length along the forearm axis), although this objective is more critical in prosthetic and mobile robots than in industrial robots.

III. SINGLE-DOF WRISTS

We first begin the review by discussing single-DOF wrist units, then discuss 2- and 3-DOF devices within their own subsequent sections. Within these sections, we arrange the wrists by the mechanism type, and, when appropriate, by the articulation type as well.

A. Serial 1-DOF

A serial 1-DOF wrist is, by the definition of serial mechanism, a standalone revolute joint placed immediately proximal to the end-effector or terminal device. We may discuss these devices broadly as belonging to one of two categories: rotators and flexors. While kinematically equivalent as a single revolute joint, the wrists in these two categories often have differing packaging requirements, aspect ratios, and additional functionality.

1) Passive Serial 1-DOF: As discussed in Section III-C, both passive and body-powered mechanisms are used exclusively as prosthetic wrists. Thus, discussion of these two types of wrists, regardless of their DOFs, will be limited to prostheses, and not robotic applications. Discussions of active wrists shall cover both prosthetic and robotic wrist devices.

Passive single-DOF wrist prostheses have been the most common wrist devices for the past 75 years, mainly due to their compactness, mechanical simplicity, and low weight. These devices may broadly be separated into two categories, namely, rotators and flexors. Rotators serve to pronate or roll the terminal devices along the longitudinal forearm axis, whereas flexors will, as their name suggests, flex or pitch the terminal device.

Passive rotators, such as [11]–[21], are the first and more common of these two categories. To enhance their functionality, these devices often include additional features. One such device, the *Hosmer-Dorrance (HD) Friction Wrists* utilizes an adjustable clutch in order to hold the terminal device at any rotated position [11]. Other friction clutch rotators are described in [12] and [13]. Some rotators incorporate locking mechanisms [11], [15]–[17], which lock the terminal device at a discrete number of points until a latch or button is pressed, unlocking the device. One such wrist, the *OttoBock (OB) Ratchet Type*

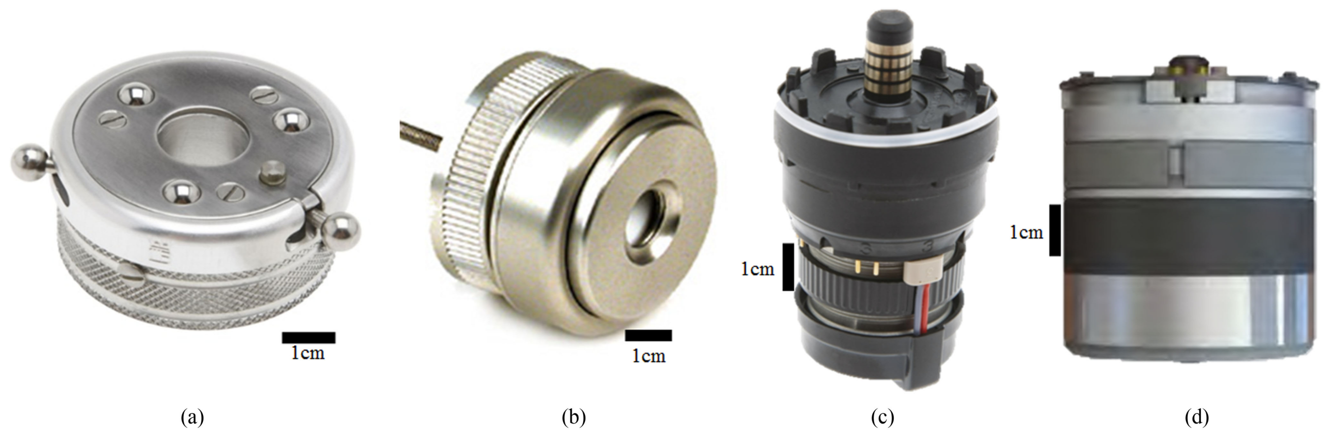


Fig. 4. Single-DOF prosthetic wrists. (a) OB Ratchet Type Rotation (R) [15]. (b) HD Rotation Wrist (R) [11]. (c) OB Electric Wrist Rotator [15]. (d) TB Supro Wrist. Size scales indicated by black bars are shown.

Rotation, can be seen in Fig. 4(a). Locking of passive wrist devices may also be achieved through the use of nonbackdriveable mechanisms, as in [19] and [20], in which the user must manually twist a collar on the wrist in order to rotate the terminal device. Further additional functionality may include the use of a "quick disconnect," allowing the users to easily switch their terminal devices [19]–[21].

Passive flexors, which are the second category of passive single-DOF wrists, are generally the devices which lock at discrete flexion intervals [11], [15], [22]–[24]. Commercially available locking flexion wrists include the *HD Sierra*, *HD Flexion Friction Wrist* [11], *OB MyoWrist Transcarpal* [22], [23], and the *OB MyoWrist 2Act* [15]. These devices usually may lock in 3–5 positions within their ranges of motion. Locking wrists of this nature are often used in concert with body-powered terminal devices, as the cable actuating the terminal device will not cause the wrist to change its position. For more continuous motion, the *OB Adapter with Flexion* [15] incorporates a frictional disk to hold the wrist in a flexed position, under limited loads. Though specifically integrated into the *i-Limb* series of prosthetic hands, the *Touch Bionics (TB) Flexion Wrist* [25] offers both locking in some flexed positions and offers spring loaded flexion while unlocked. Notably, the hydraulically actuated hand in [26] utilizes a check valve system to provide wrist flexion locking at an arbitrary position. Many flexor units are used in series with either active or passive rotators, allowing for 2-DOF motion.

All of the aforementioned passive rotators require external forces (from the user's other limb or environmental features) not only to rotate the terminal device, but also to access any additional functionality, such as locking or adjusting the friction within the clutches. This may be problematic for bilateral amputees, who will tend to experience greater difficulty in adjusting the passive wrists with a nonintact opposite arm.

2) Body-Powered Serial 1-DOF: To alleviate some of the issues of passive prostheses, body-powered prosthetic wrists employ a Bowden cable system to exert control over the wrist. As described in Section III, body-powered systems involve a body-harness-connected cable, which may either serve to actuate a prosthetic wrist or toggle a motion-locking mechanism. An example of a device actuated by body-powered cable is discussed in [27], which alternates between pronation and supination of the terminal device with subsequent cable pulls, locking when there is no tension on the cable. Alternatively, the *HD Rotation Wrist* [11] [see Fig. 4(b)] uses a cable to unlock and pronate the wrist. Pronation is resisted by a torsional spring, which tends to supinate the wrist. Releasing tension on the cable reengages the lock.

Some wrists which are considered passive in the context of this review use a Bowden cable system not to directly actuate the wrist, but to toggle or release locking mechanisms on passive joints. Devices such as the *OB Ratchet Type Rotation Series* [15] and the device detailed in [20] all utilize an elastic element for the wrist to return to a neutral pronation position when unlocked. As such, the user does not need to use their other hand to unlock the wrist.

3) Active Serial 1-DOF: Active 1-DOF wrists are often found in both prosthetic and robotic applications. Within the field of prosthetics, these are generally used with myoelectric (EMG) systems that enable a user to control rotation through muscle signals. Active wrists may be standalone units [15], [28] integrated into a prosthetic hand [29]–[32], or integrated into the forearm within larger prosthetic arms [33]. In robotics applications, single DOF units are commonly used but rarely discussed due to their simplistic nature. Similar to the passive wrists, active 1-DOF units may also be categorized into rotators and flexors.

Active rotators [15], [28]–[30], [32], [34]–[36] are the most common powered units in wrist prostheses. Standalone devices include the *Motion Control (MC) Electric Rotator* [28] and the *OB Wrist Rotator* [15] [see Fig. 4(c)], both of which have been designed for compatibility with many terminal devices, leading to relatively widespread use. The noncommercial standalone design described in [34] employs pronation about an axis skewed from the forearm longitudinal axis, with the authors claiming rotation about this axis leads to better manipulation performance when compared to other 1-DOF devices.

As powered rotators are much less compact than their passive counterparts (due to motor and drive train packaging), some rotators are incorporated directly into a terminal device in an attempt to shorten the overall length of the prosthetic system. Both the *OB Michelangelo Hand* [30] and *TB i-Limb Quantum* [36] utilize compact rotators, namely *AxonRotation* and *SuproWrist* [see Fig. 4(d)], respectively, which fit within the prosthetic socket and lower palm of the respective hands. In [32], a small motor and a spur gear pair incorporated into the base of the hand are used to impart wrist rotation with few components. The MANUS Hand [29] utilizes an ultrasonic motor and a low reduction gear train to achieve compact packaging as well as a hollow channel to pass wiring from socket to hand through the wrist.

Active flexors also tend to be incorporated into existing robotic hand or terminal device systems. In both [33] and [31], the wrist flexion mechanism and rotary actuators are located within the body of the hands. In contrast, in [37], prismatic actuators responsible for flexion are located within the forearm of the robotic arm assembly.

B. Parallel 1-DOF

As single-DOF wrists are kinematically equivalent to a single rotational joint, parallel mechanisms generally are not used as single-DOF wrist devices. The mechanical simplicity of serial devices compared to parallel devices appears to outweigh potential benefits of using a single-DOF parallel mechanism, such as a four-bar linkage. However, single-DOF parallel mechanisms often find use in other devices, such as ankle prostheses. For example, in [38], a four-bar linkage with compression springs as links serves as a passive single-DOF ankle prosthesis. This device stores and releases energy in the compression springs to provide powered push-off during gait. A four-bar mechanism is also used in an active ankle prosthesis in [39], with an electric motor injecting power during gait. In both of these cases, the customizable kinematics and increased load bearing capacity of four-bar mechanisms were reasons for incorporating them over simple revolute joints. Single-DOF wrist prostheses with similar requirements may be suitable candidates for using 1-DOF parallel mechanisms in their design.

C. Single-DOF Wrist Discussion

The clearest theme within single-DOF wrists is that most of the devices are passive prostheses with serial mechanism architecture. As these have been the standard wrist prosthesis for the most of the last century, it is not surprising they are the most prevalent in this category.

Compared to their passive counterparts, active single-DOF wrists tend to incur significantly greater length in their designs, especially with rotators. By the content of this review, it may seem that active 1-DOF wrists are either standalone wrist prostheses or additional features in hand designs, but the commonality of 1-DOF units in all fields minimizes discussion on devices outside of these applications. Improvements to the torque production, strength, and compactness of active 1-DOF rotators will allow for increased manipulation capabilities for both amputees and mobile robots. These units currently do not match the capabilities of the human wrist in terms of torque production, strength, and compactness. This limits the manipulation capabilities of amputees as well as for robotic systems (e.g., mobile humanoid robots).

IV. 2-DOF Wrists

Unlike single-DOF wrists, 2-DOF devices not only include prosthetic wrists, (including those proposed in academic environments), but wrists used in robotic applications, such as solar panel and camera orientation, as well.

