

Enhancing Hand Exoskeletons in Material Selection and Design

Guanyi Li*

Mechanical Design, Manufacturing and Automation, Foshan University, Foshan 528000, Guangdong, China

* Corresponding Author Email: guanyi367@gmail.com

Abstract. Nowadays, flexible hand exoskeletons are increasingly recognized for their applications in both rehabilitation medicine and industrial applications. This research endeavors to scrutinize and refine the choice of materials and the mechanical design for flexible hand exoskeletons, prioritizing improvements in user comfort, flexibility, durability, and lightness. The research employs a comprehensive review of the mechanical properties of commonly used materials, such as silicone, spandex, and nylon. It also evaluates their suitability in different structural designs. The study finds that silicone's air permeability is limited although it offers excellent comfort and pressure distribution. Spandex provides superior flexibility but suffers from durability reducing as time goes by. Nylon offers excellent durability and structural stability but is less effective in terms of elasticity and air permeability. The findings advise that a combination of these materials, with the help of innovative design strategies, can achieve a balanced performance. After that flexible hand exoskeletons can meet the diverse requirements. The study concludes that future designs should keep exploring material combinations and structural innovations in order to enhance user experience and extend the practical applications of flexible hand exoskeleton.

Keywords: Exoskeleton, hand, materials, design.

1. Introduction

As technology becomes more and more advanced, the fields of ergonomics are increasingly significant, particularly in the field of medical and industrial applications. Among the many innovations that have appeared, flexible hand exoskeletons stand out as groundbreaking technologies which promises to revolutionize the way we approach hand function assistance and enhancement. These devices are keys to the rehabilitation of stroke patients, where they play an important role in restoring hand functionality in clinical settings [1]. They also serve to improve hand strength and reduce fatigue in industrial environments [2]. The importance of ergonomic design in these exoskeletons is related to the user's comfort, range of motion, device durability, overall weight, and portability so it cannot be ignored.

Making a flexible hand exoskeleton is a complex challenge, which requires complete knowledge of material characteristics and adherence to mechanical engineering concepts. The selection and integration of materials are fundamental to the performance of exoskeletons. That's because they not only dictate the physical comfort for the user, but they also control the device's flexibility, which is essential for mimicking the natural movements of the hand. As materials must withstand the rigors of repetitive use, durability is another critical factor whether in the demanding conditions of industrial work or the delicate processes of medical rehabilitation. In addition, the lightweight nature of the materials is important to prevent undue strain on the users and for allowing long-terms use of the device without discomfort or exhaustion.

This paper shows several close-up views of flexible hand exoskeletons that illustrate what is the effect material choices and design bring on device performance and user experience. A close-up view of the Exo-Glove Poly is what Figure 1(a) displays. It highlights its innovative design for providing support and enhancing hand functionality. Figure 1(b) shows a flexible rehabilitation glove designed by the National University of Singapore, which demonstrates its flexibility and comfort in rehabilitation applications. Figure 1(c) exhibits a close-up view of the Compliant Hand Based on a Novel Pneumatic Actuator designed by Harvard University. It emphasizes its potential for dynamic

support and enhancement of hand functions. These images showcase the latest advancements in the design of flexible hand exoskeletons. They highlight the importance of material and design choices in meeting user needs.

In conclusion, the initial section of this paper lays the groundwork for an in-depth analysis of the key elements that shape the design and performance of flexible hand exoskeletons. By emphasizing ergonomics, highlighting material properties, and considering mechanical principles, it sets the stage for a detailed analysis of how these elements combine to create technologically advanced devices. They are also highly responsive to user needs. The content shown in Figure 1 reinforces these points and provides practical visual references for the designs in the future and material selection.



Fig. 1 shows close-up views of various exoskeleton gloves: (a) the Exo-Glove Poly; (b) a flexible rehabilitation glove, the work of the National University of Singapore; and (c) the Compliant Hand, a novel pneumatic actuator-based design by Harvard University [1].

