Experimental Testing Of A Rotational Self-Turning Mechanism For Exoskeleton Knee Joint

Zulkiffli Abd Kadir
Faculty of Engineering Universiti
Pertahanan Nasional Malaysia 57000
Kuala Lumpur, Malaysia
zulkiffli@upnm.edu.my

Nuradlan Afiq Baharum
Faculty of Engineering Universiti
Pertahanan Nasional Malaysia 57000
Kuala Lumpur, Malaysia
adlanafiq04@gmail.com

Noor Amira Ilyanie Ruslan
Faculty of Engineering Universiti
Pertahanan Nasional Malaysia 57000
Kuala Lumpur, Malaysia
amirailyanie02@gmail.com

Noor Hafizah Amer
Faculty of Engineering Universiti
Pertahanan Nasional Malaysia 57000
Kuala Lumpur, Malaysia
noorhafizah@upnm.edu.my

Nur Akmal Haniffah
Faculty of Engineering Universiti
Pertahanan Nasional Malaysia 57000
Kuala Lumpur, Malaysia
nurakmal@upnm.edu.my

Mohd Sabirin Rahmat
Faculty of Engineering and Built
Environment, Universiti Kebangsaan
Malaysia, 43600, Selangor, Malaysia
mohdsabirin@ukm.edu.my

***Abstract*— This study focuses on the design, fabrication and experimental testing of a rotational self-turning mechanism for exoskeleton knee joints, aiming to develop a mechanism that allows for natural and efficient movement in individuals with mobility impairments. The proposed mechanism incorporates a rotational self-turning feature, enabling the exoskeleton to adapt and rotate based on the desired movements of the user. The study further explores the calculation of spring stiffness as an essential factor in achieving the desired self-turning mechanism of the knee joint. Calculating the spring stiffness helps to achieve a balance between providing sufficient support and ensuring user comfort. An exoskeleton with adjustable spring stiffness can better adapt to the specific movements and needs of the user, enhancing the overall user experience. The analysis of the knee joint control system from readings of the Arduino software shows a percentage error of approximately 17% between the desired and experimental knee angles, indicating a deviation of 0.1 radians at peak performance, which shows an efficiency of about 83%.**

Keywords—exoskeleton, self-turning mechanism, walking aid

I. INTRODUCTION

Exoskeletons have gained significant attention in recent years as assistive devices for individuals with mobility impairments. These wearable robotic systems aim to enhance the user's mobility and independence by providing additional support and assistance during walking and other activities [1-4]. One important aspect of exoskeleton design is the development of efficient and natural joint mechanisms, particularly for hip and knee joints. The hip and knee joints play an important role in human motion, and replicating their functionality in exoskeletons is essential for achieving natural and comfortable movement [5-7]. Traditional exoskeleton designs often lack the ability to adapt to the user's gait and provide optimal support during different phases of walking. This limitation can result in reduced efficiency, discomfort, and potential gait abnormalities [8].

Several studies have contributed to this field, shedding light on the state of the art in exoskeleton technology and joint mechanism development. Notable references in this regard include [9], who provided a comprehensive review on lower-limb exoskeletons for rehabilitation and assistive applications, and [10] whose book "Wearable Robots: Biomechatronic Exoskeletons" offers insights into the biomechanical aspects of exoskeleton design. To address these challenges, researchers have focused on developing innovative joint mechanisms for exoskeleton hip and knee joints. The aim is to create mechanisms that can rotate and self-turn, allowing the exoskeleton to adapt to the user's movements and provide improved support and functionality [11],12]. These mechanisms need to consider factors such as biomechanics, ergonomics, and user comfort to ensure effective integration with the human body [13].

Several passive and active joint mechanisms have been proposed in the literature to assist lower-limb rehabilitation and mobility. For instance, spring-loaded hinges have been explored to provide energy-efficient support in knee motion [14], while actuator-based exoskeletons offer high precision at the cost of increased complexity and power consumption [15]. In low-cost rehabilitation devices, torsion spring systems are frequently utilized for their simplicity and natural motion feedback [15,16]. However, based on the author's knowledge, limited attention has been given to passive rotational self-turning mechanisms that reset the knee joint position without external power input. This study contributes to this area by proposing a low-cost, passive mechanism utilizing a torsion spring and rotary encoder for knee joint repositioning.