A. Serial 2-DOF

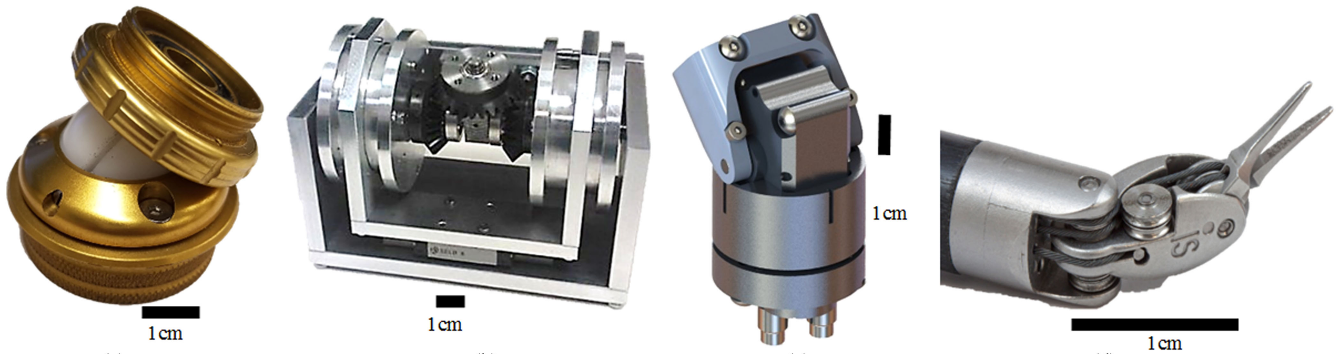
There are only two combinations of serial wrist mechanisms resulting in 2-DOF rotational motion, namely, revolute-revolute (RR) chains or universal (U) joints (see Fig. 2). Both are employed regularly to achieve 2-DOF rotational motion.

1) Passive Serial 2-DOF: While not as common as single-DOF passive wrist prostheses, there exists a variety of passively articulated, commercially available 2-DOF wrists. Many of these devices [40], [41] consist of a flexor unit in series with a rotator, forming a U joint. One such device, the *OB RoboWrist* [40], provides simultaneously lockable pronation and flexion, and while unlocked, provides frictional resistance against motion that can be adjusted by turning a collar on the wrist. The *MC Flexion Wrist* [41] similarly consists of a lockable pronation and flexion mechanism, but utilizes elastic elements to bias the wrist to a neutral position when unlocked. The *HD Four-Function* [11] wrist is a serial combination of the *HD Rotation Wrist* and *HD Sierra Wrist*, incorporating both body powered and locking functionality.

Other commercial wrist prostheses opt for a simpler and more compact design by using a constrained spherical joint to achieve passive 2-DOF motion. In both the *OB Myolino* [15] [see Fig. 5(a)] and *Liberating Technologies OmniWrist* [42], a circumferential groove around ball is constrained with a pin, thus only allowing flexion and radial deviation. Set screws around the circumference of the socket are used to adjust the amount of friction on the joint, allowing for greater torque resistance.

Noncommercial 2-DOF devices are detailed in [43] and [44]. In [43], two lockable single-DOF units are stacked with axes of rotation orthogonal (but nonintersecting) to one another, resulting in a relatively long resultant wrist. To achieve more length reduction, the wrist design in [44] [see Fig. 5(b)] uses a bevel gear differential with elastic elements connected to the input gears. This arrangement achieves flexion and radial deviation with spring return. Additionally, this wrist actively switches between two stiffness levels, allowing for different types of manipulation to occur.

Passive 2-DOF wrists also may be found integrated into some prosthetic hand designs [45], [46]. In [45], the mechanism that attaches the hand to the prosthetic socket comprises two revolute joints with intersecting axes, but the geometry of the hand and near-parallel orientation of the axes appear to limit the wrist to virtually 1-DOF motion. In [46], a universal joint serves as a 2-DOF wrist, but also as a means to transmit power from a motor in the forearm to a grasping mechanism in the hand.



(a) (b) (c) (d)

Fig. 5. Serial 2-DOF prosthetic and robotic wrists. (a) OB Myolino (U) [15]. (b) Montagnani switchable stiffness wrist (RR) [44]. (c) Verleg Hydraulic Wrist Prosthesis (RR) [61]. (d) Intuitive Surgical EndoWrist with forceps (RR) [70]. Size scales indicated by black bars are shown.

2) Body-Powered Serial 2-DOF: Due to the nature of tendon-driven systems, body-powered devices become less practical as the number of DOFs in the prosthetic system increases. Namely, each actuated DOF requires at least one tendon. Thus, in [47], two cables are routed into the wrist prosthesis to separately lock/unlock and control pronation and flexion of the wrist. Additional cables require more harnessing as well as a corresponding unique motion to “select” and apply tension to a particular cable. This leads to unwieldly systems that may sacrifice actuation of other DOF (such as the opening and closing of a terminal device).

3) Active Serial 2-DOF: Active serial 2-DOF wrists are the point at which prosthetic and robotic systems begin to overlap. Similar designs may be employed between transradial/transhumeral prostheses and the arms of humanoid robots.

Like passive 2-DOF wrists, some active designs simply place two active 1-DOF units in series with one another. Prosthetic wrists, such as [48]–[51], are composed of a pronation and a flexion unit placed together in this way. In [48], two motors are placed directly next to each other within the forearm volume, and use slightly different gearing systems to actuate their DOFs (internal ring gear versus bevel gear). In [49], however, the flexion motor is placed directly on the top of the pronation motor, resulting in an uncomplicated yet large design, occupying the forearm volume. Notably, this wrist could generate torques comparable to that of a healthy adult, though achievable speeds were not discussed.

As 2-DOF motion cannot fully replicate the capabilities of the human wrist, some wrist designs [52], [53] have implemented coupling between the flexion and radial deviation DOFs. In [52], motion statistics during ADLs were used to determine which axis (perpendicular to the pronation axis) was used most often. The subsequently proposed wrist design proposed implements a pronation unit with the coupled flexion/deviation axis in series, with the coupled axis 35° from the nominal flexion axis. Similarly, the forearm portion of the notable *DEKA Arm* [53] prosthesis uses coupled flexion/deviation in series with a powered pronation unit, presumably for similar reasons as in [52]. The designs of both of these wrists are indicative of the trade-off between the mechanical complexity and anthropomorphic motion.

The *RIC Arm* [54], a research transhumeral prosthesis designed to be within the form factor of a 25th percentile female arm, makes use of orthogonal cycloidal drives housed within the forearm to impart pronation and flexion to the terminal device. The *ToMPAW* [55], a research device designed to be a modular prosthetics testing platform (especially for myoelectric control systems), utilizes a similar pronation and flexion configuration.

The arms of humanoid robots are often similar to transhumeral prostheses, though their applications may determine size and additional functionality required in their design. One such example, the “table-top” sized *NAO humanoid* [56], [57], produced by SoftBank Robotics, is designed to mimic human motion and gesturing, but must accomplish these goals in a much smaller package. It achieves pronation and wrist flexion using micromotors and high reduction gear stages. Alternatively, the DLR TORO humanoid features an arm design [58] similar in size to the human arm, as its primary applications are related to manipulation tasks. The wrist of this robot consists of the pronation and flexion units in series with one another. As compliant manipulation is a particular application of this robot, both DOFs were designed to be variable stiffness actuators, and thus employ two motors each (to control both position and stiffness at each joint).

In order to eliminate the necessity of a constant holding torque, the wrists in [59] and [60] use worm gearing in their pronation and flexion mechanisms, rendering both DOFs in each wrists nonbackdriveable. Moreover, as these are both transhumeral prostheses, the wrist actuation motors occupy the forearm volume.

To reduce weight or mechanical complexity of wrist designs, some systems employ hydraulic [61] [see Fig. 5(c)] or pneumatic [62] actuation. Though these may achieve the aforementioned goals, additional reservoir systems, pumps, or compressors are needed in tandem with these devices, leading to additional equipment that must be transported by the user.

Constrained S joints may be used for powered 2-DOF motion. One such example is the *RSL Steeper BeBionic Wrist* [63], which constrains motion of 2-DOFs of the spherical joint at any instant via another pin-and-groove system (similar to the *OB Myolino* [15]). The unconstrained DOF is actuated by a single motor, and via a button press, may be changed from flexion to radial deviation by the user.

In [64], a bevel gear differential is used to create a wrist with pronation and flexion motors placed obliquely to the forearm longitudinal axis. While this design places more mass distally, the compact design occupies less forearm volume, making it more suitable for amputees with distal amputations. A similar differential design is employed in the transradial prosthesis design of [65], though motors are placed within the forearm volume and a tendon drive is used to actuate the input bevel gears. In both of these cases, both motors may contribute to actuate the same DOF, potentially allowing for greater mechanical power input to each DOF, though only actuated one at a time.

Other tendon-driven serial 2-DOF wrists have been designed for a variety of applications, such as transradial prostheses [66], [67], anthropomorphic robotic arms [68], surgical robots [69]–[71], and solar tracking systems [72].

The wrist of the transradial prosthesis in [66] utilizes Bowden cables to actuated a constrained S joint (resulting in a U joint). Though three motors were required for 2-DOF actuation, the motor could be placed in a way to reduce loads on the elbow or outside the forearm (due to the use of Bowden cables).

Similar to transradial prostheses, anthropomorphic robotic hands attempt to replicate the capabilities and appearance of the human hand. The anthropomorphic University of Bologna IV hand (UB-Hand IV) [68] contains a wrist composed of two R joints offset by a small distance with perpendicular axes, with each R joint driven by an antagonistic tendon pair. Tendons that actuate the hand pass through channels in line with the wrist axis, causing no net torque on the wrist due to hand actuation.

The tendon-driven surgical robotic wrists in [69]–[71] are examples of the *EndoWrist* instruments [see Fig. 5(d)] for use with the *da Vinci* surgical system produced by *Intuitive Surgical*. In [69], a coupled tendon drive actuates both the pitch and the yaw of the surgical wrist device, with the tendons routed through extruded channels on the surface of the wrist. Friction is potentially reduced in [70], in which pulleys are used for tendon routing, though the same tendon coupling scheme is used. In [71], slight modifications are implemented to the wrist design of [70] to allow for the tool distal to the wrist to be exchanged. As these wrists are intended to be used in a laparoscopic surgery, these wrists must be rather compact. Utilizing a tendon drive system allows for the actuators to be placed in a separate housing away from the wrist, and the tendons routed to the wrist through a long shaft, thus the wrist need only be large enough to route tendons. However, the size and drive system make these wrist devices exceedingly prone to friction and wear, thus requiring replacement after one to ten operations [73].

The solar tracking system in [72] utilizes two tendon drive systems to actuate the DOFs of a U joint, allowing a solar panel to track the sun optimally. Motors with pulleys route and actuate the tendons, and each tendon attaches to the panel underside on each end via a tension spring, maintaining tensegrity even when the panel is buffeted by the wind.

B. Parallel 2-DOF

Excluding planar linkages, much of parallel mechanism research and design focuses on creating mechanisms with two or more DOFs. When these mechanisms are nonplanar, either by implementing 3-DOF translational motion or 2-DOF rotational motion, these mechanisms may be called spatial linkages.

The subsequently presented parallel mechanisms are all active devices. While it is likely passive parallel mechanisms find their uses in other cases, within wrist devices, only active wrists appear to have incorporated such mechanisms.

1) Active Parallel 2-DOF: To achieve 2-DOF rotational motion in a parallel mechanism, a passive U joint may be placed in parallel with multiple actuated legs with different joint topologies. The passive U joint constrains the motion of the actuated legs, which are often higher DOF serial linkages with one actuator each. This approach is implemented in wrists used in a variety of applications [74]–[77].

