Mathematical Statistician and Engineering Applications
ISSN: 2326-9865

Implementation of Motor-Based Wearable Knee Rehabilitation Robot System using 3D Printing

Soo-Bin Cho[1], Hyeon-Jun Kim[2], Eun-Ji Lee[3] and Soo-Whang Baek[4+]
[1,2,3,4] Sangmyung University, Dept. of Human Intelligence and Robot Eng., 31 Sangmyungdae-gil, Dongnam-gu, Cheonan-si, Chungcheongnam-do, 31066, Korea
[1]dbsehd1130@gmail.com, [2]kimhj2938@naver.com, [3]eunji.jennifer@gmail.com,
[4+]swbaek@smu.ac.kr(corresponding author)

Article Info
Page Number: 527 – 536
Publication Issue:
Vol. 71 No. 3 (2022)

Abstract

This paper presents the implementation of a motor-based wearable knee rehabilitation robot (KRR) system using 3D printing. The proposed KRR is designed to support the user's rehabilitation movement when the user applies a force exceeding a certain value by utilizing the reaction force generated by the motor in a stationary state. A stepper motor attached to the user’s body rotates when the user applies a force over a certain value to a load-cell sensor. As the stepper motor rotates, a trapezoidal thread connected to the motor rotates, thereby adjusting the position of the robot's moving frame to assist the user in rehabilitation. The KRR proposed in this study was designed using 3D printing to have a lightweight structure to reduce the load on the knee when the system was worn by the user. To verify the safety of the proposed KRR, structural analysis was performed to analyze its characteristics, and it was experimentally confirmed that the KRR will be useful for the user's knee rehabilitation through the production of prototypes..

Keywords: Stepper Motor, Load Cell Sensor, Reaction Force, Knee Rehabilitation, 3D Printing, Structural Analysis

Article History
Article Received: *12 January 2022*
Revised: *25 February 2022*
Accepted: *20 April 2022*
Publication: *09 June 2022*

1. Introduction

Currently, robots are used in various fields, such as education, healthcare, agriculture, and mobility, and perform various tasks more efficiently than humans. Robots can perform various tasks, including repetitive tasks that are difficult for humans to perform, in a short span of time. The wearable robot field has been actively and continuously developed, with many companies participating in the development (Kim et al., 2019). There are many types of exoskeleton wearable robots, and existing research has mainly been conducted on these robots (Yeem et al., 2019). Wearable robots can directly support human movements and

---

[+] Corresponding author. Tel.: +82-41-550-5543; fax: +82-41-550-5549.
E-mail address: swbaek@smu.ac.kr.

provide real-time feedback on these movements. Utilizing these characteristics, they are also used in fields such as posture correction (Rajasekaran et al., 2015). Wearable robots become parts of the body, such as human arms and legs, thereby making human life more convenient. These robots may also be used to assist rehabilitation exercises to restore injured body functions.

With the accelerating aging of the population, the proportion of individuals rehabilitating at home is increasing. If a non-specialist does rehabilitation exercises at home without a professional, they will not get correct feedback. (Kim et al., 2018). Moreover, if a person repeats the exercise method and intensity for a certain period of time, they will get accustomed to the rehabilitation exercise; consequently, they will not obtain significant benefits from the exercise, and their muscle strength will not improve. These issues have led to research on rehabilitation robots and health care devices (Park, 2020). Research on related sensors is underway because rehabilitation robots must receive feedback in response to the user movement. Studies on force sensors have been extensively conducted (Kim and Kim, 2016; Jung and Kim, 2016; Jung and Kim, 2017). In addition, studies on the use of electromyography (EMG) sensors and electromagnetic sensors have been conducted (Askari et al., 2018).

Scholars have conducted studies that assist the user's knee function rather than improving their muscle strength (Karavas et al., 2015; Kim et al., 2019; Kwon et al., 2019; Kim and Park, 2021). A rehabilitation mechanism aimed at improving muscle strength has also been studied. However, the mechanism is difficult to use in a small space because the users often lie down and use it (Lee et al., 2013; Chaparro Rico et al., 2016).