Additionally, [17] and [18] have contributed to the discussion by addressing compliant actuation and adaptive control of lower limb exoskeletons, respectively. Finally, the work of [19] on an electromyography-driven exoskeleton for people with spinal cord injury showcases advancements in assistive exoskeleton technology, further emphasizing the importance of joint mechanisms in enhancing user mobility and independence. These references collectively underscore the significance of innovative joint mechanisms in the development of exoskeletons and their potential to improve the lives of individuals with mobility impairments.

Robotic exoskeletons have emerged as promising tools in enhancing mobility and assisting individuals with lower limbs issuing. However, the issue with the knee joint returning to its initial position after completing one cycle of walking is experimentally evaluated in this study. A self-turning mechanism is proposed that represents the natural motion necessary for the knee joint to return to its original position. This feature allows the exoskeleton to return to its previous position on its own, which improves movement control and stability. The exoskeleton provides greater support by automatically adapting to the knee joint when walking which reduces the possibility of misalignment or pain.

II. DESIGN AND FABRICATION OF SELF-TURNING MECHANISM FOR EXOSKELETON.

Figures 1 and 2 show the design of the proposed exoskeleton knee joint. Some improvements have been added to basic in order to ensure the knee returns to its zero or original position during walking. The rotational self-turning mechanism was designed part by part using SolidWorks software, where each component was virtually assembled using the "mate" function to visualize the complete assembly and verify the alignment before fabrication. The finalized design was then fabricated using a 3D printer with Polylactic acid (PLA) filament, an affordable and commonly used material ideal for prototyping due to its ease of use and lightweight properties.

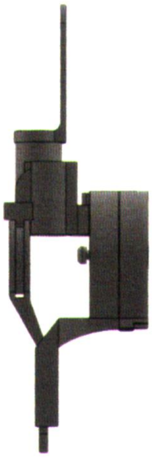

Figure 1: Overview Design of self-turning mechanism

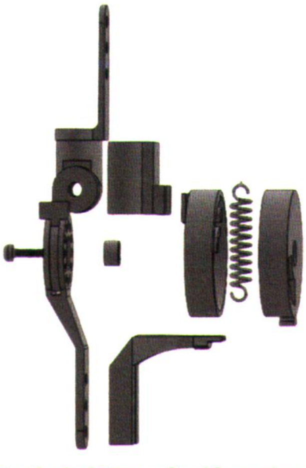

Figure 2: Exploded Part of self-turning mechanism

The upper and lower connections, which are positioned on the thigh and leg, respectively, provide the knee joint with improved functioning. In order to ensure that the spring and bearing mechanism are securely connected, these connections are essential. The purpose is to support the knee joint's stability and avoid any unintentional swaying or misalignment during walking. The bearing, an important part that enables the smooth rotation of the spring's inner and outer housing is essential to the knee joint's flawless operation. The natural flexion and extension of the knee throughout the walking cycle depends on this rotating action. In support of the bearing, the spring delivers the required force to return the knee to its straight position following every step, thus enhancing the joint's overall performance. An additional safety feature is the screw and nut mechanism as shown in Figure 3, which acts as a stop to prevent the bearing from moving too far from its initial position. In order to maintain a regulated and safe range of motion, this preventative step is essential in avoiding situations when the knee can hyperextend or over flex.