The wrists of the *NASA Robonaut 2* humanoid robot [74] utilize a U, 2PSU parallel mechanism. The U joint connects the hand to the forearm of the robot, and the PSU linkages, via P joint actuation, differentially actuate flexion and radial deviation. In [75], the same mechanism architecture is used in a solar tracking system. The workspaces, packaging constraints, and optimization goals are different between the two applications of this mechanism; thus, the geometry of these mechanisms varies quite largely. A similar mechanism is described for the use for endoscopic surgery in [76], though this instance employs 3 PSU linkages in parallel with the central U joint. Though [76] is a 2 DOF system, all three P joints are actuated, thus resulting in redundant actuation. While this may improve load bearing properties, the actuators must be carefully coordinated to result in permittable motion. All of these mechanisms impart flexion and radial deviation to their respective end-effectors.

The mechanism detailed in [77] is a U, 2RRR configuration [see Fig. 6(a)]. The platform and the base are coupled with a passive U joint, and the two RRR legs actuate the two DOF via rotary motors that drive the most proximal R joints. The axes of the R joints in the legs intersect the center of rotation of the U joint, theoretically making this a spherical mechanism. In such configurations, every component rotates about the same fixed center of rotation.

Other 2-DOF spherical mechanisms include [78]–[80]. As these are only 2-DOF mechanisms, they do not truly recreate full spherical motion. In [78], a five-bar linkage consisting of only R joints is used to preposition a camera for endoscopic surgery. As before, the revolute joints all point toward a common center of rotation, which results in all links of the mechanism being constrained to move on virtual spherical surfaces. As none of the links pass through the center of rotation, the camera may be placed such that it only undergoes rotational motion with no translation. In [79], an overconstrained, singularity free, six-bar mechanism (also utilizing only R joints with center-pointing axes) is designed to have a hemisphere of reachable workspace. However, to avoid link interference, some links use circular tracks and sliders instead of simple pin joints to create R joints, resulting in considerably more friction in the mechanism.

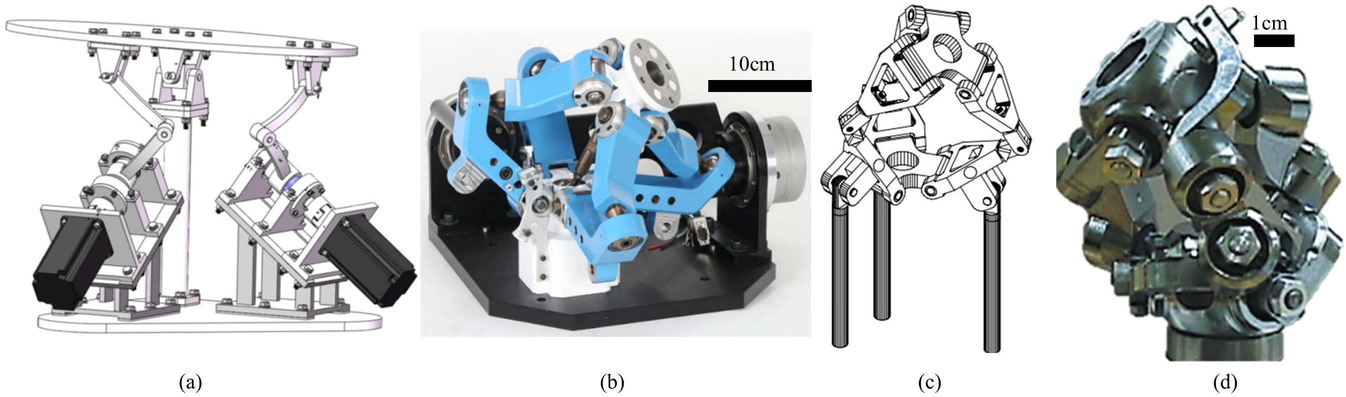


Fig. 6. Parallel 2-DOF robotic wrists. (a) Duan parallel mechanism (U, 2RRR) [77]. (b) Rosheim Omni-Wrist VI (SS, 4RSR) [82]. (c) Canfield Carpal Robot Wrist (3RSR) [83]. (d) Sone High Angle Active Link (3RRRR) [81]. Size scales indicated by black bars are shown when known.

The wrist described in [80] uses two spherical cam-roller systems in parallel to control pitch and roll of the end-effector. The geometric complexity of the cams, rollers, and other elements to support these components in this mechanism makes its fabrication quite difficult, with the spherical cams milled on a five-axis computer numerical control machine.

A design that includes only R joints, but is neither a spherical mechanism nor a single closed-loop linkage, is described in [81] [see Fig. 6(d)] capable of hemispheric pitch and yaw motion. This design uses a 3RRRR mechanism, where two of the three base R joints are actuated and the third is passive. The lower six R joints have a common center of rotation, as do the upper six (as the mechanism is symmetric from base to platform), resulting in two spherical mechanisms in series with one another. The mechanism is designed to be used as a constant-velocity joint for optical applications, though it also appears to be a 2-DOF orientation unit in its own right.

The *Omni Wrist (OW)* series [82] by Rosheim is a series of singularity free, hemispherical workspace wrist devices using similar parallel kinematic structures. The *OW V* and *OW VI* [see Fig. 6(b)] employ an SS, 3RSR and an SS, 4RSR structure, respectively. In both cases, the central SS chain constrains the platform to the surface of a virtual sphere, and two of the base R joints are actuated for active pitch and yaw motion. Careful kinematic design allows the S joints in the RSR chains to only utilize a small portion of their ranges of motion. Between, the two mechanisms, the OW VI, utilizing four RSR legs, may loosely have better load bearing properties.

Similar to both of the aforementioned designs is the Carpal Robot Wrist [83] [see Fig. 6(c)], which employs a 3RSR structure. Though this mechanism nominally has a third translational DOF, it may be constrained through the use of an SS chain in the center as well. Notably, this mechanism uses three intersecting pinned R joints to implement the S joints in the RSR chains, leading to a much greater workspace of the S joint, as the ball and socket constraints are removed. This is particularly useful if the translational motion is desired.

A variety of other 2-DOF parallel wrist units are designed for a variety of applications for specific functionality. In [84], a solar tracking mechanism using a PU, PUR architecture capable of pitch and yaw motion is described. The actuated P joints lie against the ground and offer nonbackdrivability and high force transmission with a low profile, all of which are desirable characteristics in solar power applications.

The 2-DOF wrist described in [85] uses two slider crank mechanisms in parallel, connected with a universal joint, to impart flexion and radial deviation to a humanoid robot wrist. In both the slider cranks, the sliders are linear series elastic actuators, which allows the wrist to be position or torque controlled. The *RoboRay* wrist [86] implements a flexion and radial deviation wrist using a U, 2PUR mechanism. The central U joint's flexion axis is designed with pulleys, routing tendons from the forearm to the hands for finger actuation This approach compensates for tendon length changes passively due to wrist motion, though the mechanism does twist individual tendons, which may result in wear or failure.

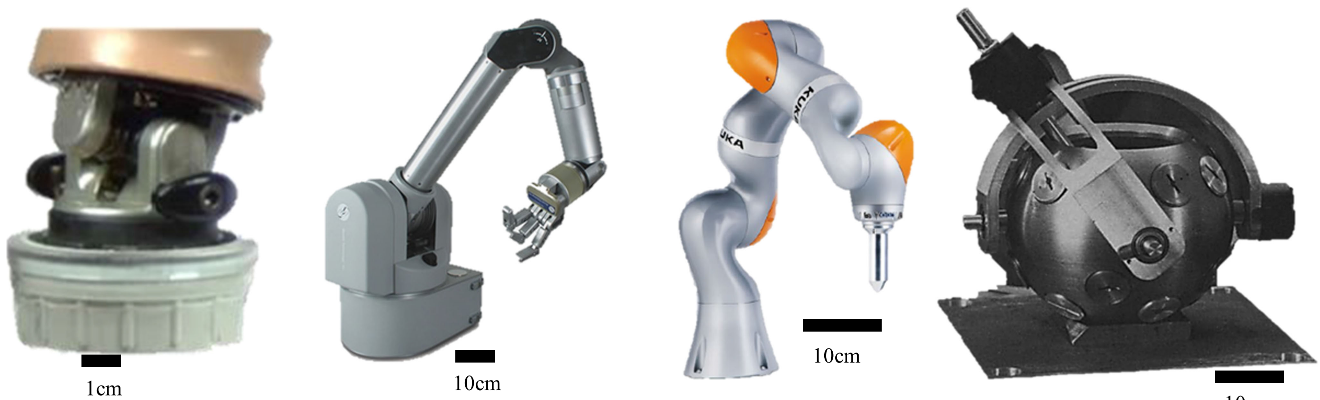
C. Hybrid 2-DOF

By the definition of hybrid mechanisms, hybrid 2-DOF wrists consist solely of a single DOF rotator in series with a 1-DOF parallel mechanism. Only active hybrid mechanisms were found, thus passive and body-powered sections shall be omitted.

1) Active Hybrid 2-DOF: The two hybrid 2-DOF mechanisms described subsequently [87], [88] are both incorporated into transradial prostheses. The SVEN Hand [87] was one of the earliest actuated transradial prostheses and actuated hands. It utilizes a rotator placed in series with a four-bar linkage that actuates flexion. Alternatively, the wrist described in [88] consists of a four-bar linkage, actuating a plate to impart flexion. Within the plate, a linearly actuated rack drives a pinion to impart pronation to the end-effector.

D. 2-DOF Wrist Discussion

Serial 2-DOF wrists are applied across a variety of applications. No single actuation system appears to be most successful within these wrists, though many have individual features particularly useful for their applications.



(a) (b) (c) (d)

Fig. 7. Serial 3-DOF wrists. (a) MC MultiFlex (RU) [89]. (b) Barrett WAM Arm (RRR) [98]. (c) Kuka LBR iiwa (RRR) [106]. (d) Chirikjian Spherical Stepper Motor (S) [112]. Size scales are indicated by black bars.

The majority of 2-DOF passive prostheses have only been available for the relatively recent past. Elastic bias [41], [44], frictional [15], [42], or continuous locking mechanisms are included in these devices more often than their 1-DOF counterparts, potentially better enabling manipulation with the prosthetic hand.

As active wrist prostheses are not often able to match the torque production capacity of the human wrist, differential mechanisms [64], [65] allowing synergistic actuation of a single DOF can result in higher torque production in a small package. The tradeoff between size and torque-production/robustness is the biggest challenge to address in these devices. Though a wrist may be able to achieve human torque levels [49], it cannot do so without occupying a larger volume than the human wrist and significant portion of the forearm. On the other hand, when compactness is required, such as in the NAO humanoid [56] or minimally invasive surgical robots, both fabrication difficulty and fragility of the devices increase significantly. Some compromise between weight/size savings and strength can be achieved by using hydraulic [61] or pneumatic [62] actuation, although these systems come with the separate considerations and issues of additional hardware requirements, such as reservoirs and pumps.

Parallel 2-DOF wrists employ a variety of different types of designs. Constraining the end-effector with a passive U joint circumvents the necessity of having a purely spherical mechanism and allows more freedom in addressing the other issues common with parallel mechanisms, such as joint limits and singularity. Moreover, many of these devices can achieve large singularity free workspaces [74], [75], [81], [82], [84].

