RICE UNIVERSITY

Hardware- versus Human-centric Assessment of Rehabilitation Robots

by

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ABSTRACT

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Individuals with disabilities arising from neurological injury require rehabilitation of the distal joints of the upper extremities to regain the ability to independently perform activities of daily living (ADL). Robotic rehabilitation has been shown to effectively conduct high intensity, long duration therapy and quantitatively assess the effects of therapy. This thesis presents methods and results for validating rehabilitation devices for training and assessment. Traditionally, methods for validating rehabilitation robots relied on robotic characterizations, which enables comparison of different designs’ performance independent of a human user. An example of this method is presented here, in particular quantifying the torque output, range of motion, closed loop position performance, and high spatial resolution of two rehabilitation devices. However, these traditional validation methods do not assess the effect wearing the robot has on the user, and a new assessment method has been developed to address this shortcoming of traditional methods. A novel hand and wrist device was assessed through kinematic analysis of synergistic movements, as quantified by velocity- and position-dependent metrics. This experimental approach is promising for the characterization of multi-articular wearable robots as measurement tools in robotic rehabilitation. Together, the two methods presented can be used to validate rehabilitation robotic devices.
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Chapter 1

Introduction

1.1 Background

An estimated four percent of adults will suffer a stroke in the United States by 2030. With the economic costs stemming from stroke treatment estimated to rise from $71.55 billion in 2010 to $183.13 billion in 2030, improving rehabilitative outcomes and techniques for evaluating these outcomes can have a significant social and economic impact for stroke therapy [12]. Over 90% of the estimated 7,000,000 stroke survivors will require rehabilitation focused on regaining function in the hand and wrist in order to perform activities of daily living and to improve their quality of life [13]. Approximately 12,000 incidences of Spinal Cord Injury (SCI) occur in the United States each year [14] with an estimated total yearly direct and indirect costs of $14.5 billion and $5.5 billion, respectively. The average age at the time of injury is approximately 41 years, creating a much younger population than is typical for stroke, living decades past injury, meaning that recovery of function has profound economic impact of their lifespan [15].

Robotic rehabilitation devices have been proposed to meet the rising number of patients requiring rehabilitation after neurological injury, and to improve the efficacy of treatments. These devices have been safely implemented for several neuromuscular conditions including stroke and SCI, providing a safe, accurate way to administer the high intensity, long duration physical therapy required for effective rehabilitation, and
record quantitative data about subjects’ progress [16, 17, 18, 19, 20]. Robotic rehabilitation exoskeletons are particularly valuable in therapy because they leverage robotic devices’ unique potential for accurate and repeatable movements, and quantitative measurement in position and force domains. The most critical part of any robotic rehabilitation device is the interaction between the robot and the patient. While this may seem trivial, this perspective is important for guiding the design of rehabilitation robotic devices for their two main purposes: training and assessment.

1.1.1 Rehabilitation Robotics Review

Generally, rehabilitation robots can be classified as either an end-effector or exoskeleton type design. In this context, an end-effector rehabilitation robot is any device that possesses only one point of contact with the user, the robot’s most distal part or end-effector. The end-effector’s position and orientation are used to assist or resist the subject during repetitive moving tasks. Some of the most well known end-effector designs include the 2-DOF, planar MIT-MANUS [21], (since commercialized as the InMotion3), as well as the 3-DOF ARM Guide [22], and a modified 6-DOF PUMA 560 robot called the Mirror Image Movement Enabler (MIME) [23].

Exoskeletons allow for the application of torques to individual joints because they possess two or more points of contact with the user, designed such that they block the more proximal link to the DOF of interest. For example, in order to actuate the wrist joints, the forearm must be attached to the exoskeleton to ensure that only the wrist moves, and other joints can’t be used to accomplish the motion. Because of this blocking, there exists a mapping between the joints of the exoskeleton and the joints of interest of the subject, which are either designed to be colocated, as in anthropomorphic designs, or can be mapped in a myriad of non-anthropomorphic ways [24].
Many ergonomic considerations, including the difficulty reproducing the movement of complex, and often variable (user-to-user, and as a function of joint angle) orientation and position of human joint axes have generated considerable interest in advanced methods for investigating hyperstaticity, or over-constraints induced by wearing a robotic exoskeleton [25] and developing non-anthropomorphic designs. With either optimized anthropomorphic or non-anthropomorphic designs, exoskeletons are more attractive for rehabilitation and research than end effector designs due to their mapping of robot to human joint movement.

Currently, there are several novel exoskeleton designs for the upper extremities, including the mPower Arm Brace (Myomo, Inc.), the ARMin III [26], CADEN 7 [27], Rupert [28], and the MAHI Exo-II [9]. Often, the anatomical, biomechanical, and functional couplings of the hand and wrist are overlooked in robotic rehabilitation. By design, most state-of-the-art devices do not allow for coordinated movement of the wrist and hand. A number of hand and wrist exoskeletons have been separately developed [29,30,31,32,33].

1.2 Characterization of Rehabilitation Robots

Before any clinical implementation, analysis of a rehabilitation robot’s performance is necessary to validate it as a suitable platform for rehabilitation and research. As detailed previously [3], a rehabilitation robot must exhibit certain key characteristics to accomplish its two goals of training and assessment. Specifically, a rehabilitation robot must possess: i) functional workspace spanning the requirements for the trained activities [34], ii) torque application to specific human joints [34] iii) quantitative evaluation of treatment [35] iv) provide ergonomically appropriate forces and torques to the human body [36], v) high backdrivability with no backlash [37], and vi) the
ability to implement advanced control algorithms [38]. Parameters such as static and viscous friction, inertia, closed-loop position bandwidth, spatial resolution, range of motion (ROM), and torque output are used to evaluate a rehabilitation robot on these criteria.

1.2.1 Performance requirements for training devices

The majority of the requirements (i, ii, iv, and vi) outlined above focus on the device’s capabilities for performing rehabilitation regimens. The requirement for functional workspace is straightforward since most therapy regimens focus on bringing ROM and torque outputs back up to those required for ADL. Often, a rehabilitation robot must apply torques greater than that required for ADL to overcome a patient’s significant muscle tone or stiffness. The requirement to enable targeting of specific joints arises from regimens focused on isolated, single DOF movements [17,39], and therapy outcomes have been shown to be maximized by training subsets of basic movements, instead of entire complex movements for the proximal joints of the upper extremity [40]. However, it is an open question in the field if these same gains can be had with the distal joints of the upper extremity, namely, the hand and wrist. Ergonomics play a crucial role in safety and comfort of the user while wearing the device. Ultimately, the goal of robotic therapy is to provide therapy that is longer in duration than traditional methods, and if the robot is uncomfortable to use, this goal cannot be achieved. The final requirement for advanced control capabilities arises from the need to actively challenge the patient during therapy. To better rehabilitate a patient, cognitive, voluntary involvement is required. Simply moving a patient through a motion cannot facilitate the increases in functionality and neuroplasticity, essentially the rewiring of the brain, which can take place when the patient is actively involved
in the motion [38]. Facilitating neuroplasticity is the only way for stroke patients to regain lost function, and is the main goal of a rehabilitation robotic device. To accomplish this goal, the device must challenge the patient, and this often requires advanced control schemes [41].

Often, only a few of the characteristics mentioned are reported in the literature. For example, torque output limits of the mPower Arm Brace (Myomo, Inc.) have been reported [42], but due to the commercial nature of the product, very little other information has been reported. ROM, maximum joint torques, powertrain and sensor specs, static friction, coulomb friction, a bandwidth measure, weight, and repeatability of the ARMin III have been presented [26]. The literature on the CADEN 7 reported ROM, a bandwidth measure, link masses, and a sample, non-optimized step response [8, 27]. The designers of the RUPERT have reported the ROM and torque capabilities, inertial characteristics, in addition to some sensor specs [28]. The maximum motor torque outputs, as well as sensor resolutions have been reported for the 2-DOF, planar MIT-MANUS [21], with similar characterizations provided for the shoulder module [43] reporting friction modes, inertia and powertrain ROM and torque outputs. There are very few characterization details provided for the 3-DOF ARM Guide [22], and the MIME [23], however general specifications such as inertia and maximum force outputs are available for the Puma 560 robot on which the MIME is based [44]. With a varied set of metrics reported, often determined with different methods, engineers and clinicians could benefit from a standardized characterization process, aiding in design and implementation decisions. These standardized characterizations have even more meaning for exoskeleton designs, which have mappings from robotic joints to human joints.
1.2.2 Performance requirements for assessment tools

The remaining two requirements (iii and v) are the most nearly related of the two. Usually, quantitative measurements are taken when the robot is being backdriven, either through an un-powered backdriving of the powertrain [17, 39], or through a controlled dynamics cancellation mode (zero impedance) if powertrains are not intrinsically backdrivable [45]. The fundamental assumption during these measurements is that the measurement process has minimal effects on the measurand. Even with comprehensive performance characterizations, it is still difficult to answer one of the current open questions in rehabilitation: are robots that are designed for treatment also efficacious for assessment? Currently, using these devices for both tasks is standard, which, from an implementation perspective is superior, because it does not require setting up two different devices. Setting up multiple devices would lengthen therapy times, especially for subjects with high muscle tone or spasticity. Further confounding this question, the hand and wrist exhibit complex characteristics not found in more proximal joints. Recent literature [46, 47] has shown that the wrist possesses curvature and asymmetries that need to be retrained in order to restore healthy movements. Also, the wrist and hand are kinematically and dynamically linked, due to tendon and muscle anatomy [48]. It is well understood that the articulations of the hand are mechanically linked, with each joint interdependent on its neighboring joints, and beholden to passive and active neuromuscular effects [49]. The muscular structure is also complex, and synergies arise from muscles, tendons, and ligaments exerting forces across multiple DOF. For example, the flexor muscles for the fingers begin in the forearm, and are also partially responsible for the supination of the forearm [50]. Unlike the more proximal DOFs of the upper extremity previously studied, the hand and wrist have biomechanical couplings as well, with previous studies identifying fin-
ger and wrist position-dependent passive properties of the hand [51,52,53,54]. While some of hand and wrist synergies can be anticipated by studying anatomy, the hand is famously difficult to model, and the interplay between musculo-skeleton anatomy and neuro-muscular control are difficult to separate [55]. Functionally, most ADL involve coordinated movement of the hand and wrist. Some impairments result in decreased coordination, such as Parkinson’s disease, [56], and therapy is focused on regaining coordination, different than some traditional proximal joint rehabilitation rehabilitation techniques. These performance characterization parameters shed some light on how using a robot would likely affect a subject’s movement for single DOF movements, but do not go so far as to quantify the degree to which these devices perturb complicated multi-joint movements. Specifically, these performance characterization parameters do not quantify the effect the devices have on the kinematic movement properties. A direct comparison between movement measured by a robotic rehabilitation device and a no robot movement condition is required to validate a device as a reliable measurement tool. For this reason, it is desirable to create new metrics and characterization methods specifically designed to solve this problem, and this thesis proposes new techniques using motion capture analysis to characterize kinematically coupled multi-joint movements.