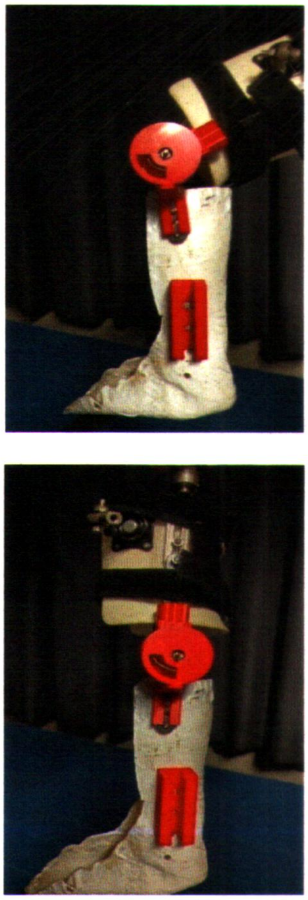

Figure 3: Actual Design of Mechanism during Bending and Straight Position

The installation of the KY-040 Arduino Rotary shown in Figure 4, which is connected to the gear mechanism of the exoskeleton. This rotary encoder functions as an angle sensor, accurately measuring the rotational position of the gear. By capturing the angle data, the sensor provides real-time feedback on the movement and positioning of the exoskeleton's components. This is for ensuring precise control and coordination of the exoskeleton's motions, enhancing both its functionality and responsiveness.

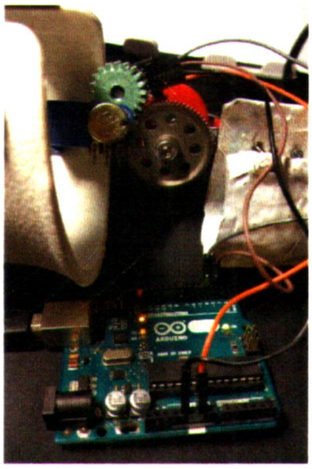

Figure 4: Installation of KY-040 Arduino Rotary

III. EXPERIMENTAL TESTING RESULT OF THE EXOSKELETON KNEE JOINT

The data for the experimental knee angle was obtained using an Arduino-based measurement system. Initially, the system was set up by installing sensors namely rotary encoder on the exoskeleton knee joint to measure the actual knee angle. This sensor was connected to an Arduino microcontroller, which was programmed to read and process the sensor data. The Arduino software was configured to interface with the sensors and collect real-time data, including recording the knee angles at specified intervals.

The experimental result as shown in Figure 5 is focusing on the position-tracking control of a knee joint system. The desired angle is set to achieve during the experiment. The results show that the actual knee joint closely follows the trend of the targeted knee angle, demonstrating the effectiveness of the position-tracking control system. For instance, when the desired knee angle reaches approximately 0.6 radians around 4 seconds, the corresponding experimental knee angle is slightly lower and shows a deviation of 0.1 radians.

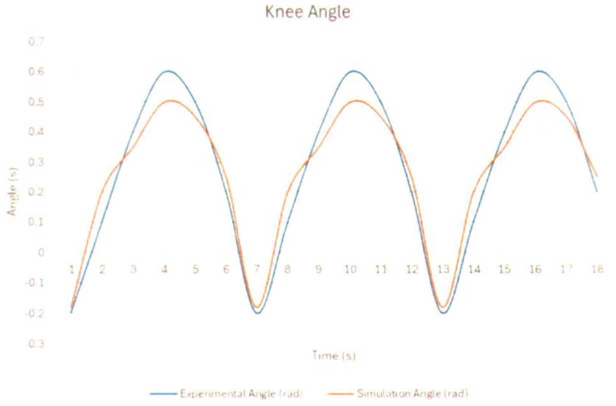

Figure 5: Graph result of both simulation and experimental results for knee angle measurements

The analysis of the knee joint control system reveals a tracking error of approximately 17% between the desired and experimental knee angles, indicating a deviation of 0.1 radians at peak performance. This shows an efficiency of about 83%, demonstrating that the control system effectively tracks the actual knee angle position. The percentage error was calculated by taking the ratio of the peak deviation to the peak angle obtained from simulation. The relatively low percentage error shows a strong correlation between the experimental result and desired angle, allowing the system's overall consistency. However, addressing the observed differences can further accuracy, leading to even more precise position-tracking performance. This evaluation highlights the importance of continual refinement in control systems to achieve optimal functionality and reliability.