2. Wearability Requirements

The wearability of the flexible hand exoskeleton is an important research direction. It involves the requirements of many aspects.

2.1. The Centrality of Comfort in Design

Comfort is the centre to the design of flexible hand exoskeletons. The tactile feel, air permeability, and skin impact of the materials directly affect the user [3]. To avoid irritation or discomfort, the materials for exoskeletons should be soft and skin-friendly. Research shows that materials with good air permeability can effectively reduce the accumulation of sweat and skin-related issues [4], consequently improving wearing comfort.

2.2. Ensuring Flexibility for Natural Movements

Flexibility refers to whether the material can support the hand's natural movements. The design of the exoskeleton needs to ensure that the joints and muscles of the hand can move freely while wearing the exoskeleton. The flexibility of the material is crucial to maintaining hand's natural movements [5]. Materials that are too rigid or lacking sufficient extensibility can limit hand flexibility and impair the performance of the exoskeleton [6].

2.3. Durability for Long-Term Reliability

Durability determines if the exoskeleton can keep certain performance levels after a long-term use. The material should be durable enough to withstand the friction and abrasion because it will face during regular use. Highly durable materials can extend the lifespan of the exoskeleton. As a result, the maintenance and the replacement frequency will be reduced [7]. Research indicates that the durability of materials can affect the economic and long-term benefits of exoskeletons directly.

2.4. The Importance of Lightness in Reducing User Fatigue

Lightness refers to the weight of the material and how it impacts the user. Lightweight materials can improve the user experience by reducing the burden on the wearer. A lighter exoskeleton is easier for the wearers to adapt to during use and reduces pressure on the hand [8]. Choosing the right lightweight material is important for comfort during prolonged wear.

All in all, the wearable requirements of flexible hand exoskeletons should include comfort, flexibility, durability, and lightness. These factors affect the actual use functionality of the exoskeleton together. As a result, they should be considered in the material selection process to achieve the best wearable experience.

3. Common Materials and Their Properties

Material selection can impact wearability significantly in the design of flexible hand exoskeletons. The following review summarizes three common materials: silicone, spandex and nylon. It also analyzes their applications in the flexible hand exoskeleton.

3.1. In-Depth Examination of Silicone and Its Mechanical Attributes

Silicone's mechanical properties are primarily evident in its response to stress and strain. That's because the silicone has a large elastic deformation range which can effectively disperse the external force and reduce the direct pressure [9], thus enhancing comfort [10]. However, silicone's low elasticity poor air permeability can cause discomfort from the heat and moisture when worn for extended periods [11].

3.2. Discussion on Spandex and Its Adaptability to Dynamic Hand Movements

Spandex's high extensibility and low elastic modulus enable it to conform effectively to the dynamic movements of hands [12]. The spandex is able to provide significant bending and stretching abilities that allow the hand joints and muscles to move freely in the design of the exoskeleton. But spandex has a disadvantage in durability. Its elasticity may decrease after being used for a long time, which will affect the functionality of the exoskeleton [13].

3.3. Exploration of Nylon's High-Performance Characteristics

Nylon has high elastic modulus and excellent wear resistance. As a result, it can withstand large mechanical stress and long wear over time. When designing an exoskeleton, nylon can effectively enhance the structural stability of the exoskeleton and reduce wear and tear. In this way, nylon extends the life of the exoskeleton [14]. Nylon fibers are utilized as artificial muscles. That's because they have the capacity to contract upon exposure to heat [15]. However, nylon's relatively low elasticity and air permeability can cause discomfort during wear which may result in sweat buildup [16].

The performance of each materials is contrasted in Table 1. It shows how silicone, spandex, and nylon differ in comfort, flexibility, durability, weight, and air permeability. This table serves as a valuable reference for designers seeking to optimize the material selection process for flexible hand exoskeletons.

