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Original Article

Study of Wearable Suit Structure Using Non-Powered Passive Actuator

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Abstract *- Wearable robots are boosting production innovation of workers by being applied to manufacturing processes. Accidents may occur due to repetitive tasks for a long period of time and accumulated work-related fatigue in the existing manufacturing process. Wearable robots have gained much attention by emerging as a next-generation technology for user convenience and safety in manufacturing processes and daily activities. Wearable robots are described as 'wearing' or 'putting on' clothing-type robots. These robots are worn by users on all or parts of the human body such as the arms, legs, waist, and others, to generally assist user's exercise ability, muscle strength and endurance. These wearable robots are categorized into active and passive types depending on the use of actuators and classified according to wearing body parts and applied areas. This study developed a wearable suit that can assist users in their work of heavy material handling using passive type, non-powered soft actuators. Moreover, this study investigated passive wearable robots that assist human muscle strength using non-powered soft actuators by improving the weaknesses of active wearable robots.*

Keywords - *Wearable suit, Non-powered soft actuator, Multi-body dynamics analysis, Power assist, Erector spinae muscles.*

1. Introduction

Body assistive devices are developed to meet the needs of the increasing aged population and industrial sites. In particular, the need for body assistive devices is steadily growing for laborers in industrial sites, and users are demanding devices that ensure intelligence, convenience and safety. Wearable robots are worn on or attached to the user's body. Typically, wearable robots include all kinds of robots that are worn on or attached to the body and designed to integrate with human body movements to assist or improve exercise ability and muscle strength. Wearable robots assist the user's muscle strength and endurance by wearing them on all or parts of the human body, such as the arms, legs, waist, etc. They are mainly classified into active and passive types depending on the use of actuators requiring power supply. They can be subdivided into detailed categories according to wearing body parts and applied areas. The first wearable robot was the Hardiman developed by General Electric in 1965. Afterwards, the University of Tsukuba in Japan and the University of California, Berkeley in the USA have begun to build gait assistive robots since the early 2000s. Wearable robots were seen with negative views from the mid-2000s to early 2010s, and only a few products were developed during this period. Several institutions independently carried out research on actuator modules, electronic circuits, control methods and others. In particular, studies on wearable robots have been actively performed since the mid-2010s. Japan, South Korea, and the USA have mainly been involved in development, and robots providing assistance at the level of single articulation only have been developed instead of assistive robots for the entire lower limb. These robots are used in the rehabilitation and treatment of patients suffering from neurological or musculoskeletal disorders and the elderly and weak experiencing inconvenience in daily living due to muscle strength weakening by aiding their assistance and rehabilitation.

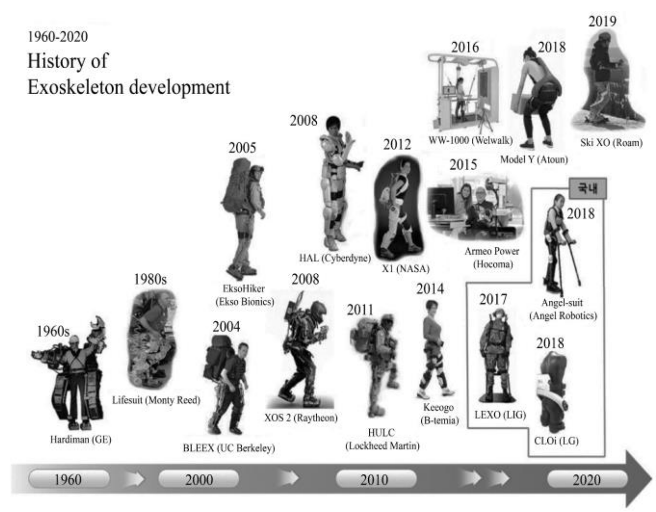


Fig. 1 Changes in wearable robot technologies

Moreover, the application of wearable robots has gained considerable attention for purposes of musculoskeletal disease prevention, fatigue reduction, and productivity improvement. In addition, wearable robots are increasingly expanding in various industrial sectors, including logistics, construction, manufacturing, service and others. Despite high interest and demand for assistive wearable robots in industrial sites and daily activities, the use of currently developed wearable robots is limited by heavy weight, discomfort of wearing, and other reasons. For the extended use of wearable robots, passive and active-soft wearable robots are being investigated aside from active-rigid wearable robots. This study is a Wearable Robot that applies a Non-Powered Passive Actuator that helps the user's strength and endurance by wearing or combining it on parts of the body, such as a person's arms, legs, and waist, or to assist the user's athletic ability or strength called 'wearing' or 'putting on' robot as a wearable robot. It is a robot study that applies lightweight passive, non-powered soft actuators beyond the existing active type of electric motor driving.

