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Dimensional Synthesis of a Minimum Torque Exoskeleton for Spastic Wrist Rehabilitation

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Abstract: Hand mobility and dexterity are crucial for daily activities, yet conditions such as stroke and wrist-related injuries can severely impair these functions. A prevalent post-stroke condition, spasticity, is characterized by high muscle tone and stiffness, making joint flexion significantly more strenuous. This study addresses the substantial torque required for effective wrist rehabilitation in stroke survivors. Our approach involves optimizing the dimensions of a Stephenson III six-bar mechanism to minimize the peak assisting torque, leveraging wrist stiffness data from stroke patients. The genetic algorithm is used to optimize the mechanism dimensions to get a nonlinear angular displacement function between the input and output links. This drastically reduces the required actuation torque. Rigorous validation of the optimized mechanism was conducted using Sims cape Multibody dynamics simulation environments. Remarkably, the optimized mechanism achieves a peak actuation torque of just 1.64 N.m when assisting users with typical wrist spasticity, a stark contrast to the 11.69 N.m required when the joint is directly actuated. This research not only offers a promising avenue for developing efficient, lightweight, and cost-effective rehabilitation devices but also holds the potential to significantly enhance the quality of life for individuals with impaired wrist mobility.

1. Introduction

The wrist is a pivotal joint that enables a wide range of daily activities and plays a crucial role in our ability to interact effectively with the environment. Proper wrist/hand function is essential for performing these daily activities [1]. Individuals who have suffered a stroke

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often encounter spasticity, a condition characterized by involuntary muscle contractions that significantly compromise wrist mobility and functionality [2]. This condition not only results in chronic pain but also impedes routine tasks, greatly affecting the quality of life [3]. The wrist joint has three degrees of freedom (DoF): flexion-extension, pronation-supination, and radial-ulnar deviation. Wrist spasticity presents a considerable challenge in rehabilitation, primarily due to the excessive force required for flexion and extension movements. The flexion-extension of the wrist is particularly demanding and is often the primary focus of rehabilitation efforts [4].

Rehabilitation strategies are mainly directed towards mitigating spasticity through physical therapies and medications, aiming to restore the normal range of motion and muscle tone. Although the rehabilitation process can be physically and mentally demanding, with the right support and care, stroke survivors can make substantial strides in restoring wrist and hand function. In recent years, robot-assisted rehabilitation has emerged as a promising approach. These advanced systems offer precise, controlled [5], and repetitive movement patterns [6], which not only lessen the physical strain on patients but also enhance therapeutic outcomes [7]. By incorporating such innovative solutions, the recovery journey becomes more efficient and less difficult for patients, ultimately leading to an improved quality of life. Wrist spasticity is a critical consideration when developing portable and lightweight rehabilitation exoskeletons, as it significantly influences the design and functionality of these devices [8]. To effectively perform the desired rehabilitation movements in individuals with spasticity, robotic systems must generate high torque output to overcome substantial muscle resistance [9]. Current rehabilitation devices that utilize high-torque motors are primarily used in stationary rehabilitation robots, which presents challenges when designing portable systems. To address these limitations, various strategies have been explored to manage torque in patients, particularly stroke survivors experiencing spasticity.

Linkage mechanisms, such as four-bar and six-bar mechanisms, have been proposed to reduce torque demands [10] while maintaining a compact design. This is accomplished by optimizing mechanism dimensions, which has become one of the key areas in research to enhance torque reduction, improve ergonomics, and facilitate effective rehabilitation for patients with spasticity in the hand and wrist. By fine-tuning the geometric parameters of these mechanisms, researchers aim to achieve a balance between force transmission efficiency and workspace adaptability, ensuring that the mechanical assistance provided closely aligns with natural limb movements.

Six-bar linkages have been incorporated into upper-limb exoskeletons for stroke patients with spasticity, optimizing workspace and reducing energy consumption during rehabilitation tasks. These mechanisms enable the replication of complex multi-joint movements, which is crucial in restoring motor functions in individuals with neuromuscular impairments. For instance, a hand rehabilitation robot was developed to address hand disabilities by incorporating real grasping motion data into the kinematic synthesis of a Watt II six-bar linkage, effectively reproducing natural hand motion and improving patient engagement in therapy [11]. The research in [12] explored a six-bar mechanism in developing a finger exoskeleton capable of precisely mimicking the user's natural finger movements. By integrating biomechanical considerations into the linkage design, the exoskeleton ensures smooth and naturalistic articulation across different degrees of motion, thereby reducing discomfort and resistance during rehabilitation exercises. Additionally, six-bar mechanisms have proven effective in generating customized torque-angle profiles to counteract the effects of spasticity in dynamic wrist splints, thereby offering a more tailored and patient-specific rehabilitation approach [13]. This customization is particularly beneficial in addressing variations in muscle stiffness and resistance, which can differ significantly between patients and throughout different stages of rehabilitation.

