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Design of an affordable dynamic arm support for motorized wheelchairs

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Abstract: Upper limb impairments, resulting from various neurological and neuromuscular conditions, significantly impact daily activities and limit social participation. Assistive technologies, particularly dynamic arm supports, offer promising solutions to enhance independence for individuals facing these challenges. This paper presents the development of an affordable dynamic arm support, designed with a focus on static balancing. The support utilizes a four-bar linkage mechanism to allow smooth vertical movement while maintaining the orientation of the armrest. Furthermore, the integration of rotational and prismatic joints enhances the device's adaptability, enabling horizontal movements. Through comprehensive mathematical modeling and prototype testing, we introduce a cost-effective arm support that effectively counterbalances the arm's weight, ensuring ease of movement and stability across various spatial orientations.

1 Introduction

A variety of neurological and neuromuscular disabilities (e.g. multiple sclerosis, muscular dystrophy, stroke, spinal cord injuries) can lead to upper limb impairments [1-3]. For instance, individuals with such impairments may encounter difficulties in grasping, reaching, and moving objects [4], which can limit their ability to perform daily activities and place an increased burden on their families by requiring significant assistance and restricting social participation. [5]. Assistive technologies (ATs) are used to increase the level of independence of people with upper limb impairments and have been proven to be an effective solution [6], such as eating assistive devices [7,8] arm supports [9], and robotic assistive devices [10]. Dynamic arm supports are a type of AT that provides support to the upper extremity while allowing movement. Hence, they can be useful for a variety of activities of daily living. These ATs are categorized into four groups, namely non-actuated devices, passively actuated devices, actively actuated devices, and devices using the functional electrical stimulation principle [11]. Non-actuated devices can include the following functionalities: tremor suppression, anti-gravity support, and facilitation of flexion and/or extension of the elbow. Passively actuated devices include mechanisms allowing the storage of potential energy within the device. They can provide the following functionalities: manipulation of specific joints, support of anti-gravity movements, and tremor suppression. These systems primarily allow for the adjustment of the compensation level through a mechanical interface, which is typically operated by a caregiver. Actively actuated devices have the same functionalities as the two precedent categories. The difference lies within the access to external energy such as electrical motors. Users can change the compensation level through an electronic switch and it generally allows them to compensate for the direction of gravity relative to the arm support's base (e.g. if the user is on a slope or the wheelchair is inclined). Finally, devices using functional electrical stimulation stimulate muscles in a task-appropriate fashion, which helps complete an activity; these are mostly used to compensate for upper limb neurological impairments.

Over the years, various dynamic arm supports have been developed [11,12]. Evidence indicates that they enhance users' experience by improving upper limb functionality and overall satisfaction. Furthermore, such supports positively affect users' functional ratings, range of motion, strength, accuracy in broad movements, and patterns of grasp [13,14].

Feedback from participants however revealed several barriers to the daily use of dynamic arm supports. A significant issue was the stationary nature of these supports, such as being attached to a table, which limited their use across multiple activities. Van Der Heide & De Witte (2016) revealed in their study that mounting the support on a wheelchair could interfere with performing daily living activities. Another concern was the bulkiness of the arm supports, suggesting a need for design considerations that prioritize user acceptance and ensure that the device does not obstruct movement through doorways [14].

The objective of the present study was to develop an affordable dynamic arm support that can be seamlessly integrated to a wheelchair while ensuring it remains unobtrusive and functional for the user. The structure of the paper is organized in the following manner: it begins with the methodology section, detailing the static balancing techniques, the design and function of a four-bar mechanism, and the analysis of horizontal movements. It concludes with a summary and implications of the findings.

2 Methods

2.1 *Static balancing*

The principle of static balancing is adopted in the proposed study. The load to be balanced is represented by the mass '*M*' (Figure 1). The torque this load applies at joint 'J_1' is given by (1):

$$T_1 = M * g * L * sin(\alpha) \qquad (1)$$

where α is the angle of the link, '*L*' is the distance between 'J_1' and '*M*', and '*g*' is the gravitational constant.

To statically balance this load, the spring must exert a torque at joint 'J_1' that closely matches 'T_1'.