2. Structure of Wearable Suit

The structure of the wearable suit system investigated in this study is applied with lightweight passive type, non-powered soft actuators powered by electric motors instead of using conventional active actuators driven by electric motors. By reducing actuator weight, this study enhanced user convenience by improving wearability and the robot's weight and others. As shown in Figure 2, the user can use non-powered soft actuators by controlling the assistive power of muscle strength on his/her own. A non-powered soft actuator consists of a rod and cylinder for reciprocating stroke motion, hinges at both ends of the actuator for attachment and fixation, and a rotatable controller at the cylinder hinge. This is designed to be connected to the coil spring inside and change repulsive force by controlling the coil spring's free length.

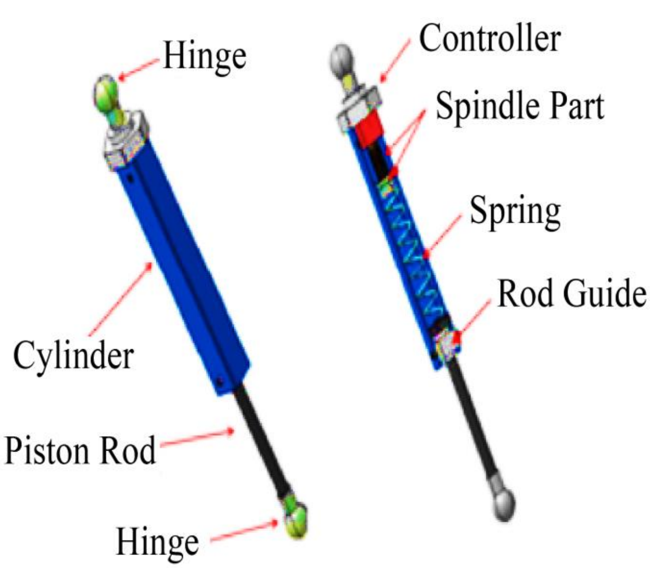


Fig. 2 Non-powered soft actuator

Table 1. Measurement of repulsive force of variable spring

Category	Repulsive force(N)	Remark
Before variable	40.7	Measurement to a vertical direction using UTM
After variable	79.2	

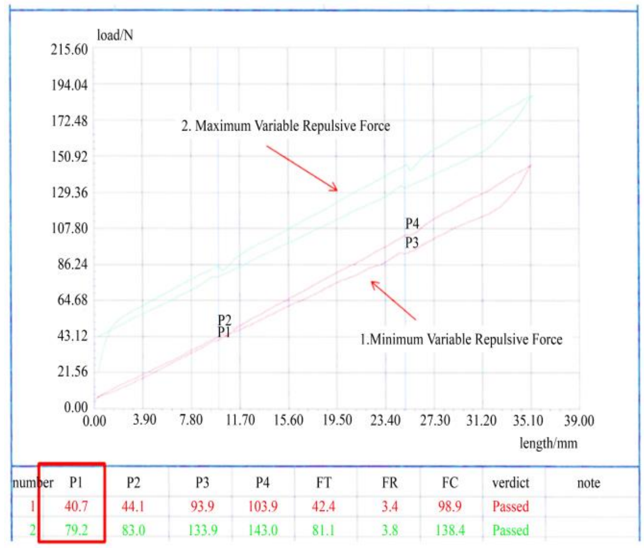


Fig. 3 Variable spring repulsive force result

The wearable suit helps enhance muscle strength as it is compressed when bending one's waist forward, and the spring extends when straightening the back. The auxiliary spring for muscle strength is designed to apply force appropriate for the user's body type and muscle strength by regulating muscle strength on their own. The suit is designed as the structure of joints capable of bending motion of the waist, similar to the human body, for a sense of activity and wearability when wearing it. For the ease and convenience of wearing and taking off, the suit is designed to be capable of spreading the shoulder, waist, and legs in both directions from the spine and to attach non-powered soft actuators on both sides of the chest after putting it on the body.

In addition, structural multibody analysis was performed based on wearable suit design. Structural analysis was done by reviewing the mobility and force of the wearable suit designed with four passive, non-powered soft actuators. In the analysis, the constant value of the passive non-powered soft actuator spring was 4.29 N/mm, and the structure was made of aluminium 2024.

