Abstract—Robotic exoskeletons for the hand have the potential to enhance physical rehabilitation and augment functional recovery following neurological injury. However, before such devices can be deployed to the home and clinic, robust experimental validation of performance capabilities is required. Currently, researchers rely on human subjects for these validations, but this method makes the separation of device and active wearer contributions difficult to determine. To address the need for a robust mechanical analog of the human hand in exoskeleton validation, we have produced a low-cost, open-source, instrumented hand. This design features variable stiffness joints with position sensing, anthropomorphic palm and finger phalanges with human-like joint couplings, thumb origin location, and kinematic structure. Importantly, the novel joint design enables human-like double exponential finger joint stiffness. It improves on the state of the art, which comprises linear joint stiffness profiles, non-anthropomorphic size and shape, and inaccurate thumb kinematics. In this paper, we detail the design of this device and validate its performance for use in the design and validation of wearable systems.

I. INTRODUCTION

The hand, with numerous degrees of freedom, muscles, and mechanoreceptors is highly intricate and essential to activities of daily living (ADLs) [1]. Hand impairment resulting from neurological injuries such as spinal cord injury and stroke, can impede ADLs [2]. Robotic devices have shown great potential for assisting impaired individuals in ADLs, and enhancing recovery after upper extremity impairment [3]. Recent advances in soft exoskeleton design have resulted in lighter, more adjustable wearables with higher power-to-weight ratios than traditional rigid designs [4].

A. Robot Characterization

A central challenge in the design and validation of hand exoskeletons is accurate and repeatable performance characterizations. Key metrics include range of motion (RoM), position accuracy, torque accuracy and closed loop bandwidth [5], [6]. To conduct these characterizations, soft exoskeletons rely on a wearer to provide structure and reaction forces, complicating necessary assessments of comfort, fit, as well as position and torque control accuracy [7].

Despite the need for accurate validation of such devices, insufficient effort has been applied towards developing robust testing and validation methods to verify their performance. Common methods currently employed for hand exoskeleton validation in assistance and rehabilitation include optical motion capture of human wearers (often healthy) [8], [9]. First, it is difficult for human subjects to provide purely passive joint responses, which is required in validating exoskeleton joint torque output. This can result in inconsistencies in subject joint torque response that reduce the accuracy and reliability of testing [10]; for example, repeated use with the device may influence performance, as was evident in inconsistencies found during the validation of the HandSOME device [11], during which subject inability to maintain passive joint response negatively affected the consistency of grip strength measurements. Further, motion capture is not only complicated and expensive but also difficult to rely on because the exoskeleton obscures the wearer. Motion capture is also not able to measure kinetic features of exoskeletons such as joint torque output.

B. Mannequins for Characterization

To address the shortcomings of both motion capture and using human wearers in exoskeleton validation, mechanical models have been proposed. However, previous works have
not yielded a consolidated mechanical hand model capable of serving as an accurate, robust and anthropomorphic platform for the validation of exoskeletons for the hand. Yun et al. [12] and Rose and O’Malley [13] used an instrumented finger to characterize aspects of their exoskeleton designs such as RoM or joint torque control accuracy. However, neither could validate grip strength and other relevant performance metrics.

Extending these works, Yousaf et al. developed a passive instrumented hand, which provided the capability of measuring joint position and joint torques through magneto-resistive rotational encoders and torsion springs embedded in each joint [14]. However, the joints provided linear stiffness profiles about a fully-extended (0° flexion) neutral position, whereas joints of the human hand exhibit double exponential torque response [14] and have a flexed neutral position [15]. Further, in close proximity with one another, the magneto-resistive rotational encoders experienced significant interference from the the magnets in other joints [10].

To establish double exponential stiffness in a mechanical joint of similar size and shape as the human finger joints, Kuo et al. developed a novel passive parallel compliance mechanism [16]. The lack of anthropomorphic dimensions, joint angle measurement, and the exposed joint couplings precludes its use as an exoskeleton validation testbed.

Seeking to overcome the aforementioned drawbacks, we have designed and fabricated a novel low-cost, open-source instrumented hand, shown in Fig. 1, which exhibits human-like passive double exponential joint torque profiles [14], accurate joint angle sensing [10] and anthropomorphic geometries of finger segments [15], [17], [18]. Our device overcomes many of the limitations presented in previous works to better serve developers of hand exoskeletons.

In this manuscript, we describe the design guidelines for instrumented hands in Section II. In Section III, we describe the design of the proposed hand, discussing our development of a variable stiffness joint that enables human-like passive finger joint torque response. In Section IV, we describe methods used to validate the torque response and joint angle measurement accuracy for the design as well as the results of these methods. In Section V, we discuss our results as well as the limitations of the design, and make recommendations for future development before concluding in Section VI.