Table 1. Material Performance Comparison

Performance	Silicone	Spandex	Nylon
Comfort	Good	Good	Moderate
Flexibility	Moderate	Excellent	Poor
Durability	Moderate	Poor	Excellent
Lightness	Moderate	Good	Good
Air permeability	Poor	Moderate	Poor

The content and definitions of the material properties and their implications for exoskeleton design are clearly shown in Table 1, and this information is crucial for making informed decisions regarding material selection in the development of flexible hand exoskeletons.

4. Application of Materials in Flexible Hand Exoskeletons

The properties of the flexible hand exoskeleton are influenced by the physical properties of the material and its structural design. Figure 2 shows a variety of structural forms that allow for a reasonable balance between comfort, and flexibility, durability and lightness.

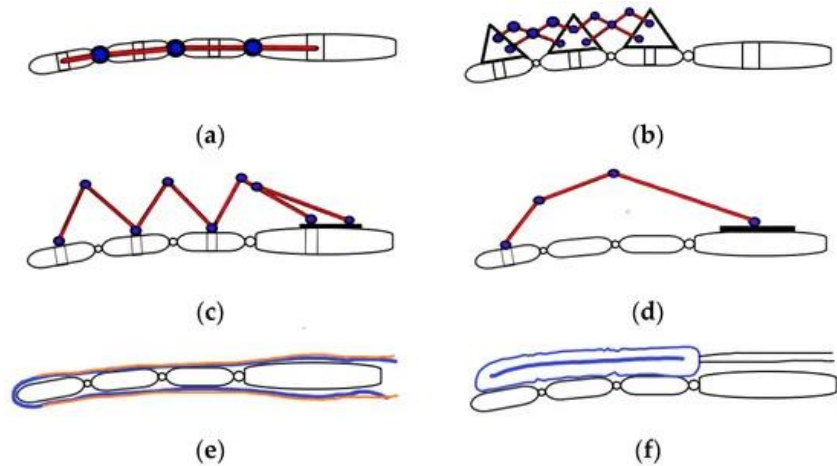


Fig. 2 This figure displays diverse designs of hand exoskeletons, each representing core design principles: (a) Matched-axis, (b) RCR, (c) Four-bar links, (d) Base-to-distal, (e) Tendon-driven, and (f) Jointless, with actuation by pneumatics or hydraulics [17].

Figure 2 showed different existing hand exoskeleton designs. Various designs exist for each category, although the fundamental design idea is illustrated. (a) Matched-axis design. (b) Remote center of rotation (RCR) design. (c) Redundant mechanism (four-bar link mechanisms). (d) Base-to-distal design. (e) Tendon driven glove (complaint). The tendon/cables are illustrated in orange, and the blue represents a glove or flexible base structure. (f) Jointless structure. Can either be actuated from compressed air (aerodynamics) or hydraulic fluids [17].

Figure 2a shows a series structure arranged along the finger joint that can be made with silicone material. This structure distributes the pressure of the exoskeleton through highly elastic silicone evenly over each joint of the finger, thereby improving wearing comfort [9]. The soft touch of the silicone gel also reduces the direct irritation to the skin.

Figure 2b depicts a complex multi-segment crossover structural design with a spandex material. With its excellent elasticity and extension, the structure can fully adapt to the natural movements of the hand, especially in the dynamic movement of the hand can show a very high flexibility [12]. This design allows the hand to move freely during wearing, without being restricted by the exoskeleton.

Figure 2c and 2d show the exoskeleton structure with high geometric stability, which uses nylon material. The high elastic modulus and wear resistance of nylon enable it to withstand large mechanical stress, and it is especially suitable for use in the junction site of the exoskeleton. The

structure in Figure 2d probably provides stable support through the high strength of nylon, which extends the service life of the exoskeleton [14].

Figures 2e and 2f show a more lightweight exoskeleton structure, with a combination of spandex and nylon, to achieve an optimal strength to weight ratio. In these designs, lightweight materials and structural optimization are the core. By optimizing the material distribution and load path of the exoskeleton, it can not only reduce the weight, but also maintain sufficient support force, using a parametric conformal lattice [18]. For example, Figure 2f may combine flexible and rigid materials to both ensure natural hand movement and effectively disperse the pressure on the exoskeleton, thus improving wearing comfort and adaptability.