This study proposes a wearable knee rehabilitation robot (KRR) that does not assist knee function but practically helps improve the user's muscle strength. Because a user performs the rehabilitation exercise while sitting in a chair, the user can easily perform the exercise in a narrow space. The proposed KRR helps users to sit in a chair and lift and lower their legs to build strength, they can easily perform rehabilitation exercise in a relatively narrow space. Using the reaction force generated by the stationary motor, the fixed motor supports the force with which the user tries to move. When a force above a certain value is detected, the motor rotates to assist the user's movement and improve muscle strength. In this paper, we present the structural design and control system design of the KRR for this purpose. Furthermore, 3D structural analysis of the mechanism is presented to confirm the mechanical safety of the designed KRR. We manufactured a prototype of the KRR using a 3D printer and verified the design validity of the proposed KRR through experiments.

2. Knee Rehabilitation Robot

2.1. Structure of knee rehabilitation robot

The model of the proposed KRR is shown in Fig. 1. The KRR causes the frame connected to the trapezoidal thread to move back and forth according to the rotational direction of the stepper motor to bend and extend the knee. The state in which the knee is bent is shown in Fig. 1(a). When the user bends their knee, the robot's stepper motor rotates clockwise and the frame connected to the trapezoidal thread moves forward, thus allowing the user to bend their knee. In contrast, the state in which the knee is straightened is shown in Fig. 1(b). When the user straightens the knee, the stepper motor rotates counterclockwise so that the trapezoidal screw enters the back, thereby shortening the frame and assisting the user in extending the knee.

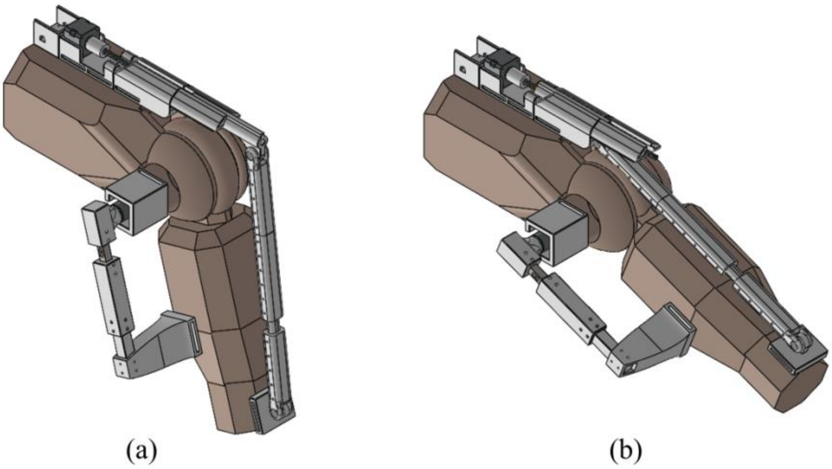


Fig 1: Model of KRR (a) Knee bent, (b) Knee straightened

The main part of the KRR, as shown in Fig. 2, consists of a stepper motor, trapezoidal screws, micro controller unit (MCU), fixed frame, and moving frame. Fig. 2(a) shows the fixed and moving frames of the main part. The moving frame is coupled with a nut. Fig. 2(b) shows the main part in which all the above-mentioned parts are assembled. In this study, the moving frame was designed to have smooth movement. The moving frame composed of the trapezoidal thread coupled to the stepper motor performs linear motion.

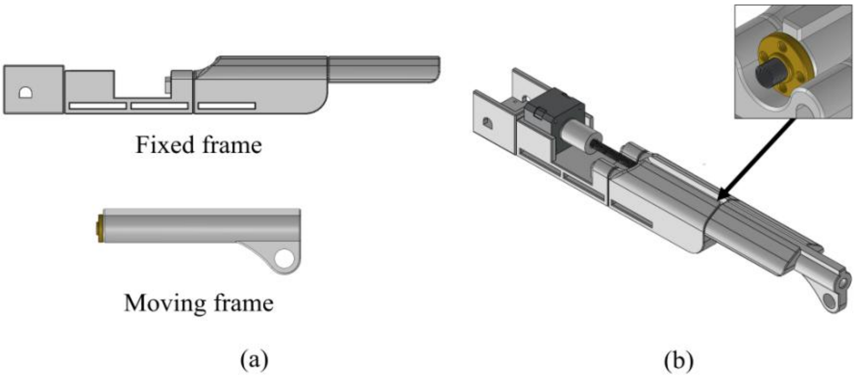


Fig 2: Main part of KRR: (a) Main part frame. (b) Combined main part

The measuring part of the KRR is shown in Fig. 3. The part consists of a fixed frame, stepper motor, and load-cell sensor. The stepper motor of the part is attached to the rotational axis of the knee and calf. The load-cell sensor fixed to the measured part was used to measure the lifting or lowering force of the user’s foot.