Several factors could contribute to these errors, such as mechanical tolerances, sensor inaccuracies and dynamic effects not fully captured in the control development. To optimize the knee joint system's performance and reduce errors, further investigation and adjustments are required. Possible improvements include fine-tuning the control parameters, enhancing sensor accuracy and accounting for additional dynamic factors to the actual system. Overall, the close alignment between the experimental data lays a solid foundation for future enhancements and applications, particularly in areas requiring precise joint angle control, such as assistive exoskeletons for individuals with mobility challenges.

Additionally, a qualitative comparison was performed between the proposed self-turning mechanism and other mechanisms reported in recent literature. Traditional exoskeleton systems that utilize electric actuators such as brushed or brushless DC motors offer high precision control but often result in higher energy consumption, increased system complexity and higher maintenance demands [16]. In contrast, the proposed design uses passive mechanical torque for the reset motion which eliminates the reliance on active power sources. This approach not only reduces energy requirements but also improves system reliability by minimizing the risk of electronic malfunctions.

The proposed mechanism allows for smoother and more natural motion during the return phase compared to rigid-link spring-based designs, which may restrict rotational freedom and result in abrupt or unnatural joint movements. This design strategy aligns with recent advancements that emphasize biomechanical compatibility and continuous joint movement to enhance comfort and effectiveness in wearable assistive systems [20]. Furthermore, the compact and modular construction of the mechanism used commonly available components which are easier to apply into rehabilitation platforms. Such modularity supports scalability and adaptability, which are essential for the continued development of user-specific and application-oriented exoskeleton technologies [21].

IV. CONCLUSION

In conclusion, this research successfully achieved its objectives by designing and fabricating a rotational self-turning mechanism that mimics the natural movement of human walking and evaluating its effectiveness in actual exoskeletons with a focus on knee angles. The results showed that the exoskeleton equipped with this mechanism could accurately replicate natural knee movements, achieving knee angles within a range that closely aligns with human biomechanics which shows an efficiency of about 83%. This efficiency can be measured and analyzed to enhance the system further.

However, this study has several limitations which the current prototype was tested without actual human loading, which may influence the dynamics of actual use. In addition, the limited resolution of the KY-040 rotary encoder and mechanical tolerances also may reduce the precision and consistency of knee angle measurements, while long-term wear in components such as the spring and bearing system could further degrade the performance over time. To address these limitations, future work should explore the use of higher-resolution sensors, perform dynamic testing under human load conditions, assess system durability, and include ergonomic evaluations with actual users to enhance reliability and practical usability.

As a result, the study provided understandings into the application of biomechanically inspired mechanisms in wearable robotics, opening opportunities for further research and development. Overall, the project confirms the capability and effectiveness of the designed mechanism, ensuring a step forward in the development of more natural and efficient exoskeletons with the potential to significantly enhance the quality of life for individuals requiring mobility assistance.

ACKNOWLEDGMENT

The research was conducted under the Self-Funded Research Grant SF0141-UPNM/2023/SF/TK/3 at the Faculty of Engineering, Universiti Pertahanan Nasional Malaysia. The authors also wish to acknowledge the support of the Universiti Pertahanan Nasional Malaysia for providing the financial assistance necessary for this publication.

REFERENCES

[1] B. M. Pillai, P. Owatchaiyapong, S. Treratanakulchai, D. Sivaraman, S. Ongwattanakul, and J. Suthakorn, "Lower limb exoskeleton with energy-storing mechanism for spinal cord injury rehabilitation," *IEEE Access*, vol. 11, pp. 133850–133866, 2023.

[2] U. Martinez-Hernandez, B. Metcalfe, T. Assaf, L. Jabban, J. Male, and D. Zhang, "Wearable assistive robotics: A perspective on current challenges and future trends," *Sensors*, vol. 21, no. 20, Oct. 2021.

[3] G. Forte *et al.*, "Exoskeletons for mobility after spinal cord injury: A personalized embodied approach," *J Pers Med*, vol. 12, no. 3, Mar. 2022.

[4] C. McGibbon *et al.*, "Effect of using of a lower-extremity exoskeleton on disability of people with multiple sclerosis," *Disabil Rehabil Assist Technol*, vol. 18, no. 5, pp. 475–482, 2023.

