Modelling and optimisation of a mechanism-based metamaterial for a wrist flexion-extension assistive device

Raghavendra Kulkarni, Suhas; Noronha, Bernardo; Campolo, Domenico; Accoto, Dino

2021

Raghavendra Kulkarni, S., Noronha, B., Campolo, D. & Accoto, D. (2021). Modelling and optimisation of a mechanism-based metamaterial for a wrist flexion-extension assistive device. 2021 IEEE International Conference on Robotics and Automation, 7020-7026.
<https://dx.doi.org/10.1109/ICRA48506.2021.9562099>

<https://hdl.handle.net/10356/153174>

<https://doi.org/10.1109/ICRA48506.2021.9562099>

© 2021 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, creating new collective works, for resale or redistribution to servers or lists, or reuse of any copyrighted component of this work in other works. The published version is available at:
<https://doi.org/10.1109/ICRA48506.2021.9562099>.

Downloaded on 26 Apr 2023 21:21:02 SGT

Modelling and optimisation of a mechanism-based metamaterial for a wrist flexion-extension assistive device*

Suhas Raghavendra Kulkarni¹, Bernardo Noronha¹, Domenico Campolo¹ and Dino Accoto¹

Abstract—In this paper we present a methodology for optimising the design of a metamaterial structure with one degree of freedom that is able to simultaneously bend and stretch. The structure is intended for assisting flexion-extension of the wrist joint. The metamaterial is comprised of serially connected, individually designed cells. The design parameters can be chosen to optimally fit a desired planar curve such as the curvature of the skin on a plane normal to the flexion/extension axis of the wrist joint. A tool for the optimised design is described and the experimental validation of the output is conducted, to show the ability of the mechanism to conform to a 2D curve, also exhibiting a change in length, which is desirable for reducing sliding and shear on the skin. The design tool allows the generation of metamaterials optimised for a multitude of other applications where actuated mechanisms must be worn by a user for rehabilitation or assistance purposes.

Index Terms—Wearable robotics, Metamaterials, Exoskeletons, Wrist, Assistance, Rehabilitation.

I. INTRODUCTION

Human hands are fundamental for physically interacting with the peripersonal space. However, these interactions, which may require adjusting the posture of the wrist, can be difficult for people suffering from certain neurological conditions like stroke [1]. It is therefore of utmost importance to recover upper-limb functionality in post-stroke rehabilitation [2]. Robots have been touted to assist therapists due to their ability to provide high-intensity, task-specific and repeatable treatments [3]. This has led to the development of several interesting mechanisms for wrist assistance and rehabilitation [4–6].

Traditionally, rigid robotic mechanisms have been preferred as they offer precise and efficient force transfer while also affording accurate positional control [7, 8]. The coupling between a rigid wearable system and the user might lead to a mismatch between the joints of the robot and the patient's limb, which could potentially cause discomfort to the wearer due to eccentric loads [9] or impediments to user's movement [10]. For this reason, the popularity of soft wearable robots is increasing. Soft wearable robots typically employ inflatable bladders [11] or cable-driven mechanisms [12] to transfer the forces and torques to the various joints. Pneumatically actuated soft mechanisms are comfortable to wear and provide smooth actuation. However they can be difficult to control

[13]. Also, portability may be compromised owing to the pneumatic power sources required by these mechanisms. On the other hand, tendon-driven mechanisms, which largely utilise Bowden cables for force transmission, are lightweight and portable, but the pose-dependant friction between the wire and its sheath may introduce inaccuracies in the force control [14].

Most previously developed wearable robots lie on either end of the spectrum, spanned by soft robots on one end and rigid robots on the other. Hybrid soft-rigid robots lie between these extremes, combining features characteristic of each of these robot types. These robots utilise the advantages of rigid structures—large load transfer and accurate position control—, while emulating soft robots in terms of the relatively large number of Degrees of Freedom (DOFs) in the mechanism compared to the actuated DOFs of the wearer's limb. This is associated with large adaptability, making this a promising approach. Hybrid mechanisms have been explored for finger support [15, 16]. However, to the authors' knowledge, there is no hybrid device so far purposely developed for wrist assistance.