V. 3-DOF Wrists

Wrist designs capable of 3-DOF rotational motion can arbitrarily orient their end-effectors (up to a workspace limit). While the human wrist is naturally capable of 3-DOF motion, some of the subsequently described wrists outperform the human wrist in some aspects, such as range of motion or torque output, but generally not size or compactness.

A. Serial 3-DOF

Serial 3-DOF wrist devices are prevalent in robotic applications, though some prosthetics incorporate 3-DOF wrists into their designs. As no 3-DOF body-powered wrists were found, we shall not dedicate a subsection to them.

1) Passive Serial 3-DOF: Few 3-DOF passive wrists exist outside of those that are simply combinations of off-the-shelf 1-DOF prosthetic wrist units, which were described in Section IV-A-1. However, the *MC Multiflex* [89] [see Fig. 7(a)] uses a 1-DOF rotator in series with an elastically biased U joint, forming an RU chain. The design is similar to the MC *Flexion Wrist* [41], described in Section V-A-1, though incorporating the third DOF (radial deviation) into the *Multiflex* only results in a 6 mm length increase compared to the *Flexion Wrist*.

The prosthetic hand described in [90] employs a passive S joint as a wrist in its design. The S joint is a simple ball and socket design, though the ball has a channel running through it, allowing tendons to pass from the forearm to the hand. The encapsulation required for the ball and socket joint restricts the range of motion, and as the wrist cannot be locked, manipulation may be difficult due to instability without high friction in the joint. Passing the tendons through the center of the ball does decrease their respective torques on the wrist, however.

2) Active Serial 3-DOF: The most common approach for achieving 3-DOF active motion is by arranging active rotators in series, with axes at different orientations. This approach is used within both prosthetics and robotics. The Modular Prosthetic Limb [91], designed by the Johns Hopkins University's Applied Physics Laboratory, uses a rotator located proximally to pronate, and two identical motorized units placed in series with a 90° offset between the two for flexion and deviation. The same approach is used in the Osaka City University Hand [92].

The serial RRR approach is exceedingly common within industrial robot arm applications. Many commercially available industrial arms, such as the *Kuka KR-16* [93], *Kawasaki K-Series* [94], *Fanuc M Series* [95], *Durr EcoPaint* [96], *Hon Hai / Foxconn* robot arms [97], and *Barrett WAM* [98] [see Fig. 7(b)], utilize the roll-pitch-roll arrangement for their wrist design. The axes of the three joints intersect at a common point, allowing for spherical end-effector motion, and for the more proximal joints of the robot arms to provide translational movements decoupled from the spherical wrist motion. This design often results in a singularity at the zero position, when the two "roll" axes are collinear. However, the range of motion and flexibility in packaging constraints (roll motors and gear train can be placed away from the center of rotation) make this configuration appealing and suitable for industrial arms. It is worth noting that the pitch and one of the roll DOFs within these arms are often actuated via a bevel gear differential, which allows motors to be placed along the longitudinal direction of the wrist, saving space and potentially reducing rotational inertia.

The roll-pitch-roll design is also used in humanoid robots [99], [100], robotic arms for satellite servicing [101], and in surgical robotic wrists [102].

Instead of using a second inline roll joint, some wrist designs achieve 3-DOF motion via a roll-pitch-yaw configuration. In this case, the yaw axis is perpendicular to both the roll and pitch axes and would correspond to radial deviation in the human wrist. When the yaw axis intersects the pitch and roll axes, the mechanism is generally considered a spherical wrist, and could be considered an RU chain. This architecture is used in surgical robots, such as the *DLR Mirosurge* [103] and in some of the *EndoWrist Instruments* by *Intuitive Surgical* [104], [105], all of which use tendon-driven systems for actuation due to packaging constraints (merits and disadvantages common of tendon-driven surgical wrists systems were discussed in Section V-A-3). Compared to roll-pitch-roll wrists, the relative workspaces of roll-pitch-yaw wrists tend to be smaller due to geometric constraints, as the pitch and yaw joints cannot usually achieve 360° rotation without physically colliding with other parts of the wrist. The same issue can be seen with two-yoke universal joints [see Fig. 2(d)], which can be described as pitch-yaw devices. Some robotic arms, such as the *Kuka LBR iiwa* [106] [see Fig. 7(c)] alleviate this issue by not using the dual-yoke type of geometry, and only constrain the R joints on a single side. The resulting geometry looks much like a roll-pitch-roll wrist with the pitch joint at 90°, which is considered the neutral position of the wrist. This allows for a larger range of motion while potentially sacrificing strength or payload.

Besides surgical and industrial arms, roll-pitch-yaw wrists are often used in humanoid or anthropomorphic robotic arms due to their resemblance to the human wrist. The *ARMAR III* humanoid [107] as well as the anthropomorphic arm described in [108] utilizes direct drive to actuate the pronation (roll) DOF, and two tendon drives actuated via ball screws to actuate the universal joint at the wrist for flexion and radial deviation (pitch and yaw, respectively). The *Humanoid Robot Prototype HRP-4* [109] utilizes a servo motor and harmonic drive in each of its three wrist DOF, and use a belt system to ensure the axes all intersect despite the motors being placed serially. In [110], McKibben actuators are used to actuate each DOF of an RU wrist mechanism of an anthropomorphic arm, reducing the mass and rotational inertia of the arm, though requiring an air compressor.

An interesting RU mechanism that uses slotted disks is implemented in the hand/wrist system described in [111]. A motor and an internal ring gear pronate the distal end of the forearm, which houses the flexion, radial deviation, and hand actuators. An S joint with a pin protruding radially is actuated by two disks: one with a spiral track cut into it, and the other with a simple diametric track. The pin is constrained to lie in the track of both disks, which are stacked upon one another. By rotating the disks either in opposition or together, the wrist is flexed or radially deviated, respectively.

Some serial wrist designs opt to use a single spherical joint instead of a serial chain [112]–[114]. Spherical stepper motors are described in both [112], [113] [see Fig. 7(d)]. While the overall geometry is that of a ball and socket joint, the ball is actually the rotor and the socket is the stator. The ball is impregnated with permanent magnets, and the socket houses a plurality of electromagnet windings, thus no wires cross the joint. Activating the electromagnets in different configurations and sequences results in rotation of the ball about different axes. Using a more traditional approach, the prosthetic wrist detailed in [114] actuates a spherical joint with five equally spaced tendons connecting to its platform. As tendons are only capable of exerting tension, the authors determined that at least five were necessary to actuate the 3-DOF joint.

B. Parallel 3-DOF

Parallel 3-DOF motions are capable of exhibiting fully spherical motion, though some mechanisms are cable of coupled translation with 3-DOF rotation. Moreover, these mechanisms are all active devices, so passive and body-powered subsections shall be omitted.

1) Active Parallel 3-DOF: Of all purely rotational parallel mechanisms, the most well known is the *Agile Eye* [115] [see Fig. 8(a)]. This mechanism, designed for camera orientation, is a symmetric 3RRR mechanism, with base R joints actuated with rotary motors. As all of the R joint axes must intersect at a central point, high precision is necessary in both fabrication and assembly of the Agile Eye. However, the Agile Eye remains a point of inspiration for 3-DOF spherical mechanisms.

A mechanism that uses similar architecture to the Agile Eye is the *Spherical Haptic Device* [116], hereon known as *SHaDe*, is a 2RRR, RRRU spherical mechanism designed to be used as a haptic feedback tool for spherical MC. The RRRU leg is used in place of an RRR chain to allow for a larger unobstructed volume between the base and platform of the mechanism. This allows the user to operate *SHaDe* over a large range of motion without their hand contacting any of the legs of the mechanism.

Though the *Agile Eye* has a large pitch and yaw workspace, roll capability is small in comparison. To achieve continuous rotation, a 3RRR, RUR mechanism was designed and described in [117]. This mechanism essentially consists of the standard Agile Eye design with an additional RUR mechanism running centrally from the base to the platform with actuation at the base R joint. The platform contained a bearing in which the distal R joint was housed, thus the 3RRR portion of the mechanism resulted in redundant actuation. Torsional movement was achieved by rotating the U joint, allowing for continuous rotation up to certain angular limits dictated by the U joint.

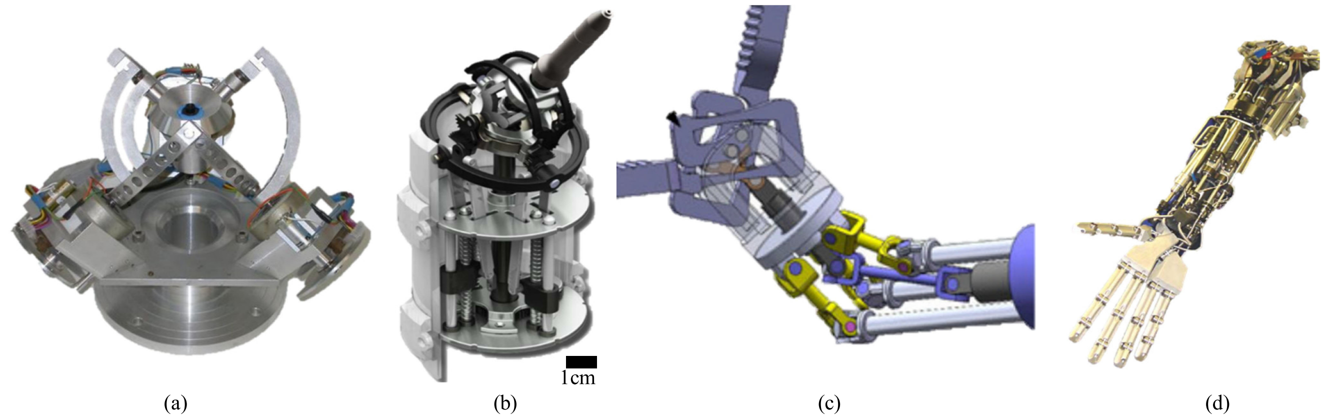


Fig. 8. Parallel and hybrid 3-DOF mechanisms. (a) Agile Eye (3RRR) [115]. (b) Hammond Micromanipulation Wrist (2PRRU, RUUR) [122]. (c) Hong Surgical Wrist and instrument (3PSR, RUUR) [121]. (d) Vanderbilt Gas Actuated Arm Prosthesis (Hybrid: [R][RPR, SPS]) [123]. Size scales indicated by black bars are shown when known.

To address the difficulty in precision fabrication of the Agile Eye, the *Agile Wrist* [118] was designed, employing a 3RRRP architecture. In this mechanism, the revolute joint axes are not required to intersect exactly at the center of rotation, and the addition of a passive prismatic joint prevents the mechanism from becoming overconstrained if intersection does not occur. Though the motion of the end-effector is not perfectly spherical, the spatial displacements apply small contributions to the overall platform pose.

Another mechanism that attempted to simplify the manufacturing issues of the Agile Eye while still only allowing spherical motion is *Argos* [119]. Argos is nominally a 3RRRS mechanism, with the base R joints actuated via rotary motors. However, the second and third R joints in each of the legs are implemented via a steel cable pantograph mechanism. As a result, each of the legs is a planar mechanism, simplifying the fabrication process, and the combination of the three legs then fully constrains the platform. Argos is suggested to be the rotational equivalent of the translational Delta parallel robot [120].

A spatial mechanism intended for use in minimally invasive surgery is described in [121] [see Fig. 8(c)]. The wrist described therein uses a 3PSR, RUUR parallel architecture, in which the P joints and the base R joint are actuated. While the 3PSR portion of the mechanism can accomplish 3-DOF motion, the central RUUR constrains the motion and enables roll of the end-effector, as the distal R joint sits in a bearing.

