REALISTIC DESIGN CONSIDERATIONS OF A 3-DOF PROSTHETIC WRIST DEVICE

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ABSTRACT

This work discusses the hardware implementation details of a three degree of freedom prosthetic wrist device. To address some issues in current state of the art wrist design, we employ a hybrid mechanism architecture, consisting of a serial and parallel mechanism. This requires a combined view of both theoretical and practical physical considerations when designing such a device. We discuss kinematic analysis of the device, simulation methods and metrics that lead to informative physical implementation details, and actual physical implementations of the prosthetic wrist device. We show that these implementation characteristics can make different physical designs with the same nominal kinematics more suitable for different types of amputees.

INTRODUCTION

In activities of daily living, the human wrist may contribute as much to successful and timely completion of tasks as the fully dexterous, unaffected human hand [1]. Despite this, the design of prosthetic wrist devices has typically lagged behind that of prosthetic hands [2], though recently, more attention has been paid to wrist design, e.g. [3]–[7].

While the space of serial type wrist designs (i.e. joints placed in series) has been the standard for design of many wrist prostheses, borrowing ideas from parallel mechanism design has allowed for more freedom in wrist design. This additional freedom may be quite beneficial for prosthetic devices, for example, by allowing actuators to be placed proximal to the elbow (reducing elbow torque) and reducing the overall length of the wrist (making devices more suitable for amputees with long residual limbs). While these characteristics are obviously desirable in prosthetic wrist devices, designing parallel mechanisms to be incorporated into them can be quite challenging, particularly because of kinematics, actuation, and sensing considerations, combined with the small size scale of prosthetic devices.

We discuss the kinematic and physical design considerations in our proposed 3 DOF powered wrist prosthesis. The proposed device utilizes a hybrid (parallel and series) mechanism topology. Simulation of the kinematics is used to optimize the geometric parameters to improve the quality of motion and uniformity of torque production over the desired range of motion. Furthermore, we pay attention to key geometric metrics that would greatly affect the physical implementation of the prosthetic wrist, such as interference of the links of the mechanism on the structure, and range of motion of passive joints in the mechanism. We discuss further considerations that allow simple sensing schemes to be used, reducing the amount of hardware and cost of sensors required to provide closed loop feedback on the wrist.

METHODS

Kinematic Considerations

The proposed wrist design herein is composed of a hybrid mechanism, which is composed of a serial and parallel mechanism combined. Specifically, it is a RU serial mechanism a 2DOF parallel U, PRUR, PSSR mechanism, where the underlined joints correspond to the actuated joints in each chain. The kinematic architecture and the methods of actuation can be seen in Fig. 1. The mechanism may be further broken into a flexion mechanism comprising the PRUR portion, a deviation mechanism comprising the PSSR portion, and the pronation mechanism comprising the RU chain. This architecture creates spherical 3 DOF motion about the center of rotation, which is the passive Universal joint. As it can roll, a 2 DOF Universal joint becomes a 3 DOF Spherical joint, creating spherical motion emulating wrist motion.