II. MANNEQUIN DESIGN REQUIREMENTS

Since soft devices rely on the user’s hand provide reaction forces to properly apply joint torques, a mannequin must match the intended wearer as closely as possible for the characterization experiments to be useful. First, this requires that the mannequin be anthropometric in size and shape. Such a device should have phalax length, joint locations, joint orientations, joint kinematics and joint neutral positions representative of a robust sample of the user population for whom the device is designed [17]–[19]. Typically, this requires at least the thumb, index, and middle fingers, which are the most commonly used during ADLs and are supported by most exoskeleton devices [10]. We posit that biomechanically-sound joint stiffnesses are crucial for validating performance. These stiffnesses should be reasonably described by a double exponential model [14], and the parameters of this model should be tailored to represent the intended population. Lastly, a mannequin should accurately measure joint positions and joint torques, to establish important metrics such as RoM, position and torque control accuracy, grip strength, and closed loop bandwidth.

III. INSTRUMENTED HAND DESIGN

We have produced a novel mechanical hand to serve as an analog for human hands in the testing and validation of robotic exoskeletons. The model includes human-like finger joint stiffnesses, joint position sensing, and anthropometric design, meeting the design requirements proposed in Section II and exceeding the capabilities of the state of the art. Together, these contributions enable the proposed device to serve as a functional standard for designers of hand devices.

A. Anthropometric Design

The proposed hand, shown in Fig. 2 simulates the Distal Interphalangeal (DIP), Proximal Interphalangeal (PIP), and Metacarpophalangeal (MCP) joints of the index and middle fingers, as well as the Interphalangeal (IP) and MCP joints of the thumb as single axis rotational joints, which is a reasonable approximation [10], [16]. The simple, repeatable design of the single axis joints and finger segments can be expanded to a full hand including the ring and little fingers. These fingers were not essential in our design, as hand exoskeletons often focus only on the thumb, index and middle fingers. The Carpometacarpal (CMC) joint of the thumb is represented using a 2-axis joint, shown in Fig. 3. The CMC joint flexion/extension (FE) and abduction/adduction (AA) axes are approximated as orthogonal, but spaced from each other by 3.5 mm, to mimic natural joint axis orientations [18]. Previously reported data, compiled in Tables I and II, was used to define the dimensions of the phalanges [17], relative positions and orientations of
finger origins (MCP joints of index and middle fingers [18] and the AA axis origin of the thumb CMC joint), joint RoMs [19], and finger joint stiffness profile [16]. The data presented in I and II is reflected in our design.

### TABLE I
FINGER SEGMENT LENGTHS [17] OF THE MANNEQUIN

<table>
<thead>
<tr>
<th>FINGER SEGMENT</th>
<th>DP (mm)</th>
<th>MP (mm)</th>
<th>PP (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thumb</td>
<td>21.7</td>
<td>n/a</td>
<td>31.6</td>
</tr>
<tr>
<td>Index</td>
<td>15.8</td>
<td>22.4</td>
<td>39.8</td>
</tr>
<tr>
<td>Middle</td>
<td>17.4</td>
<td>26.3</td>
<td>44.6</td>
</tr>
</tbody>
</table>

### TABLE II
FINGER JOINT RANGES OF MOTION [19] OF THE MANNEQUIN

<table>
<thead>
<tr>
<th>FINGER JOINT</th>
<th>FE</th>
<th>FE</th>
<th>FE</th>
<th>AA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Index</td>
<td>90°</td>
<td>110°</td>
<td>90°</td>
<td>0°</td>
</tr>
<tr>
<td>Middle</td>
<td>90°</td>
<td>110°</td>
<td>0°</td>
<td>0°</td>
</tr>
<tr>
<td>Thumb</td>
<td>0°</td>
<td>90°</td>
<td>90°</td>
<td>6 0°</td>
</tr>
</tbody>
</table>

The design supports biomimetic RoM in flexion and extension (FE) for the index, middle and thumb finger joints as well as adduction and abduction (AA) in the thumb CMC joint. RoMs for the thumb, index, and middle finger, summarized in Table II, reflect measurements of healthy adult subjects [19] and are matched by our design. The AA pose of the index and middle fingers can be adjusted and constrained at the palm with rigid dowel pins (Fig. 2). The distal, middle, and proximal phalanx (DP, MP and PP) dimensions reflect those of healthy adults [17] with phalanx lengths being measured from the center of each joint. The phalanx dimensions can be adjusted and adapted to reflect other user populations, including adolescents [20].

Internal wire-based joint coupling pulleys containing SAPLIZE nylon thread (Fig. 4) are used to impose anthropomorphic joint coupling between the DIP and PIP joints. This coupling facilitates the motion coupling that many devices rely on, such as the Maestro [12] and SPAR Glove [13].