From the analysis of Figure 2, we can see how the combination of material properties and structural design impacts the overall performance of flexible hand exoskeletons in practical applications. It is important to make flexible hand exoskeletons comfortable, flexible, durable, and lightweight, so we need to choose the right materials and refining the structure.

5. Discussion

In rehabilitation medicine and industrial applications, the flexible hand exoskeleton's design has great potential [19]. The performance of the exoskeleton depends on the choice of material properties and mechanical structure. The earlier analysis studied the characteristics of silicone, spandex, and nylon, and how they can be used in exoskeletons. When choosing materials like silicone, spandex, and nylon and designing the structure, multiple factors need to be considered completely to achieve a balance between comfort, flexibility, durability and portability.

Comfort and flexibility are extremely important in rehabilitation applications [19]. Silicone is good at spreading out pressure and minimizing the skin's irritation because of its comfortable feel and broad elasticity [10]. Yet, its lack of air permeability may make it less comfortable during extended use, for which upcoming designs might improve [11], for example, introducing ventilation holes and blending it with more breathable materials.

Durability and portability play a vital role in industrial applications. With excellent wear resistance and elasticity, nylon has a long service life and endures substantial mechanical stress [14]. But it has low elasticity and air permeability, making it uncomfortable [16] to wear which requires designers to make trade-offs in material selection or to mitigate these effects through structural optimization.

In subsequent studies, further exploration of combinations of multiple materials is needed. What's more, through innovative mechanical structural designs, the performance and user experience of the exoskeleton can be further enhanced, such as using composite materials and new artificial muscle technology [15].

By considering material properties and structural design, the needs of users in different scenarios can be better satisfied. It can also advance the development of flexible hand exoskeleton technology. Future studies should focus on both performance improvement of a single material and overall design optimization under the synergy of multiple materials.

6. Conclusion

This study's comprehensive analysis highlights the crucial importance of material properties and structural design in developing flexible hand exoskeletons. The study has revealed the complex interplay among material choice, ergonomics, and mechanical design, which shows the importance of finding a balance among comfort, flexibility, durability, and lightness for various applications in rehabilitation and industry.

Findings in this study reiterate that silicone has superior comfort and pressure distribution, but its limited air permeability must be carefully integrated considering. Spandex's high flexibility is outstanding. Yet its reduced durability as time goes by brings a significant challenge. Contrarily, nylon has exceptional durability and structural stability. But it also shows poor elasticity and

inadequate air permeability. The innovative combination of these materials, as what the research advises, presents a promising way for future designs, potentially leading to exoskeletons that are high-performing and putting users first.

The exploration of various structural forms in Figure 2 has displayed how different designs can be customized to enhance specific aspects of exoskeleton functionality. For example, designs with matched-axis and remote center of rotation mimic the hand's natural movements, while tendon-driven systems bring their own benefits in terms of simplicity and flexibility.

Focusing future research and development on the synergistic integration of material science and mechanical engineering is really important. That's because the field of exoskeleton technology keeps evolving. This includes exploring new material combinations, such as the combination of spandex and nylon, to create exoskeletons that are durable and flexible. What's more, the incorporation of advanced technologies like artificial muscles and smart materials may be key to produce a new generation of exoskeletons with enhanced adaptability and responsiveness.

Above all, the future of flexible hand exoskeletons depends on the continuous pursuit of innovation, where material selection and design optimization develop together. By really pushing the limits with the materials and designs that we have now, we can envision a future of exoskeletons that are incredibly comfortable, functions exceptionally well, and are completely reliable. This could totally change the way people use them, not just in medicine but in all kinds of industries too.