This paper addresses the challenge of high torque requirements in assisting patients with spastic wrists. A Stephenson six-bar mechanism has been designed to mitigate peak torque demands during wrist flexion-extension movements. The mechanism features a nonlinear angular displacement function between the input and output, tailored to minimize the required input torque. The dimensions of the Stephenson III mechanism are optimized to minimize the required assisting torque for the flexion/extension motion of stroke survivors with spastic wrists. This problem is formulated as a function generation problem, aiming to determine the mechanism dimensions that establish the necessary relationship between the input and output motions. The exact solution to this problem for up to 11 accuracy points can be obtained by solving the resultant equations using a homotopic polynomial solver, as demonstrated in [13]. This method generates millions of solutions, which must be evaluated to identify a solution free of branch and circuit defects [14]. In this study, optimization techniques are used to iteratively minimize the difference between the desired input-output function and the candidate design, repeating the process until the convergence criteria are met. The optimization problem is solved using the genetic algorithm, ensuring the mechanism is finely tuned for assisting patients with spastic wrists. To validate the performance of the optimized mechanism, simulations are conducted using the Sims cape Multibody dynamic.

The main contributions of the paper can be summarized as follows:

- Tackles the high torque demands for effective wrist rehabilitation in stroke survivors with spasticity by optimizing a Stephenson III six-bar mechanism to minimize peak assisting torque during wrist flexion-extension movements.
- Utilizes wrist stiffness data from stroke patients to formulate the dimensional synthesis problem of the Stephenson III six-bar mechanism and employs a genetic to find the optimal mechanism dimensions.
- Validates the optimized design through Sims cape Multibody dynamics simulations.
- Introduces a cost-effective wrist exoskeleton based on the optimized mechanism.

The remainder of this paper is structured as follows: Section 2 details the derivation of the kinematics for the Stephenson III six-bar mechanism. Section 3 addresses the dimensional synthesis problem aimed at achieving a minimum peak torque design. Finally, Sections 4 and 5 present the results and conclusions respectively.

2. Kinematic Analysis of Stephenson III Six-bar Mechanism

The six-bar mechanism is known for its versatility and ability to execute complex movement and functionality than simpler systems. The Stephenson III, the most common inversion of Stephenson's six-bar mechanism [15], which can have a large range of output motion. It is frequently used to enhance transmission angles by connecting a driven dyad to its coupler. The Stephenson III mechanism is secured to the ground link through three fixed pivots (Figure 1), which provide more stability. These characteristics make the Stephenson III an ideal choice for developing exoskeletons designed for spastic wrist rehabilitation.

Although the equations derived in this section are lengthy, the analysis is standard and widely implemented in the literature. The detailed procedures for deriving the kinematic and differential kinematics of planar mechanisms are explained in [15, 16, and 17].

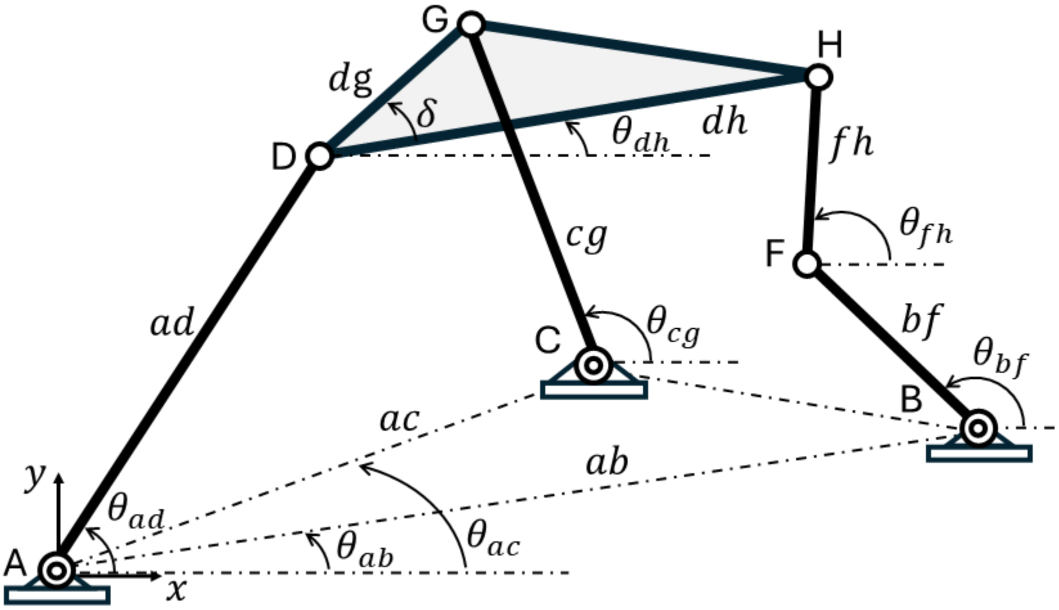

Figure 1: Schematic of the Stephenson III 6-bar mechanism.

The Stephenson III six-bar mechanism consists of two ternary links and four binary links where ternary links are not directly connected. The schematic of the mechanism is shown in Figure 1. In this design, the link BF is the input or the driver link (actuated by the motor), and the link AD is the output link (connected to the user's wrist). The joints at points A, B and C are fixed pivots, thus the points ABC represent the ground link.