As demonstrated in Figure 5, the model had a non-powered soft actuator on the left and right sides in the upper and lower parts of the waistband. The height of the model was 175 cm. The upper band was open-type to facilitate wearing the suit using clips, while the lower band was designed to tighten the lower cover. In the waistband, the upper band and the lower cover joint were linked together. The shoulder band was not included in the model analysis.

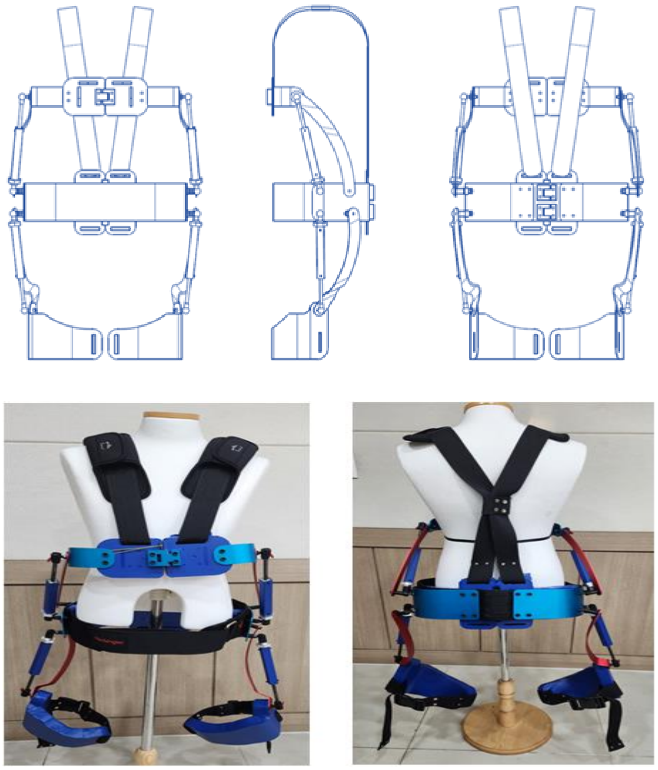


Fig. 4 Structure of wearable suit

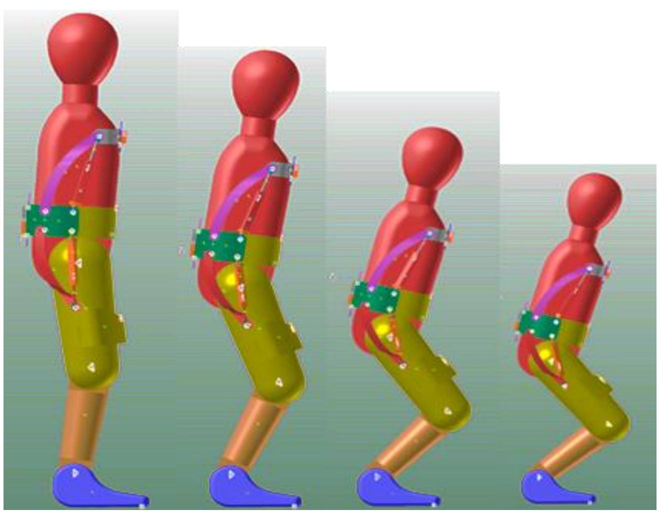


Fig. 5 Motion analysis of wearable suit

Based on the design, universal-revolute joints were used as the suit joint, as shown in Figure 5. Translate joints were used in the lower cover and thighs of the model. This study used revolute joints for the joints of the human model and translated joints for non-powered soft actuators. Figure 5 demonstrates the motions of the human model after wearing the wearable suit. Figure 6 represents the force of the non-powered soft actuator when the model is moving. The force loaded to the non-powered soft actuator was approximately 188 N, indicating the maximum load capacity of a spring. Figure 7 presents changes in velocity and acceleration of variable spring by motion according to the model's movements. The maximal displacement of the non-powered soft actuator was 39mm. Moreover, the structural analysis according to apply load was additionally performed to identify high-stiffness plastic and alternative materials for the future advancement of lightweight wearable suits by reflecting the above analysis results of multibody dynamic.