A wrist meant for micromanipulation is detailed in [122] [see Fig. 8(b)]. The architecture is a 2PRRU, RUUR. Similar to the previously described wrist, the RUUR provides unlimited roll motion to the end-effector. The 2PRRU mechanism actuates an intermediate platform, coupled to the distal platform with a rolling gear pair for each leg. This results in the distal platform having twice the pitch and yaw of the intermediate platform.

C. Hybrid 3-DOF

Hybrid 3-DOF mechanisms generally use a 2-DOF parallel mechanism in series with a rotator, either proximal or distal to the 2-DOF orientation mechanism. Once again, we limit the discussion to solely active mechanisms for the same reasons stated previously.

1) Active Hybrid 3-DOF: Hybrid mechanisms wrists incorporated in transradial prostheses [123]–[125] all consist of a pronation mechanism in series with a 2-DOF flexion and radial deviation mechanism. In [123] [see Fig. 8(d)], the pronation mechanism is driven via pneumatic actuation of a lead-screw against a slotted cylinder. The flexion and radial deviation mechanism employs a U, RPR, SPS configuration. The prismatic joints are pneumatically actuated, and all actuators are placed near the elbow. Alternatively, in [124], the pronation mechanism, a simple rotator, is placed distal to the 2-DOF flexion/radial deviation device, which uses an SS, 2RPU mechanism.

The surgical wrist robot detailed in [126] uses a spherical five-bar mechanism to actuate pitch and yaw motion, and a rotary motor with a center pointing axis rolls the end-effector.

D. 3-DOF Wrist Discussion

Perhaps most striking observation regarding 3-DOF wrists is the similarities in architecture and even physical design between devices. Robots across all applications utilize a roll-pitch-roll configuration due to the simple design and high range of motion. As evidenced by the industrial arms, roll-pitch-roll and roll-pitch-yaw systems can be used in high load applications, despite their serial construction.

As serial 3-DOF wrists are often part of larger arm systems, it is a priority for actuators to be far from the wrist, and as proximal to the elbow as possible. This can be accomplished simply through tendon systems, as in [102], [105], [107], and [108]. However, these systems are far weaker than the standard transmission counterparts, such as gear and belt drives. A trade-off clearly exists between the actuator placement flexibility and torque production capabilities.

The 3-DOF parallel mechanisms previously presented appear to belong to two groups: namely, those that utilize a central passive constraining joint (universal or spherical) which has lower mobility than the actuated legs [117], [121], [122], and those that have legs of equal mobility to the platform [115], [116], [118], [119], [126]. Though the former category often requires more components than the latter as the legs have higher mobility, the legs need not to be fabricated as precisely. The passive central constraint enforces the lower DOF mobility of the platform, as opposed to the legs themselves limiting its mobility. This relaxes some of the constraints on the leg design and geometry, such as intersecting joint axes in the *Agile Eye* [115], potentially making their fabrication simpler.

VI. Discussion

Physical specifications of a number of wrist devices are presented in Table I. Because the joint axes do not always follow the same order that they appear in the human wrist for some of the presented wrist devices, the torque and range of motion values in the table appear in the same order of the joints when listed from proximal to distal. As industrial robotic arms may come in a large variety of form factors with different physical specifications, the smallest arm (by mass) from each catalog was selected to be featured in Table I for better comparability with other mechanisms.

Apart from the major trends identified at the conclusion of each section, other comparisons may be made between various groups of wrists. Namely, we discuss differences between serial and parallel wrists, commercial and research devices, and prosthetic and robotic wrists.

A. Serial Versus Parallel

A great number of differences exist between serial and parallel wrist mechanisms. Notably, serial mechanisms tend to be longer than their parallel counterparts when comparing across devices with the same number of DOFs, though the use of tendon drives and bevel gear differentials may alleviate this issue, due to some freedom conferred in actuator placement. If differential couplings are not used, only a single actuator is responsible for an output DOF. Though this only allows power input from a single motor, it is much simpler to introduce compliance [41], [44], [89] or measure loads than it would be in a parallel counterpart.

With serial mechanisms, range of motion and torque specifications is often simply determined by actuator selection (in the case of active devices) and basic shape geometry, and is not configuration dependent. Moreover, the use of fewer components can potentially lead to greater robustness, though loads must be transferred through the entire wrist mechanism.

Parallel mechanisms often have many more architectures and geometric design parameters that can affect the ROM and producible torque. However, this additional complexity allows greater freedom in the design process. For example, collocating axes of rotation may be feasible (e.g., [78], [81], [115], and [116]), and actuators may be placed proximally to reduce inertia of the device (e.g., [74], [84], and [86]. Passive constraints, such as a central universal joint [74]–[77], [117], [123], can be used to bear loads away from actuators and increase stiffness of the mechanisms. However, issues that are not present in serial wrists, such as link/end-effector interference [74], [116] and individual joint ROM, must be addressed in successful implementations of parallel wrist designs. These issues become more difficult to deal with as the desired workspace of a mechanism grows larger, indicating a tradeoff between range of motion and stiffness. This tradeoff not only serves as a major difference between serial and parallel mechanisms, but also within parallel mechanisms themselves.

In most of the parallel wrist mechanisms, motion along an arbitrary DOF requires tandem actuation of multiple motors [74], [75], [119]. This coupling allows multiple actuators to contribute to a single motion. However, in some configurations, actuators may actually work in opposition to one another, or the wrist may be in a singular configuration, unable to actuate in a particular direction. Singular configurations also exist in serial wrists, such as in the roll-pitch-roll configuration when the pitch is neutral, but other configurations such as roll-pitch-yaw only experience a singularity when either pitch or yaw reaches 90°. The singularities are much more predictable, and mechanisms are easily designed for singularities to lie outside of the desired workspace.

The variety of architectures within parallel mechanisms leaves much room for wrist development within the subfield, especially when compared to serial mechanisms. Within serial wrist mechanisms, only a few types of architectures are possible, though improvements to the actuation systems (motors, transmission, etc.) in terms of size, reliability, and power density still may be made. Though the architectures of many parallel mechanisms, and specifically spherical mechanisms, have been described exhaustively and indexed in atlases, physical implementations remain scarce. Part of this may be attributed to the difficulty in creating the successful physical implementation of a parallel mechanism. Small manufacturing errors can lead to overconstraint and large increases of internal forces. Difficulty can also arise in the software and method used to control the mechanism as the forward kinematics are difficult to solve. For some redundantly actuated parallel mechanisms, mitigation of internal forces requires additional sensors and sophisticated control methods.

B. Commercial Versus Research Wrists

Stark differences exist between commercial and research-based wrists as well. Commercially available wrists come as standalone devices in prostheses or are an integrated part of industrial and surgical arms. Commercial prosthetic wrists tend to be passive devices with discrete locking positions, adjustable friction clutches, or elastic joints, all of which are potentially useful for manipulation. Active wrist prostheses are also commercially available [15], [28], [36], though they are restricted to 1-DOF devices.

Almost all multi-DOF commercial active wrists covered in this review utilize a serial roll-pitch-roll (e.g., [93] and [102]) or roll-pitch-yaw architecture (e.g., [98] and [105]), driven by belts (or tendons) and/or bevel gear differentials. Tendon drives are popular among commercially available surgical robots, whereas belt drives are more common amongst heavy duty industrial robots. Both of these drivetrain systems allow for actuator placement away from the wrist and end-effector, this reducing size

TABLE I
WRIST SPECIFICATIONS

TABLE. I. WRIST SPECTFICATIONS

Name / Reference	Commercial (Yes/No)	#-DOF	Actuation (Passive/ Active)	Configuration	Diam. (mm)	Length (mm)	Weight* (g)	Range of Motion** (°)	Torque*** (Nm)
HD Rotation Wrist [11]	Y	1	P	R	--	--	--	360	--
HD Sierra Wrist [11]	Y	1	P	R	50	36	113	50	--
Plettenburg [13]	N	1	P	R	50	38	20	360	--
OB Ratchet Type Rotation [15]	Y	1	P	R	50	25	120	360	--
OB Ratchet Type Rotation- Short [15]	Y	1	P	R	50	19	100	360	--
OB Myowrist 2Act [15]	Y	1	P	R	36	26	55	80	--
OB Myolino [15]	Y	2	P	U	40	39	49	60	--
TB Flexion Wrist [25]	Y	1	P	R		32	161	80	--
MC Wrist Rotator [28]	Y	1	A	R	47	70	143	360	1.13
Pons et. al. (MANUS Hand) [29]	N	1	A	R	--	--	--	170	2
Zinck et al. [34]	N	1	A	R	40	65	87	360	0.06
TB SuproWrist [36]	Y	1	A	R	--	57	154	--	--
OB RoboWrist [40]	Y	2	P	RR	50	41	164	360, 86	--
MC Flexion Wrist [41]	Y	2	P	RR		48	54	--	--
Montagnani et. al. [44]	N	2	P	RR	95	65	450	90, 90	--
Abd Razak et al. [49]	N	2	A	RR	--	--	690	--	3.9, 3.9
Ito et al. [51]	N	2	A	RR	--	115	700*	162, 133	0.17, 1.02
Fan et al. [52]	N	2	A	RR	--	--	200	360, 90	--
Sensinger et al. (RIC Arm) [54]	N	2	A	RR	--	--	325	360, 180	0.9, 1.0
Kyberd et al. [55]	N	2	A	RR	96	50	200	--	0.07, --
Gouaillier et al. (NAO) [56]	N	2	A	RR	--	--	143	240, 210	8.0, --
Friedl et al. (DLR Toro) [58]	N	2	A	RR	--	--	1200	180, --	--
Verleg [61]	N	2	A	RR	30	52.5	73	90, 90	0.75, --
Polhemus et al. (u-GRIP II) [62]	N	2	A	RR	--	--		90, 90	--
Controzzi et al. [65]	N	2	A	RR	76	--	240	--	--
Ahmad et al. [66]	N	2	A	U	47	--	870	175, 60	--
Sone et al. [81]	N	2	A	3RRRR	49	48	75*	360, 90	--
Kim et al. [86]	N	2	A	U, 2PUR	--	--	--	180, 90	2.5, 0.5
Roose [88]	N	2	A	RRRR, R	53	--	95	84, 103	0.32, --
Mahmoud et al. [92]	N	3	A	RRR	--	--	--	--	0.93, 0.21, 0.21
Kawasaki KF121 [94]	Y	3	A	RRR	--	--	--	270, 145, 360	7.8, 7.8, 2.9
Fanuc CR-4iA [95]	Y	3	A	RRR	--	--	48000*	380, 200, 720	8.86, 8.86, 4.9
Wyrobeck et al. [99]	N	3	A	RRR	--	--	--	360,--,360	2.5, 3.6, 4.7
Schuler et al. (DEXARM) [100]	N	3	A	RRR	114	108	--	360, 180, 360	72, --, --
Kuka LBR iiwa [106]	Y	3	A	RRR	--	--	23900*	170, 120, 175	110, 40, 40
Gosselin et al. (Agile Eye) [115]	N	3	A	3RRR	--	--	--	140, 140, 30	--
Birglen et al. (SHaDe) [116]	N	3	A	2RRR, RRRU	350	290	6500	90, 45, 45	1.0, 0, 0
Hess-Coelho [117]	N	3	A	3RRR, RUR	--	--	--	140, 140, 360	--
Hammond et al. [122]	N	3	A	2PRRU, RUUR	--	--	--	180, 180, 360	--
Fite et al. [123]	N	3	A	R, RPR, SPS	--	--	--	170, 60, 150	--
Degirmenci et al. [126]	N	3	A	RRRRR, R	--	--	--	72, 144, 360	4.5, 4.5, 4.2

*Indicates weight of the entire arm system, including wrist device.
**For multi-DOF devices, ROM is listed for each DOF, separated by commas. If ROM of a particular DOF is unknown, a null sign (--) appears in the list.
***For multi-DOF devices, torque is listed for each DOF, separated by commas. If torque of a particular DOF is unknown, a null sign (--) appears in the list.

in surgical robots and inertia in industrial arms. Industrial arms utilize bevel gear differentials [93], [95], [96], [98] to collocate axes of revolution in a compact volume, and potentially allow multiple motors to contribute to a single DOF. Though many commercial products exist that use these designs already, there is likely a room to develop devices that depart from this architecture and actuation scheme.