The purpose of the kinematic analysis is to find the function that maps the input link motion to the output link motion. Assuming the angle θ_{ad} of link AD (required wrist angle) is known, the angle of the other four movable links needs to be determined. The Stephenson six-bar mechanism can be represented as a pair of four-bar linkages moving in parallel, with two of their links being common. Thus, the kinematic analysis can be accomplished by writing the loop equation of two closed loops $ADGCA$ and$ADHFBA$. The closed chain $ADGCA$ can be represented as follows:

$$\overrightarrow{AD} + \overrightarrow{DG} - \overrightarrow{CG} - \overrightarrow{AC} = 0 \tag{1}$$

Similarly, the closed chain ADHFBA can be represented as follows:

$$\overrightarrow{AD} + \overrightarrow{DH} - \overrightarrow{FH} - \overrightarrow{BF} - \overrightarrow{AB} = 0 \tag{2}$$

The components of equations (1) and (2) be written as follows:

$$ad \cos\theta_{ad} + dg \cos\theta_{dg} - cg \cos\theta_{cg} - ac \cos\theta_{ac} = 0 \tag{3}$$

$$ad \sin\theta_{ad} + dg \sin\theta_{dg} - cg \sin\theta_{cg} - ac \sin\theta_{ac} = 0 \tag{4}$$

$$ad \cos\theta_{ad} + dh \cos\theta_{dh} - fh \cos\theta_{fh} - bf \cos\theta_{bf} - ab \cos\theta_{ab} = 0 \tag{5}$$

$$ad \sin\theta_{ad} + dh \sin\theta_{dh} - fh \sin\theta_{fh} - bf \sin\theta_{bf} - ab \sin\theta_{ab} = 0 \tag{6}$$

Where θ_{ij} is the angle of link ij relative to the x-axis?

Equations (3) through (6) can be solved for $\theta_{bf}, \theta_{fh}, \theta_{cg}$ and θ_{dg} by manipulating the equation as presented in [16] and then applying the half angle substitution that yields:

$$\theta_{bf} = 2\tan^{-1}\frac{-\epsilon_2 \pm \sqrt{\epsilon_2^2 - 4\epsilon_1\epsilon_3}}{2\epsilon_1} \tag{7}$$

$$\theta_{fh} = 2\tan^{-1}\frac{-\lambda_2 \pm \sqrt{\lambda_2^2 - 4\lambda_1\lambda_3}}{2\lambda_1} \tag{8}$$

$$\theta_{cg} = 2\tan^{-1}\frac{-\xi_2 \pm \sqrt{\xi_2^2 - 4\xi_1\xi_3}}{2\xi_1} \tag{9}$$

$$\theta_{dg} = 2\tan^{-1}\frac{-\sigma_2 \pm \sqrt{\sigma_2^2 - 4\sigma_1\sigma_3}}{2\sigma_1} \tag{10}$$

Where

$$\epsilon_1 = ab^2 + bf^2 + ad^2 + dh^2 - fh^2 + 2ad\, bf \cos\theta_{ad} - 2ab\, bf \cos\theta_{ab} - 2ab\, ad \cos(\theta_{ab} - \theta_{ad}) - 2ab\, dh \cos(\theta_{ab} - \theta_{dh}) + 2bf\, dh \cos\theta_{dh}$$

$$\epsilon_2 = -4bf(ad \sin\theta_{ad} - ab \sin\theta_{ab} + dh \sin\theta_{dh})$$

$$\epsilon_3 = ab^2 + ad^2 + dh^2 + bf^2 - fh^2 - 2ab\, ad \cos(\theta_{ab} - \theta_{dh}) + 2ab\, bf \cos\theta_{ab} - 2bf\, dh \cos\theta_{dh} - 2ab\, dh \cos(\theta_{ab} - \theta_{dh}) + 2ad\, dh \cos(\theta_{ad} - \theta_{dh})$$

$$\lambda_1 = ab^2 + ad^2 + fh^2 - bf^2 + dh^2 - 2ab\, ad \cos(\theta_{ab} - \theta_{ad}) + 2ad\, dh \cos(\theta_{ad} - \theta_{dh}) - 2ab\, dh \cos(\theta_{ab} - \theta_{dh}) + 2ad\, fh \cos\theta_{ad} - 2ab\, fh \cos\theta_{ab} + 2dh\, fh \cos\theta_{dh}$$

$$\lambda_2 = -4fh\,(ad \sin\theta_{ad} - ab \sin\theta_{ab} + dh \sin\theta_{dh})$$

$$\lambda_3 = ab^2 + ad^2 + fh^2 - bf^2 + dh^2 - 2ab\, ad \cos(\theta_{ab} - \theta_{ad}) + 2ad\, dh \cos(\theta_{ad} - \theta_{dh}) - 2ab\, dh \cos(\theta_{ab} - \theta_{dh}) - 2ad\, fh \cos\theta_{ad} - 2dh\, fh \cos\theta_{dh} + 2ab\, fh \cos\theta_{ab}$$

$$\xi_1 = ac^2 + ad^2 + cg^2 - dg^2 - 2ac\, ad \cos(\theta_{ac} - \theta_{ad}) - 2ac\, cg \cos\theta_{ac} + 2ad\, cg \cos\theta_{ad}$$

$$\xi_2 = 4ac\, cg \sin\theta_{ac} - 4\, ad\, cg \sin\theta_{ad}$$

$$\xi_3 = ac^2 + ad^2 + cg^2 - dg^2 - 2ad\, cg \cos\theta_{ad} - 2ac\, ad \cos(\theta_{ac} - \theta_{ad}) + 2ac\, cg \cos\theta_{ac}$$