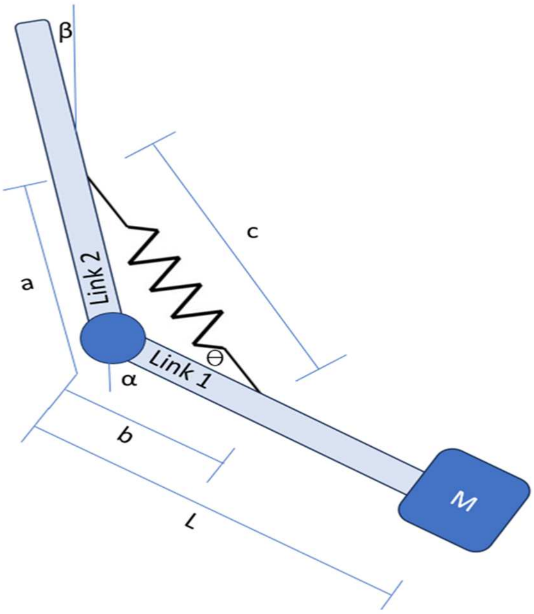


Figure 1 Static balancing parameters

The force exerted by the spring is described by (2):

$$F_k = K * (c - x_0) \qquad (2)$$

where *c* is the spring's length and 'x_0' is its free length. The torque applied by the spring at 'J_1' is (3):

$$T_2 = K * (c - x_0) * b * sin(\theta) \qquad (3)$$

where '*b*' is the distance between 'J_1' and the spring's attachment, and θ is the angle between Link 2 and the spring (refer to Figure 1).

The sine law is used to relate the angles and side lengths of the triangle formed by the spring and the links in the system. This helps determine the angle between Link 2 and the spring, which is important for calculating the torque applied by the spring at joint J1. This geometric relationship allows for an accurate description of how the spring's force is distributed throughout the system, based on the angles and lengths of the components involved. Hence using the sine law we have (4):

$$\frac{\sin(\theta)}{a} = \frac{\sin(180 - \alpha + \beta)}{c} \qquad (4)$$

where beta is the angle of Link 1 with the vertical. This results in the equation (5):

$$\frac{T_2 = K * (c - x_0) * b * a * \sin(180 - \alpha + \beta)}{c} \qquad (5)$$

Figure 2 Four bar mechanism prototype with an arm rest

The parameters, *a*, *b*, *k*, and x_0, are then determined through iteration that best fit so that T_2 is as close to T_1 as possible for different values of *M*. The length '*a*' can be adjusted to fit different masses *M*. Van Dorsser et al. (2007) presented the static balancing principle in detail [15].

2.2 Four-bar mechanism

The basis of the dynamic arm support is a four-bar linkage that allows one to perform vertical movement while the armrest remains horizontal thanks to the four-bar linkage movement. The static balancing for the four-bar mechanism is the same as with the single bar presented above. The four-bar mechanism replaces the wheelchair armrest so that it has a minimal lateral footprint and is not cumbersome. In this prototype, the parameter '*a*' (as shown in Figure 1) can be adjusted using a worm screw to adjust the vertical force compensation level. This principle has also been adopted in earlier models of arm supports.

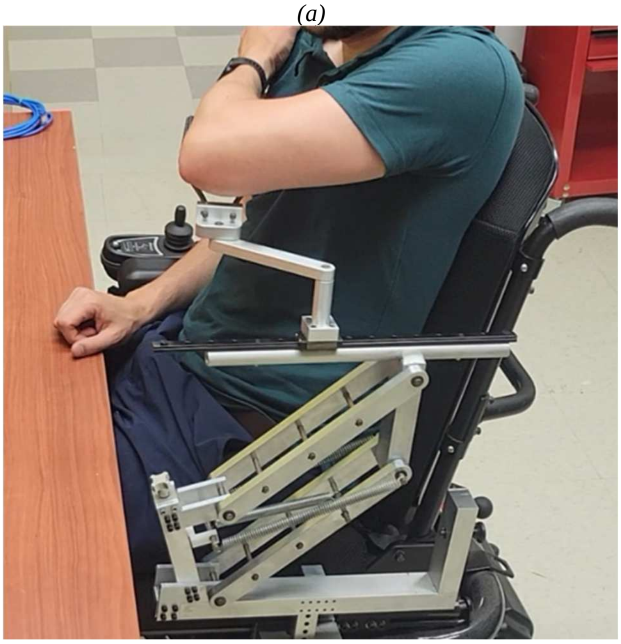
2.3 Horizontal movements

For the horizontal movements, links with rotational joints could be used [16,17]. However, in order to be less cumbersome, especially to allow the wheelchair passing through doors, a prismatic joint combined with two rotary joints is adopted, as shown in Figure 2 and Figure 3.

3 Results

To validate the vertical balancing, the vertical force exerted by the springs is measured for different adjustments of the length '*a*' and in different alpha positions with a Wagner FDX 100 dynamometer. Figure 4 presents the results in terms of vertical force (Figure 4a) and torque (Figure 4b). For the force, in Figure 4a, the ideal curve for a given '*a*' would be a straight line, implying that the force compensation level is the same no matter the angle α. Based on the machining data we gathered during the device manufacturing process, it is estimated that for a production run of 100 devices, the manufacturing cost would be $1,750 USD. This is significantly lower than similar arm support devices, which typically cost between $20,000 and $60,000.