Quantitative assessment of movement in rehabilitation has relied primarily on motion capture for both upper extremity [57] and gait [58] assessment. Most systems track the position and sometimes the orientation of special markers, either passive or active [59,60], or magnetic tracking devices [61] in order to get position and orientation information of human joints and segments in real time. These studies rely on the measurement system to minimally affect and accurately determine human joint kinematic information [62], investigate complex biomechanics of the hand and
wrist [51,52], study human motor control [63], or the interactions between all biome-
chanics and control [46,47]. Recent developments have been in developing markerless
tracking systems, such as the Kinect™ system [64], a low-cost device with far reaching
applications in the measurement of large body segments.

Rehabilitation robotic devices have also been used for measurement, and are the
basis for many clinical assessments that rely on the mapping between robotic and
human joints and the robots’ highly accurate sensing [17, 35, 65] as well as use in
non-human neurological trials [66]. Measuring human joint angles through physical
contact with a robot also allows for the measurement of force, instead of position
only, and gives insight into strength capabilities as a function of workspace as well as
strength changes over the course of therapy.

Some prior experiments have compared measurements by different systems of the
same measurand in order to validate their accuracy. For example, a goniometer [67]
can be used to confirm the output of a tracking tool, or the Vicon™ optical marker
tracking system to validate the Kinect™ [68]. Rehabilitation robotic devices as
measurement tools have not had the same breadth or depth of study. One distinct
difference between the motion tracking systems and the exoskeleton systems is the
potential effect of the act of measurement on human kinematics. The assumption
that rehabilitation robotic systems are sufficiently transparent, therapy insignificantly
affecting movement characteristics, is possibly invalid.

1.3 Device Overviews

As a reference, the three devices studied in this thesis are detailed in this section: two
wrist exoskeletons, the RiceWrist and the RiceWrist-S, as well as an integrated hand
and wrist exoskeleton called the READAPT. The wrist module of the READAPT
was based on the RiceWrist-S following the results of the characterization of the two wrist devices.

1.3.1 RiceWrist

The RiceWrist was designed to be an exoskeleton capable of training the three intersecting DOF at the wrist, namely, forearm pronation/supination, wrist flexion/extension, and wrist radial/ulnar deviation. As shown in Fig. 1.1, the RiceWrist consists of a parallel mechanism which is less inertial than a serial mechanism. The RiceWrist began as the wrist module of a haptic arm exoskeleton first presented in 2004 [69], and subsequently refined [70,71,72]. The hardware analyzed in this chapter is a component of the MAHI Exo-II [3,9], which utilizes a RiceWrist as the three most distal DOF, and an additional elbow DOF. To enable this combination, the RiceWrist had a few design modifications, namely, the replacement of a direct-drive brushless motor with a brushed DC motor and capstan cable transmission for the forearm DOF, as well as increased size of the spherical joints used in the parallel mechanism. Safety is ensured through the use of hard stops on all capstan cable transmissions, current limits set in the amplifiers, as well as emergency stops.

1.3.2 RiceWrist-S

The RiceWrist-S is a serial mechanism with three rotational joints (RRR mechanism) which actuates forearm pronation/supination, wrist flexion/extension and wrist radial/ulnar deviation DOF, which has undergone a few minor design modifications since its original introduction [73,74]. In addition to the actuated joints, the RiceWrist-S has one additional passive linear degree of freedom to resolve kinematic over-constraints. These overconstraints are caused by the three rotational axes of
the RiceWrist-S intersecting at one point, whereas the three DOF in a human wrist are non-perpendicular and skew. Safety is insured through the use of three separate stops or limiters, namely, mechanical stops placed within the reachable range of healthy subjects, software limits on the current supplied to the motors, and two mechanical emergency stop buttons located within reach. The RiceWrist-S is being used in clinical trials and as a testbed for adaptive, assist-as-needed controllers [41].
1.3.3 READAPT: Robotic Exoskeleton to Promote Assist Distal Arm Physical Therapy

By design, most state-of-the-art devices do not allow for coordinated movement of the wrist and hand. As set forward in Section 1.2.2, the anatomic, biomechanical, and functional couplings of the hand and wrist are crucial for efficacious robotic rehabilitation. The READAPT, shown in Fig. 1.3, leverages the design of the RiceWrist-S [5] and the UT Hand exoskeleton [75], to enable coordinated hand and wrist therapy. This device actuates 11 degrees of freedom (DOF) of the hand and wrist, with passive constructions to prevent over-constraining the kinematics. As a measurement device, the READAPT utilizes dynamic cancellation control for the hand and unpowered backdriving for the wrist DOF.

![READAPT](image)

(a) Dorsal View  
(b) Volar View

Figure 1.3: READAPT, implemented with wrist, finger, and thumb DOF

1.4 Thesis Outline

This thesis is structured as follows: Chapter 2 provides background on traditional characterization, along with the performance characterization of two rehabilitation
robotic devices, the RiceWrist and RiceWrist-S. Chapter 3 details the development of new metrics for device characterization, which aims at quantifying the degree to which a robot perturbs healthy movement. Specifically, Chapter 3 presents a motion-based transparency assessment of the device, showing the device’s motion dependent effect on hand and wrist kinematic couplings.
Chapter 2

Characterization of Device Static and Dynamic Properties

2.1 Introduction

As set forward in Section 1.2.1, the literature on the characterization of novel upper extremity exoskeletons does not consistently provide a set of metrics. To address this shortcoming, two performance characterizations were undertaken to be similar in scope to previous studies on a wrist exoskeleton [6], allowing for direct comparison between these three wrist exoskeletons, as well as creating a basis for comparison with future novel designs. The performance characterization in this chapter * focuses on quantifying how the RiceWrist and the RiceWrist-S address the requirements of rehabilitation robots, listed in Section 1.2. Pertinent design information for each wrist exoskeleton precedes the characterization. Then their functional workspace and torque capabilities compared to human range of motion (ROM) and torque outputs were investigated. Next, the devices are evaluated by investigating their static friction characteristics. Static friction perturbs movement and should be minimized, since compensation via control is not an option when the robot is being backdriven, as is common during subject assessments. To complete the prediction of device back-

* Portions of this thesis originally appeared in a paper submitted by French, Rose, and O’Malley in April 2014 [3]. Here, the work is expanded to include information previously published on the dynamic characterization of the RiceWrist-S [74], as well as new commentary.
drivability, inertia and viscous friction characteristics are determined, because they are more problematic to eliminate in control schemes than static friction. Then the closed-loop bandwidth of the devices is established, further supporting how well the exoskeletons match healthy human capabilities. Closed loop position bandwidth is a valuable bandwidth measurement which differs from some previously presented bandwidth measurements [8, 26, 27], since it reflects the capabilities of the hardware as implemented, instead of a theoretical bandwidth. The performance characterization concludes with determining the devices’ spatial resolution, which should be optimized in order to provide accurate subject assessment. A discussion of the results and future work for the exoskeletons follows, along with the conclusions.

2.2 Device Details

The ergonomic considerations of the exoskeleton design, as well as the second points of contact on the user, are very similar between the two devices. Both assume that the three DOF of the wrist are intersecting, and have a fourth DOF (actuated for the RiceWrist, passive for the RiceWrist-S) to resolve over-constraint. In general, both exoskeletons rely on blocking the forearm and using a handle, either through voluntary user grasp or by wrapping the user to the handle if they do not possess the grip strength to make firm grasp, to create two points of contact. With these two points of contact, the ergonomic considerations put forward in the literature [36] are met because the handle is padded and the forearm is a desirable point of contact for normal forces [76], and a mapping between human joint torques and robot joint torques can be assumed.
2.2.1 RiceWrist

The RiceWrist is comprised of one forearm and two wrist DOF. The forearm DOF consists of a revolute joint actuated by a DC motor and cable drive transmission. Key design components are summarized in Table 2.1. The coordinate frames assigned to the DOF of the system are shown in Fig. 2.1. Frame \{1\} is fixed to the forearm joint, frames \{2\} and \{3\} are fixed to the base plate and the wrist ring, respectively.

The grounded part of the structure consists of a base plate to which three extensible links \( (l_1, l_2, \text{ and } l_3) \) are attached by pin joints \( (R_1, R_2, \text{ and } R_3) \). These links connect the base plate to a moving platform, to which the end effector (a handle) is attached, by ball joints \( (B_1, B_2, \text{ and } B_3) \) situated 120° apart. The wrist module is a parallel mechanism actuated by three DC motors located near the pin joints that extend and retract rigid links via cable drives for minimal backlash and friction with a transmission ratio of 1 rotation to 3.6 centimeters of extension/retraction. As the link lengths change, the position and orientation of the wrist ring and end effector change accordingly [70, 72]. A parallel structure was chosen for the wrist module due to the inherent high rigidity and strength-to-weight ratio of parallel devices, which enables a more compact, lightweight design. The basic kinematic structure is a 3-revolute-prismatic-spherical (RPS) mechanism, discussed extensively in the literature [1]. The RPS mechanism has another DOF, the platform height \( z_4 \), which, with a slotted attachment for the handle, increases the range of compatible forearm lengths.