During the actuation of a user's limb, which is always accompanied by skin stretch-compression, most existing wearable mechanisms exhibit a relative motion between the mechanism and the wearer's limb, which can cause: *i.* discomfort to the wearer; *ii.* a change in the point of application of interaction forces, which in turn could increase the misalignment with the human joints. Devices and mechanisms have been developed to address the misalignment issue either by use of passive compliant elements in the device [17] or through the use of separate compensating mechanism subsystems [18]. However, these additions increase overall device complexity and may lead to decreased portability of a wearable device. To address such wearability issue, we propose the use of metamaterials, i.e. structures that derive their properties from the geometric parameters of their individual cells [19]. Metamaterials can be designed to exhibit specific repeatable transformations. These structures have a large number of internal DOFs and as such they can approximate continuum structures while allowing accurate position control due to the constituent rigid cells.

In this paper, we describe a metamaterial structure (Fig. 1) for wrist flexion-extension support. The metamaterial adapts to the change in length of the skin during wrist motion. The mechanical design of the structure is inspired by the work of Ou *et al.* [20], who developed a 4-bar mechanism cell that is able to transform out of the plane. Our structure is able to adapt to the trajectory of the wrist during flexion-extension.

*This research was partially supported by the Singapore Agency for Science, Technology and Research (A*STAR) under the project "Intelligent Human-Robot interface for upper limb wearable robots" (Award Number SERC 1922500046) and by NTU SUG grant - "Building blocks for next generation soft robots"

¹The authors are with the Robotics Research Centre, School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore 639798. daccoto@ntu.edu.sg

Fig. 1. Overview of the mechanism-based metamaterial. The cells are sequentially mounted and are comprised of rigid links connecting revolute joints.

This is achieved by varying certain design parameters. We further extend on Ou *et al.*'s work by presenting a design tool, which provides the user a set of optimised design parameters for a structure that is able to conform to a given planar curve when transformed from an initial flat state. Parametric Computer Aided Design (CAD) modelling of each cell of the mechanism allows for rapidly creating physically realisable designs for the entire structure. Using these tools we describe a customised structure for wrist assistance in flexion-extension, which, to the best of our knowledge, is the first attempt for the intended application.

This paper is organised as follows. In Sections II-A and II-B, we describe the overall mechanism, modeling and its forward kinematics. The methodology for optimisation is explained in section II-C. In Section III, the results of the automatic design program and the prototype tests are elaborated on. Finally, in Section IV, the potential impact and applications of the mechanism and the automatic design tools are described.

II. MODELLING, OPTIMISATION AND TESTING

A. Mechanism Overview

The metamaterial structure shown in Fig. 1 is able to transform via 3D bending-stretching, bending-contraction and planar transformations of the constituent cells. In its initial configuration, the structure lies flat on the X-Y plane. The structure is symmetric about the plane of symmetry S , coincident with the X-Z plane. The behaviour of a structure with n cells is dependent on the design of each cell which can be one of two types: planar or bending. Each cell comprises 4 revolute joints. Let's consider a generic cell C_i ($i = 1 \dots n$). The axes of the two joints ($P_{B,i-1}$ and $P_{B,i}$) lying on the symmetry plane S are denoted by $\mathbf{W}_{i-1}$ and $\mathbf{W}_i$. In the initial configuration both axes are parallel to $\hat{\mathbf{k}} = (0, 0, 1)$.

Fig. 2. Schematic representation of the left half of a unit cell C_i . The axis ω_i at joint $P_{A,i}$ lies on Plane D_i , which is parallel to the plane Y-Z. Vectors $\lambda_{A,i}$ and $\lambda_{B,i}$ in blue have the same length l_i and they respectively connect $P_{A,i}$ with $P_{B,i-1}$ and $P_{B,i}$.

The other two joints lie on either side of the symmetry plane (S). In Fig. 2, only one of such joints is shown ($P_{A,i}$). Their axes lie on the plane D_i , which is parallel to the Y-Z plane in the initial flat state. The axis of the joint on the left side of S is denoted as ω_i and is defined as:

$$\omega_i = [\omega_{i,1} \ \omega_{i,2} \ \omega_{i,3}]^T = [0 \ \cos \beta_i \ \sin \beta_i]^T. \quad (1)$$

In this paper, the notation of the joint axis described in eq. 1 is derived from the conventions followed by Lynch and Park [21]. It should be noted that all axes $\mathbf{W}_i$ remain on S in the entire range of transformation. If $\omega_i = \hat{\mathbf{k}}$, then C_i is a planar cell. Conversely, if $\omega_i \neq \hat{\mathbf{k}}$, then C_i is a bending cell, whose rotation is determined by the angle β_i .