[5] J. Jiang, P. Chen, J. Peng, X. Qiao, F. Zhu, and J. Zhong, "Design and optimization of lower limb rehabilitation exoskeleton with a multiaxial knee joint," *Biomimetics*, vol. 8, no. 2, Jun. 2023.

[6] A. F. Pérez Vidal *et al.*, "Soft exoskeletons: development, requirements, and challenges of the last decade," Jul. 01, 2021, *MDPI AG*.

[7] J. Ma, D. Sun, and X. Chen, "Hip–knee coupling exoskeleton with offset theory for walking assistance," *Front Bioeng Biotechnol*, vol. 9, Jan. 2022.

[8] C. W. Wang, Y. T. Wang, K. Osawa, K. Nakagawa, and E. Tanaka, "Adaptive gait model with hybrid control for mass production oriented exoskeleton," in *ICARM 2024 - 2024 9th IEEE International Conference on Advanced Robotics and Mechatronics*, Institute of Electrical and Electronics Engineers Inc., 2024, pp. 146–151.

[9] A. Plaza, M. Hernandez, G. Puyuelo, E. Garces, and E. Garcia, "Lower-limb medical and rehabilitation exoskeletons: A review of the current designs," 2023, *Institute of Electrical and Electronics Engineers Inc.*

[10] J.L. Pons, "Wearable robots: biomechatronic exoskeletons," 1st ed. Hoboken, NJ, USA: *John Wiley & Sons*, 2008.

[11] Y. Wang, W. Zhang, D. Shi, and Y. Geng, "Design and control of an adaptive knee joint exoskeleton mechanism with buffering function," *Sensors*, vol. 21, no. 24, Dec. 2021.

[12] G. Li, X. Liang, H. Lu, T. Su, and Z. G. Hou, "Development and validation of a self-aligning knee exoskeleton with hip rotation capability," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 32, pp. 472–481, 2024.

[13] T. Wang *et al.*, "A Review on the rehabilitation exoskeletons for the lower limbs of the elderly and the disabled," Feb. 01, 2022, *MDPI*.

[14] R. Hidayah, D. Sui, K. A. Wade, B. C. Chang, and S. Agrawal, "Passive knee exoskeletons in functional tasks: Biomechanical effects of a SpringExo coil-spring on squats," *Wearable Technologies*, vol. 2, 2021.

[15] K. B. Bumbard, H. Herrington, C. H. Goh, and A. Ibrahim, "Incorporation of torsion springs in a knee exoskeleton for stance phase correction of crouch gait," *Applied Sciences (Switzerland)*, vol. 12, no. 14, Jul. 2022.

[16] G. Marinou, I. Kourouma, and K. Mombaur, "Development and validation of a modular sensor-based system for gait analysis and control in lower-limb exoskeletons," *Sensors*, vol. 25, no. 8, p. 2379, Apr. 2025.

[17] D. Su, Z. Hu, J. Wu, P. Shang, and Z. Luo, "Review of adaptive control for stroke lower limb exoskeleton rehabilitation robot based on motion intention recognition," 2023, *Frontiers Media SA*.

[18] M. D. C. Sanchez-Villamañan, J. Gonzalez-Vargas, D. Torricelli, J. C. Moreno, and J. L. Pons, "Compliant lower limb exoskeletons: A comprehensive review on mechanical design principles," May 09, 2019, *BioMed Central Ltd*.

[19] N. S. S. Sanjeevi, Y. Singh, and V. Vashista, "Recent advances in lower-extremity exoskeletons in promoting performance restoration," Dec. 01, 2021, *Elsevier B.V.*

[20] D. Eguren, M. Cestari, T. P. Luu, A. Kilicarslan, A. Steele, and J. L. Contreras-Vidal, "Design of a customizable, modular pediatric exoskeleton for rehabilitation and mobility," in *2019 IEEE international conference on systems, man and cybernetics (SMC)*, IEEE, 2019, pp. 2411–2416.

[21] D. M. G. Preethichandra *et al.*, “Passive and active exoskeleton solutions: Sensors, actuators, applications, and recent trends,” Nov. 01, 2024, *Multidisciplinary Digital Publishing Institute (MDPI)*.