References

- [1] Liu C, Lu J, Yang H, Guo K. Current State of Robotics in Hand Rehabilitation after Stroke: A Systematic Review. *Applied Sciences*. 2022; 12(9):4540
- [2] Ha T.-J., Lee J.-S., Back S.-H., Kim S.-H., Lee J.-Y. Wearable robot design for industrial application. *Journal of the Korean Society of Precision Engineering*, 2012, 29(5): 433-440.
- [3] Asbeck A.T., Rossi S.M.M.D., Holt K.G., Walsh C.J. A biologically inspired soft exosuit for walking assistance. *International Journal of Robotics Research*, 2015, 34(6): 744-762.
- [4] Xiloyannis M., Chiaradia D., Frisoli A., Masia L. Characterisation of pressure distribution at the interface of a soft exosuit: Towards a more comfortable wear. *Wearable Robotics: Challenges and Trends*, 2019, 22: 135-147.
- [5] Tijjani I., Kumar S., Boukheddimi M. A survey on design and control of lower extremity exoskeletons for bipedal walking. *Applied Sciences*, 2022, 12(5): 2395.
- [6] Rose C.G., O'Malley M.K. Hybrid rigid-soft hand exoskeleton to assist functional dexterity. *IEEE Robotics and Automation Letters*, 2019, 4(1): 73-80.
- [7] Secciani N., La Scalia G., Mencattelli M., Conti A., Carrozza M.C. Wearable robots: an original mechatronic design of a hand exoskeleton for assistive and rehabilitative purposes. *Frontiers in Neurorobotics*, 2021, 15: 1-12.
- [8] Chaichaowarat R., Prakthong S., Thitipankul S. Transformable wheelchair-exoskeleton hybrid robot for assisting human locomotion. *Robotics*, 2023, 12(1): 16.
- [9] Jin J., Yang S., Bae B.-S. Mechanically improved sol-gel derived methacrylate-siloxane hybrid materials with urethane linkage. *Journal of Sol-Gel Science and Technology*, 2012, 61(3): 321-329.
- [10] Kim Y.H., Bae J.Y., Jin J.H., Kwak S.Y., Bae B.S. Microcellular foaming of silicone rubber with supercritical carbon dioxide. *Korean Journal of Chemical Engineering*, 2010, 28(4): 679-688.
- [11] Jiang S., Yong Z. Modulation of mechanical properties of silica-filled silicone rubber by cross-linked network structure. *Polymers*, 2024, 16(16): 2304.
- [12] Tang K.-P.M., Kan C.-W., Fan J.-T., Tso S.-L. Effect of softener and wetting agent on improving the flammability, comfort, and mechanical properties of flame-retardant finished cotton fabric. *Cellulose*, 2017, 24(6): 2619-2634.
- [13] Frigione M., Rodríguez-Prieto A. Can accelerated aging procedures predict the long-term behavior of polymers exposed to different environments? *Polymers*, 2021, 13(16): 2688.

- [14] Mimaroglu A., Unal H. Friction and wear characteristics of glass fiber- and nylon-reinforced polymers under various sliding speeds and loads. *IntechOpen*, 2021, 9(4): 1021-1030.
- [15] Djouani K., Oosthuizen C. A review of active hand exoskeletons for rehabilitation and assistance. *Robotics*, 2021, 10(1): 40.
- [16] Midha V., Kumar S.S., Kumar M.N. Investigation on permeability and moisture management properties of different denim fabrics after repeated laundering. *Journal of the Textile Institute*, 2017, 108(1): 71-77.
- [17] Du Plessis T., Djouani K., Oosthuizen C. A review of active hand exoskeletons for rehabilitation and assistance. *Robotics*, 2021, 10(1): 40.
- [18] Young A., Ferris D. State of the art and future directions for lower limb robotic exoskeletons. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 2017, 25(2): 171-182.
- [19] Saldarriaga A., Gutierrez-Velasquez E.I., Colorado H.A. Soft hand exoskeletons for rehabilitation: approaches to design, manufacturing methods, and future prospects. *Robotics*, 2024, 13(1): 50.