On the Development of a Soft Wearable Exo-glove for Rehabilitation Assistance: An Application of Knitted Shape Memory Alloy

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Introduction

The aging of the disabled population is an important issue. Particularly, hemiplegia results in a challenge to control voluntary movements owing to muscle paralysis, and the stiff hands of hemiplegic patients can experience difficulties during daily activities (Cauraugh et al., 2000). Actual user satisfaction and usability of assistive devices are low, owing to their low wearability although research has been conducted on hand assistive devices for hemiplegic patients (Yeung et al., 2016). To increase user satisfaction, it is necessary to design devices with minimize the burden on the human body (Walsh, 2018). Some flexible actuators by designing the knitted shape memory alloy (SMA) with the characteristic of returning to its memorized shapes were recently developed (Granberry et al., 2019). The knitted SMA can be made as lightweight and flexible actuators without additional materials through the inherent flexibility of weft knit, so it is suitable for application to user-oriented assistive devices that can be applied to body motions. Therefore, we aimed to develop and evaluate a soft wearable exo-glove using a knitted SMA for hemiplegic patients. To this end, we applied an ergonomic wearable design approach to optimize the desired functionality and positive user experience.

Methods

We recruited three hemiplegic patients aged 60 years or older (2 men and 1 woman) and one physical therapist, from a rehabilitation center for a multiple-case study. All patients had a disability grade of 1+ or lower on the Modified Ashworth Scale, but excluded those with mental disorders. This study was approved by the participating university's IRB office (No. 2112/002-019). We identified participants' needs using the FEA Consumer Needs Model (Lamb & Kallal, 1992). We analyzed the joint range of motion (ROM) using a 3D body scanner (Artec 3D, Luxembourg) in the patients to gauge the required mobility range for the exo-glove with knitted SMA. We prototyped the exo-glove using the knitted SMA selected through performance analysis, and evaluated its functionality and wearability with a mixed-method test. First, the joint ROM changes before and after glove actuation were measured using a goniometer (Meloq, Sweden). The differences in the joint ROM and grip force (Camry, USA) were analyzed before and after the four stimuli to confirm the multiple effects of thermal stimulation and assistance. The stimuli were S1) extension exercise (20 times), S2) thermal stimulation (60 s), S3) S1 + S2

(20 times), S4) S3 + using glove actuation (20 times) and S0) without stimulus. Then, donning/doffing times of the glove were evaluated, and the subjective satisfaction using the Quebec user evaluation of satisfaction with assistive technology. The skin temperatures of the patients' hands were analyzed for 1 min to evaluate the thermal effect during glove actuation using the iButton (Dallas Instruments, USA). Finally, a subjective thermal assessment of perception and comfort was performed (ISO 10551, 2019).

Results & Discussions

Hemiplegic patients had functional needs for ease of donning/doffing, comfort and heating function. A physical therapist commented muscle contraction and wrist drop problems of the patients. Patients had expressive needs to be seen as confident, and the therapist indicated a familiarity need as patients were reluctant to use new devices. Patients had aesthetic needs for the minimization of details and inconspicuous color. To this end, we led to the open-type enclosure system in the exo-glove for ease of donning/doffing. Elastic materials were used for the joints for comfort. We provided thermal stimulation using the Joule heat generated when operating the SMA to relax stiff muscles. For familiarity, the device was designed in the same form as regular gloves. Achromatic colors were used for an inconspicuous design.

We developed a soft wearable exo-glove comprised four layers through iterative prototyping: 1) an insulation fabric for safety against the heat; 2) the elastic material for the joint area for comfort and double neoprene material used for preventing wrist drops; 3) 14 knitted SMA modules attached to 2); 4) A porous fabric to cover the SMA and dissipate heat. Based on the analysis of the knitted SMA, the actuation force and bending angle tended to be higher in the plain knit than in the double knit. The double-knit module had a longer phase-change time because the two modules were driven, and less electrical power tended to be consumed during the plain-knit operation. Thus, plain-knit modules with higher bending angles and actuation forces were applied to the distal interphalangeal and proximal interphalangeal joints, with the tendency for small joint ROM. Double-knit modules with a small actuation force and bending angle were applied to the metacarpal phalangeal joint, which tended to have a greater joint ROM.

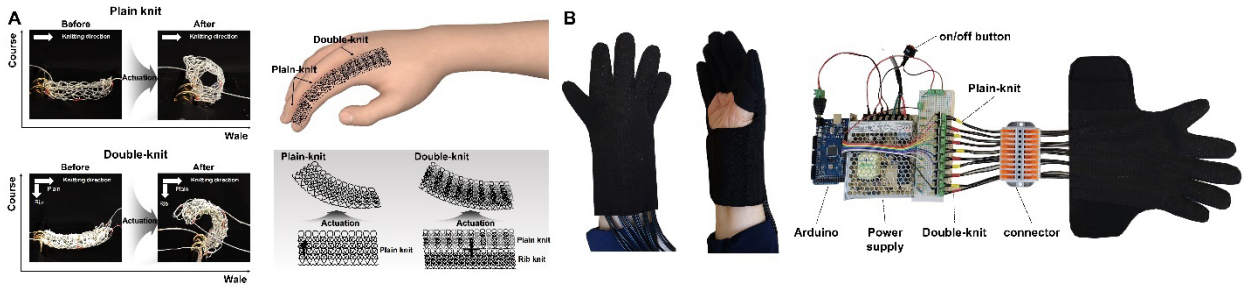

Fig. 1. Exo-glove: A. actuation motion and application method of knitted SMA and B. prototype.

According to the functional evaluation, the joint ROM increased by 13.71% (p =.006) after actuating the exo-gloves. The ROM increased after the four stimuli in the following order: S4 > S3 > S2 > S1 (all p = .000). Compared with S0, the ROM increased after the four stimuli (p = .000). The difference between the grip forces was significant after the four stimuli (p = .000), and increased in the following order: S4 > S3 ≈ S2 > S1. Compared to S0, the grip forces tended to increase after each stimulation. All patients can don and doff an exo-glove themselves, and more time was required for donning than doffing (p = .008). Eight items of subjective satisfaction scored higher than average, and six of them were evaluated as 'satisfaction'. After actuating the gloves, the skin temperature increased by 2.21 °C for 60 s (p = .000). The subjective thermal perception and comfort were positively evaluated as ‘slightly warm’ and between ‘comfortable’ and ‘slightly comfortable’.

Conclusion

We demonstrated that a soft wearable exo-glove applied with an ergonomic wearable design approach could assist in finger extension and provide positive thermal stimulation for hemiplegic patients. We suggested the knitted SMA materials for flexible and lightweight actuators, and provided the desired functionality and high wearability of the exo-glove developed based on the needs and anthropometric data of hemiplegic patients. These findings indicated the applicability of the knitted SMA as a promising actuator for an ergonomic software wearable robot through shape deformation and thermal stimulation. Despite the evaluation of patients with the same disability grade, our multidimensional evaluation approach can help with the advanced design and evaluation methods of the software wearable robot market.

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