For the kinematic description of the metamaterial, we will use the vector $\lambda_{A,i}$ connecting $P_{B,i-1}$ and $P_{A,i}$ and the vector $\lambda_{B,i}$ connecting $P_{A,i}$ and $P_{B,i}$. To reduce the number of design variables, we set $|\lambda_{A,i}| = |\lambda_{B,i}| = l_i$. The description of the geometry of the cell C_i is finally determined by the angles $\alpha_{A,i}$ and $\alpha_{B,i}$, which, in the initial flat configuration, is formed by the vectors $\lambda_{A,i}$ and $\lambda_{B,i}$, respectively, with S . During the transformation of a structure containing bending cells, each plane D_i ($i = 1, \dots, n$) changes orientation with respect to the initial state, while remaining perpendicular to S and the respective plane spanned by $\lambda_{A,i}$ and $\lambda_{B,i-1}$. If however there are no bending cells in the structure, the planes D_i ($i = 1, \dots, n$) remain parallel to their initial orientation, throughout the transformation.

The number M of DOFs can be found using the Chebyshev-Grübler-Kutzbach criterion for a mechanism containing N rigid bodies connected by h joints having f_i DOFs at

joint h_i :

$$M = 3(N - 1 - h) + \sum_1^h f_i \quad (2)$$

In the proposed metamaterial, $N = 2n + 2$, $h = \frac{3N-4}{2}$ and $f_i = 1$ ($i = 1, \dots, h$). This provides $M = 1$, showing that the proposed structure has one single DOF.

B. Kinematic Modelling

The mechanism is modelled as a set of two serial kinematic chains, which are symmetric about plane S . Such symmetry can be exploited to simplify the modelling, which can be limited to one half of the structure, without any loss of information. The position of the joints in the cell C_i depends on the configuration of the cell C_{i-1} , as shown by the following recursive expression:

$$P_{A,i} \equiv [(P_{B,i-1})_x + l_i \cos(\alpha_{A,i}), l_i \sin(\alpha_{A,i}), 0] \quad (3)$$

$$P_{B,i} \equiv [(P_{A,i})_x + l_i \cos(\alpha_{B,i}), 0, 0] \quad (4)$$

where $(P)_x$ means the x -coordinate of P . $P_{B,0}$ is placed at the global origin (0,0,0) for ease of calculation.

The rotation matrix R_j by an angle θ_j about an axis ω_j is given by [21]:

$$R_j = e^{[\omega_j]\theta_j} = I_3 + \sin \theta_j [\omega_j] + (1 - \cos \theta_j) [\omega_j]^2, \quad (5)$$

where

$$[\omega_j] = \begin{pmatrix} 0 & -\cos(\omega_{j,3}) & \cos(\omega_{j,2}) \\ \cos(\omega_{j,3}) & 0 & -\cos(\omega_{j,1}) \\ -\cos(\omega_{j,2}) & \cos(\omega_{j,1}) & 0 \end{pmatrix} \quad (6)$$

The total transformation matrix T_j is:

$$T_j = \begin{pmatrix} R_j & \lambda_r \\ \mathbf{0}^T & 1 \end{pmatrix} \quad (7)$$

Where $R_j \in SO(3)$ and $\lambda_r \in \mathbb{R}^3$. The final position of the joints are given by:

$$P_{A,i}^f = T_{A,i} T_{B,i-1} T_{A,i-1} \dots T_{B,1} T_{A,1} \lambda_{A,i} \quad (8)$$

$$P_{B,i}^f = T_{B,i} T_{A,i} T_{B,i-1} \dots T_{B,1} T_{A,1} \lambda_{B,i} \quad (9)$$

Vectors $\lambda_{A,i}$ and $\lambda_{B,i}$ are column vectors as defined in section II-A, but a "1" has to be appended to match the matrix dimensions.

Considering that a ternary link connects $P_{B,i-1}$, $P_{A,i}$ and $P_{A,i-1}$, the two vectors $\lambda_{A,i}$ and $\lambda_{B,i}$ must move together. Therefore,

$$R_j = I_3 \quad \forall j = (A, i) \quad (i = 2, \dots, n) \quad (10)$$

The constraint introduced by eq. (10) propagates the motion of one link to the entire metamaterial. Furthermore, all $P_{B,i}$ remain on S throughout the transformation. This can be represented by setting the y-coordinate of $P_{B,i}$ equal to zero:

$$(P_{B,i}^f)_y = 0 \quad (11)$$

The solution to the forward kinematics problem for C_i is obtained by solving eq. (11) when the orientation of one

Fig. 3. Images of the user's arm with the markers placed for the consistent extraction of points. On the left, user's wrist in flexion and on the right, user's wrist in extension.

of the links is changed by an angle θ_{in} . This solution is then propagated to C_{i+1} using eq. (10) starting from C_1 sequentially until C_n .