\(^{†}\)Please note that this is the sensor resolution in terms of link extension, for a complete discussion of spatial resolution, see Section 2.3.5.
Table 2.1: Sensor and Actuator Specifications of the RiceWrist

<table>
<thead>
<tr>
<th>Joint</th>
<th>Actuator</th>
<th>Transmission</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forearm P/S</td>
<td>Maxon RE-40 (148877)</td>
<td>Cable-Drive (14.7:1)</td>
</tr>
<tr>
<td>Wrist Parallel</td>
<td>Maxon RE-35 (273761)</td>
<td>Cable-Drive (1 [rot]: 3.6 [cm])</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Joint</th>
<th>Sensor</th>
<th>Sensor Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forearm P/S</td>
<td>Avago HEDS 5540</td>
<td>0.003°</td>
</tr>
<tr>
<td>Wrist Parallel</td>
<td>Avago HEDS 5540</td>
<td>1.6 mm†</td>
</tr>
</tbody>
</table>

Table 2.2: Link Parameters for the RiceWrist-S

<table>
<thead>
<tr>
<th>Joint</th>
<th>rot(x)</th>
<th>tr(x)</th>
<th>rot(z)</th>
<th>tr(z)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forearm P/S</td>
<td>$-\frac{\pi}{2}$</td>
<td>0</td>
<td>$\theta_{PS}$</td>
<td>0</td>
</tr>
<tr>
<td>Wrist F/E</td>
<td>$\frac{\pi}{2}$</td>
<td>0</td>
<td>$\theta_{FE}$</td>
<td>0</td>
</tr>
<tr>
<td>Wrist R/U</td>
<td>0</td>
<td>0</td>
<td>$\theta_{RU}$</td>
<td>0</td>
</tr>
</tbody>
</table>

2.2.2 RiceWrist-S

The RiceWrist-S utilizes a straightforward serial design, and is actuated by DC motors and capstan cable transmissions for the wrist flexion/extension and radial/ulnar DOF, and a direct-drive frameless, brushless motor for the forearm pronation supination DOF, providing low friction and backlash-free operation. Denavit Hartenburg parameters are listed in Table 2.2, and key design components are listed in Table 2.3. Of particular note is that each of the capstan cable transmissions and cable routings are designed to minimize gravitational and inertial effects reflected to the handle.
### Table 2.3: Sensor and Actuator Specifications of the RiceWrist-S

<table>
<thead>
<tr>
<th>Joint</th>
<th>Actuator</th>
<th>Transmission</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forearm P/S</td>
<td>Applimotion 165-A-18</td>
<td>Direct-Drive</td>
</tr>
<tr>
<td>Wrist F/E</td>
<td>Maxon RE-40 (148877)</td>
<td>Cable-Drive (18:1)</td>
</tr>
<tr>
<td>Wrist R/U Dev.</td>
<td>Maxon RE-30 (310009)</td>
<td>Cable-Drive (24:1)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Joint</th>
<th>Sensor</th>
<th>Sensor Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forearm P/S</td>
<td>MicroE Mercury 1500</td>
<td>0.002°</td>
</tr>
<tr>
<td>Wrist F/E</td>
<td>Avago HEDS 5540</td>
<td>0.01°</td>
</tr>
<tr>
<td>Wrist R/U</td>
<td>Avago HEDS 5540</td>
<td>0.0075°</td>
</tr>
</tbody>
</table>

### 2.3 Characterization of Performance

To evaluate the exoskeletons’ suitability for rehabilitation implementation, I present the experimentally determined performance characteristics of the RiceWrist and RiceWrist-S, including their ROM, torque outputs, static friction, inertia, viscous friction, spatial resolution, and closed-loop position bandwidth. The results are summarized in Tables 2.4 and 2.5. For each test, gravitational effects were reduced or eliminated by orienting the exoskeleton so that the axis of rotation of the DOF of interest was aligned with the direction of gravity. All tests on the parallel mechanism RiceWrist were performed at a platform height (distance between base plate and wrist ring) of 9 cm, typical for the average user.

#### 2.3.1 ROM and Torque Output

Ascertaining the range of motion for both the RiceWrist and RiceWrist-S involves using the forward kinematics of the devices, which have been previously discussed.
in detail [72, 74]. Determining the maximum torque outputs for the RiceWrist-S, a serial manipulator, involves straightforward applications of maximum motor outputs and transmission ratios, and is not workspace dependent. However, determining the torque outputs of the RiceWrist required the development of the device Jacobian. The device Jacobian developed in the following section is grounded in geometric constraints of the platform, as shown in Fig. 2.1, repeated from Section 1.3.1 for convenience.

As defined in the literature, [1], the Jacobian of a parallel manipulator such as the RiceWrist possesses a homogenous transformation from the base plate to the end effector plate of the form:

\[
3_4T = \begin{bmatrix}
    n_1 & o_1 & a_1 & x_c \\
    n_2 & o_2 & a_2 & y_c \\
    n_3 & o_3 & a_3 & z_c \\
    0 & 0 & 0 & 1
\end{bmatrix},
\]  

(2.1)

The components of this transformation matrix are given by XYZ Euler angles and can be defined as the following:

\[n_1 = \cos \beta \cos \gamma, \quad n_2 = \cos \alpha \sin \gamma + \cos \gamma \sin \alpha \sin \beta, \quad n_3 = \sin \alpha \sin \gamma - \cos \alpha \cos \gamma \sin \beta\]

\[o_1 = -\cos \alpha \sin \gamma, \quad o_2 = \cos \alpha \cos \gamma - \sin \alpha \sin \beta \sin \gamma, \quad o_3 = \cos \gamma \sin \alpha + \cos \alpha \sin \beta \sin \gamma\]

\[a_1 = -\sin \beta, \quad a_2 = -\cos \beta \sin \alpha, \quad a_3 = \cos \alpha \cos \beta\]

\[X_c = \rho(n_1 - o_2)/2, \quad Y_c = -\rho n_2, \quad Z_c = z,\]

where \(\rho = \frac{r}{R}\) a ratio of the radii of the end effector and base plate, \(X_c = \frac{x_c}{R}, Y_c = \frac{y_c}{R}, Z_c = \frac{z_c}{R}\), resulting in the normalized lengths \(L_i = \frac{l_i}{R}\).

By using the above transformation in equation 2.1, the following link lengths of the parallel mechanism can be determined by subtracting the location of the pin joints
Figure 2.1: Kinematic structure of the RiceWrist, repeated for convenience. The 3-RPS wrist structure was adopted from Lee and Shah [1]. This figure was adapted from Pehlivan [2].

(attached to the base plate) from the pin joints (attached to the end effector plate), shown best in Fig. 2.1.

\[
L_i = ^3T \begin{bmatrix} ^4P_{bi} \\ 0 \end{bmatrix} - \begin{bmatrix} ^3P_{pi} \\ 0 \end{bmatrix}.
\] (2.2)

Solving for the magnitude of each \( L_i \) yields

\[
L_1^2 = (n_1\rho + X_c - 1)^2 + (n_2\rho + Y_c)^2 + (n_3\rho + Z_c)^2
\] (2.3)

\[
L_2^2 = \frac{1}{4} \left( (-n_1\rho + \sqrt{3}o_1\rho + 2X_c + 1)^2 + (-n_2\rho + \sqrt{3}o_2\rho + 2Y_c - \sqrt{3})^2 + (-n_3\rho + \sqrt{3}o_3\rho + 2Z_c)^2 \right)
\] (2.4)

\[
L_3^2 = \frac{1}{4} \left( (-n_1\rho - \sqrt{3}o_1\rho + 2X_c + 1)^2 + (-n_2\rho - \sqrt{3}o_2\rho + 2Y_c + \sqrt{3})^2 + (-n_3\rho - \sqrt{3}o_3\rho + 2Z_c)^2 \right)
\] (2.5)
While the RiceWrist has only three DOF ($\alpha$, wrist flexion/extension, $\beta$, wrist radial/ulnar deviation, and $Z$ (platform height)), there exists another angle, $\gamma$, that is a mathematical necessity. This angle $\gamma$ completes the XYZ euler angles and is required in order to prevent the system of forward kinematic equations from becoming over-constrained. However, through simulation, it has been shown that $\gamma$ has the form

$$\gamma = 2 \sin \alpha \sin \beta,$$

leading to two important conclusions. Firstly, during the 1 DOF movements trained during rehabilitation, and simulated in the following text, $\gamma = 0$, aligning this formulation with the literature on the RiceWrist [69, 70, 72]. Secondly, during movements where $\beta \neq 0$, there is some non-zero $\gamma$ that results from the mechanism’s design. The presence of this $\gamma$ will be crucial for multi-DOF movements, however, these movements fall outside the scope of this thesis.

Next, by taking into consideration that the $\dot{y}$ components of $L_1, L_2, L_3$ are governed by the relations $y = 0$, $y = -\sqrt{3}x$, $y = \sqrt{3}x$, respectively, the following equations can be generated:

From $L_1$ and $y = 0$:

$$n_2 \rho + Y_c = 0; \quad (2.7)$$

From $L_2$ and $y = -\sqrt{3}x$:

$$n_2 \rho + \sqrt{3}0_2 \rho + 2Y_c = -\sqrt{3}[-n_1 \rho + \sqrt{3}0_1 \rho + 2X_c]; \quad (2.8)$$

From $L_3$ and $y = \sqrt{3}x$:

$$n_2 \rho - \sqrt{3}0_2 \rho + 2Y_c = \sqrt{3}[-n_1 \rho - \sqrt{3}0_1 \rho + 2X_c], \quad (2.9)$$

which generate the following relationships for $X_c, Y_c$

$$X_c = \frac{\rho}{2} (n_1 - o_2) \quad (2.10)$$
\[
Y_c = -n_2 \rho. 
\] (2.11)

The literature presents a thorough discussion of these manipulations [1].