(a)

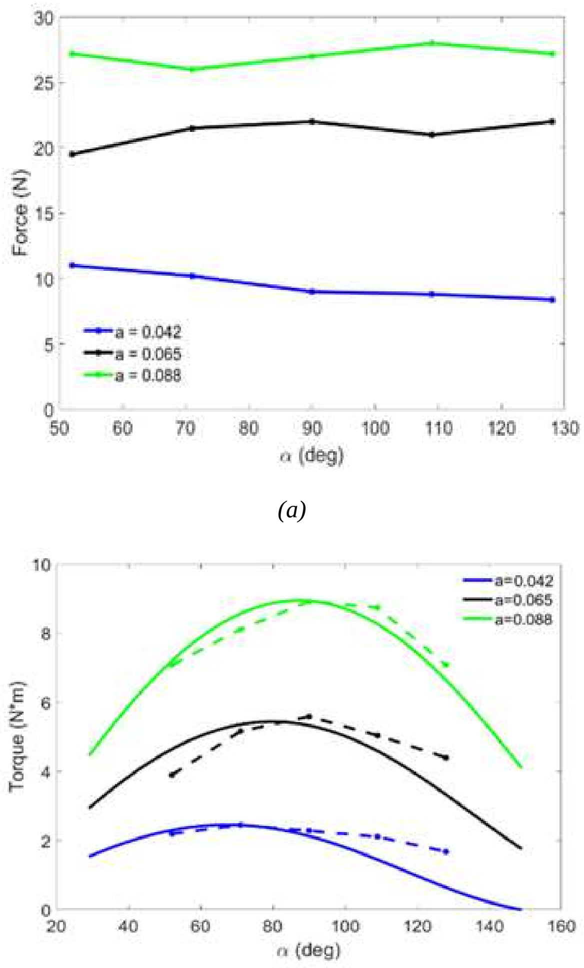


(b)

Figure 3 Prototype with (a) the four-bar mechanism and (b) horizontal movement

4 Discussion

The quest to improve the quality of life for individuals with upper limb impairments has led to the development of a wide array of assistive technologies. Among these, dynamic arm supports stand out as a pivotal tool in providing the necessary support while ensuring mobility.



(a)

(b)

Figure 4 (a) Vertical force measured at the arm rest level for three different 'a' parameter for different alpha angles; (b) Transformation of the force measurement into torque at the base joint for different 'a' parameter for different alpha angles. Full lines represent the results from the theoric simulation model and dotted lines represents the measured values on the prototype.

This paper presents the concept of a low-cost dynamic arm support, emphasizing the principle of static balancing, that also has a minimal lateral footprint without being cumbersome by replacing the wheelchair armrest. Through meticulous analysis and application of mathematical models, a mechanism that adeptly counterbalances the arm's weight in any spatial orientation is developed. The foundation of this arm support is a four-bar linkage, which ensures vertical movement while maintaining the arm rest's orientation. Furthermore, the design incorporates both rotational and prismatic joints, optimizing the device for horizontal movements. The significance of this research lies not just in the creation of a functional prototype but in its potential to be a cost-effective solution for many. By understanding and applying the principles of static balancing and leveraging the benefits of four-bar mechanisms, we have taken a step closer to making dynamic arm supports accessible to a broader audience. Future endeavors in this domain should focus on refining the design, ensuring user comfort, and further reducing costs, thereby making it a ubiquitous solution for those in need. Future works will consist of validating the prototype with participants and pursuing iterations.

5 Conclusion

This study presents the development of a cost-effective dynamic arm support designed to assist individuals with upper limb impairments. By employing a four-bar linkage and integrating static balancing principles, the device successfully facilitates vertical and horizontal movements while maintaining minimal lateral footprint. Prototype testing demonstrated effective weight counterbalancing, making the device a promising solution for enhancing mobility and independence. Future research should focus on user validation, further design refinements, and cost reduction to increase accessibility and usability.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

Author Contributions

ACL: Conceptualization, Mechanical design, Project administration, Methodology, Analysis, Writing- original draft.
CL: Mechanical design, Conceptualization
CD: Mechanical design, Conceptualization
SL: Mechanical design, Conceptualization
TL: Mechanical design, Conceptualization
JSR: Writing – review & editing, Validation Conceptualization
VF: Writing – review & editing, Validation Conceptualization

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Conflict of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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