As most of these wrists belong to industrial robots, their designs show high robustness and torque capacity when compared to research wrists, which have varied designs and design goals.

Research wrists are seen in broad applications, including from prostheses, humanoids, solar trackers, and surgical robots. The designs employ serial, parallel, and hybrid mechanisms. As expected, research devices incorporate a greater variety of coupling schemes [34], [52], [86] and actuation technology [29], [51], [112].

C. Prosthetic Versus Robotic

Though robotic wrists encompass a wide variety of applications, many comparisons may still be made between prosthetic and robotic wrists. Many of the differences are enforced simply by the fact that prostheses require direct human interaction to function. For example, prosthetic wrists may be passive or body powered, whereas robotic wrists are solely active devices. Prosthetic wrists also include externally adjustable functionality, such as adjustable friction or locking. Any adjustment of robotic wrists is generally accomplished within the control system.

Still, a number of nonobvious differences exist between these two categories. Whereas robotic wrists may be serial, parallel, or hybrid devices, all standalone prosthetic wrists are serial chains, though in a few cases transradial and transhumeral prostheses may incorporate parallel or hybrid wrists [123]–[125]. This may be indicative of a minimum amount of space needed to implement a parallel mechanism based wrist with comparable performance to a serial chain.

Coupling of output DOFs is more common amongst prosthetic wrist devices [34], [52], [53] as well. These devices are results of efforts to reduce the complexity, size, etc., of wrist prostheses by sacrificing actuation and motion capabilities. Robotic applications instead tend to utilize the normal design approach of multiple orthogonal axes of rotation, such as those seen in roll-pitch-roll wrists and similar architectures.

Though intended for use as prostheses, there are no major differences between transhumeral/transradial prostheses and anthropomorphic humanoid arms besides the control scheme (inputs generated from user instead of autonomous system). However, design and design goals are more varied in anthropomorphic robots (such as tendon decoupling mechanisms in [68], [86] or housing power components in [74]), which often utilize portions of the forearm to house actuation drivetrains or power components for the end-effector. On the other hand, the thrust for prostheses design is to generally reduce weight. Moreover, limitations on available control inputs to prostheses, especially multiarticulated hands and limbs, reduce the need or feasibility of dexterous wrists in prosthetics compared to anthropomorphic humanoid robots.

While it may appear that active prosthetic wrists are simply a subset of robotic wrist technologies, backdrivability is often different between the two. As a prosthetic wrist user must also carry the power source, a device with low power consumption is generally beneficial. Use of nonbackdrivable transmission elements such as lead screws is an effective way to minimize power consumption by resisting external loads passively when the motors are deactivated. The design goals of minimized size and weight make it sensible for prostheses to utilize small, though highly geared rotary motors to achieve somewhat human levels torque output, rather than heavy motors with minimal gearing. These high gear ratios make even the nonlocking transmission relatively nonbackdrivable. Heavily geared systems also introduce significant backlash when multiple gear stages are placed in series. Combined with the nonbackdrivabililty, this may make prosthetic wrists rather vulnerable to impulsive loading and collisions.

While some robotic wrists also use screw elements or highly geared motors, the looser size restrictions allow use of larger motors with smaller gear ratios, or even direct drive. Backdrivability can then be implemented on some robotic hardware, which may then allow the "teaching" of a robotic arm by physically manipulating the robot externally. These low gear ratios also may enable force sensing at the actuator, or even force control.

VII. Conclusion and Takeaways

Considering the entire group of designs, it is apparent that the intended use of the design greatly affects the performance and physical implementation of a particular wrist. Where miniaturization or low distal inertia is key, tendon drives are a clear strategy for successful implementation. Alternatively, implementation of wrists in industrial settings tends to use a variety of gear drives. Investigating ways to take smaller wrist designs and scaling them to the larger size (and taking larger wrist designs and scaling them to the smaller size) would likely yield interesting solutions and different implementations of specific transmission elements that would enable them for the different size scale.

Though wrist designs have not been a particularly active field of study over the last few decades (compared to hand development), a number of gaps in the literature would benefit from additional focus. Namely, identifying factors that make parallel mechanisms more tractable or appropriate for commercial cases would allow their benefits to be conferred more easily. Automating parallel mechanism design to allow for entry into commercial devices such that expert knowledge is not required, or developing more utilitarian architectures is one such development direction. Mechanically, developing ways to more easily be fabricate the passive subcomponents of parallel mechanisms (especially at small size scales) and making these subcomponents more robust may also lead to more confidence and adoption of these architectures.

While it appears that serial wrists may have little room left for development, the design of a 3-DOF serial wrist which does not occupy the entire forearm volume of a prosthesis, humanoid robot arm, industrial arm, etc., is still a challenge. While this is likely due to the fact that actuators have greater constraints on their positioning, some transmission elements (tendons, belts, etc.) can be leveraged to achieve more freedom in actuator position.

The use of hybrid mechanisms (combinations of serial and parallel mechanisms) could be especially beneficial in achieving this remote positioning without the complexity of coupled DOFs. For example, using separate four-bar linkages in parallel with one another could allow for proximal actuator positioning, with only simple, passive elements at the wrist joint itself.

The majority of the active wrists described herein use electric motors as the primary source of actuation. Use of pneumatics, whether in rigid pistons, McKibben Actuators [127], or other soft actuators, may be a good method to distribute weight and actuation away from the wrist, though practicality may be limited outside of fixed base robotic systems. Similarly, shape memory alloy (SMAs) actuation systems such as that in [90], or ultrasonic motors as in [29] and [51] may be beneficial in future wrist designs, though the technology still appears relatively immature compared to electric motor, or even pneumatic, actuation.

As of yet, it appears quite difficult to achieve torque and speed capacity of the human wrist while maintaining similar size, weight, and inertia. Many robotic systems easily outperform the human wrist in terms of torque and speed, but their use of large motors with high gear ratios prevent miniaturization and can also preclude backdrivability. While the latter point may not be as important in systems specifically requiring accurate positioning, systems which are meant to interact with an external environment in a manner similar to humans generally require some amount of compliance or modulable impedance, especially when trying to control forces. Developing lightweight, compact actuators, and transmissions with high torque capacity would be of great benefit in the fields of prosthetics and humanoid robots.

Finally, establishing methods to evaluate wrists, and developing insightful metrics and sets of hardware specifications required to complete tasks, may further help designers and end users alike assess suitability of a particular wrist device for their purposes, and drive development toward useful goals.

References

[1] F. Montagnani, M. Controzzi, and C. Cipriani, “Is it finger or wrist dexterity that is missing in current hand prostheses?” *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 23, no. 4, pp. 600–609, Jul. 2015.

[2] N. M. Bajaj, A. J. Spiers, and A. M. Dollar, “State of the art in prosthetic wrists: Commercial and research devices,” in *Proc. IEEE Int. Conf. Rehabil. Robot.*, 2015, pp. 331–338.

[3] M. E. Rosheim, *Robot Wrist Actuators*. New York, NY, USA: Wiley, 1989.

[4] M. M. Marshall, J. R. Mozrall, and J. E. Shealy, “The effects of complex wrist and forearm posture on wrist range of motion,” *Human Factors*, vol. 41, no. 2, pp. 205–213, 1999.

[5] D. C. Boone and S. P. Azen, “Normal range of motion of joints in male subjects,” *J. Bone Joint Surg. Amer.*, vol. 61, pp. 756–759, 1979.

[6] J. M. Soucie *et al.*, “Range of motion measurements: Reference values and a database for comparison studies,” *Haemophilia*, vol. 17, pp. 500–507, 2011.

[7] J. Ryu, W. P. C. Iii, L. J. Askew, K. An, and E. Y. S. Chao, “Functional ranges of motion of the wrist joint,” *J. Hand Surg.*, vol. 16, pp. 409–419, 1991.

[8] D. L. Nelson, M. A. Mitchell, P. G. Groszewskv, S. L. Pennick, and P. R. Manske, “Wrist range of motion in activities of daily living,” in *Advances in the Biomechanics of the Hand and Wrist*. Boston, MA, USA: Springer, 1994, pp. 329–334.

[9] M. Sardelli, R. Z. Tashjian, and B. A. MacWilliams, “Functional elbow range of motion for contemporary tasks,” *J. Bone Joint Surg. Amer.*, vol. 93, pp. 471–477, 2011.

[10] R. H. Brumfield and J. A. Champoux, “A biomechanical study of normal functional wrist motion,” *Clin. Orthopaedics Related Res.*, vol. 187, pp. 23—25, 1984.

[11] Hosmer, Chattanooga, TN, USA, Homer Dorrance, 2017. [Online]. Available: www.hosmer.com

[12] W. C. Prout, “Prosthetic wrist unit,” U.S. Patent 3 159 847, 1965.

[13] D. H. Plettenburg, “The WILMER passive hand prosthesis for toddlers,” *JPO J. Prosthetics Orthotics*, vol. 21, pp. 97–99, 2009.

[14] S. C. Jacobsen, D. F. Knutti, and R. T. Johnson, “Electrically driven artificial arm,” U.S. Patent 4 521 924, 1985.

[15] Otto bock, Duderstadt, Germany, 2017. [Online]. Available: http://www.ottobock.com/

[16] D. R. W. May, “Prosthetic wrist fitting,” U.S. Patent 4 156 945, 1979.

[17] Northrop Aircraft, “Prosthetic wrist,” U.S. Patent 2457316A, 1946.

[18] G. M. Motis, “Artificial arm with stepped up wrist drive and automatic wrist lock,” U.S. Patent 2638604A, 1953.

[19] K. Vesper, “Wrist mechanism for artificial arms,” U.S. Patent 2605476A, 1952.

[20] W. C. Prout, “Universal wrist system,” U.S. Patent 3798680, 1974.

[21] E. Horvarth, “Artificial wrist and arm prosthesis,” U.S. Patent 4010495, 1977.

[22] T. Bertels, “Biomechanic aspects and patient needs lead the path to a unique wrist joint for myoelectric prosthesis,” in *Proc. MEC Conf.*, 2005, pp. 17–20.

[23] T. Bertels and T. Grob, “Verriegelbares prothesengelenk,” Eur. Patent 1 852 092 A1, 2007.

[24] G. M. Motis, “Wrist flexion unit,” U.S. Patent 2692390, 1954.