In order to develop the Jacobian, it is common practice to take the partial of Cartesian velocities and angular velocities with respect to joint space variables. However, the most direct formulation for the equations at hand will be to develop the inverse Jacobian matrix by taking the partial derivatives of the link lengths \([l_1, l_2, l_3]^T\) with respect to \([\alpha, \beta, Z_c]^T\).

\[
\begin{bmatrix}
\alpha \\
\beta \\
Z_c
\end{bmatrix} = J^{-1} \begin{bmatrix} l_1 \\
l_2 \\
l_3
\end{bmatrix} \quad \text{(2.12)}
\]

\[
J^{-1} = \begin{bmatrix}
\frac{\partial l_1}{\partial \alpha} & \frac{\partial l_1}{\partial \beta} & \frac{\partial l_1}{\partial Z_c} \\
\frac{\partial l_2}{\partial \alpha} & \frac{\partial l_2}{\partial \beta} & \frac{\partial l_2}{\partial Z_c} \\
\frac{\partial l_3}{\partial \alpha} & \frac{\partial l_3}{\partial \beta} & \frac{\partial l_3}{\partial Z_c}
\end{bmatrix}. \quad \text{(2.13)}
\]

For the RiceWrist detailed in [3], the torque output for single DOF movements is shown in Fig. 2.2a and 2.2b. The magnitudes and shapes of both Fig 2.2a and 2.2b were validated through intuitive experiments using spring scales to determine the maximum torque outputs of the device. This combination of analytical derivation and simple experimental checks supports the derivation of this section.

This mapping of the torque outputs of the RiceWrist shows that it has sufficient torque abilities to train ADL, as evidenced in Table 2.4, but that the RiceWrist-S possesses higher, constant torques across the workspace, which is more favorable for a wide range of rehabilitation regimens. This is especially noticeable in regimens focused on resisting, rather than assisting patient movement.
Figure 2.2: The maximum torque output in flexion/extension movements is at the center of the device workspace, as a function of the device geometry. However, the radial/ulnar movements are largely generated by the top actuator, which is geometrically perpendicular at the bottom of the workspace, creating an asymmetrical torque profile.

Table 2.4: Device characteristics for RiceWrist, RiceWrist-S [5], and wrist module of the MIT-MANUS [6].

<table>
<thead>
<tr>
<th>Joint</th>
<th>Max Static Friction [Nm]</th>
<th>Inertia [kg·m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RW</td>
<td>RW-S</td>
</tr>
<tr>
<td>F P/S</td>
<td>0.139 (5.1%)</td>
<td>0.221 (13.1%)</td>
</tr>
<tr>
<td>W F/E</td>
<td>0.109 (7.5%)</td>
<td>0.152 (4.5%)</td>
</tr>
<tr>
<td>W R/U</td>
<td>0.112 (7.7%)</td>
<td>0.211 (10.0%)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Joint</th>
<th>Viscous Friction [Nm·s/rad]</th>
<th>CL Pos.</th>
<th>BW [Hz]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RW</td>
<td>RW-S</td>
<td>RW</td>
</tr>
<tr>
<td>F. P/S</td>
<td>0.0167</td>
<td>0.428</td>
<td>4.2</td>
</tr>
<tr>
<td>W. F/E</td>
<td>0.0283</td>
<td>0.085</td>
<td>13.3</td>
</tr>
<tr>
<td>W. R/U</td>
<td>0.0225</td>
<td>0.135</td>
<td>10.6</td>
</tr>
</tbody>
</table>
Table 2.5: Normal values for ROM (NORM) [7], ROM and torque of ADL [8], RiceWrist, RiceWrist-S [5], wrist module of the MIT-MANUS [6]. The values listed in parentheses for the RiceWrist are for the previously presented design [9]

<table>
<thead>
<tr>
<th>Joint</th>
<th>Range of Motion [deg]</th>
<th>Torque [Nm]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NORM</td>
<td>ADL</td>
</tr>
<tr>
<td>Forearm P/S</td>
<td>180</td>
<td>150</td>
</tr>
<tr>
<td>Wrist F/E</td>
<td>160</td>
<td>115</td>
</tr>
<tr>
<td>Wrist R/U</td>
<td>90</td>
<td>70</td>
</tr>
</tbody>
</table>
2.3.2 Static Friction

To investigate the static friction characteristics of the RiceWrist and RiceWrist-S, I implemented proportional control acting on a custom movement profile. This profile consisted of setting the desired joint position to continuously ramp up for a certain duration, pause at a constant desired position for the same duration, and then repeat, as shown in Fig. 2.3. For each DOF, the slope and duration of each ramp was held constant to slowly gather data across the workspace, and was optimized in order to create enough data points throughout the workspace for each DOF. Static friction was computed by logging the task-space torque at which the joint’s angular velocity became nonzero. For both exoskeletons, the minimum static friction values at the extremes of the workspace (when the joint reversed direction) were discarded to provide a more conservative (higher) estimate of average static friction. For the RiceWrist testing, the ramp and wait periods were altered in order to ensure that for the wrist flexion/extension and radial/ulnar DOFs, the linear sliders would come to a full stop before the next ramp period began, and to improve the number of times the robot’s velocity would reach zero during a movement. As seen in Figures 2.5a, 2.5b, 2.6a, and 2.6b there were considerably more logged data points than shown in Figures 2.4a and 2.4b. This was chosen to ensure that the most accurate representation of the friction of the wrist DOFs could be determined. Even with the more conservative estimates of static friction, the static friction as a percentage of continuous torque output remains small (no more than 7.7% for any DOF of the RiceWrist, and 13.1% for any DOF of the RiceWrist-S). Table 2.4 reports the maximum static friction for the each DOF of the RiceWrist-S and the forearm DOF of the RiceWrist, and the average static friction for the parallel DOFs of the RiceWrist (wrist flexion/extension and radial/ulnar deviation), along with the percentage of maximum continuous torque
it represents in parentheses. The static friction values for the wrist flexion/extension and radial/ulnar deviation DOFs of the RiceWrist were averaged due to the geometry of the parallel mechanism which allows gravity to perform virtual work even when the axis of rotation is aligned with (and therefore the direction of the movement is perpendicular to) the direction of gravity. Note that maximum torque for the parallel mechanism is a function of orientation, and that the torque maximums reported in Table 2.4 are the maximum possible output of the wrist mechanisms.

Figure 2.3: Commanded position trajectory used in static friction experiments on elbow flexion/extension of the RiceWrist, but representative of trajectories used for all DOFs. The ramped commanded position signal was chosen along with proportional control to step through the device’s workspace, and allow for a slow increase of the commanded torque up to the point of overcoming static friction.

Static friction was logged as a function of position for each DOF of each exoskeleton, as shown in Figures 2.4a, 2.4b, 2.5a, 2.5b, 2.6a, and 2.6b. Figure 2.4a shows that the forearm DOF of the RiceWrist possesses relatively constant static friction throughout the workspace, with some hysteresis and a ripple effect. The hysteresis
could be caused by a slight misalignment of the axis of rotation to the direction of gravity, or perhaps a characteristic of the bearing in this DOF, although it is my opinion that gravity is the cause of the hysteresis. The exoskeleton was leveled using the SmartTool Angle Sensor Module (M-D part number 92346) within 0.1°; however, this slight error could cause the hysteresis effect visible in Fig. 2.4a. The ripple in the stiction values is likely caused by a misalignment between the motor output shaft and the capstan arc, and could be avoided somewhat through machining with tighter tolerances. Since this change in static friction magnitude is on the order of 0.05 Nm, it is within acceptable variability ranges, and is constant enough to allow for feed-forward friction compensation.

![Diagram](image)

(a) RiceWrist Stiction Pronation/Supination  (b) RiceWrist-S Stiction Pronation/Supination

Figure 2.4: Torque commanded to the forearm joint of the RiceWrist and RiceWrist-S during static friction experiments to overcome static friction, as a function of the DOF workspace. The blue dots represent the moment that the joint overcame static friction. This figure shows that the forearm DOF of the RiceWrist possesses relatively constant static friction throughout the workspace, with some hysteresis potentially caused by misalignment between the axis of rotation and the direction of gravity, and a ripple effect likely caused by a misalignment between the motor output shaft and the capstan arc. The plot for the RiceWrist-S shows a much greater rippling, with small and large amplitude ripples, likely caused by deformations in the motor bearing.
Fig. 2.4b shows one particular area of the RiceWrist-S that could use attention, the brushless, direct drive motor used for forearm pronation/supination. The motor shows both ripples of small and large amplitude, likely caused by deformations in the motor bearing from mechanically locking of the DOF via clamps, or insufficient machining tolerances.

Fig. 2.5a shows some of the difficulties when performing some of the standard characterization experiments on parallel mechanisms. In particular, the “bowtie” shape is caused by the geometry of the parallel mechanism. Even though the axes of end effector rotation were aligned with the direction of gravity, gravity could still perform virtual work in the form of a torque in the direction of the axis of rotation of the sliders, most evident at the edges of the workspace. This torque was caused by limits imposed on the parallel mechanism by the limits of the spherical joints, pushing the end effector into the position of lowest potential energy.

Fig. 2.5b shows that the static friction characteristic of the wrist flexion/extension DOF of the RiceWrist-S may be directionally dependent, but it is more likely that this hysteresis is explained by the contribution of gravity. That being said, it would seem that an average value is more likely a reasonable estimate, but to be conservative, the maximum value was recorded. This DOF in particular is a good candidate for feedforward static friction compensation, if the assumption that the hysteresis was caused by gravity holds, and the static friction is relatively constant.

To a lesser extent than in the wrist flexion/extension static friction test of the RiceWrist, the wrist radial/ulnar static friction test also exhibited some of the same problems of removing the effects of gravity, plotted as a function of the workspace in Fig. 2.6a. For this reason, average values were taken instead of maximum values of experimentally determined static friction.
Figure 2.5: Torque commanded to create wrist flexion/extension movement of the RiceWrist and RiceWrist-S during static friction experiments to overcome static friction, as a function of the DOF workspace. The blue dots represent the moment that the joint overcame static friction. The RiceWrist’s ‘bowtie’ output was caused by the effect of gravity on the parallel mechanism, whereas the effect of gravity on the RiceWrist-S causes a more straightforward hysteresis.

Fig. 2.6b shows some of the same rippling effects noticed in other static friction tests, also caused by misalignments between the motor shaft and the capstan arc in the capstan cable transmission, which could be fixed through tighter machining tolerances, which could also reduce the prominence of the spikes where maximum static friction occurred.