B. Joint Design for Biomechanically-Sound Stiffness

Our work builds upon principles including joint torque extrapolation via motion detection and single-axis joint motion modeling as a reasonable simplification of human finger joint motion [10], [13], [16]. Kuo et al.’s variable stiffness joint design [16] was adapted to support anthropomorphic design and embedded joint angle sensing (Fig. 5).

Each finger finger phalanx is composed of two halves which in turn are further segmented (Fig. 5a). This segmented interlocking design allows the axis of rotation for our variable stiffness joint to be shorter than in previous designs [16] and thus facilitates anthropomorphic joint size. By fully constraining the bearing and sensor, the design enables the physical stability of joint motion, while enabling parts to be quickly replaced when damaged without the need of full joint disassembly. The bisected phalanx segments are interlocked during assembly and then constrained using heat set threaded inserts and machine screws. This mechanism allows for compliant material to be anchored on either side of each joint and stretched during rotation by rigid pulleys (Fig. 5b). This arrangement, as indicated by Kuo et al., provides the single axis rotational joints in our design with a passive joint stiffness that exhibits a human-like double exponential torque resistance profile [14]. The geometry and material properties of the compliant inserts can be tuned to adjust joint pretension.

Durometer 60A rubber of approximately ‘medium’ hardness was used as illustrated in Fig. 5. The passive resting position of each joint is not horizontal at 0°, but is approximately 18° flexion, which is characteristic of the neutral pose of human finger joints [15].

C. Position and Torque Measurement

Bourns 3382G-1-103G rotary position sensors [21] are housed in cutouts placed within each joint as shown in Fig. 5b, and allow for accurate and effective measurement of joint torques. These sensors are lightweight and effective for our application, providing robust analog position sensing. Joint angle measurements can be measured, and considered in the
context of the known joint stiffness response profile (Eq. 1) to estimate the torque experienced by each joint and thereby validate exoskeleton capabilities. To achieve the desired accuracy, structural integrity and surface resolution of the 3D-printed hand, we recommend using either method shown in Fig. 1, namely, stereolithographic (SLA) (blue-gray colored material), or PLA 3D printing (black material).

![Diagram of exoskeleton joint design](image)

**IV. EXPERIMENTAL VALIDATION**

To demonstrate that the design provides the double exponential joint torque response characteristic of human finger joints, and is instrumented sufficiently so that validation experiments for hand exoskeletons can be carried out confidently using this design, two experimental validations of the design were conducted on the index DIP joint.

**A. Joint Position Measurement**

First, analog sensor data from the rotational encoder embedded in the joint was recorded with an Arduino Uno at 5° intervals from 0° to 90°. A mechanical goniometer was used to measure the true joint angle. This was done in order to establish the reliability of our joint angle sensor housing mechanism shown in Fig. 5b, which enables a more accurate finger joint size than previous designs [10], [16]. The results from this test are shown in Fig. 6. The maximum variation from the line of best fit was found to be no more than 5°.

![Graph showing joint angle variation](image)

**B. Torque Measurement and Joint Stiffness Validation**

Second, the stiffness of the index DIP joint was characterized using measurements of joint position while the joint was deected. The hand was secured in a horizontal configuration and the end of the distal phalanx was loaded with weights; the joint deflection was measured using a mechanical goniometer, as shown in Fig. 7. This was performed three times in both flexion and extension and for both loading and unloading paths to analyze hysteresis effects.

As predicted, the joint demonstrated double exponential joint torque response profile, as shown in Fig. 8. This stiffness is described by model put forth by Kuo. *et al.* [14].

\[ a \cdot e^{b \cdot \theta} + c \cdot e^{d \cdot \theta} = \tau(\theta) \]  

(1)

The parameters governing the model, a, b, c, and d are -12.2, -0.05677, 8.414, and 0.06161, respectively. Some hysteresis effects were observed, however, all values were within 1
Fig. 7: To establish the joint stiffness profile of the proposed finger joint, the phalanx was loaded at the location specified by the arrow pointing downward and weight was added and removed in 10 g increments to create the loading and unloading response. Joint position was measured via goniometer.

standard deviation, a stricter tolerance than the 95% confidence interval. The $R^2$ values for linear (0.8887, 0.9337), power (0.9599, 0.9712) and exponential (0.9794, 0.9820) regression of the flexion and extension data, respectively, were collected to ensure that the highest confidence was associated with the double exponential profile.

V. DISCUSSION

The proposed device meets the need for an instrumented passive hand as a testbed for validating wearable hand robots. With position sensing, human-like double exponential joint stiffnesses, and anthropometric sizing, the proposed device improves on the state of the art, and provides a valuable, open-sourced option for hand exoskeleton designers.