A tool has been developed in Matlab® (MATHWORKS) for obtaining this solution when $\lambda_{A,1}$ is rotated by θ_{in} about axis $\mathbf{W}_0$. The tool uses the numerical solver `vpasolve`. The initial flat configuration of the structure is described by providing to the Matlab script all the values of $\{l_i, \omega_i, \alpha_{A,i}, \alpha_{B,i}\}$ for each cell C_i . The output is the set of points $P_{A,i}^f$ and $P_{B,i}^f$ for each C_i .

C. Optimised Design of Bending Mechanism

The curve that this structure can conform to is controlled by the geometric parameters of the cell $\{l_i, \omega_i\}$. In this section, the optimisation approach adopted to obtain $\{l_i, \omega_i\}$ for a structure to conform to a user defined 2D curve is detailed.

The set of points Q , used to describe a desired 2D curve is extracted from an image as shown in Fig. 3. For this, a Point Extraction Tool (PET) has been implemented using `digitize07` [22]. The `digitize07` tool overlays an X-Y grid over the imported image. The user selects $n + 1$ points on the image, corresponding to the markers, and enters two points (in red in Fig. 3) at a known distance relative to the camera and the plane containing Q as a reference for lengths. The PET scales pixel coordinates of the image using the reference points and the distance between the plane containing Q and the plane of the reference points such that the output is a set of points that lie on the global X-Z plane with the first point at the global origin. The selected points on the image are exported as the set of desired points $Q^{(1)}$ that the structure would conform to for an input rotation of $\theta_{in}^{(1)}$ of $\lambda_{A,1}$. This process is repeated with a second image to obtain the set of desired points $Q^{(2)}$ that the same structure would need to achieve for a different input rotation $\theta_{in}^{(2)}$ of $\lambda_{A,1}$. Parameters $\{l_i, \omega_i\}$ for each C_i of the structure are obtained through the optimisation process. The parameters $\{\alpha_{A,i}, \alpha_{B,i}\}$ and the values $\theta_{in}^{(1)}$ and $\theta_{in}^{(2)}$ are supplied as user inputs. The overall optimisation problem for each cell C_i has 2 objective functions. The primary objective function $O_i^{(1)}$ is defined as the Euclidean distance between $P_{B,i}^{f,1}$ corresponding to $\theta_{in}^{(1)}$, and the point $Q_i^{(1)}$ in the first desired

Fig. 4. The anthropometric data for a 50% percentile man used from [24].

Fig. 5. The test setup. 1 - User Hand Platform; 2 - Metamaterial Structure; 3 - Motor; 4 - Sliders attached to linear guides; 5 - Connecting links; 6 - Extension Springs; 7 - Linear guides; 8 - Cables to apply forces for wrist flexion.

curve:

$$O_i^{(1)} = \|P_{B,i}^{f,1} - Q_i^{(1)}\| \text{ at } \theta_{in}^{(1)} \quad (12)$$

where $P_{B,i}^{f,1}$ is obtained from (9). Similarly the secondary objective function $O_i^{(2)}$ is defined for an input $\theta_{in}^{(2)}$ as:

$$O_i^{(2)} = \|P_{B,i}^{f,2} - Q_i^{(2)}\| \text{ at } \theta_{in}^{(2)} \quad (13)$$

The optimisation problem is formulated as an ϵ -constraint minimisation problem [23], and formally defined as:

$$\begin{aligned} & \text{minimize} && O_i^{(1)} \\ & \{l_i, \omega_i\} \\ & \text{subject to} && O_i^{(2)} - \epsilon_i \leq 0, \\ & && P_{B,i}^{f,1}(y) = 0 \text{ at } \theta_{in}^{(1)}, \\ & && P_{B,i}^{f,2}(y) = 0 \text{ at } \theta_{in}^{(2)} \end{aligned} \quad (14)$$

To ensure convergence of the solution, the value for ϵ_i has been heuristically chosen as $0.2l_i$. The problem defined by eq. (14) is solved sequentially starting from C_1 until C_n . The set of obtained values from each solution of eq. (14) describes each cell in a structure that is able to transform from the initial flat configuration and conform to $Q^{(1)}$ for an input rotation of $\theta_{in}^{(1)}$ to $\lambda_{A,1}$ and also conform to $Q^{(2)}$ for an input rotation of $\theta_{in}^{(2)}$ to $\lambda_{A,1}$. The optimisation tool has been implemented using the built in MATLAB®(MATHWORKS) function for constrained minimisation `fmincon`, available from the Global Optimization Toolbox.