2.3.3 Inertia and Viscous Friction

To investigate the viscous friction and inertia characteristics of each device, I analyzed the robots’ step responses. Again, I implemented proportional control for each DOF to generate a step response containing multiple oscillations without reaching the limits of the workspace. For analysis of the step response, I used a logarithmic decrement method that isolates the inertial and viscous effects by iteratively charac-
Figure 2.6: Torque commanded to the wrist radial/ulnar deviation joint of the RiceWrist and RiceWrist-S during static friction experiments to overcome static friction, as a function of the DOF workspace. The blue dots represent the moment that the joint overcame static friction. Both joints exhibit a more constant static friction than previous DOF, possibly as a result of this being the most distal DOF. Of note are some of the ‘sticking’ points in the RiceWrist-S plot, likely caused by mechanical deformation in the bearing.

Characterizing sequential peaks and troughs [4]. The step responses of each of the DOFs of the RiceWrist and RiceWrist-S are shown in Figures 2.7a, 2.7b, 2.8a, 2.8b, 2.9a, and 2.9b.

The forearm step plot of the RiceWrist, seen in Fig. 2.7a, also had some unique characteristics, largely predicted by the literature [4], concerning the effect of dry friction on a step response. The early, high amplitude oscillations were not as affected by dry friction as some of the later, lower amplitude oscillations, likely affecting the estimates for determining the viscous friction coefficient. While it is suggested to use the early oscillations to determine the viscous friction coefficient [4], it was difficult to achieve a large number of oscillations for DOF with higher inertias, so the average values were reported in order to standardize the process. Even with this averaging,
this estimate of a first order damping model ($b\dot{x}$) is likely fairly accurate, considering the relatively low speeds at which these oscillations took place.

![Figure 2.7](image-url)

(a) RW Step Response Pronation/Supination  (b) RW-S Step Response Pronation/Supination

Figure 2.7: Step response from $0^\circ$ to $30^\circ$ for forearm pronation/supination of the RiceWrist, originally appearing in [3], and the step response from $0^\circ$ to $45^\circ$ for forearm pronation/supination of the RiceWrist-S, used for the logarithmic decrement method [4].

Fig. 2.7b shows a similar response to that of Fig. 2.7a, but it would seem that the dry friction seems to have less of an effect than in the RiceWrist forearm pronation/supination DOF. This is likely caused by the larger inertia of the RiceWrist-S, and is likely not a function of decreased dry friction.

Unlike the high inertia of the forearm DOF, the inertia of the wrist DOFs of the RiceWrist are very low as a result of the parallel structure and materials choice, estimated from Figures 2.8a and 2.9a. This inertia could be reduced further by replacing the end effector with lightweight composites or plastics instead of the machined aluminum. This low inertia is especially important in wrist rehabilitation due to the very low torque capabilities of stroke and SCI subjects. It is for this same reason that the torque outputs supplied by the RiceWrist are sufficient for therapy.
Figures 2.8b and 2.9b show the higher inertia and viscous friction that results from the serial design of the RiceWrist-S. This is the trade-off that was made for the increase in torque output and workspace over the RiceWrist. Both plots exhibit the predicted effects of dry friction dominating the later, smaller amplitude oscillations, as well as the DOFs’ higher inertias making obtaining responses with high frequency oscillations difficult.

2.3.4 Closed-loop Position Bandwidth

To determine closed-loop position bandwidth, I commanded the robot to track a chirp signal trajectory of constant magnitude. The sine sweep began at a frequency 0.1 Hz that slowly increased until sufficient output attenuation was reached. The amplitude was set to 10° for all tests on the RiceWrist and RiceWrist-S, with the exception of the stiffness ($K_p$) and damping ($K_d$) gains used for this trajectory tracking were
the same gains that produced a critically damped step response. The frequency responses for the RiceWrist are shown in Fig 2.10a, and the frequency responses for the RiceWrist-S are shown in Fig 2.10b. The frequency responses were computed using the MATLAB command `tfestimate`, which determines a vector comprised of an estimate of the transfer function and corresponding frequencies determined from the supplied system input and output information. Specifically, the outputs defined as cross power spectral density of in the input and output divided by the power spectral density of the input [77]. This frequency domain characterization shows that the RiceWrist and the RiceWrist-S exhibit bandwidth in the forearm DOF within the range of human capability and that the wrist DOFs exceed human capability, in general established to be between 2 and 5 Hz [78]. Specifically, arm movements that demand the precise application of both high joint torques and high frequency movement, such as competitive curling, are typically less than 5 Hz for elite
players [79]. For the purpose of restoring specialized movements such as these, or the ability to independently perform ADL, all DOF are more than adequate.

The one concerning feature of Fig. 2.10b is the abrupt fall of the magnitude and phase of the RiceWrist-S forearm DOF after the resonance peak. It’s possible that this peak could be explained by higher order dynamics or the increase in input power, since the sine chirp does not have a flat power spectrum. However, movements of frequencies in this range are not currently used in any therapy regimens, which are often limited to slow movements of less than 1 Hz.

Figure 2.10 : Frequency response for each DOF of the RiceWrist, originally appearing in [3], and the RiceWrist-S. Bandwidth is considered the point at which the magnitude of the output decreases to -3 dB, originally appearing in [3]. The bandwidth values for the RiceWrist are 2.8 Hz, 4.2 Hz, 13.3 Hz, and 10.6 Hz, and 3.6 Hz, 6 Hz, and 8.3 Hz for the RiceWrist-S, for the elbow, forearm, wrist FE, and wrist RU DOF, respectively.

2.3.5 Spatial Resolution

The spatial resolution of the RiceWrist and RiceWrist-S were determined by evaluating the Jacobian at 10,000 points over the workspace, in a similar method to that
presented in [80]. However, since the rehabilitation focuses on single DOF movements, the entire workspace of the RiceWrist was not gridded, but rather the DOFs were isolated and their respective “worst case scenarios” were determined by sweeping through the motion iteratively. The minimum detectable change was determined to be $5.216 \times 10^{-5}$ radians for forearm pronation/supination, $1.313 \times 10^{-4}$ radians for wrist flexion/extension, and $1.219 \times 10^{-4}$ radians for wrist radial/ulnar deviation. This spatial resolution is on the same order as the RiceWrist-S [5], which was determined in the same manner to be always less than $2.1816 \times 10^{-4}$ radians. Since both of the exoskeletons possess favorable spatial resolution characteristics, combined with backlash-free capstan cable transmissions, they will allow for highly accurate subject assessment.

### 2.4 Discussion

Rehabilitation robots’ performance can be evaluated with several characteristics, such as static and viscous friction, inertia, and closed-loop position bandwidth. Specifically, the RiceWrist and the RiceWrist-S exhibit favorable static friction characteristics, both in magnitude and as a percentage of maximum continuous torque output, and the relatively constant magnitude of the static friction of each DOF enables effective compensation via feedforward techniques. Both the inertial and viscous friction characteristics of the device are suitable for administering high quality therapy however, future designs would benefit from the use of advanced composites in the distal elements of the exoskeleton. Since the RiceWrist-S is a serial robot, reducing the weight of the distal DOFs of the robot would have a large impact on every more proximal DOF. This reduction of device inertia would improve the frequency responses and bandwidth of every DOF, in particular the pronation/supination DOFs of the
RiceWrist and RiceWrist-S. Additionally, reducing the device inertia will increase the backdrivability of the devices. Closed-loop bandwidth tests showed that the devices have capabilities to match healthy human movement; however, future frequency domain analyses could benefit from the utilization of input signals with flat power spectrums, such as the Schroeder multisine [81], instead of a sine chirp, to reduce the effect of signal input power changes resulting for more accurate frequency responses. As shown in Tables 2.4 and 2.5, the RiceWrist and the RiceWrist-S have capabilities comparable to other state-of-the-art serial wrist exoskeletons [6]. In comparison to the RiceWrist-S, the parallel mechanism of the RiceWrist offers lower inertia, viscous coefficient, and static friction, but the design sacrifices torque output and workspace to achieve these desirable characteristics. However, both of these exoskeletons are sufficient for rehabilitation purposes. Additional future work identified by this characterization for the RiceWrist includes increasing the torque outputs of the parallel wrist structure by using a larger motor, namely a Maxon Re-40 could prove beneficial for creating even more rigorous training regimens. However, upsizing the motors will increase the reflected inertia in the forearm DOF, and to a lesser extent, the inertia felt in the elbow DOF. Further design iterations should trade weight reductions from the use of advanced composites to offset the increases from changing motors for the RiceWrist.

Future work for the RiceWrist-S includes replacing the direct drive motor used in the forearm pronation/supination joint with the motor and capstan cable transmission design from the RiceWrist, to improve both the torque and static friction characteristics of the DOF and to reduce cost. This would also likely increase the bandwidth of the forearm pronation/supination DOF, and possibly reduce the undesirable frequency response characteristics experienced around the closed-loop bandwidth.
Future work in developing characterization metrics will include standardizing methods used to remove the effect of gravity, particularly when geometry does not allow for simple changes in orientation to remove its effects. For example, some sort of paired rotation of the parallel mechanism during movements could help reduce the effects of gravity seen in Figures 2.5a and 2.6a. Also, this characterization does not include any quantification of power/weight ratios, cost, or any other traditional robotics metrics such as manipulability, which could be added to the standard list contained in this chapter. These further characterizations could provide the opportunity for comparison with a wider range of actuation types, including pneumatic, hydraulic, piezoelectric, etc.

2.5 Conclusion

The RiceWrist and RiceWrist-S have been validated as a high performance exoskeleton that meets the established requirements for rehabilitation. In particular, the RiceWrist and RiceWrist-S possess the workspace, torque outputs and bandwidth to match human capabilities, low inertia, static friction and viscous damping that will result in high backdrivability, and the hardware capabilities, discussed in further detail in Chapter 1, to complement the implementation of complex control.