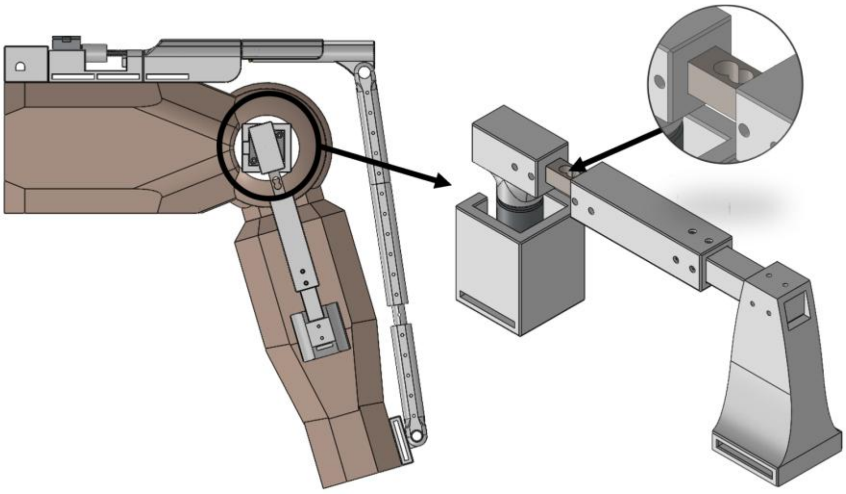


Fig 3: Measuring part of KRR

2.2. Control system

The system block diagram for implementing the KRR algorithm is shown in Fig. 4. The system consists of an input unit that receives the input from the load-cell sensor, a control unit that uses MCU, and an output unit that drives a stepper motor. We used two stepper motors and a load-cell sensor to implement a system for effective control of the KRR. When a force is applied to the load-cell sensor, an electric output is generated in proportion to its magnitude. When a force is applied to the load cell, the elastic body is strained, and the force applied by the user can be measured through a strain gauge that measures this strain value.

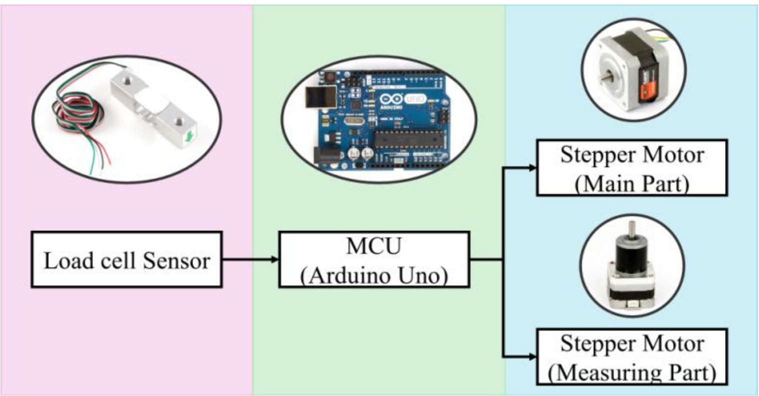


Fig 4: Configuration diagram of KRR system

The control unit of the KRR determines the drive of the KRR by the control unit according to the force applied by the user. The stepper motor attached to the fixed frame of the measuring part provides a reaction force to the force applied by the user. Initially, the load cell is stationary, but when it experiences a certain force, it rotates to assist the user in movement. The stepper motor of the main part drives the main part. When the trapezoidal thread rotates with the rotation of the stepper motor, the moving frame moves linearly. It directly helps the user to stretch and bend the knee, depending on the position of the moving frame. The input value of the load-cell sensor and the two stepper motors uses the Arduino board to process and control the data. The process of KRR algorithm configuration is shown in Fig. 5. The