$$\sigma_1 = ac^2 + ad^2 - cg^2 + dg^2 - 2ac\, ad \cos(\theta_{ac} - \theta_{ad}) + 2ac\, dg \cos\theta_{ac} - 2ad\, dg \cos\theta_{ad}$$

$$\sigma_2 = 4\, ad\, dg \sin\theta_{ad} - 4\, ac\, dg \sin\theta_{ac}$$

$$\sigma_3 = ac^2 + ad^2 - cg^2 + dg^2 - 2\, ac\, ad \cos(\theta_{ac} - \theta_{ad}) - 2ac\, dg \cos\theta_{ac} + 2ad\, dg \cos\theta_{ad}$$

Referring to Figure 1, we can observe that points D, G, and H represent a single rigid link. Thus, the angle θ_{dh} and θ_{dg} can be related as follows:

$$\theta_{dh} = \theta_{dg} + \delta \qquad (11)$$

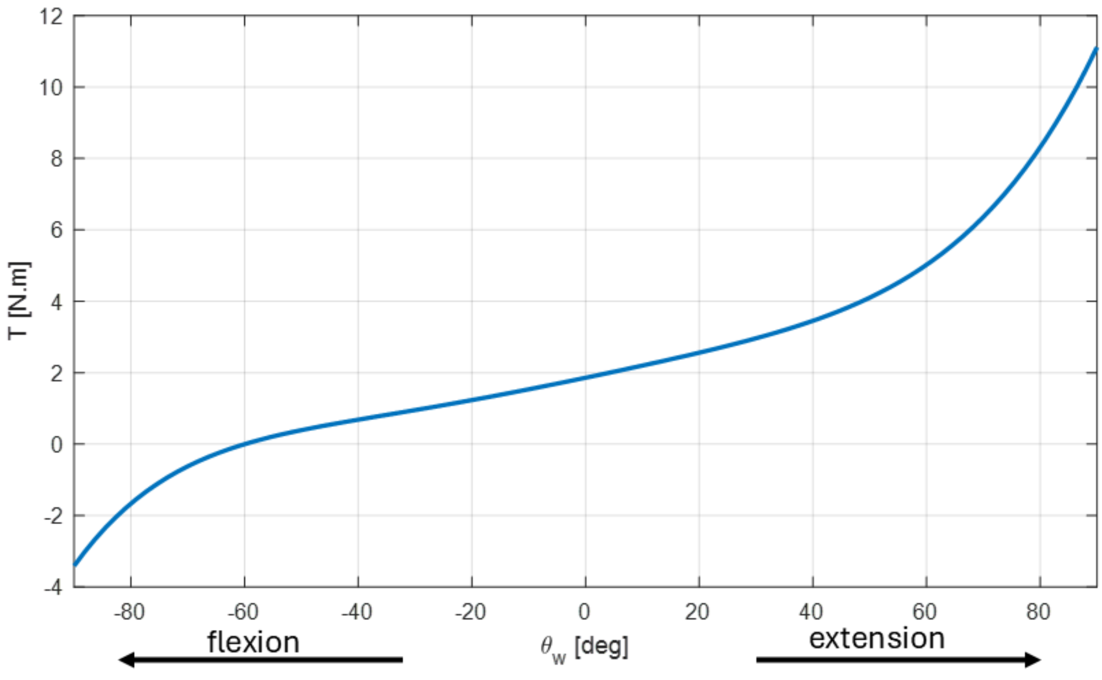

Figure 2: Torque profiles of spastic wrist as reported in [13].

2.1. Differential Kinematic

Differential kinematics establish a relationship between the angular velocity of the input link BF and the output link AD. This can be accomplished by differentiating equations (3) through (6). This results in a system linear of linear equation, which can be solved as follows:

$$x = A^{-1}b \tag{12}$$

Where

$$x = [\omega_{dg} \quad \omega_{cg} \quad \omega_{fh} \quad \omega_{bf}]^T$$

$$b = ad\ \omega_{ad}[\sin\theta_{ad} \quad -\cos\theta_{ad} \quad \sin\theta_{ad} \quad \cos\theta_{ad}]^T$$

$$A = \begin{bmatrix} -dg\,sin\,\theta_{dg} & cg\,sin\,\theta_{cg} & 0 & 0 \\ dg\,cos\,\theta_{dg} & cg\,cos\,\theta_{cg} & 0 & 0 \\ -dh\,sin\,\theta_{dh} & 0 & fh\,sin\,\theta_{fh} & bf\,sin\,\theta_{bf} \\ -dh\,cos\,\theta_{dh} & 0 & fh\,cos\,\theta_{fh} & bf\,cos\,\theta_{bf} \end{bmatrix}$$

In which ω_{ij} is the angular velocity of the linkij.

The angular velocity obtained in equation (12) are used in Section 3.1 to derive the relation between the input (motor) and output (assisting) torques.