The outputs of the optimisation design tool are used to create a physical mechanism using the parametric modelling capabilities of SOLIDWORKS® (DASSAULT SYSTEMES).

D. Experimental Setup and Testing

The length of the mechanism has been chosen to be 100 mm based on corresponding anthropometric data [24] (Fig. 4). This length is chosen so that 2/3 of the distance

Fig. 6. Schematic representation of the test setup.

between the wrist joint and the grip line (refer to Fig. 4) is covered by one-half of the mechanism and the same length is used for the coverage on the forearm. Eight equally spaced markers spanning the intended length and location of the mechanism are placed on the user's skin (Fig. 3). Additionally, 2 markers are placed 20 mm apart on a plane in the background of the setup to use as dimension reference in the image. The reference points are placed equidistant from the camera. Furthermore, compensation for the offset between the plane containing the reference points and the plane containing the desired points $Q^{(1)}$ and $Q^{(2)}$ are built into the PET through initial calibration. Images of the user's wrist are captured in the flexed and extended states (Fig. 3) and processed using the PET.

For this experimental demonstration, the structure is designed to conform to $Q^{(1)}$ (wrist flexion) at $\theta_{in}^{(1)} = 15^\circ$ and conform to $Q^{(2)}$ (wrist extension) at $\theta_{in}^{(2)} = -15^\circ$. The designs obtained as a result of these inputs are then translated into a physical structure using the parametric modelling tool created using Solidworks®. The structure was fabricated using Stereolithography (material: Somos ®NeXt) and the parts were connected using metal dowel pins (Parallel Pin Type B, Steel EN 1.1191 Equivalent, diameter 1 mm, Himeno Precision, Toyama, Japan) to obtain a mechanism weighing 13 g.

The conformance of the structure to the wearer's wrist when it is actuated has been demonstrated in an experimental testing setting as shown in Fig. 5. The test setup is schematically detailed in Fig. 6. The mechanism is mounted on the the user's forearm and wrist using Velcro straps connected to the structure via two bolts at joints $P_{B,0}$ and $P_{B,7}$, and the forearm is resting on a raised platform fixed to the testing bench. The structure is actuated by two connecting links of length $L = 40$ mm connected through a revolute joint to a sliding mechanism. A cable is attached to the slider and connected to the motor (Maxon EC 60 flat, connected to Planetary Gearhead GP 52 C and Encoder MILE 4096 CPT) via pulleys. The sliders are connected to each other using extension springs which apply restoring force to actuate wrist

Fig. 7. Schematic representation of the structure's transformation from complete wrist flexion to complete wrist extension

extension through the structure. The structure is actuated by controlling the position of the motor, hence controlling θ_{in} . The setup is calibrated such that the motor position is zero when the structure is in its initial state, while the extension springs are loaded to 15% max extension. As the motor rotates and pulls the cables, the sliders move away by 2.4 mm from the initial state to fully actuate wrist flexion. As the tension in the cable is released, the extension springs apply a restoring force to bring the sliders closer together. A 4.8 mm travel of the sliders from the complete wrist flexion position will actuate complete wrist extension.

III. RESULTS

The designed mechanism is able to transform reversibly between the flexion and extension states (Fig. 7). Also, in the structure the movement of the joints at $P_{B,0}$ and $P_{B,7}$ is minimised with respect to the wearer's arm during the transformation. During wrist extension, there is no relative motion between the wearer's arm and the structure, but in wrist flexion a shift of 7.3 mm is recorded at joint $P_{B,7}$ with respect to the desired point $Q_7^{(2)}$ due to the allowed error ϵ_i . Alternately, if $O_i^{(2)}$ is treated as the primary objective function and $O_i^{(1)}$ is treated as the secondary objective function, although there is no relative motion between the wearer's arm and the structure in wrist extension state, the shift at joint $P_{B,7}$ is observed to be 16.2 mm in the wrist flexion state with respect to desired point $Q_7^{(1)}$. Additionally, it is observed from the results that the structure has a length of 121.8 mm in the wrist flexion state and 106.4 mm in the wrist extension state.