KRR can be divided into two algorithms according to the starting direction of the knee rehabilitation exercise. The first method is to start the rehabilitation by applying force to straighten the knee in the initial state of a bended knee using the KRR. The stepper motor attached to the measuring part of the KRR is initially stopped, and it remains in this state until the user applies a force above a certain value to extend the knee. When the user applies a force over a certain value to the load-cell sensor to straighten the knee, the stationary stepper motor attached to the main part and measuring part of the KRR rotates. Consequently, the moving frame moves linearly while the trapezoidal screw connected to the stepper motor rotates, and the user moves to extend the knee. The second method is the opposite of the first method. It is a knee rehabilitation method using the reaction force of the force to bend the knee from its initial straightened state. The user's initial state is opposite to that in the previous method, and a force to bend the knee is applied to the KRR in a state where the knee is straightened. At this time, when the load-cell sensor value becomes equal to or less than a specific value, the stepper motor rotates to drive the KRR. Consequently, the moving frame moves linearly while the trapezoidal screw connected to the stepper motor rotates, and the user moves to bend the knee.

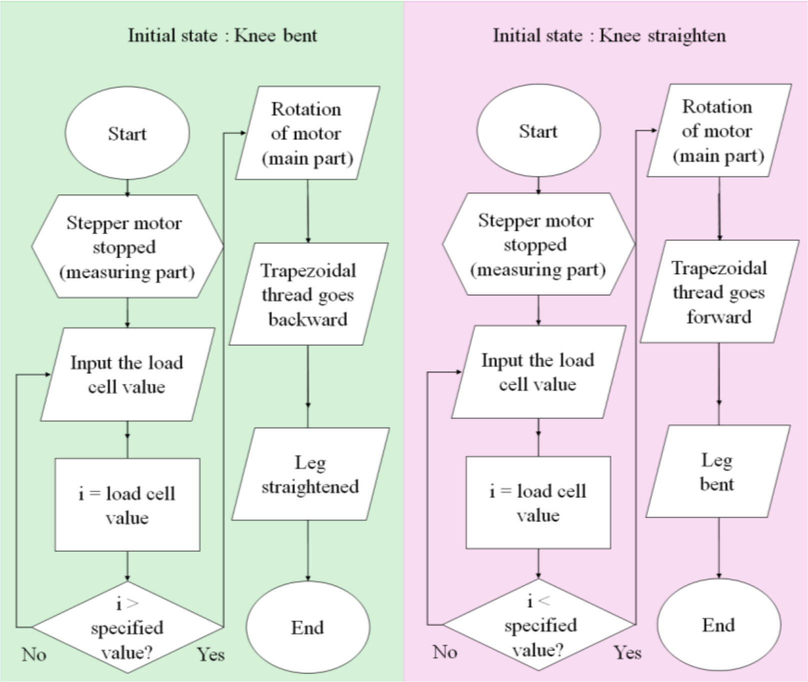


Fig 5: Flowchart of KKR algorithm

3. Structural analysis

The load-cell sensor measurement was measured according to the force applied to the KRR, and a three-dimensional structural-analysis simulation was performed to analyze the safety of the structure. The material properties of the frame and load cell are listed in Table 1. For structural analysis, PLA was used as the frame material for KRR, and AISI 4340 steel was used as the material for the load-cell sensor.

Table 1: Material properties

Items	KRR's frame	Load cell	Unit
Material	PLA	AISI 4340 steel	-
Modulus of elasticity	3500	205000	N/mm²
Poisson's ratio	0.36	0.285	-
Shear modulus	673	80000	N/mm²
Mass density	1250	7850	kg/m³
Tensile strength	36.73	745	N/mm²
Thermal conductivity	0.24	44.5	W/(m·k)
Specific heat	3016	475	J/(kg·K)

Figure 6. shows the structural-analysis characteristic result of the measurement part. The conditions while performing the structural analysis are displayed in Fig. 6(a). The lower surface of the measurement frame that fixes the stepper motor was fixed, and a force was applied to the lower surface of the frame attached to the user's calf to enable movement. The direction of the force is parallel to the lower surface and is set to be the same as the direction in which the user applies the force. When a force of 100 N was applied with such a setting, the stress-distribution characteristics were confirmed by the structural analysis, as shown in Fig. 6(b).