3. Optimal Design of Stephenson III for Minimum Assisting Torque

Linkage mechanisms can provide mechanical advantages between input and output, amplifying forces/torques. One straightforward way to achieve this is through a function generator mechanism, which establishes a relationship between the movements of the input and output links. The simplest form of this mechanism is the four-bar linkage. In the four-bar mechanism, the rotation of the rocker (output link) is limited to approximately 120 degrees to ensure efficient force and torque transmission by maintaining the transmission angle above 30 degrees [15]. Increasing the range of the rocker above this limit significantly reduces the transmission angle, increasing the risk of jamming the mechanism. However, to support full wrist flexion and extension range of motion a 180-degree rotation is needed. Thus, a six-bar mechanism is used in this study, and the dimensional synthesis is formulated as an optimization problem. The Genetic Algorithm (GA) is an evolutionary optimization algorithm, which is widely used for mechanism dimensional synthesis [17, 18] due to its ability to search for the global minimum of the objective function. Thus, the dimensions of the Stephenson III mechanism that minimizes the maximum needed motor torque are obtained using GA.

3.1. Torque profile of spastic wrist

This study employs the typical wrist stiffness of 21 stroke patients reported in [3]. The stiffness profile is obtained by fitting the data in [3] to a 5^{th}-degree polynomial curve [13].

The curve is integrated with respect to the wrist angle to obtain the torque profile, T_w of a spastic wrist, which can be presented as follows [13]:

$$T_w = -0.057\theta_w^6 + 0.475\theta_w^5 + 0.3587\theta_w^4 - 0.071\theta_w^3 + 0.269\theta_w^2 + 1.904\theta_w + 1.860 \quad (13)$$

Where θ_w is the wrist angle in radian, which can be related to the angle θ_{ad} as follows?

$$\theta_w = \theta_{ad} - \theta_{ad_0} \quad (14)$$

Where θ_{ad_0} is the value of the angle θ_{ad} at zero wrist flexion angle, the torque profile presented in equation (13) is depicted in Figure 2.

3.2. Dimensional Synthesis

In order to provide the needed assistance, the torque of the spastic wrist acted on link AD is counteracted by the motor torque acted on link BF. The motor torque, T_a needs to compensate for the wrist torque,T_w. To simplify this problem, the dynamic effect and losses due to friction are neglected. Assuming the input and output powers are equal, that yields the following:

$$\omega_{ad} T_w = \omega_{bf} T_a \quad (15)$$

The objective function for minimum peak torque design can be expressed as follows:

$$f(\chi) = max\left(\frac{\omega_{ad}}{\omega_{bf}} T_w\right) \quad (16)$$

Where χ is the design vector

The Stephenson mechanism (Figure 1) has 12 design variables that determine the performance of the mechanism. This includes the dimensions of the movable links ($ad, dg, cg, bf, dh, fh, \delta$), dimension of the ground link ($ab, ac, \theta_{ab}, \theta_{ac}$) and the value of the angle θ_{ad} at zero wrist flexion angle, θ_{ad_0}.Thus, the vector χ can be defined as the following:

$$\chi = \left[ad, dg, cg, ac, ab, bf, dh, fh, \theta_{ab}, \theta_{ac}, \delta, \theta_{ad_0}\right]^T \quad (17)$$

Where θ_{ad_0} is the value for angle θ_{ad} at zero zero wrist flexion angle. To that the optimization yields a compact design, constraints on links' length are imposed.

Hence, the optimization problems can be presented as follows:

$$\begin{array}{ll} \textit{minimize} & f(\chi) \\ \textit{subject to} & 20 \leq L_{ij} \leq 200(mm) \end{array} \tag{18}$$

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$$\begin{array}{ll} \textit{minimize} & f(\chi) \\ \textit{subject to} & 20 \leq L_{ij} \leq 200(mm) \end{array} \tag{18}$$

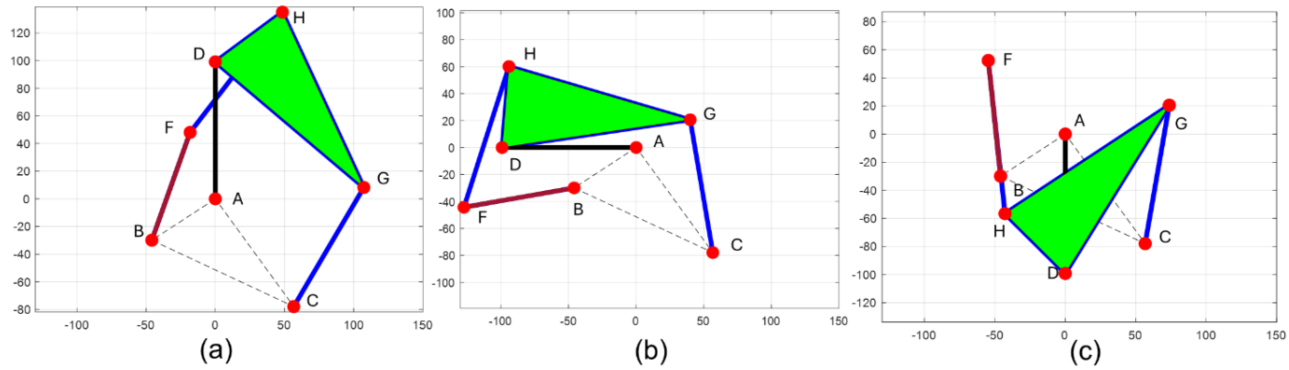


Figure 3: The optimized Stephenson III six-bar mechanism with the optimized dimensions at the wrist flexion angle of a) -90 b) 0° and c) 90°.