While the characterization presented here provides both a valuable record for the literature as well as an insight into the performance of these devices during rehabilitation regimens, they do not directly address how these robots perturb healthy movement during rehabilitation regimens or assessment sessions.
Chapter 3

Characterization of a rehabilitation robot via kinematic analysis of redundant pointing tasks

3.1 Introduction

As established in Chapter 1, traditional characterizations do not directly validate exoskeletons as measurement devices. Specifically, these robotic measures do not test the fundamental assumption that the measurement process has minimal effects on the measurand. This fundamental assumption is particularly suspect during the measurement of the hand and wrist, which have anatomical, biomechanical, and functional couplings, discussed previously. For this reason, it is desirable to create new metrics and characterization methods specifically designed to solve this problem, and the motion-based characterization in this chapter proposes new techniques using motion capture analysis to characterize kinematically coupled multijoint movements.

3.1.1 READAPT Design

The hand portion of the READAPT was designed to minimize unnecessary forces on the finger by design and through control. The exoskeleton is equipped with five angular displacement sensors and two series-elastic-actuators (SEA) to control the

*Please note that portions of this thesis originally appeared in a paper submitted to the 2015 International Conference on Rehabilitation Robotics (ICORR) by Rose, Sergi, Yun, Madden, Deshpande and O’Malley in March 2015. However, this work was expanded to include new analysis and commentary.
flexion and extension torques at the metacarpophalangeal (MCP) and proximal interphalangeal (PIP) human finger joints. These features also allow for estimation of the MCP, PIP, and distal interphalangeal (DIP) joint angles during flexion and extension, and the MCP joint angle during abduction and adduction. The underlying four bar mechanisms that make up the exoskeleton minimize any actuator-induced finger joint reaction forces and prevent misalignment between the robot joints and the human joints. The hand exoskeleton is designed to be lightweight in order to minimize the inertia of the hand-robot system, preserve the dexterity of hand movements, and promote dynamic transparency of the device. Selective Laser Sintering (SLS), a type of additive manufacturing, of Nylon-12 plastic components and a remote actuation system that uses Bowden cables effectively reduced the weight of the device to a mere 75g. However, Bowden cables introduce a significant amount of friction, which prevents the exoskeleton from achieving passive backdrivability [82]. To ensure that a subject does not have to work against the device to perform finger movements, the exoskeleton utilizes active control methods to apply zero torque to the human joint. The applied force of the exoskeleton can be estimated by measuring the displacement of the SEA linear springs. Thus, the exoskeleton can achieve backdrivability if the displacement of the linear springs are controlled to be zero.

The wrist portion of the device is a RRR mechanism with forearm pronation/supination, wrist flexion/extension and wrist radial/ulnar deviation degrees of freedom (DOF). The wrist portion of this device is actuated by DC motors and capstan cable transmissions, providing low friction and backlash-free operation. A thorough characterization of the RiceWrist-S was previously presented [41], and information unchanged from this design is included in Table 2.5. For the READAPT, the radial/ulnar DOF supports and capstan cable transmission of the RiceWrist-S were
modified to allow for straightforward Bowden cable routing and interfacing with the UT Hand Exoskeleton, shown in blue in Fig. 3.1. The new interface with the hand module was moved to the ulnar side of the hand, so as not to interfere with any thumb DOF, visible under the hand exoskeleton in Fig. 1.3a. Also, the radial/ulnar deviation capstan cable transmission was relocated to the outside of the flexion/extension capstan arc, to allow for more finger ROM, as seen in the bottom of Fig. 1.3.

As a therapy tool, the new device meets the functional workspace criteria for rehabilitation devices, with pertinent torque and ROM listed in Table 3.1. See Chapter 2 for the detailed characterization of the RiceWrist-S, which was the basis for the wrist portion of the READAPT. Note that the 70° refers to 60° of flexion and 10° of extension and the 74° refers to 72° of flexion and 2° of extension for ADL and device ROM, respectively. Of particular note is that the maximum torque outputs of the devices exceed the requirements for ADL to overcome joint stiffnesses that arise from neurological injury.
Table 3.1: Normal Values for ROM (Norm) [7], ROM and torque required for ADL [8,10,11], and capabilities of the READAPT [5].

<table>
<thead>
<tr>
<th>Joint</th>
<th>ROM [deg]</th>
<th>Torque [Nm]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Norm</td>
<td>ADL</td>
</tr>
<tr>
<td>Forearm pro./sup.</td>
<td>180</td>
<td>150</td>
</tr>
<tr>
<td>Wrist flex./ext.</td>
<td>160</td>
<td>115</td>
</tr>
<tr>
<td>Wrist radial/ulnar dev.</td>
<td>90</td>
<td>70</td>
</tr>
<tr>
<td>Index Finger MCP flex./ext.</td>
<td>120</td>
<td>70</td>
</tr>
<tr>
<td>Joint</td>
<td>Actuator</td>
<td>Transmission</td>
</tr>
<tr>
<td>---------------------</td>
<td>---------------------------------------</td>
<td>--------------------------------------------------</td>
</tr>
<tr>
<td>Forearm P/S</td>
<td>Applimotion 165-A-18</td>
<td>Direct-Drive</td>
</tr>
<tr>
<td>Wrist F/E</td>
<td>Maxon RE-40 (148877)</td>
<td>Cable-Drive (18:1)</td>
</tr>
<tr>
<td>Wrist R/U Dev.</td>
<td>Maxon RE-30 (310009)</td>
<td>Cable-Drive (24:1)</td>
</tr>
<tr>
<td>Finger MCP</td>
<td>Maxon A-max 32 (236669)</td>
<td>Maxon Gearhead GP32A (166169) (111:1) + Bowden Cable</td>
</tr>
<tr>
<td>Finger PIP/DIP F/E</td>
<td>Maxon A-max 32 (236669)</td>
<td>Maxon Gearhead GP32A (166169) (111:1) + Bowden Cable</td>
</tr>
<tr>
<td>Thumb CMC F/E</td>
<td>Maxon A-max 32 (236669)</td>
<td>Maxon Gearhead GP32A (166169) (111:1) + Bowden Cable</td>
</tr>
<tr>
<td>Thumb MCP F/E</td>
<td>Maxon A-max 32 (236669)</td>
<td>Maxon Gearhead GP32A (166169) (111:1) + Bowden Cable</td>
</tr>
<tr>
<td>Thumb MCP Ab/Ad</td>
<td>Maxon A-max 32 (236669)</td>
<td>Maxon Gearhead GP32A (166169) (111:1) + Bowden Cable</td>
</tr>
<tr>
<td>Thumb DIP F/E</td>
<td>Maxon A-max 32 (236669)</td>
<td>Maxon Gearhead GP32A (166169) (111:1) + Bowden Cable</td>
</tr>
<tr>
<td>Joint</td>
<td>Sensor Resolution</td>
<td>Sensor</td>
</tr>
<tr>
<td>-----------------</td>
<td>-------------------</td>
<td>---------------------------------------------</td>
</tr>
<tr>
<td>Forearm P/S</td>
<td>0.002°</td>
<td>MicroE Mercury 1500</td>
</tr>
<tr>
<td>Wrist F/E</td>
<td>0.01°</td>
<td>Avago HEDS 5540</td>
</tr>
<tr>
<td>Wrist R/U</td>
<td>0.0075°</td>
<td>Avago HEDS 5540</td>
</tr>
<tr>
<td>Finger MCP</td>
<td>0.1°</td>
<td>Maxon MR (225787) + Magnetoresistive sensor KMA 210</td>
</tr>
<tr>
<td>Finger PIP/DIP</td>
<td>0.1°</td>
<td>Maxon MR (225787) + Magnetoresistive sensor KMA 210</td>
</tr>
<tr>
<td>Thumb CMC F/E</td>
<td>0.1°</td>
<td>Maxon MR (225787) + Magnetoresistive sensor KMA 210</td>
</tr>
<tr>
<td>Thumb MCP F/E</td>
<td>0.1°</td>
<td>Maxon MR (225787) + Magnetoresistive sensor KMA 210</td>
</tr>
<tr>
<td>Thumb MCP Ab/Ad</td>
<td>n/a</td>
<td>3382 G - 1 - 103 G potentiometer</td>
</tr>
<tr>
<td>Thumb DIP F/E</td>
<td>0.1°</td>
<td>Maxon MR (225787) + Magnetoresistive sensor KMA 210</td>
</tr>
</tbody>
</table>
3.2 Experimental Methods

We are interested in understanding the suitability of our device for rehabilitation, but also as an assessment device. To this end, we devised a redundant planar pointing task using the index finger metacarpalphalangeal (MCP) and wrist flexion/extension joints. The selected task activates all joints of interest, enabling the identification of kinematic couplings and the analysis of their variation based on specific experimental conditions. The task is redundant, since the task solution space is defined by a 1D manifold of wrist and MCP joint angles. A redundant task creates the opportunity to measure not only the path chosen to accomplish the task, but also the final solution chosen. Thematically similar movements, such as eye and head movements are famous experiments on human motor control [83]. Even though a redundant task has an infinite number of solutions, motions activating both joints can be categorized as either in-phase, where the MCP and wrist both flex or extend relative to an initial starting position, or out-of-phase, where the MCP and wrist joints rotate in opposite directions. In order to investigate different pose-dependent synergies, the pointing tasks are modeled after previous experiments [51] via obstacles to generate in-phase, and out-of-phase movements in addition to obstacle-free unconstrained tasks. Additionally, through this experiment we aim at developing generalizable characterization methods and metrics for motion-based device transparency assessments.