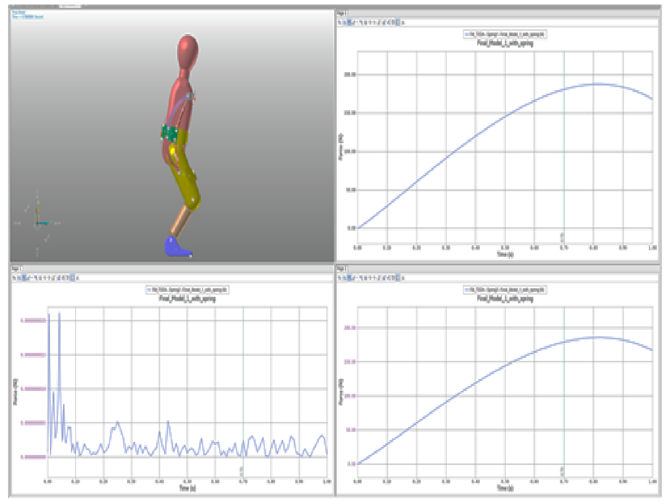


Fig. 6 Force analysis of non-powered soft actuators

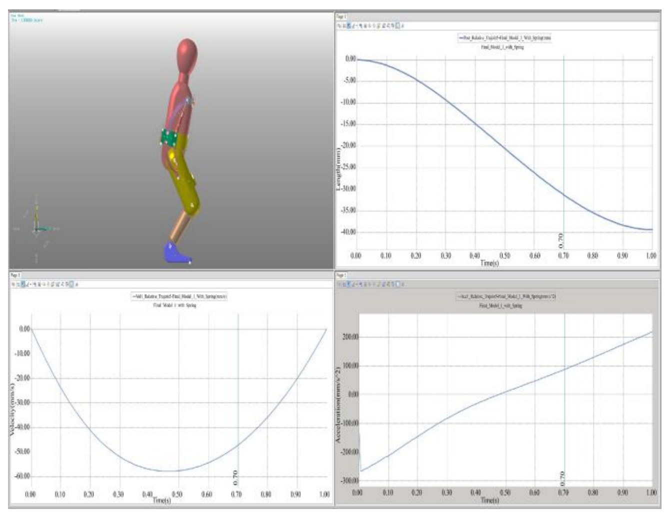


Fig. 7 Velocity and acceleration analysis of non-powered soft actuators

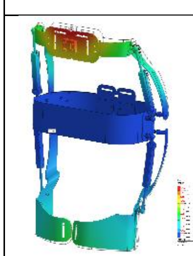
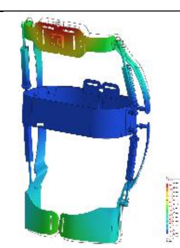
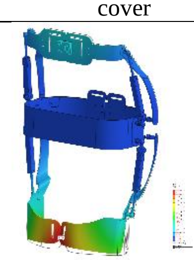
Change in displacement by applying load		
70N_Joint surface	70N_Joint Axis	200N_Lower cover
		

Fig. 8 Analysis of displacement by applying load

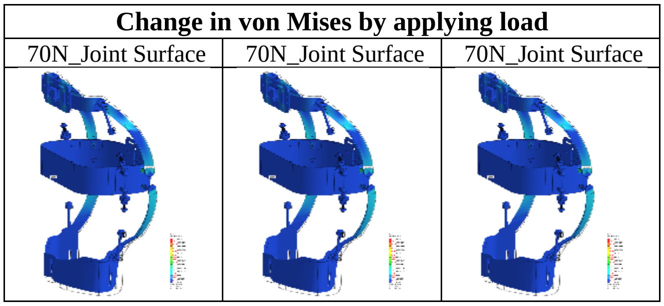


Fig. 9 Analysis of stress by applying load

The maximal displacement at 200 N was 9 mm at the end of the lower cover. However, the displacement at the end of the lower cover appeared to be an insignificant problem since the lower cover was fixed by the band of the model's thighs. The outcome of the structural analysis revealed that the von Mises stress was approximately 550MP and temporarily high in link rotating pins of the waistband. To prevent this, the design of pins was altered. Stress at the link was modified by reinforcing thickness by 1-2 mm thicker than the previous one.

3. Measurement of Muscle Strength Assistance

After making wearable suits, patches for electromyography were attached to the user's erector spinae and biceps femoris muscles for measurement of muscle activity before and after wearing the wearable suit to assess the muscle strength assistance in the upper and lower body. The subject wearing the wearable suit was asked to repeatedly perform motions of lifting up and putting down a 15 kg heavy object for a certain period of time and section. To ensure the objectivity of the experiment, the measurement was carried out by asking five subjects to wear the same wearable suit. Table 2 shows the comparison of the decreased amount of muscle activity (%MVIC) by measuring the muscle activity of erector spinae and biceps femoris muscles when the users lift up a heavy object before and after wearing the suit. All five subjects showed a decrease in muscle activity by a minimum of 42% or higher. The test results indicate the wearable suit is helpful in handling heavy objects.