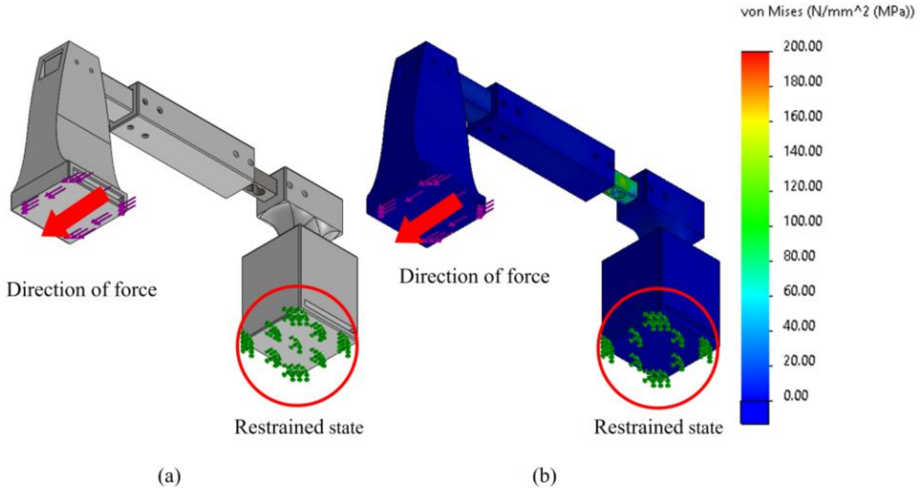
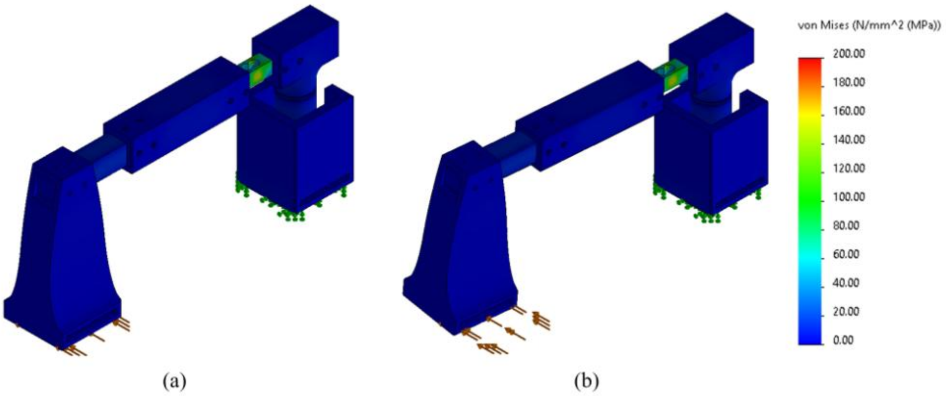


Fig 6: Stress analysis of measuring part: (a) Analysis conditions, (b) Analysis result

Stress analysis was performed on the KRR structure to check the deformation state of the frame that appears when a force is applied to the frame, and the results are shown in Fig. 7. When a force of 100 N was applied, the pressure applied to the load-cell sensor was 120–150

MPa. Meanwhile, it can be seen that the pressure applied to the frame of the KRR is less than 10 MPa, and almost no pressure is applied. Therefore, the force applied to the measured part of the KRR is fully transmitted to the load-cell sensor. Fig. 7(a) shows the frame shape before the deformation due to force. The deformation that occurs when a force is applied in the state shown in Fig. 7(a) is shown in Fig. 7(b). It can be observed in the figure that the KRR frame does not deform when the force is applied.

Because the KRR targets patients undergoing a rehabilitation exercise, it was determined that the magnitude of the force applied to the KRR will be small, and in the range of 1–100 N, force was increased by 10 N to perform the analysis. Subsequently, in the range of 100–500 N, the analysis was interpreted as a condition for increasing the magnitude of the force by 100 N. The results of the structural analysis are shown in Table 2.