The output from the automatic design tool is obtained as shown in Table I. This is used to fabricate the physical structure. The images of the tests show the ability of the mechanism to transform from a flat state and follow the profile of the wearer's wrist in the flexion and extension states. The trajectory traversed by the point Q_7 in the wrist flexion-extension motion and the trajectory of joint $P_{B,7}$ in

TABLE I
PARAMETERS OBTAINED FROM OPTIMISED DESIGN TOOL FOR WRIST FLEXION/EXTENSION OF USER ($\alpha_A = \alpha_B = 45^\circ$)

Cell	$ \lambda_{A,i} = \lambda_{B,i} = l_i$	$\beta_i (^\circ)$
1	11.65	90
2	13.15	90
3	12.10	44.6
4	14.84	-54.3
5	12.10	44.6
6	12.54	90
7	12.01	90

Fig. 8. (A) User's wrist in flexion due to actuation from the mechanism; (B) user's wrist in extension.

the mechanism worn by the user (obtained using the PET on a series of images of the user's wrist) and the trajectory of joint $P_{B,7}$ obtained from the MATLAB@tool for forward kinematics are plotted as shown in the Fig. 9. One can see that the trajectory of the structure closely follows the corresponding point on the user's hand, while also closely following the result from the simulation. It can be seen from the table I and the Fig. 7 that the mechanism contains 2 planar cells each, at the beginning (C_1, C_2) and the end (C_6, C_7) while the bending cells are in the middle (C_3, C_4, C_5). The planar cells aid in the mounting of the mechanism on the arm, while the bending cells help to achieve the desired curve while compensating for the stretching-compression of the skin and minimise relative motion between the skin and the structure. The test also highlights relative motion between the wearer's arm and the structure due to the stiffness of the Velcro straps. However, this motion is seen to be much smaller than the change in length of the structure, still allowing it to compensate for the change in the wearer's skin length.

IV. DISCUSSION

In this paper we presented the modelling of a metamaterial structure, described as serially connected cells, each characterised by 4 parameters. This structure allows specific desired curvature to be achieved in a discretised fashion through the actuation of just one DOF (eq. (2)).

The applicability of this structure is enhanced by the optimisation design methodology implemented as an interactive tool. This tool helps us to easily design an entire structure to transform from a flat initial state to any desired planar curve. This eliminates the possibly complex and cumbersome process of a heuristic design approach. The parametric CAD

Fig. 9. A comparison of the trajectory of W_7 on the user's hand wearing a mechanism, trajectory of Q_7 on the user's hand without the mechanism as obtained from test images and trajectory of W_7 as obtained from MATLAB®.

model simplifies the translation of the structure from a kinematic model to a physically realisable design. Additionally, this tool also demonstrates that an entire mechanism can perform the bending transformation without the use of planar cells as seen in the middle section (C_3, C_4, C_5) of the described structure. The use of the ϵ -constraint method for the multi-objective optimisation is fuelled by the ability to obtain an exact Pareto optimal solution for this system due to the mono-objective approximation in the problem formulation [25]. However, the authors intend to explore Multi-Objective Evolutionary Algorithms (MOEA) and compare the quality of solution and the requested computation time.

The possibility of approximating desired poses, controlling not just the curvature but also the length of the mechanism, enables several applications, e.g. in the rehabilitation of other body segments, such as the hand [26] or the lower limbs, where wearability can be an issue [27].

The number of cells n in the described structure has been chosen as 7 through a heuristic approach. However, increasing the total number of cells in the mechanism could lead to better conformance of the structure with the user's limb. But increasing the total number of cells comes with the disadvantage of reducing the link lengths which would introduce difficulty in assembly.

In modelling this structure, it is considered that the links are precisely connected at the respective revolute joints. However, in reality, since the joints are defined by pins located in holes, the manufacturing inaccuracies (which also lead to overall dimensional inaccuracies) lead to movement of the pin within the hole, and thus, variations are observed from the predicted results in the final configuration. While the current method of assembly for the structure using pins affords us a good demonstrator, a possible alternative is the use of flexural joints as revolute joints. This approach would reduce the time between manufacturing by 3D printing and deploying the wearable system. The described test setup and structure are intended as a demonstration of the automatic design tool and a proof of concept for the wearable system, which the authors intend to develop for future applications. The wearable device is intended to be able to incorporate metamaterial structures that are custom designed for each individual and would be evaluated for conformance, along

with several parameters such as wearability, user comfort and overall device usability. Furthermore, device dynamics would be articulated along with the description of the actual wearable device. The authors would also be evaluating the forces applied on the user's limb through this structure.