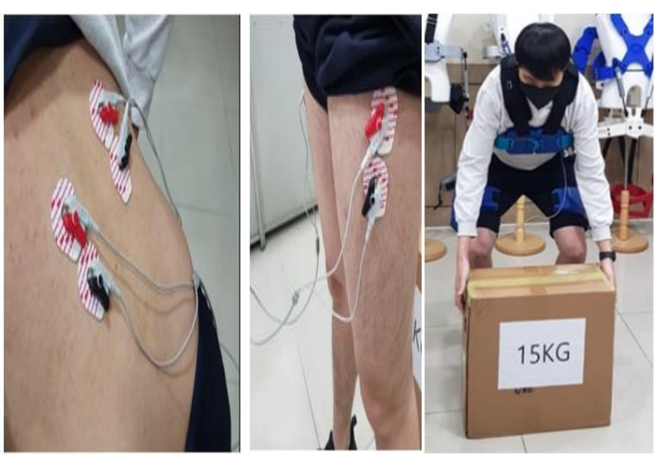


Fig. 10 Patches attached for measurement of muscle strength assistance

Table 2. Decreased amount of muscle activity

Person	Test Measurement	Decreasing Amount (%)
#1	Erector spinae muscles	30.3
	Muscle biceps femoris	28.3
#2	Erector spinae muscles	38.3
	Muscle biceps femoris	34.0
#3	Erector spinae muscles	28.0
	Muscle biceps femoris	33.7
#4	Erector spinae muscles	34.9
	Muscle biceps femoris	29.9
#5	Erector spinae muscles	31.3
	Muscle biceps femoris	35.6

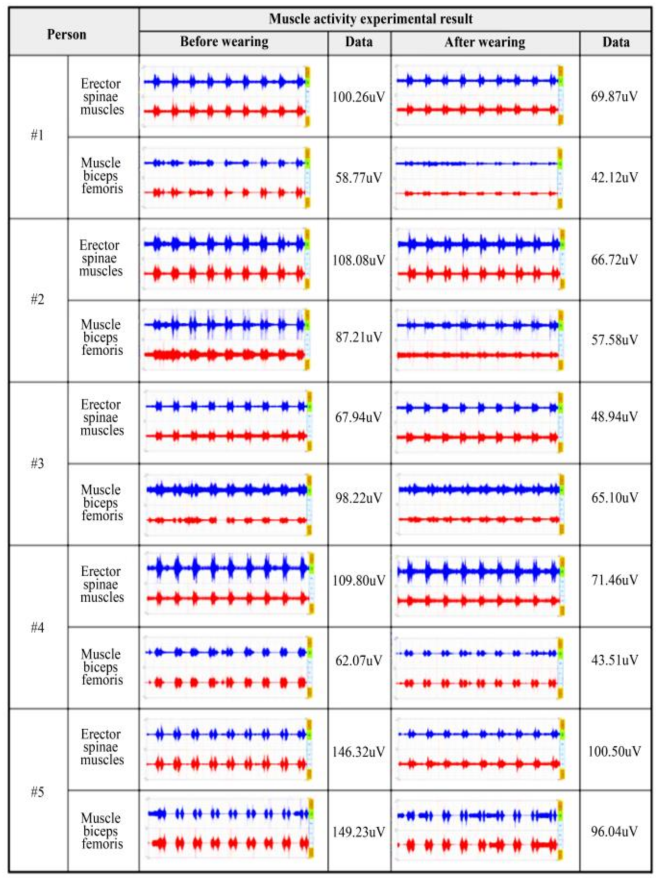


Fig. 11 Graph of muscle activity measurement before and after wearing the wearable suit

4. Conclusion

Non-powered soft actuators were developed as passive types that do not require an external power supply and can be used permanently as a device for muscle strength assistance. The wearable suit has the appearance of a damper structure. It is lightweight and can be flexibly used, suitable for the user's physical conditions and situations by controlling repulsive force on his/her own after wearing it. The controller is located outside to be accessible for the user to adjust the repulsive force, and the size of the repulsive force can be regulated by controlling the constant values of the medial cylinder rod and coil spring. Compared to the active type wearable robot, the lightweight and highly active wearable suit was structured appropriately for the user's motion range and improved with activity and wearability adequate for left-to-right and rotational movements. In the measurement of the muscle activity (%MVIC) of erector spinae and biceps femoris muscles, the muscle activity was found to be decreased by at least more than 42%.

Acknowledgements

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