(a)

(b)

Fig 7: Stress analysis result of measuring part: (a) Before deformation, (b) After deformation

Table 2: Pressure applied to the load cell according to the force

Power to move the leg (N)	**Pressure applied to the load cell (MPa)**
1	1–1.5
10	10–16
20	20–30
30	36–46
40	48–60
50	60–75
60	78–91
70	90–105
80	102–119
90	114–133
100	126–150
200	258–340
300	360–470

400	500–600
500	600–720

4. Prototype design and experimental evaluation

The designed KRR was manufactured using a 3D printer, and Fig. 8 shows the printed prototype. Fig. 8(a) depicts the KRR parts printed using the 3D printer. Fig. 8(b) depicts assembled printed parts worn by the user. The frame that is fixed in front of the calf and supports the user's leg has several holes, similar to a belt; therefore, it can be adjusted to fit the length of the leg and fixed by inserting a pin. In addition, to fix the KRR and the user's legs, a space was created in the frame of the thighs, knees, and ankles to accommodate the straps made of hook-and-loop fastener material, and the straps were passed through to wrap and fix the legs.

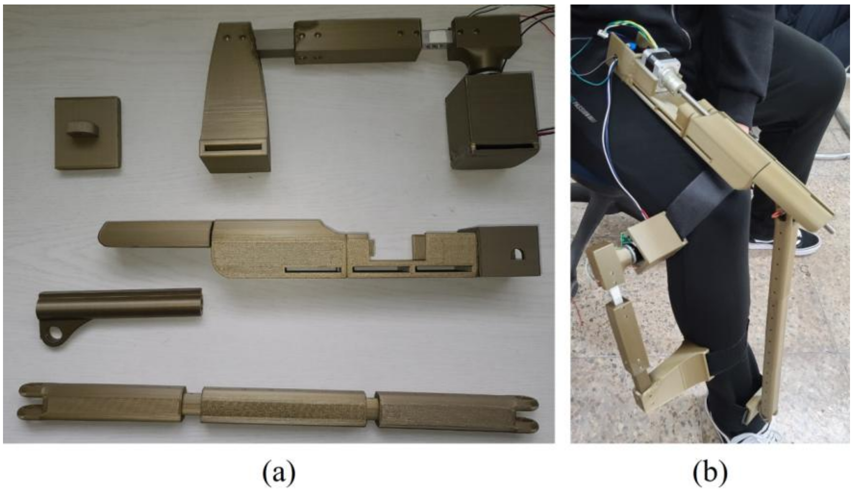

(a) (b)

Fig 8: KRR designed using a 3D printer: (a) Printed parts, (b) Prototype worn by a user

After the user wore the KRR, when the experiment proceeded, it was confirmed that the stepper motor rotates clockwise and counter-clockwise according to the direction of the force applied by the user. Accordingly, it was confirmed that the connected trapezoidal screws rotate and the moving frame of the KRR moves its position. The user also repeated the motion of bending and straightening the leg, thereby confirming that the device operates properly.

5. Conclusion

In this study, structural control system designs of the KRR were conducted via a 3D-modeling program. The load-cell sensor measured the force generated when the user bends and spreads their knees. The stepper motor was driven with the measurements and allowed the trapezoidal thread connected to it to rotate. This helped realize a function to control the position of the moving frame of the KRR. When the moving frame was moved to the front of the KRR, it helped the user to bend their leg. When the position of the moving frame was moved to the back of the KRR, a rehabilitation-exercise robot was manufactured to perform the motion of straightening the knee. When a force was applied to the KRR through three-dimensional structural analysis, the force applied to the load cell sensor was measured. Because a rehabilitation exercise robot was manufactured for patients, the instrument was controlled in consideration of safety. Thus, it was confirmed that the function and structural safety of KRR were guaranteed. In the future, we plan to improve the KRR and implement a healthcare robot that is significantly helpful for users by linking the KRR with an IoT system.

6. Acknowledgements

This study was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No. 2021R1F1A1061567).