[25] H. Gill, “Wrist device for a prosthetic limb,” WO Patent 2016051138 A1, 2016.

[26] I. N. Gaiser, C. Pylatiuk, S. Schulz, A. Kargov, R. Oberle, and T. Werner, “The FLUIDHAND III: A multifunctional prosthetic hand,” *JPO J. Prosthetics Orthotics*, vol. 21, no. 2, pp. 91–96, 2009.

[27] G. M. Motis, “Linear to rotational movement converter,” U.S. Patent 3466937, 1969.

[28] Motion Control, Salt Lake City, UT, USA, “Motion control wrist rotator and ProWrist electric wrist rotator,” 2000.

[29] J. L. Pons *et al.,* “The MANUS-HAND dextrous robotics upper limb prosthesis: Mechanical and manipulation aspects,” *Auton. Robots*, vol. 16, pp. 143–163, 2004.

[30] G. Puchhammer, “Michelangelo hand (articulated hand prosthesis),” U.S. Patent 8 690 963, 2014.

[31] G. Rennerfelt, “Artificial hand,” E.P. Patent 0219478A1, 1988.

[32] J. Zajdlik, “The preliminary design and motion control of a five-fingered prosthetic hand,” in *Proc. Int. Conf. Intell. Eng. Syst.*, 2006, vol. 2, pp. 202–206.

[33] M. Johnsson and C. Balkenius, “LUCS haptic hand III an anthropomorphic robot hand with proprioception,” Tech Rep., Lund Univ. Cognitive Sci., 2006, pp. 1–5.

[34] A. Zinck, Ø. Stavdahl, E. Biden, and P. J. Kyberd, “Design of a compact, reconfigurable, prosthetic wrist,” *Appl. Bionics Biomech.*, vol. 9, no. 1, pp. 117–124, 2012.

[35] M. Troncossi, E. Gruppioni, M. Chiossi, A. G. Cutti, A. Davalli, and V. Parenti-Castelli, “A novel electromechanical shoulder articulation for upper-limb prostheses: From the design to the first clinical application,” *JPO J. Prosthetics Orthotics*, vol. 21, pp. 79–90, 2009.

[36] Touch Bionics, Livingston, U.K., SuproWrist, 2017.

[37] I. Kato, S. Yamakawa, K. Ichikawa, and M. Sano, “Multifunction myoelectric hand prosthesis with pressure sensory feedback system. Waseda hand 4P,” in *Proc. 3rd Int. Symp. External Control Human Extremities*, 1963, pp. 155–170.

[38] J. J. Rice, J. M. Schimmels, and S. Huang, “Design and evaluation of a passive ankle prosthesis with powered push-off,” *J. Mech. Robot.*, vol. 8, no. 2, 2015, Art. no. 21012.

[39] B. J. Bergelin and P. A. Voglewede, “Design of an active ankle-foot prosthesis utilizing a four-bar mechanism,” *J. Mech. Des.*, vol. 134, no. 6, 2012, Art. no. 61004.

[40] OttoBock, Duderstadt, Germany, 10V41 Robo-Wrist, 2017.
[41] S. L. Archer *et al.*, "Wrist device for use with a prosthetic limb," U.S. Patent 7144430B2, 2006.
[42] Liberating Technologies, Inc., Holliston, MA, USA, 2017. [Online]. Available: http://www.liberatingtech.com/.
[43] M. W. Razink, "Prosthetic wrist," U.S. Patent 8795387, 2014.
[44] F. Montagnani, M. Controzzi, C. Cipriani, and S. Member, "Preliminary design and development of a two degrees of freedom passive compliant prosthetic wrist with switchable stiffness," in *Proc. IEEE Int. Conf. Robot. Biomimetics*, Dec. 2013, pp. 310–315.
[45] B. D. Veatch and J. D. Scott, "Pre-positionable prosthetic hand," U.S. Patent 20080188952A1, 2008.
[46] N. Dechev, W. L. Cleghorn, and S. Naumann, "Multiple finger, passive adaptive grasp prosthetic hand," *Mech. Mach. Theory*, vol. 36, pp. 1157–1173, 2001.
[47] J. H. Rouse, R. H. Farquharson, and C. G. Betts, "Multifunction body powered prosthetic wrist unit and method," U.S. Patent 7048768B1, 2003.
[48] S. L. Phillips, K. J. De Laurentis, and C. E. I. Pfeiffer, "Joint prosthetic device," U.S. Patent 20090326677, 2009.
[49] N. A. Abd Razak, N. A. Abu Osman, H. Gholizadeh, and S. Ali, "Development and performance of a new prosthesis system using ultrasonic sensor for wrist movements: A preliminary study," *Biomed. Eng. Online*, vol. 13, 2014, Art. no. 49.
[50] K. Ohnishi, T. Morio, T. Takagi, and I. Kajitani, "Multimodal sensor controlled three degree of freedom transradial prosthesis," in *Proc. IEEE 13th Int. Conf. Rehabil. Robot.*, 2013, pp. 1–6.
[51] K. Ito, T. Tsuji, A. Kato, and M. Ito, "An EMG controlled prosthetic forearm in three degrees of freedom using ultrasonic motors," in *Proc. 14th Annu. Int. Conf. IEEE Eng. Med. Biol. Soc.*, 1992, vol. 4, pp. 1487–1488.
[52] S. Fan, S. Fan, L. Jiang, and H. Liu, "A design of a miniaturized prosthetic wrist based on repetition rate of human wrist daily tasks," in *Proc. Int. Conf. Robot. Biomimetics*, 2016, pp. 1643–1648.
[53] L. Resnik, S. L. Klinger, and K. Etter, "The DEKA arm: Its features, functionality, and evolution during the veterans affairs study to optimize the DEKA arm," *Prosthetics Orthotics Int.*, vol. 38, pp. 492–504, 2013.
[54] J. Sensinger *et al.*, "Initial experiences with the RIC arm," in *Proc. Myoelect. Controls Symp.*, 2014, pp. 227–229.
[55] P. J. Kyberd, A. S. Poulton, L. Sandsjo, S. Jonsson, B. Jones, and D. Gow, "The ToMPAW modular prosthesis - a platform for research in upper limb prosthetics," *J. Prosthetics Orthotics*, vol. 19, pp. 15–21, 2007.
[56] D. Gouaillier *et al.*, "Mechatronic design of NAO humanoid," in *Proc. IEEE Int. Conf. Robot. Automat.*, Jun. 2009, pp. 769–774.
[57] Aldebaran Robotics, Tokyo, Japan, "All purpose humanoid robot," 2012.
[58] W. Friedl, H. Hppner, F. Petit, and G. Hirzinger, "Mechanical design, shape analysis and experimental validation wrist and forearm rotation of the DLR hand arm system," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, 2011, pp. 1836–1842.
[59] R. A. Frosch, G. A. Wiker, and W. A. Mann, "Compact artificial hand," U.S. Patent 4149278, 1979.
[60] D. Gow, "Upper limb prosthesis," U.S. Patent 6 361 570, 2002.
[61] M. N. Verleg, "Wrist prosthesis: New two degrees-of-freedom hydraulic wrist mechanism for hand prostheses," M.S. thesis, Dept. Biomech. Eng., TU Delft, Delft, The Netherlands, 2015.
[62] A. Polhemus, B. Doherty, K. Mackiw, R. Patel, and M. Paliwal, "uGrip II: A novel functional hybrid prosthetic hand design," in *Proc. Annu. Northeast Bioeng. Conf.*, 2013, no. 39, pp. 303–304.
[63] RSL Steeper, Leeds, U.K., Bebionic wrist, 2015.
[64] P. J. Kyberd *et al.*, "Two-degree-of-freedom powered prosthetic wrist," *J. Rehabil. Res. Develop.*, vol. 48, no. 6, pp. 609–617, 2011.
[65] M. Controzzi, C. Cipriani, B. Jehenne, M. Donati, and M. C. Carrozza, "Bio-inspired mechanical design of a tendon-driven dexterous prosthetic hand," in *Proc. Annu. Int. Conf. IEEE Eng. Med. Biol. Soc.*, 2010, pp. 499–502.
[66] S. Ahmad, A. Masood, and U. S. Khan, "Bowden cable based powered ball and socket wrist actuator," *Int. J. Mech. Aerosp., Ind. Mechatronic Manuf. Eng.*, vol. 6, no. 9, pp. 932–935, 2012.
[67] H. Takeda, N. Tsujiuchi, T. Koizumi, H. Kan, M. Hirano, and Y. Nakamura, "Development of prosthetic arm with pneumatic prosthetic hand and tendon-driven wrist," in *Proc. 31st Annu. Int. Conf. IEEE Eng. Med. Biol. Soc.*, 2009, pp. 5048–5051.
[68] U. Scarcia, C. Melchiorri, and G. Palli, "Towards simplicity: On the design of a 2-DOFs wrist mechanism for tendon-driven robotic hands," in *Proc. IEEE Int. Conf. Robot. Biomimetics*, 2015, pp. 1317–1322.
[69] W. A. Burbank, "Four-cable wrist with solid surface channels," U.S. Patent 8 821 480, 2014.
[70] T. E. Murphy and M. M. Nixon, "Surgical instrument wrist," U.S. Patent 8 540 748, 2013.
[71] S. Manzo and L. Heaton, "Wristed robotic surgical tool for pluggable end-effectors," U.S. Patent 8 398 634, 2013.
[72] S. Lo *et al.*, "Design, operation, and performance evaluation of a cable-drawn dual-axis solar tracker compared to a fixed-tilted system," *Energy Sci. Eng.*, vol. 3, no. 6, pp. 549–557, 2015.
[73] Intuitive Surgical, Sunnyvale, CA, USA, "EndoWrist instrument & accessory catalog," 2015.
[74] L. B. Bridgwater *et al.*, "The robonaut 2 hand-designed to do work with tools," in *Proc. IEEE Int. Conf. Robot. Automat.*, 2012, pp. 3425–3230.
[75] A. Cammarata, "Optimized design of a large-workspace 2-DOF parallel robot for solar tracking systems," *Mech. Mach. Theory*, vol. 83, pp. 175–186, 2015.
[76] D. Sanchez and S. Barbara, "Surgical instrument with a universal wrist," U.S. Patent 7 121 781, 2006.
[77] X. Duan, Y. Yang, and B. Cheng, "Modeling and analysis of a 2-DOF spherical parallel manipulator," *Sensors (Switzerland)*, vol. 16, no. 9, pp. 1–15, 2016.
[78] B. M. Schena, "Center robotic arm with five-bar spherical linkage for endoscopic camera," U.S. Patent 8 469 945, 2013.
[79] J. M. Wiitala and M. M. Stanisic, "Design of an overconstrained and dextrous spherical wrist," *J. Mech. Des.*, vol. 122, no. 9, pp. 347–353, 2000.
[80] S. Hernandez, S. Bai, and J. Angeles, "The design of a chain of spherical stephenson mechanisms for a gearless robotic pitch-roll wrist," *J. Mech. Des.*, vol. 128, no. 2, pp. 422–429, 2006.
[81] K. Sone, H. Isobe, and K. Yamada, "High angle active link," NTN, Osaka, Japan, Tech. Rev., 2004, pp. 70–73.
[82] M. E. Rosheim, "Multiple rotatable links robotic manipulator," U.S. Patent 5 893 296, 1999.
[83] S. L. Canfield and C. F. Reinholtz, "Development of the carpal robotic wrist," in *Experimental Robotics V*. Berlin, Germany: Springer, 1998, pp. 423–434.
[84] L. Barker, M. Neber, and H. Lee, "Design of a low-profile two-axis solar tracker," *Sol. Energy*, vol. 97, pp. 569–576, 2013.
[85] Y. Lee, C. Chu, J. Xu, C. Lan, and S. Member, "Two-dimensional series elastic actuation for accurate force/torque interaction," *IEEE/ASME Trans. Mechatronics*, vol. 21, no. 3, pp. 1315–1325, Jun. 2016.
[86] Y. J. Kim *et al.*, "RoboRay hand: A highly backdrivable robotic hand with sensorless contact force measurements," in *Proc. IEEE Int. Conf. Robot. Automat.*, 2014, pp. 6712–6718.
[87] H. Lymark and F. Mohl, "An electromechanical forearm and hand," in *Advances in the Control of Human Extremities*. *3rd Int. Symp. Control of Human Extremities*, Dubrovnik, Croatia, 1966, pp. 142–150.
[88] C. Roose, "Pneumatically powered wrist prosthesis," Master's thesis, TU Delft, 2014.
[89] S. L. Archer *et al.*, "Wrist device for use with a prosthetic limb," U.S. Patent 7 914 587, 2011.
[90] K. J. De Laurentis and C. Mavroidis, "Mechanical design of a shape memory alloy actuated prosthetic hand," *Technol. Health Care*, vol. 10, pp. 91–106, 2002.
[91] M. S. Johannes, J. D. Bigelow, J. M. Burck, S. D. Harshbarger, M. V. Kozlowski, and T. Van Doren, "An overview of the developmental process for the modular prosthetic limb," *Johns Hopkins APL Tech. Dig. (Appl. Phys. Lab.)*, vol. 30, no. 3, pp. 207–216, 2011.
[92] R. Mahmoud, A. Ueno, and S. Tatsumi, "Dexterous mechanism design for an anthropomorphic artificial hand: Osaka City University Hand I," in *Proc. 10th IEEE-RAS Int. Conf. Humanoid Robot. Humanoids*, 2010, pp. 180–185.
[93] S. Roth, "Robot arm," U.S. Patent 2014/0165771 A1, 2014.
[94] T. Inada, T. Tsujimori, S. Kitamura, and R. Taniuchi, "Robot," U.S. Patent 7 622 001, 2009.
[95] N. Torii, K. Mizuno, and H. Iwasaki, "Wrist assembly for an industrial robot," U.S. Patent 4 972 735, 1990.
[96] T. Hezel, I. Leiensetter, F. Herre, B. Maxharraj, and N. Maxaharaj, "Multi axis robot wrist and method," U.S. Patent 7 870 807, 2011.
[97] Z.-X. Liu, "Robot arm assembly," U.S. Patent 2012/0103127 A1, 2012.
[98] N. Ulrich and W. T. Townsend, "Robotic wrist," U.S. Patent D 352, 050, 1989.