REFERENCES

- [1] J. R. Wolpaw, N. Birbaumer, D. J. McFarland, G. Pfurtscheller, and T. M. Vaughan, "Brain-computer interfaces for communication and control," eng, *Clinical neurophysiology : official journal of the International Federation of Clinical Neurophysiology*, vol. 113, no. 6, pp. 767–791, Jun. 2002, ISSN: 1388-2457 (Print). DOI: 10.1016/s1388-2457(02)00057-3.
- [2] A. Pollock, S. E. Farmer, M. C. Brady, P. Langhorne, G. E. Mead, J. Mehrholz, and F. van Wijck, "Interventions for improving upper limb function after stroke," *Cochrane Database of Systematic Reviews*, vol. 2014, no. 11, Nov. 2014, ISSN: 1469493X. DOI: 10.1002/14651858.CD010820.pub2.
- [3] G. B. Prange, M. J. a. Jannink, C. G. M. Groothuis-Oudshoorn, H. J. Hermens, and M. J. Ijzerman, "Systematic review of the effect of robot-aided therapy on recovery of the hemiparetic arm after stroke," *Journal of rehabilitation research and development*, vol. 43, no. 2, pp. 171–184, 2006, ISSN: 0748-7711. DOI: 10.1682/JRRD.2005.04.0076.
- [4] H. I. Krebs, J. Celestino, D. Williams, M. Ferraro, B. Volpe, and N. Hogan, "A Wrist Extension for MIT-MANUS," in *Advances in Rehabilitation Robotics*, vol. 306, Springer Berlin Heidelberg, Aug. 2006, ch. 24, pp. 377–390. DOI: 10.1007/10946978_24.
- [5] A. Gupta, M. K. O'Malley, V. Patoglu, and C. Burgar, "Design, control and performance of RiceWrist: A force feedback wrist exoskeleton for rehabilitation and training," *International Journal of Robotics Research*, vol. 27, no. 2, pp. 233–251, Feb. 2008, ISSN: 02783649. DOI: 10.1177/0278364907084261.
- [6] M. R. Sajadi, A. Nasr, S. A. A. Moosavian, and H. Zohoor, "Mechanical design, fabrication, kinematics and dynamics modeling, multiple impedance control of a wrist rehabilitation robot," in *International Conference on Robotics and Mechatronics, ICRoM 2015*, Institute of Electrical and Electronics Engineers Inc., Dec. 2015, pp. 290–295, ISBN: 9781467372343. DOI: 10.1109/ICRoM.2015.7367799.
- [7] P. Maciejasz, J. Eschweiler, K. Gerlach-Hahn, A. Jansen-Troy, and S. Leonhardt, "A survey on robotic devices for upper limb rehabilitation," *Journal of NeuroEngineering and Rehabilitation*, vol. 11, no. 1, p. 3, Jan. 2014, ISSN: 17430003. DOI: 10.1186/1743-0003-11-3.
- [8] C. Majidi, "Soft Robotics: A Perspective - Current Trends and Prospects for the Future," *Soft Robotics*, vol. 1, no. 1, pp. 5–11, 2014, ISSN: 21695172. DOI: 10.1089/soro.2013.0001.
- [9] A. Schiele and F. C. Van Der Helm, "Kinematic design to improve ergonomics in human machine interaction," *IEEE Transactions on neural systems and rehabilitation engineering*, vol. 14, no. 4, pp. 456–469, 2006.
- [10] A. Villoslada, C. Rivera, N. Escudero, F. Martín, D. Blanco, and L. Moreno, "Hand Exo-Muscular System for Assisting Astronauts During Extravehicular Activities," eng, *Soft robotics*, vol. 6, no. 1, pp. 21–37, Feb. 2019, ISSN: 2169-5180 (Electronic). DOI: 10.1089/soro.2018.0020.
- [11] N. W. Bartlett, V. Lyau, W. A. Raiford, D. Holland, J. B. Gafford, T. D. Ellis, and C. J. Walsh, "A soft robotic orthosis for wrist rehabilitation," *Journal of Medical Devices, Transactions of the ASME*, vol. 9, no. 3, Sep. 2015, ISSN: 1932619X. DOI: 10.1115/1.4030554.
- [12] H. Choi, B. B. Kang, B. K. Jung, and K. J. Cho, "Exo-Wrist: A Soft Tendon-Driven Wrist-Wearable Robot with Active Anchor for Dart-Throwing Motion in Hemiplegic Patients," *IEEE Robotics and Automation Letters*, vol. 4, no. 4, pp. 4499–4506, Oct. 2019, ISSN: 23773766. DOI: 10.1109/LRA.2019.2931607.
- [13] H. Lipson, "Challenges and Opportunities for Design, Simulation, and Fabrication of Soft Robots," *Soft Robotics*, vol. 1, no. 1, pp. 21–27, Mar. 2014, ISSN: 21695172. DOI: 10.1089/soro.2013.0007.