7. References

1. Askari, H. Asadi, E. Saadatnia, Z. Khajepour, A. Khamesee. MB, & Zu, J. (2018). A flexible tube-based triboelectric–electromagnetic sensor for knee rehabilitation assessment. *Sensors and Actuators A: Physical*, 279, 694-704. https://doi.org/10.1016/j.sna.2018.05.016
2. Chaparro Rico, BDM. & Castillo Castañeda, E. (2016). Design of a 2DOF parallel mechanism to assist therapies for knee rehabilitation. *Ingeniería e Investigación*, 36(1), 98-104. https://doi.org/10.15446/ing.investig.v36n1.53191
3. Jung, J-H. & Kim, G-S. (2016). Design of three-axis force/torque sensor for rehabilitation robot. *Journal of the Korean Society for Precision Engineering*, 33(4), 309-316. https://doi.org/10.5302/J.ICROS.2016.16.0067
4. Jung, J-H. & Kim, G-S. (2017). Design of force sensors of rehabilitation robot for knee rehabilitation. *Journal of Institute of Control, Robotics and Systems*, 23(1), 46-52. https://doi.org/10.5302/J.ICROS.2017.16.0176
5. Karavas, N. Ajoudani, A. Tsagarakis, N. Saglia, J. Bicchi, A. & Caldwell, D. (2015). Tele-impedance based assistive control for a compliant knee exoskeleton, *Robotics and Autonomous Systems*, 73, 78-90. https://doi.org/10.1016/j.robot.2014.09.027.
6. Kim, ES. & Park, KN. (2021). Development of walking and rehabilitation assistance device for knee joint. *Journal of Rehabilitation Welfare Engineering & Assistive Technology*, 15(3), 158-163. https://doi.org/10.21288/resko.2021.15.3.158
7. Kim, H. Lee, H. & Kim, J. (2018). Electromyography-signal-based muscle fatigue assessment for knee rehabilitation monitoring systems. *Biomedical engineering letters*, 8(4), 345-353. https://doi.org/10.1007/s13534-018-0078-z
8. Kim, H-S. & Kim, G-S. (2016). Design of two-axis force/torque sensor for hip joint rehabilitation robot. *Journal of Institute of Control, Robotics and Systems*. 22(7), 524-529. https://doi.org/10.5302/j.icros.2016.16.0067
9. Kim, HS. Koo, DS. Nam, YJ. Cho, K-J. & Kim, S. (2019). Research on technology status and development direction of wearable robot. *Fashion & Textile Research Journal*, 21(5), 640-655. https://doi.org/10.5805/SFTI.2019.21.5.640
10. Kim, JU. Kim, GE. Ji, YB. Lee, AR. Lee, HJ. & Tae, KS. (2019). Development of a knee exoskeleton for rehabilitation based EMG and IMU sensor feedback. *Journal of Biomedical Engineering Research*, 40(6), 223-229. https://doi.org/10.9718/JBER.2019.40.6.223
11. Kwon, H-G. Ko, H-G. Song, Y-O. Son, E-S. & Lee, B-J. (2019). Knee rehabilitation system through EMG signal analysis and BLDC motor control. *The Journal of the Korea Institute of*

Electronic Communication Sciences, 14(5), 1009-1018. https://doi.org/10.13067/JKIECS.2019.14.5.1009

12. Lee, G.-H., Kim, Y.-J., Park, S.-H., Lee, H.-S., & Cho, H.-A. (2013). A study on the rehabilitation equipment for knee joint. *Journal of manufacturing engineering & technology*. 22(3-1), 509-517. https://doi.org/10.7735/ksmte.2013.22.3.509
13. Park, B. (2020). A study on the latest trends and development prospects of wearable healthcare industry focusing on healthcare products and latest research of a renowned international journal. *Journal of Next-generation Convergence Technology Association*, 4(2), 161-172. https://doi.org/10.33097/JNCTA.2020.04.02.161
14. Rajasekaran, V. Aranda, J. Casals, A. & Pons, JL. (2015). An adaptive control strategy for postural stability using a wearable robot. *Robotics and Autonomous Systems*, 73, 16-23. https://doi.org/10.1016/j.robot.2014.11.014
15. Yeem, S. Heo, J. Kim, H. & Kwon, Y. (2019). Technical Analysis of Exoskeleton Robot. *World Journal of Engineering and Technology*, 7, 68-79. https://doi.org/10.4236/wjet.2019.71004