A. Joint and Torque Measurement Capabilities

The maximum variation from the line of best fit was found to be no more than 5°, a reasonable standard for joint angle measurement accuracy for instrumented hands [10]. The maximum errors in torque approximation that could be caused by this 5° sensor error would necessarily occur at extreme boundaries in the joint RoM and were found to be 36% at 90° flexion and 33% at 90° extension.

The joint torque response can be estimated by the double exponential model (Eq. 1), with parameters that provide a more realistic representation of human joint stiffness than many previously explored designs. Our variable stiffness joint, a modification of the joint designed by Kuo et al., is capable of receiving compliant inserts of varying stiffnesses and geometries, and of being modified further in the size, shape and location of the rigid components which interact with the compliant material [16]. Such modifications would allow the developer of the hand to adjust the stiffness profile of the joint. Our design also seeks to reproduce anthropomorphic finger phalanx geometries and finger orientations. In doing so, we have also established a more accurate representation of the thumb CMC joint than has been explored in previous designs [10], [16].

While a more robust validation would include analysis of all joints of the middle and thumb fingers and testing with a wearable device, our experimental validation indicated that the design meets the requirements previously specified. Our validation indicated some variability in stiffness, as shown in Fig. 8. This variation remained within the 95% confidence interval for the double exponential model that best described the data, and the average error between the double exponential model and average joint response was found to be 18% and 14% for loading and unloading in flexion and 20% and 21% for loading and unloading in extension, respectively. Improving the position measurement accuracy with better shielding and a broader voltage range than 0 to 5 V should improve performance.

B. Potential Design Improvements

The device does possess some frictional loss in interactions between the bearings and adapters as well as within the resistive rotational potentiometer, which may have contributed the inconsistencies in the joint torque response seen in Fig. 6. A smaller or less resistive position sensor is desirable. Magneto-resistive sensors have been explored in this application [10], but have significant interference effects between joints. Some of the broader simplifications in the joint mechanics of our design included single-axis joint motion, lack of tendon and ligament influences on joint stiffness, orthogonality of the CMC AA and FE axes, and lack of hemodynamic effects arising from the compression of hand exoskeleton mounting structures. These simplifications, while reasonable in validating and comparing the performance of exoskeleton designs in terms of RoM and joint torque accuracy [14], [22], [23], could impact the validation of precise, dexterous movements.

C. Future Work

In addition to improving the biomechanical fidelity of the instrumented hand, and conducting more robust validation experiments including a modified Kapandji finger opposition test [24], various disease states could be modeled by modifying the geometry and material properties of the compliant material.
in the joints and by altering tendon routing paths. Another limitation is the lack of MCP joint freedom in the AA. This could be improved by more accurate approximations of skin friction, along with additional sensing of joint reaction forces to investigate the effects of soft robots on joints and joint health. While the proposed hand is modeled after a healthy, adult hand, it will also be necessary to model increased tone and stiffness which can occur after neurological injury. However, such requirements may need multiple mannequins, each suited to a part of the device.

VI. CONCLUSION

Active wearable devices may provide significant long-term benefits to individuals with hand impairment and have yet to achieve wide-scale practical application in the clinical setting. Effective and robust validation of such devices is necessary to help designers translate these devices out of the lab and into the clinic and the world. To this end, we have developed a low-cost, open-source design can be used as a consistent, and reliable platform for hand exoskeleton validation. This design improves on the state of the art with its single-axis, instrumented variable stiffness joint, capable of accurate position and torque measurement as well as displaying human-like double exponential stiffness profile. Additionally, this design provides anthropomorphically-scaled phalanges, as well as more biomechanically-sound thumb origin and kinematics. The testbed could be expanded with joint stiffnesses to simulate various injuries or impairments, skin-like surface properties and joint reaction force sensing to provide designers with a higher-quality design tool. The design files can be found online at https://github.com/WeBRLab/InstrumentedHand.

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We thank Pei-hsin Ku and Saad Yousaf for their previous work and Job D. Ramirez for fabrication insights.

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[24] D. Leamy, J. Kocijan, K. Domijan, J. Dufn, R. Roche, S. Commins, and reliable platform for hand exoskeleton validation. This design improves on the state of the art with its single-axis, instrumented variable stiffness joint, capable of accurate position and torque measurement as well as displaying human-like double exponential stiffness profile. Additionally, this design provides anthropomorphically-sized phalanges, as well as more biomechanically-sound thumb origin and kinematics. This testbed could be expanded with joint stiffnesses to simulate various injuries or impairments, skin-like surface properties and joint reaction force sensing to provide designers with a higher-quality design tool. The design files can be found online at https://github.com/WeBRLab/InstrumentedHand.

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