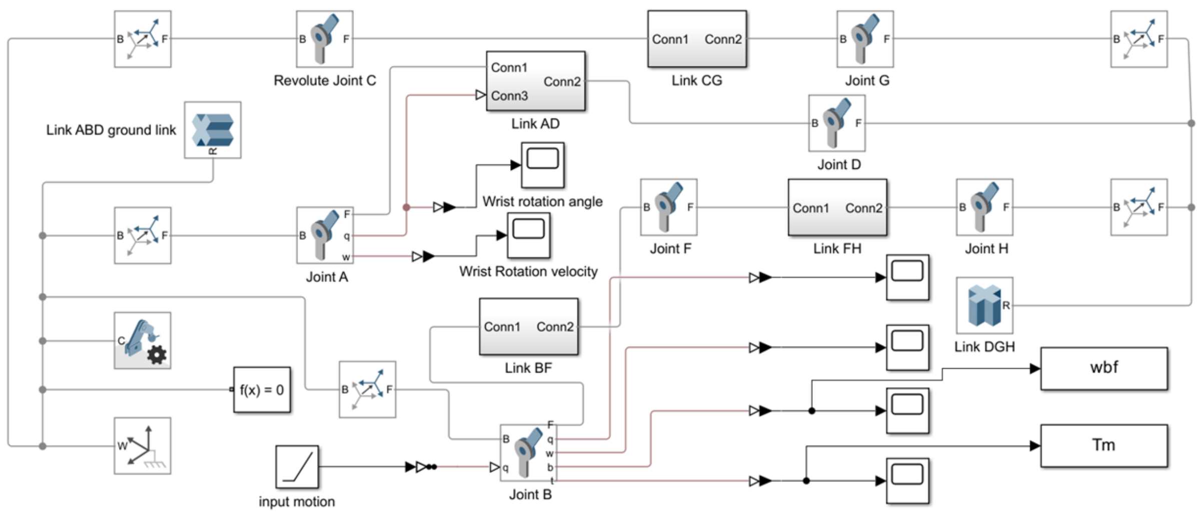


Figure 4: The Sims cape Multibody model of the mechanism

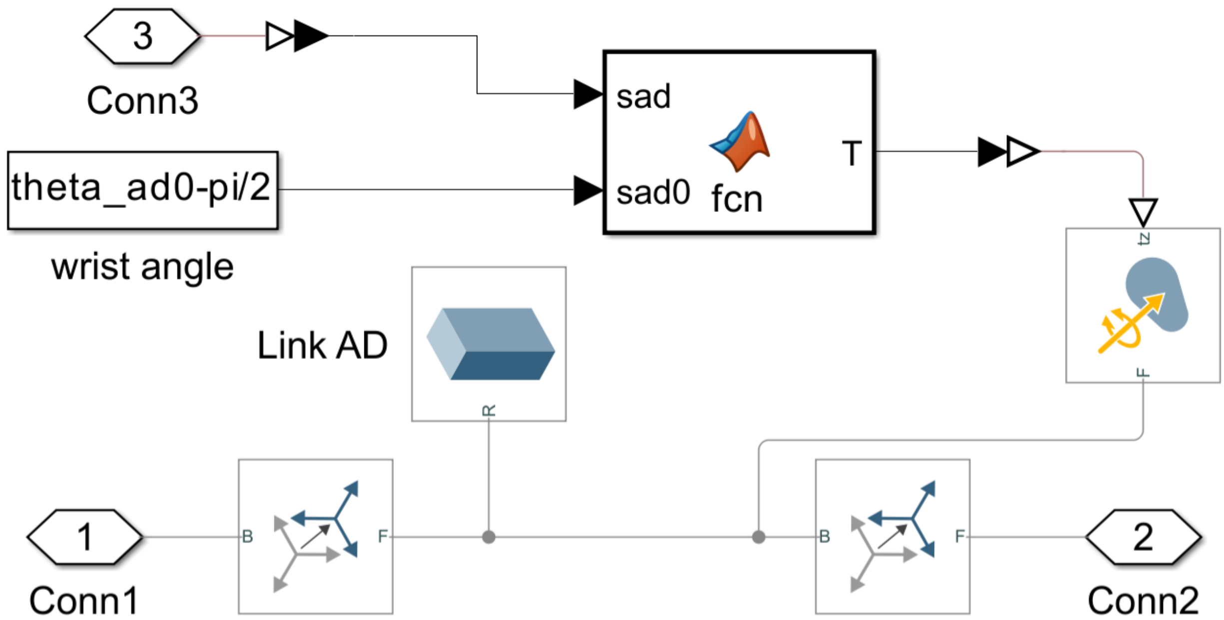


Figure 5: Sims cape function block that represents the spasticity torque of the wrist according to equation (13).