[99] K. A. Wyrobek, E. H. Berger, H. F. M. Van Der Loos, and J. K. Salisbury, "Towards a personal robotics development platform: Rationale and design of an intrinsically safe personal robot," in *Proc. IEEE Int. Conf. Robot. Automat.*, 2008, pp. 2165–2170.
[100] S. Schuler, V. Kaufmann, P. Houghton, and G. S. Székely, "Design and development of a joint for the dextrous robot arm," in *Proc. 9th ESA Workshop Adv. Space Technol. Robot. Automat.*, 2006, no. 1, pp. 1–8.
[101] R. D. Howard, "Design of a robotic wrist and tool-exchange mechanism for satellite servicing," Univ. Maryland, College Park, MD, USA, Presentation, 2002.
[102] T. A. Morley and D. T. Wallace, "Roll-pitch-roll surgical tool," U.S. Patent 7 398 707, 2008.
[103] U. Hagn *et al.*, "DLR MiroSurge: A versatile system for research in endoscopic telesurgery," *Int. J. Comput. Assisted Radiol. Surg.*, vol. 5, no. 2, pp. 183–193, 2010.
[104] A. J. Madhani and J. K. Salisbury, "Articulated surgical instrument for performing minimally invasive surgery with enhanced dexterity and sensitivity," U.S. Patent 5 792 135, 1998.
[105] T. A. Morley and D. T. Wallace, "Roll-pitch-roll-yaw surgical tool," U.S. Patent 6 676 684, 2004.
[106] Kuka AG, Augsburg, Germany, 2017. [Online]. Available: www.kuka.com
[107] A. Albers, S. Brudniok, J. Ottnad, C. Sauter, and K. Sedchaicharn, "Upper body of a new humanoid robot - the design of ARMAR III," in *Proc. 6th IEEE-RAS Int. Conf. Humanoid Robots*, 2006, pp. 308–313.
[108] K. Berns, H. Vogt, T. Asfour, and R. Dillmann, "Design and control architecture of an anthropomorphic robot arm," in *Proc. 3rd Int. Conf. Adv. Mechatronics*, 1998, vol. 35, pp. 945–962.
[109] K. Kaneko *et al.*, "Humanoid robot HRP-4 - humanoid robotics platform with lightweight and slim body," in *Proc. IEEE Int. Conf. Intell. Robots Syst.*, 2011, pp. 4400–4407.
[110] B. Tondu, S. Ippolito, J. Guiochet, and A. Daidie, "A seven-degrees-of-freedom robot-arm driven by pneumatic artificial muscles for humanoid robots to cite this version," *Int. J. Robot. Res.*, vol. 24, no. 4, pp. 257–274, 2005.
[111] G. T. Pinson, "Digitally controlled artificial hand," US patent 4,246,661, 1981.
[112] G. S. Chirikjian and D. Stein, "Kinematic design and commutation of a spherical stepper motor," *IEEE/ASME Trans. Mechatronics*, vol. 4, no. 4, pp. 342–353, Dec. 1999.
[113] R. B. Roth and K.-M. Lee, "Design optimization of a three degrees-of-freedom variable-reluctance spherical wrist motor," *J. Eng. Ind.*, vol. 117, pp. 378–388, 1995.
[114] S. K. Mustafa, G. Yang, S. H. Yeo, W. Lin, and C. B. Pham, "Development of a bio-inspired wrist prosthesis," in *Proc. IEEE Conf. Robot. Automat. Mechatronics*, 2006, vol. 1, pp. 3–8.
[115] C. M. Gosselin, E. St. Pierre, and M. Gagné, "On the development of the agile eye," *IEEE Robot. Automat. Mag.*, vol. 3, no. 4, pp. 29–37, Dec. 1996.
[116] L. Birglen, C. Gosselin, N. Pouliot, B. Monsarrat, and T. Laliberté, "SHaDe, a new 3-DOF haptic device," *IEEE Trans. Robot. Automat.*, vol. 18, no. 2, pp. 166–175, Apr. 2002.
[117] T. A. Hess-Coelho, "A redundant parallel spherical mechanism for robotic wrist applications," *J. Mech. Des.*, vol. 129, pp. 891–895, Aug. 2007.
[118] K. Al-Widyan, X. Q. Ma, and J. Angeles, "The robust design of parallel spherical robots," *Mech. Mach. Theory*, vol. 46, no. 3, pp. 335–343, 2011.
[119] P. Vischer and R. Clavel, "Argos: A novel 3-DoF parallel wrist mechanism," *Int. J. Robot. Res.*, vol. 19, pp. 5–11, 2000.
[120] R. Clavel, "Device for the movement and positioning of an element in space," U.S. Patent 4 976 582, 1989.
[121] M. B. Hong and Y. H. Jo, "Design of a novel 4-DOF wrist-type surgical instrument with enhanced rigidity and dexterity," *IEEE/ASME Trans. Mechatronics*, vol. 19, no. 2, pp. 500–511, Apr. 2014.
[122] F. L. H. Iii, R. D. Howe, and R. J. Wood, "Dexterous high-precision robotic wrist for micromanipulation," in *Proc. 16th Int. Conf. Adv. Robot.*, 2013, pp. 1–8.
[123] K. B. Fite, T. J. Withrow, X. Shen, K. W. Wait, J. E. Mitchell, and M. Goldfarb, "A gas-actuated anthropomorphic prosthesis for transhumeral amputees," *IEEE Trans. Robot.*, vol. 24, no. 1, pp. 159–169, Feb. 2008.
[124] D. S. V. Bandara, R. A. R. C. Gopura, K. T. M. U. Hemapala, and K. Kiguchi, "A multi-DoF anthropomorphic transradial prosthetic arm," in *Proc. BIOROB*, 2014, vol. 1, pp. 1039–1044.
[125] S. K. Kundu and K. Kiguchi, "Development of a 5 DOF prosthetic arm for above elbow amputees," in *Proc. IEEE Int. Conf. Mechatronics Automat.*, 2008, pp. 207–212.
[126] A. Degirmenci, F. L. Hammond, J. B. Gafford, C. J. Walsh, R. J. Wood, and R. D. Howe, "Design and control of a parallel linkage wrist for robotic microsurgery," in *Proc. IEEE Int. Conf. Intell. Robots Syst.*, Dec. 2015, pp. 222–228.
[127] C. Chou and B. Hannaford, "Measurement and modeling of McKibben pneumatic artificial muscles," *IEEE Trans. Robot. Automat.*, vol. 12, no. 1, pp. 90–102, Feb. 1996.

Neil M. Bajaj (S'18) received the B.S. degrees in mechanical engineering and in kinesiology, both in 2014, from University of Massachusetts, Amherst, MA, USA, and the M.S. and M.Phil. degrees in mechanical engineering in 2016 and 2017, respectively, from Yale University, New Haven, CT, USA, where he is currently working toward the Ph.D. degree in mechanical engineering.

His research focuses on the design, construction, and evaluation of powered prosthetic wrists for upper limb amputees.

Adam J. Spiers (M'17) received the B.Sc. degree in cybernetics and control engineering and the M.Sc. degree in engineering and information sciences from University of Reading, Reading, U.K., in 2004 and 2006, respectively, and the Ph.D. degree in mechanical engineering from University of Bristol, Bristol, U.K., in 2011.

He is currently a Research Scientist with the Haptic Intelligence Department, Max Planck Institute for Intelligent System, Stuttgart, Germany. His research interests include haptic interfaces, human and robot manipulation, and upper limb prosthetics.

Aaron M. Dollar (SM'13) received the B.S. degree in mechanical engineering from University of Massachusetts, Amherst, MA, USA, in 2000, and the S.M. and Ph.D. degrees in engineering sciences from Harvard University, Cambridge, MA, USA, in 2002 and 2007, respectively.

He is currently the John J. Lee Associate Professor of mechanical engineering and materials science with Yale University, New Haven, CT, USA. He was involved in two years of postdoctoral research with the Massachusetts Institute of Technology Media Lab. His research interests include human and robotic grasping and dexterous manipulation, mechanisms and machine design, and assistive and rehabilitation devices, including upper limb prosthetics and lower limb orthoses.

Prof. Dollar is the recipient of the 2014 NASA Early Career Faculty Award, the 2013 DARPA Young Faculty Award, the 2011 AFOSR Young Investigator Award, the 2010 Technology Review TR35 Young Innovator Award, and the 2010 NSF CAREER Award.