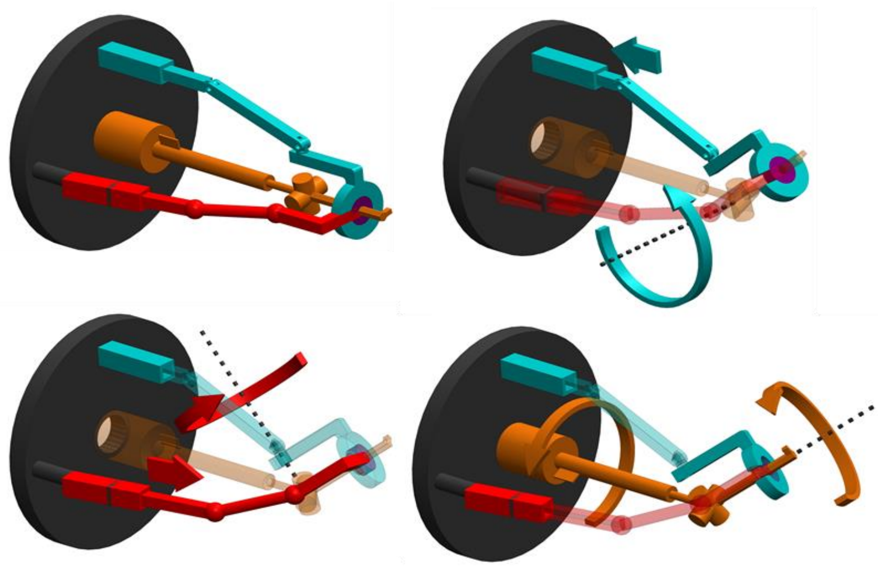

Figure 1: (Top left) kinematic representation of the 3 DOF prosthetic wrist device. (Top right) Actuating the PRUR flexion mechanism by actuating the blue prismatic joint. (Bottom left) Actuating the PSSR deviation mechanism about the indicated axis by actuating the red prismatic joint. (Bottom right) Actuating the RU pronation mechanism by actuating the pronation motor, creating roll about the indicated dashed axis.

This mechanism has a total of 7 geometric design parameters which may be changed to alter the motion and torque profiles of the overall mechanism. Moreover, an advantage of this mechanism architecture is that it partially decouples flexion, deviation, and pronation, meaning that only a single motor is largely responsible for each of the aforementioned wrist angles. This allows the flexion mechanism, deviation mechanism, and pronation mechanism to be simulated and optimized separately, and then the actual physical actuator may be changed to further alter the torque or speed characteristics, potentially to emulate anthropomorphic values. The kinematics are further described in [8].

To optimize each mechanism, we vary the geometric design parameters and then average the torque production capacity over a fixed range of motion (100º for flexion and deviation, 360º for pronation). Furthermore, we also track quantities relevant to the physical implementation. Namely, these are the minimum and maximum distance of any of the links from the central longitudinal axis of the wrist, and the range of motion required for each passive joint. Both of these factors are exceedingly important in the physical implementation and are often neglected in mechanism design, which hinders the transition from kinematic representation to physical prototype.

The minimum and maximum distance of the links from the central axis are important because they determine what the overall size scale of the mechanism will be when used in a wrist prosthesis. As this architecture can place actuators remotely, in a prosthetic device, they may be placed around the residual limb and socket. However, the mobile links of the mechanism must therefore not intersect or contact the socket during motion. The minimum distance metric therefore informs the designer of how much a mechanism with fixed geometric parameters would have to be scaled up to accommodate a residual limb of a fixed radius to avoid contact issues. The maximum distance is then related to this, as it then described how far from the central axis any link will need to be given this fixed radius. This tells a designer what the overall envelope of a particular design would be, and how “bulky” a mechanism would be compared to the residual limb.

Often, there will be loosely defined requirements on the minimum and maximum distance that would rule out some kinematic designs, especially when considering anthropomorphic proportions. These metrics are also closely related to the reversed workspace [9], and thus are related to the physical limitations of a wrist due to form factor.

Secondly, the range of motion of the passive joints is critical in being able to implement a particular design. Generally, passive joints (except revolute joints) have bounded ranges of motion that may often be exceeded in kinematic simulation. This is especially true for spherical and universal joints, though some work has been done to study and enlarge the range of motion of these joints [10]. Without considering their range of motion, during normal actuation of a mechanism, a passive joint will contact its physical joint limit, and large contact forces will arise on the links. Thus, it is critical that one constrain designs to those that have physically realizable passive joints.

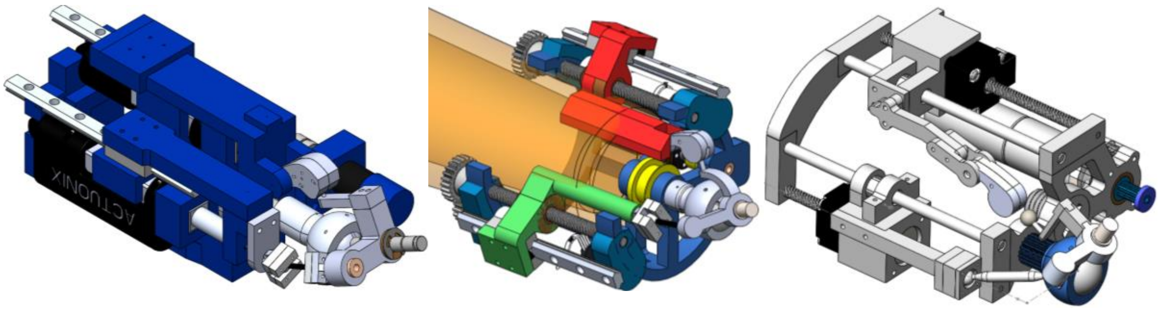

Figure 2: (Left) Minimum overall size implementation, compatible with a very short residual forearm or transhumeral prosthesis (no forearm remaining). (Center) Surrounding socket design, socket shown in transparency. (Right) Compromised design, compatible with short residual limb socket. Note that all wrists share the same size scale, with the central ball shown in each as a 1 inch (2.54cm) diameter sphere.