4. Results

The optimization problem is solved using Genetic Algorithm (GA) in the MATLAB global optimization toolbox. The optimal design vector χ^* is obtained as follows:

$$\chi^* = [99\ 141\ 100\ 96\ 55\ 83\ 60\ 110\ -2.56\ -0.94\ -1.34\ 3.14]^T \quad (19)$$

Equations (7) through (10) were employed to draw the schematics of the Stephenson III mechanism with the optimal dimensions at various wrist flexion angles, as shown in Figure 3. The mechanism successfully completed the wrist range of motion without encountering circuit or branch defects. The optimized design features a four-bar mechanism comprising links AC, AD, DG, and GC, which is classified as non-Grashof. Consequently, the mechanism restricts flexion beyond90°, providing a safeguard against hyperextension of the user's wrist. This built-in protection reduces the risk of wrist sprain injuries and ensures safe and effective rehabilitation. Furthermore, the non-Grashof classification indicates that the mechanism maintains smooth and consistent motion throughout the entire range of wrist flexion, enhancing the overall user experience and efficacy of the rehabilitation process.

To validate the performance of the optimized Stephenson III mechanism, the system was implemented using the Sims cape Multibody dynamics within the MATLAB Simulink simulation environment, as illustrated in Figure 4. The torque resulting from wrist spasticity was modelled as a resistance torque on link AD. The torque equation (13) was implemented in a MATLAB Function block, which takes the wrist angle as input and outputs the spasticity torque according to equation (13). This torque was then applied to link AD as an external torque, as depicted in Figure 4.

The simulation results, shown in Figure 6(a), closely matched those derived analytically, demonstrating that the assumptions used to derive equation (15) do not significantly affect the resulting relationship between input and output torque. The peak required actuator torque for the optimized mechanism is 1.64 N.m (Figure 6), which is significantly lower than the peak value of the spastic wrist torque profile, 11.69 N.m (Figure 2). This significant reduction in peak torque highlights the effectiveness of the optimized mechanism in addressing high torque demands during wrist rehabilitation.

Furthermore, the simulation environment allows for comprehensive testing of the mechanism's performance under various conditions, ensuring robustness and reliability. The successful implementation and validation of the optimized mechanism indicate its potential for practical applications in portable and lightweight rehabilitation devices, offering a promising solution for enhancing the quality of life for individuals with wrist spasticity.

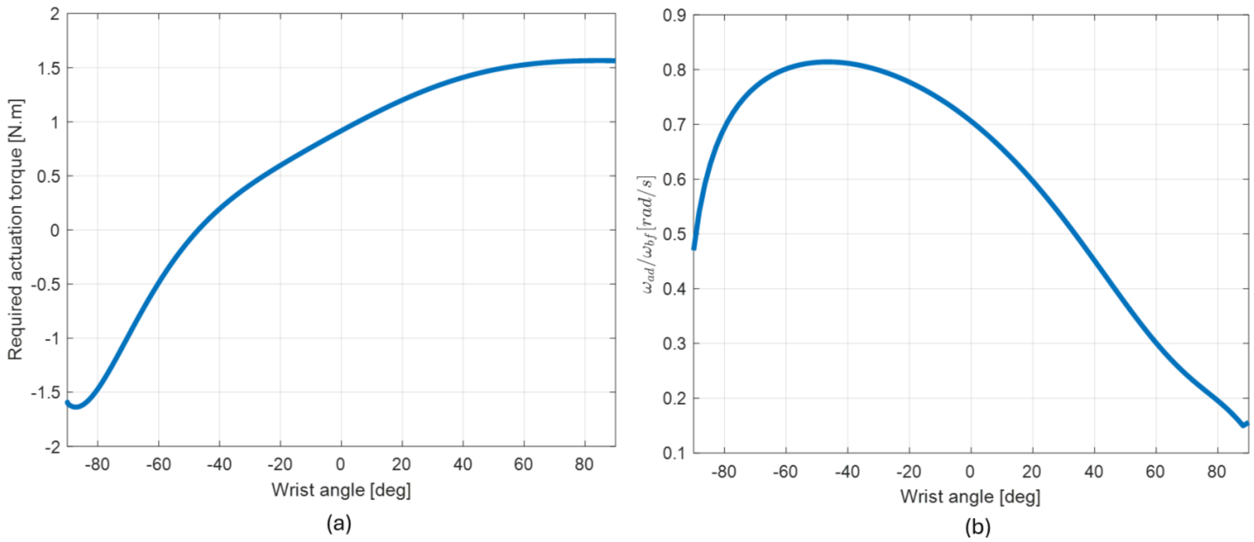
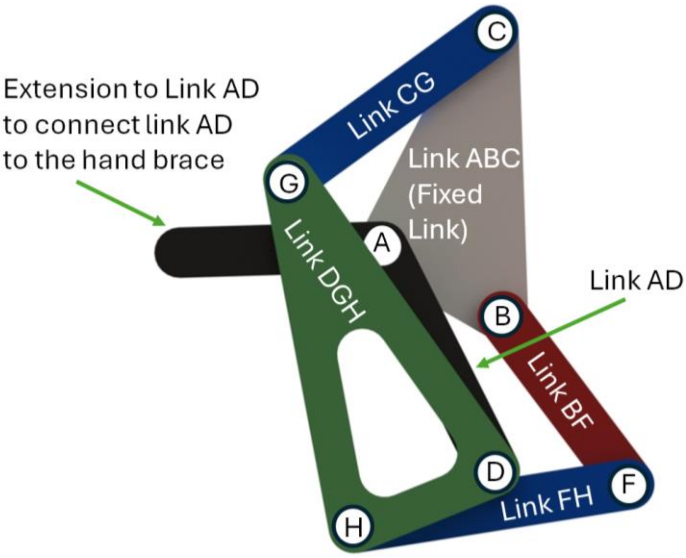