3.2.1 Subjects

Nine subjects, ages 21-30, eight female and one male, all right hand dominant and having no known neuromuscular deficit or hand injury, completed the study in compliance with the Rice Institutional Review Board.
3.2.2 Motion Capture

Six Optitrack Flex V100R2 (now Flex 3) 100 FPS cameras, 5 mm passive reflective markers, running in soft real time through Quarc and Simulink in Windows were used to measure the relative joint angles during the pointing tasks. Passive markers were placed on the distal phalange and the lateral elbow crease as line endpoints, and on the bony landmark for the MCP in a similar manner to related experiments [84, 85] and the top of the radial head [86] as joint axes, as seen in Fig. 3.2. As shown in Fig 3.2b, the radial head bony landmark was not readily visible for marker placement when wearing the device, so a secondary marker location above the radial head was selected, and was visually inspected to minimize travel during wrist flexion/extension. In order to prevent proximal interphalangeal (PIP) joint or distal interphalangeal (DIP) joint flexion/extension, subjects’ fingers were taped and splinted consistent with similar protocols [87]. The 3D positions of each marker were projected onto a plane perpendicular to the rotation axes.
The joint angles, $\theta_n$, $n = 1, 2$, were determined by first approximating the four markers, numbered from proximal to distal, as coplanar endpoints of three lines $L_i$, $i = 1, 2, 3$, then determining the relative angle between the lines:

$$\theta_n = \text{sign}((L_n \times L_{n+1}) \cdot \hat{j})\cos\left(\frac{L_n \cdot L_{n+1}}{\|L_n\| \|L_{n+1}\|}\right)$$

(3.1)

The axes were defined following the ISB recommendations [88]. The positive direction for each joint angle was defined to be counter-clockwise as viewed from above, so that for each joint, flexion was positive, and extension was negative, and would follow the right-handed rule convention for the world frame $y$ axis, shown in Fig. 3.2c and used in equation 3.1.

3.2.3 Experimental Protocol

The planar pointing tasks were conducted with three within-subject factors: condition (robot R or no-robot NR), category of movement (unconstrained, in-phase, or out-of-phase), and target location (requiring wrist flexion or extension). Subjects completed the tasks first when using the READAPT as a measurement device, and then repeated the protocol without the robot. The pointing task was represented in a virtual display seen in Fig. 3.3 which maps the horizontal plane of the table onto the screen, imitating the view of looking down at your hand as you point, shown in Fig. 3.2c.

The visualization consisted of two black lines, representing the hand and finger, and red circles representing joint axes, along with targets and obstacles. Subjects’ forearms were constrained to a planar surface by the exoskeleton or a splint. Before the start of each task, subjects first had to match a specified pose of $0 \pm 3^\circ$ wrist flexion, and $20 \pm 3^\circ$ MCP flexion, estimated to be a comfortable, near-neutral position, shown in Fig. 3.3a as a thick gray outline of the starting pose. As soon as this start
pose had been reached, subjects were shown a target (Fig. 3.3b), requiring either wrist flexion or extension, and one of three possible constraint conditions (unconstrained, in-phase, out-of-phase), shown in Fig. 3.4. Fig. 3.4 shows the visualization presented to the subject on top, mapped as shown in Fig. 3.2c. Below, is the solution manifold, and shown in red are joint angles that successfully reach the target and avoid the obstacle, plotted over the workspace, with the MCP and wrist flexion/extension ROM.
as the horizontal, and vertical axes, respectively. The pose required to complete the
task is shown in the bottom of each subfigure. For each pointing task, subjects were
instructed to point quickly at each target as they appeared, and one second after
reaching the target (Fig. 3.3c), the visualization would disappear, and subjects were
instructed to return to a relaxed pose pointing along the $z$ axis in the world frame,
for marker identification. Unconstrained targets had no obstacles (Fig. 3.4a, 3.4b),
whereas in-phase (Fig. 3.4c, 3.4d) and out-of-phase (Fig. 3.4e, 3.4f) targets had ob-
stacles requiring poses within a reduced solution manifold. Subjects performed a
set of ten practice tasks, then fifty randomized tasks for each constraint condition
(unconstrained, in-phase, out-of-phase).

### 3.3 Results and Analysis

A set of measures were defined to assess whether the interaction with the robotic
device would change the hand-wrist coordination patterns observed during the re-
dundant pointing tasks. Initial analysis has focused on the inter-peak time delay
between wrist and finger joint velocity maxima, and the maximum straight line de-
viation of trajectories in a joint angle phase portrait. Both of these metrics examine
coordination across the MCP and wrist flexion/extension joints, in that a coordinated
movement is expected to consist of simultaneous multi-DOF movements with similar
peak velocity times. Dis-coordination caused by the exoskeleton is hypothesized to
distort synergistic multi-DOF trajectories into successions of single-DOF movements,
which will increase straight line deviation in the joint angle phase portrait and the
time between peaks in the joint velocity profiles.
3.3.1 Data processing

Individual tasks were segmented by assigning the start of the movement to the minimum of the absolute value of the sum of the MCP and wrist joint velocities after the start position had been reached (Fig. 3.3a), and the end of the movement to be one second after reaching the target (Fig. 3.3c). This method provided a more consistent result than typical segmentation based on surpassing velocity thresholds due to the experimental design allowing subjects to ‘swing-through’ the initial position or target position. Filtering and differentiation was accomplished through the use of a third order Savitzky-Golay filter with a 21-sample (200 ms) window similar to related work [89]. These parameters correspond to a cutoff frequency of approximately 6.7 Hz, determined in equation 3.2 [90], where the polynomial order $N = 3$ and the half window length $M = 10$.

$$f_c = \frac{\omega_c}{\pi} = \frac{N + 1}{3.2M - 2}. \quad (3.2)$$

While this cutoff frequency is lower than some rapid, uncontrolled human movement, it is within the limits of some high force and high frequency movements used by professional athletes, which presumably will have much faster movements than the average lay person [79], the limitations imposed by the relatively slow sampling rate of the system (100 Hz) required more samples to generate a good fit, which led to the lower cutoff frequency.

For each combination of the three factors a) condition (robot, no-robot), b) category of movement (unconstrained, in-phase, out-of-phase), c) target location (flexion, extension), the inter-peak delay and straight line deviation metrics were averaged across subjects and analyzed through a factorial repeated measures ANOVA.
3.3.2 Inter-peak time

The first characteristic investigated is the time delay between the velocity peaks of the flexion-extension axes of the MCP and wrist, shown in Fig. 3.5 and defined as:

\[ \Delta T = t_{p,W} - t_{p,MCP}. \] (3.3)

As such, positive values of \( \Delta T \) imply that the peak in the MCP velocity profile anticipates that of the wrist. Fig. 3.6 shows the inter-peak times for all sub-

![Figure 3.5: Sample velocity trajectory after segmentation, in this case, a no-robot, unconstrained flexion target](image)

jects completing robot and no-robot trials, with each task grouped next to its corresponding robot/no-robot condition. Inter-peak time means were considered outliers if they fell outside of three interquartile ranges from the 25\(^{th}\) or 75\(^{th}\) percentile. The ANOVA showed an interaction between robot/no-robot and category of movement \((F(1.26, 10.05) = 5.4, p = 0.04, \eta^2_p = .40)\). This interaction was decomposed using simple main effects, summarized in Table 3.4, which shows an effect for unconstrained and in-phase movements, but not for out-of-phase movements.

Unconstrained and in-phase no-robot inter-peak times were tightly grouped around zero, suggesting that natural pointing tasks involve simultaneous finger and wrist
Figure 3.6: Inter-peak time delay between finger and wrist velocities shows significant difference in unconstrained and in-phase conditions between robot (left in red in each sub plot) and no-robot (right in blue) conditions. Points which were more than 1.5 times the difference between the 25\textsuperscript{th} and 75\textsuperscript{th} quartile above or below the 25\textsuperscript{th} and 75\textsuperscript{th} quartiles, respectively, were considered outliers and are not shown in this plot.

movement, as shown in the first four columns of Fig. 3.6. The robot condition perturbed this coupling by increasing the magnitude and variability of inter-peak time, which could be attributed to impedance, inertial, and friction mis-match across the robot DOF. The greater inertial and friction characteristics of the wrist module of the exoskeleton are hypothesized as the cause of this variance. However, this statistically significant difference was not found in the out-of-phase movements, which may be unfamiliar, and do not possess the same strong coordination as in-phase movements.

3.3.3 Straight line deviation

Analysis of the trajectories in the phase plane defined by joint angles enables the assessment of linearity of synergistic hand and wrist rotations. In order to aid in
Table 3.4: Effect of robot on inter-peak time

<table>
<thead>
<tr>
<th>SME</th>
<th>F(1,8)</th>
<th>p</th>
<th>$\eta^2_p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unconstrained</td>
<td>28.6</td>
<td>0.001</td>
<td>0.781</td>
</tr>
<tr>
<td>In-Phase</td>
<td>36.7</td>
<td>&lt;0.001</td>
<td>0.82</td>
</tr>
<tr>
<td>Out-of-phase</td>
<td>3.6</td>
<td>0.095</td>
<td>0.31</td>
</tr>
</tbody>
</table>

discussion and analyses of this metric, one subject’s trajectories are shown here, in Fig. 3.7 through Fig. 3.12. Note the differences in number of trajectories in these plots result from the random assignment during each session, as well as the omission of trajectories in which the subject did not reach the target. In general, these plots show a decrease in coordinated movement, represented by a greater curvature of the trajectory in the phase plane for the robot condition. This increase in curvature was characterized by the maximum deviation from a straight line path for each trajectory. Fig. 3.7 shows the segmented paths for the unconstrained flexion tasks. This figure is particularly interesting since the availability of multiple solutions in the redundant task resulted in a different preferential solution. The robot condition trajectories in Fig. 3.7b show not only a greater variance, contrastingly sharply with the tightly grouped, straight paths of Fig. 3.7a. This increase in variance is not captured in the deviation metric, but this is acceptable since the metric is also not fundamentally affected by variation from trial to trial. Also noteworthy is that the maximum straight line deviation metric is not solution dependent, and there were still significant differences between the curvature of robot and no robot tasks for this task.

Fig. 3.8 shows unconstrained extension trajectories in both R and NR conditions. This type of movement is ideal for analysis with the deviation metric, since the solutions are similar for robot and no robot conditions, and the variance is similar.
Figure 3.7: Comparison of robot (R) and no robot (NR) tasks, with the solution manifold in red, starting position represented by a green circle, individual paths in blue, and an average path in thick black.

The curvature in the robot trial was likely caused by the limitations of the exoskeleton. The finger moves much more at the start of the motion, seen as a more horizontal trajectory than in the no robot condition. However, once the finger ROM limits are reached, the wrist completes the movement. Removing discoordinations of this sort will be crucial for developing the READAPT into an effective measurement device.