- [14] U. A. Hofmann, T. Bützer, O. Lambercy, and R. Gassert, "Design and Evaluation of a Bowden-Cable-Based Remote Actuation System for Wearable Robotics," *IEEE Robotics and Automation Letters*, vol. 3, no. 3, pp. 2101–2108, 2018, ISSN: 23773766. DOI: 10.1109/LRA.2018.2809625.
- [15] S. S. Yun, B. B. Kang, and K. J. Cho, "Exo-glove PM: An easily customizable modularized pneumatic assistive glove," *IEEE Robotics and Automation Letters*, vol. 2, no. 3, pp. 1725–1732, Jul. 2017, ISSN: 23773766. DOI: 10.1109/LRA.2017.2678545.
- [16] C. G. Rose and M. K. O'Malley, "Hybrid Rigid-Soft Hand Exoskeleton to Assist Functional Dexterity," *IEEE Robotics and Automation Letters*, vol. 4, no. 1, pp. 73–80, Jan. 2019, ISSN: 23773766. DOI: 10.1109/LRA.2018.2878931.
- [17] N. Omarkulov, K. Telegenov, M. Zeinullin, I. Tursynbek, and A. Shintemirov, "Preliminary mechanical design of NU-Wrist: A 3-DOF self-Aligning Wrist rehabilitation robot," in *Proceedings of the IEEE RAS and EMBS International Conference on Biomedical Robotics and Biomechanics*, vol. 2016-July, IEEE Computer Society, Jul. 2016, pp. 962–967, ISBN: 9781509032877. DOI: 10.1109/BIOROB.2016.7523753.
- [18] A. Otten, C. Voort, A. Stienen, R. Aarts, E. Van Asseldonk, and H. Van Der Kooij, "LIMPACT: A Hydraulically Powered Self-Aligning Upper Limb Exoskeleton," *IEEE/ASME Transactions on Mechatronics*, vol. 20, no. 5, pp. 2285–2298, Oct. 2015, ISSN: 10834435. DOI: 10.1109/TMECH.2014.2375272.
- [19] K. Bertoldi, V. Vitelli, J. Christensen, and M. van Hecke, "Flexible mechanical metamaterials," *Nature Reviews Materials*, vol. 2, no. 11, p. 17066, 2017, ISSN: 2058-8437. DOI: 10.1038/natrevmats.2017.66.
- [20] J. Ou, Z. Ma, J. Peters, S. Dai, N. Vlavianos, and H. Ishii, "KinetiX - designing auxetic-inspired deformable material structures," *Computers and Graphics (Pergamon)*, vol. 75, pp. 72–81, Oct. 2018, ISSN: 00978493. DOI: 10.1016/j.cag.2018.06.003.
- [21] K. M. Lynch and F. C. Park, "Modern robotics: Mechanics, planning, and control," 2017.
- [22] T. Pataky, *DIGITIZE07*, 2007. DOI: 18April2007. [Online]. Available: <https://www.mathworks.com/matlabcentral/fileexchange/14703-digitize07> (visited on 09/02/2020).
- [23] G. Mavrotas, "Effective implementation of the ϵ -constraint method in Multi-Objective Mathematical Programming problems," *Applied Mathematics and Computation*, vol. 213, no. 2, pp. 455–465, 2009, ISSN: 00963003. DOI: 10.1016/j.amc.2009.03.037.
- [24] A. R. Tilley and H. D. Associates, *The Measure of Man and Woman: Human Factors in Design*, ser. Interior design.industrial design. Wiley, 2001, ISBN: 9780471099550.
- [25] A. Messac and A. A. Mullur, "Multiobjective optimization: Concepts and methods," in *Optimization of structural and mechanical systems*, World Scientific, 2007, pp. 121–147.
- [26] F. Cordella, L. Zollo, A. Salerno, D. Accoto, E. Guglielmelli, and B. Siciliano, "Human hand motion analysis and synthesis of optimal power grasps for a robotic hand," *International Journal of Advanced Robotic Systems*, vol. 11, 2014.
- [27] N. L. Tagliamonte, F. Sergi, G. Carpino, D. Accoto, and E. Guglielmelli, "Human-robot interaction tests on a novel robot for gait assistance," in *2013 IEEE 13th International Conference on Rehabilitation Robotics (ICORR)*, 2013, pp. 1–6.