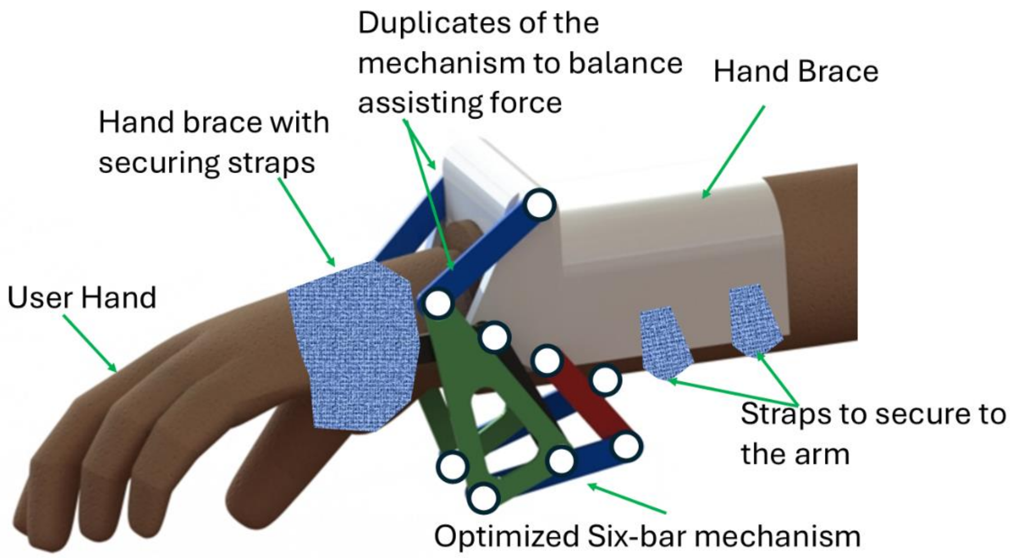
Figure 6: Results obtained from The Sims cape multibody, (a) required actuator torque, (b) The ratio between output and input angular velocities.

Furthermore, Figure 6(b) illustrates the obtained nonlinear relationship between the output and input angular velocities (ω_{ad}/ω_{bf}) as a function of the wrist flexion angle. This relationship governs the mechanical advantages of the mechanism, effectively controlling the ratio between input and output torques. These findings highlight the effectiveness of the optimized mechanism in reducing the peak required assisting torque. Consequently, this can facilitate the design of more affordable rehabilitation exoskeletons by enabling the use of smaller motors.

Additionally, the successful implementation and validation of the Stephenson III mechanism in a simulated environment underscores its potential applicability in real-world scenarios, paving the way for enhanced therapeutic interventions for patients with wrist spasticity. By demonstrating the wear ability of exoskeletons based on the optimized mechanism, a 3D model of the user arm with the proposed wrist exoskeleton is depicted in Figure 7. It is important to note that the optimal dimensions derived in Equation (19) can be scaled to accommodate various designs. The optimized mechanism will retain its performance, provided the relative proportions between the various links are preserved.



a) Schematic of the Optimized Mechanism with Labeled Links and Joints.



b) A 3D model of the user arm with the proposed wrist exoskeleton.

Figure 7: Design of the wrist exoskeleton based on the optimized mechanism.

Moreover, the compact and lightweight nature of the mechanism ensures user comfort and ease of use, which are crucial factors in designing effective rehabilitation devices. Future work should focus on integrating this optimized mechanism into portable exoskeletons and conducting clinical trials to evaluate its efficacy in real-world therapeutic settings. This could ultimately lead to the development of cost-effective and user-friendly rehabilitation solutions, significantly improving the quality of life for individuals with wrist spasticity.

5. Conclusions

This study presents an innovative approach to addressing the challenges of wrist rehabilitation for stroke survivors, particularly those suffering from spasticity. By optimizing the dimensions of a Stephenson III six-bar mechanism to account for the stiffness of spastic wrist joints, the research significantly reduces the peak torque required for wrist movement. The application of a genetic algorithm has yielded a mechanism with a nonlinear angular displacement function, minimizing the torque demand during rehabilitation exercises. Validation through Sims cape Multibody dynamics simulations demonstrates the mechanism's effectiveness, achieving a peak actuation torque of only 1.64 N.m compared to 11.69 N.m for direct actuation. The findings of this study underline the potential of tailored rehabilitation devices that leverage optimized mechanical designs to enhance usability while reducing cost. The reduced torque requirements not only lower the operational burden on actuation systems but also pave the way for creating lightweight and cost-effective rehabilitation solutions. Ultimately, this work contributes to improving the quality of life for individuals with impaired wrist mobility, offering a promising foundation for future advancements in rehabilitation technology. The future work will focus on testing the optimized Stephenson III six-bar mechanism on a broader population of stroke survivors to validate its efficacy in real-world scenarios. Additionally, the integration of the mechanism into portable rehabilitation exoskeletons should be explored, with a particular emphasis on assessing its performance and user experience in daily activities.

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