While the previous unconstrained tasks clearly showed continuous, coordinated movements, the in-phase tasks seen in Fig. 3.9 have both isolated and coordinated movements. Fig. 3.9a has an initial section of isolated finger movement, which was reproduced in the robot trials. However, the coordinated movement which followed was not reproduced. Similarly, it is hypothesized that the ROM limits of the exoskeleton contribute to this discoordination.

Fig. 3.10 shows sample trajectories for in-phase extension tasks, which are quite similar to the unconstrained tasks shown in Fig. 3.8. This similarity is not seen
between the in-phase and unconstrained flexion tasks since the solution most often selected in the unconstrained flexion tasks was removed from the solution manifold. Since the trajectories are so similar between in-phase and unconstrained extension, it is hypothesized that the default flexion pointing movement possesses in-phase joint rotations, and it is therefore expected that any results for one condition will apply to the other.

Fig. 3.11 shows sample trajectories for out-of-phase flexion tasks. The relative difficulty of the out-of-phase flexion task caused a higher variability in the no robot conditions, and decreased the overall number of successful trials in the robot condition. Also of note is that large portions of the no robot out-of-phase flexion tasks exhibited coordinated movement, whereas the robot condition tasks were almost exclusively isolated joint movements.

Fig. 3.12 shows sample trajectories for out-of-phase extension tasks. Similar to
Figure 3.9: Comparison of robot (R) and no robot (NR) tasks, with the solution manifold in red, starting position represented by a green circle, individual paths in blue, and an average path in thick black.

The out-of-phase flexion tasks, the robot condition tasks exhibited isolated movements almost exclusively. It is also hypothesized that the increased difficulty of the out-of-phase tasks led to the increase in variability for the no robot trials, but it is interesting to note that this variability seemed to be reduced by the presence of the robot.

The first and final positions of the filtered and segmented position trajectories were used to create a straight line path, and straight line deviation is defined as the maximum distance between the measured profile and the calculated straight line path. Mean deviations for all subjects are shown in Fig. 3.13. The ANOVA showed an interaction between robot/no-robot and category of movement ($F(1.45, 11.6) = 17.35, p = 0.001, \eta^2_p = .68$). This interaction was decomposed using simple main effects, which showed an effect for unconstrained and in-phase movements, but not for out-of-phase movements, and the results are summarized in Table 3.6.
Figure 3.10: Comparison of robot (R) and no robot (NR) tasks, with the solution manifold in red, starting position represented by a green circle, individual paths in blue, and an average path in thick black.

Table 3.5: Mean and standard error (SE) of straight line deviation for robot (R) and no robot (NR) conditions

<table>
<thead>
<tr>
<th>Type</th>
<th>R Mean</th>
<th>R SE</th>
<th>NR mean</th>
<th>NR SE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unconstrained</td>
<td>6.037</td>
<td>.467</td>
<td>3.111</td>
<td>.322</td>
</tr>
<tr>
<td>In-Phase</td>
<td>7.24</td>
<td>.623</td>
<td>4.638</td>
<td>.274</td>
</tr>
<tr>
<td>Out-of-phase</td>
<td>17.9</td>
<td>1.951</td>
<td>19.184</td>
<td>2.009</td>
</tr>
</tbody>
</table>

3.4 Discussion

As expected, the robot has an effect on the kinematic coupling of the hand and wrist as measured by inter-peak time delay and maximum straight line deviation. The robot possesses non-negligible inertial, friction, and impedance characteristics that should alter movement. Second, there is a distinction on the types of movement, as neither metric showed a significant difference between robot and no robot conditions for out-of-phase movements. It is possible that this dependency on phase is the
Figure 3.11: Comparison of robot (R) and no robot (NR) tasks, with the solution manifold in red, starting position represented by a green circle, individual paths in blue, and an average path in thick black.

Table 3.6: Effect of robot on straight line deviation

<table>
<thead>
<tr>
<th>SME</th>
<th>F(1,8)</th>
<th>p</th>
<th>$r_p^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unconstrained</td>
<td>20.4</td>
<td>0.002</td>
<td>0.710</td>
</tr>
<tr>
<td>In-Phase</td>
<td>26.6</td>
<td>0.001</td>
<td>0.769</td>
</tr>
<tr>
<td>Out-of-phase</td>
<td>2.1</td>
<td>0.185</td>
<td>0.208</td>
</tr>
</tbody>
</table>

result of familiarity with in-phase movements, which are more commonplace than out-of-phase movements. Commonplace movements may have more refined internal models [91] which are disturbed by the robot, whereas the out-of-phase models are less developed and therefore less likely to be disturbed.

The difference in straight line deviation between robot and no-robot conditions can be explained by two observations. First, most subjects avoided or delayed moving the wrist during robot condition experiments as compared to the no-robot condition experiments. This delay was likely due to an increased inertia and static friction at
the wrist, which caused the discoordination. Second, MCP flexion/extension range of motion seemed to be limited for subjects by varying degrees, with an example shown in Fig. 3.12b. This variable decrease in ROM may have been caused by limitations of the particular interface components of the hand exoskeleton. Inclusion criteria for this study centered on finger length, but individuals with similar finger lengths do not necessarily have the same diameter fingers, and the sub-optimal fit of the interfacial parts for the exoskeleton prevented full range of motion. These plots show that although subjects were able to fit inside the exoskeleton, they are still sensitive to improper interfacing, further supporting the need for low-cost, rapid production of interface components.

During certain out-of-phase flexion no robot condition target tasks (Fig. 3.4e), another kinematic coupling was observed, circled in Fig. 3.14. It appears that the wrist drags the finger into flexion before the finger extends to complete the task. While
Figure 3.13: Maximum straight line deviation for all subjects shows difference in unconstrained and in-phase conditions between robot (left in red in each sub plot) and no-robot (right in blue in each sub plot) conditions. Points which were more than 1.5 times the difference between the 25\textsuperscript{th} and 75\textsuperscript{th} quartile above or below the 25\textsuperscript{th} and 75\textsuperscript{th} quartiles, respectively, were considered outliers and are not shown in this plot.

This behavior was exhibited too frequently to be readily attributed to user error, it did not appear consistently in all trials or in all subjects. The effects of training were also not apparent, as the presence of the coupling did not seem to change over time. It is hypothesized that the difficulty of the out-of-phase tasks could have contributed to its sporadic appearance, and further experiments aimed specifically at this new coupling are warranted.

These results indicate a need for further analysis of the device’s effects on pointing tasks, both with regard to a deeper analysis of results, and recommendations for modifications to our experimental protocol. In future analysis, we will explore inter-peak delay over tasks, as well as its variance as a function of impedance. It is
hypothesized that after training this delay could be compensated for by healthy subjects for a constant impedance, and that at lower levels of impedance, this variance will be reduced. Therefore, comparisons between impedances of varying levels across the different joints of the exoskeleton are planned. Future experiments validating rehabilitation robots as measurement tools will need to focus on comparisons between the measured outputs of a validated measurement tool and the robot for the same movement.

Regarding our experimental methods, subjects were allowed to complete a task as soon as they reached the requisite pose, causing difficulties in segmenting the movements, requiring the changed segmentation procedure which still resulted in some skewed start positions in Fig. 3.7. All future experiments should require that subjects reach and remain on the target for a prescribed amount of time, or have some velocity threshold that they must remain below before being allowed to proceed, to prevent the ‘swing-through’ completions of tasks. To increase measured joint angle accuracy, experiments should consider performing initial calibrations [92,93] to determine MCP and wrist flexion/extension axes. This calibration process will also avoid the difficulty
of locating joint axes with a passive marker, and prevent the visual inspection required in Section 3.2.2. Finally, having more interfacing components in a wider variety of sizes could prevent some of the ROM limitations suspected in Section 3.3.3 and allow widening of the inclusion criteria.
Chapter 4

Conclusions

Robotic devices have been implemented in post-neurological injury therapy, and have been used by many groups for a variety of applications. The RiceWrist and RiceWrist-S are two wrist devices which utilize different mechanism design approaches to meet the requirements of a rehabilitation exoskeleton. However, these devices are similar to current approaches in rehabilitation robot design in that the focus on isolated joint movements, and do not seek to train coordinated movements across anatomically, biomechanically, or functional DOF. The READAPT is a step towards an integrated hand and wrist exoskeleton to train coordinated wrist and hand movements to improve rehabilitation outcomes.

The RiceWrist and RiceWrist-S meet the robotic performance requirements for high performance rehabilitation exoskeletons. Specifically, the characterization presented in this thesis showed that the RiceWrist and RiceWrist-S exhibit favorable static friction characteristics since static friction for each DOF is only as a small percentage of maximum continuous torque output. Both the inertial and viscous friction characteristics of the devices are suitable for administering high quality therapy, however, future designs would benefit from the use of advanced composites in the distal elements of the exos to improve performance and most importantly, backdrivability. In addition to ROM and torque capabilities, closed-loop bandwidth tests showed that each device can match rapid, controlled movements. Future bandwidth tests could benefit from the utilization of input signals with flat power spectrums, in-
stead of a sine chirp, for more accurate frequency responses. As shown in Tables 2.4 and 2.5, the RiceWrist and the RiceWrist-S have capabilities comparable to other state-of-the-art serial wrist exoskeletons. The parallel RiceWrist offers lower inertia, viscous coefficient, and static friction, but has reduced torque output and workspace than the serial RiceWrist-S, which ultimately proved to be more important for implementation in the READAPT. The characterization presented here is the basis for a set of characterization metrics, which if standardized across many different devices, will benefit clinicians and designers alike by enabling in-kind comparisons between different designs.

Complex movements require more complex analyses, and measurement systems analyses need to be designed to validate devices for implementation in assessment. The assessment method presented in this thesis is a first step towards quantifying the relationship between device transparency and the kinematic coupling of the hand and wrist during synergistic movements. These results show that hand and wrist kinematic couplings are sensitive to inertial and friction disturbances and kinematic constraints. The motion based characterization of this pointing task is the beginning of the development of new measurement validation methods for robotic rehabilitation devices.
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