Physical Implementation

To verify and explore the importance and accuracy of the different metrics explored, we designed a series of physical representations of the optimal kinematic design. These designs correspond to 1) the minimal packaging required for the wrist, as if it would be placed directly on the end of the residual limb on the socket, 2) the design which would minimize the additional length required for the prosthetic wrist by placing as much of the wrist around an average prosthetic socket, and 3) a compromise design. Design 1 corresponds to the smallest maximum distance possible, design 2 corresponds to the smallest minimum distance that would accommodate a long residual limb socket, and design 3 corresponds to a short residual limb.

RESULTS

We present the physical implementations of the optimized design of the wrist device. All implementations share similar kinematic parameters with some overall scaling and translating of the actuators, though a comprehensive discussion of the allowable changes to facilitate comparison is too exhaustive for this paper. We also implemented the most size reducing actuator and drivetrain configuration possible (given a number of commercial and packaging constraints).

Figure 2 shows the three separate design implementations of the optimized prosthetic wrist prototype. The designs clearly show the effect of packaging requirements on the resulting physical design, where the actuators may be placed and what type of actuators and drivetrains must be used to accommodate the constraints on size. Design 1 allows for use of off the shelf linear servo motors, and package the pronation shaft about the center. The resulting design is discussed more in [5], but the overall size of 8.6cm length and a circumscribing radius of 4cm. Design 2 has an overall additional length on the end of the residual limb of 4.5cm, and a radius of 6.2cm. Moreover, the design can utilize a dc motor, gear reduction, and lead screw drive train for the actuated P joints, potentially increasing the mechanism torque and speed, though at the expense of complexity due to additional load bearing components. Finally, design 3 has an additional length on the residual limb of 5.6cm, with a cylindrical radius of 4.9cm. Note that this design could not fit linear servo motors or lead screw based drivetrains within its packaging limits while maintaining comparable torque to the other designs, so noncaptive linear stepper motors were used instead.

These designs also have a variety of different spherical joint range of motion requirements. We note that designs 1 and 2 require a large range of motion (130º conical range of motion), whereas design 3 requires a much smaller range of motion (70º conical range of motion). This affects the physical implementation of the spherical joints from the slot type design in design 1 and 2, and a symmetric standard ball and socket spherical joint in design 3. Moreover, the required passive hardware in design 1 and 2 may lead to much thicker components, affecting the necessary clearance to avoid collision.

To examine the validity of our simulations, the physical implementation of design 1 was tested for its torque and speed. Initial results are shown in figure 3. We characterize how quickly the wrist may actuate to different points in

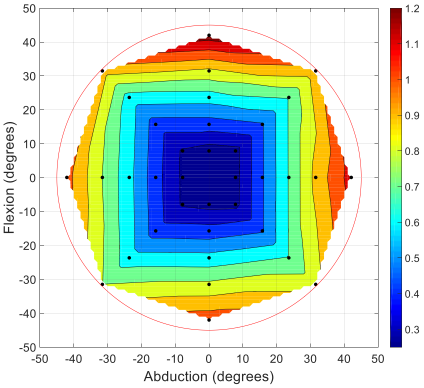

Figure 3: Time to actuate to the center speed over the range of motion of design 1. The distance between the contours is proportional to the maximum speed near that particular area, and is thus inversely proportional to the torque capacity of the mechanism.

its circumduction workspace. Through the use of electric motors, the speed of any point in the workspace is inversely proportional to the maximum torque at that point as well.

DISCUSSION

In this paper, we present practical implementation details of a 3DOF prosthetic wrist device, and show how under some constraints, this vastly affects the resulting physical implementation. We note that clearance and packaging constraints may influence the type of actuators used in a particular design, but more importantly, affect the type of residual limb geometry that is compatible with each design, potentially making different implementations of the same kinematics required for different amputees.

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