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Tools and techniques

The hybrid assisted limb (HAL) for Care Support, a motion assisting robot providing exoskeletal lumbar support, can potentially reduce lumbar load in repetitive snow-shoveling movements

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ABSTRACT

An excessive lumbar load with snow-shoveling is a serious problem in snowfall areas. Various exoskeletal robots have been developed to reduce lumbar load in lifting work. However, few studies have reported the attempt of snow-shoveling work using exoskeletal robots. The purpose of the present study was to test the hypothesis that the HAL for Care Support robot would reduce lumbar load in repetitive snow-shoveling movements. Nine healthy male volunteers performed repetitive snow-shoveling movements outdoors in a snowfall area for as long as possible until they were fatigued. The snow-shoveling trial was performed under two conditions: with and without HAL for Care Support. Outcome measures were defined as the lumbar load assessed by the VAS of lumbar fatigue after the snow-shoveling trial and the snow-shoveling performance, including the number of scoops, and snow shoveling time and distance. The mean of VAS of lumbar fatigue, the number of scoops, and snow-shoveling time and distance without HAL for Care Support were 75.4 mm, 50.3, 145 s, and 9.6 m, while with HAL for Care Support were 39.8 mm, 144, 366 s, and 35.4 m. The reduction of lumbar fatigue and improvement of snow-shoveling performance using HAL for Care Support were statistically significant. There was no adverse event during snow-shoveling with HAL for Care Support. In conclusion, the HAL for Care Support can reduce lumbar load in repetitive snow-shoveling movements.

1. Introduction

In northern Japan, snow-shoveling work is needed routinely in winter. Snow-shoveling is especially strenuous work, and can lead to musculoskeletal injury and cardiovascular disorder [1–3]. The lower back is the most common region of snow shoveling-related musculoskeletal injury [3]. Lower back pain associated with snow-shoveling work often makes additional snow-shoveling difficult, which is problematic for communities in snowfall areas. Moreover, the population in heavy snowfall areas is aging rapidly. An excessive physical load with snow-shoveling for the elderly is a serious social problem. Thus, an approach to reduce the lumbar load in snow-shoveling work is warranted. However, few studies have reported the attempt of snow-shoveling work using wearable robots.

To date, various wearable robots have been developed to reduce lumbar load in lifting work, and have been circulated in the market. Among them, we focused on a hybrid assistive limb for lumbar support or HAL for Care Support (Cyberdyne, Ibaraki, Japan) [4]. HAL is a new wearable robot suit that interactively provides motion according to the wearer's voluntary drive. Various types of HAL, including for lower limbs, for single joints, and for lumbar support, have been developed [5–9]. The HAL for Care Support received a certificate for the international safety standard of life support robots (ISO 12342) in November, 2014 and is already circulated in the market for the lifting heavy load and care business (Fig. 1). The HAL for Care Support comprises exoskeletal frames and power units. Exoskeletal frames are fixed to the wearer's body with molded fastening equipment to the lumbar region and thigh.

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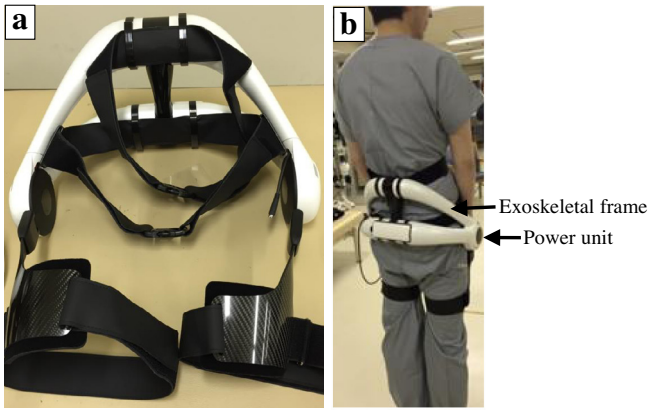

Fig. 1. (a) Photograph of HAL for Care Support from the front. (b) Photograph of worn HAL for Care Support from the rear. The HAL for Care Support consists of exoskeletal frames and power units on bilateral hip joints.

The lumbar mold assumes a role to limit movement of the lumbar vertebrae. A triaxial accelerometer is located in the exoskeletal frame to measure the absolute angle of the wearer's trunk. Power units consist of angular sensors and actuators on bilateral hip joints. Potentiometers are attached to the power units to measure relative angles. The torque on the actuators is transmitted from HAL for Care Support to the wearer's body through the molded fastening equipment. Muscle action potentials are detected through electrodes on the skin surface of the lumbar erector spinae. The HAL for Care Support can support the wearer's lifting motion by adjusting the level and timing of the assistive torque provided to hip joints according to surface muscle action potentials of the lumbar elector spinae. In order to support various people, the HAL for Care Support has a hybrid control system comprising 2 subsystems: cybernetic voluntary control (CVC, coordinated support to the voluntary motion triggered by a surface muscle action potential) and cybernetic autonomous control (CAC, gravity compensatory support to the wearer's weight so as to reduce moment caused by trunk flexion). CAC activates only when its support does not obstruct the wearer's intended motion, depending on the wearer's state estimated by the hip angle and angular velocity. The HAL for Care Support supports hip and trunk extension moment through a combination of these two subsystems [4–9]. The purpose of this study was to test the hypothesis that the HAL for Care Support would reduce lumbar load during repetitive snow-shoveling movements.

2. Methods

2.1. Participants

After approval of the Ethics Committee of the Iwate Medical University School of Medicine, 9 healthy, injury-free men volunteered to participate in this study. All participants had experience with snow shoveling. The mean of age of the participants was 31 years (range, 26–44 y), their mean height was 171 ± 6.1 cm (range, 161–180 cm), and mean weight was 66 ± 5.8 kg (range, 59–74 kg). Informed consent was obtained from all individual participants included in the study.

2.2. Snow-shoveling protocol

The weather conditions during snow-shoveling study were stable, with minimal wind, and minimal temperature change. Ambient temperature was about −4 °C. The snow-shoveling test was conducted in about 25-cm-deep snow around 20 m^2. The participants used a commercially available straight-shaft snow shovel. The overall length of the shovel was 106 cm, the width was 24.5 cm, and its mass was 756 g. The participants were asked to scoop up snow and throw it to more than half their height (Fig. 2). The foot position and method of holding the shovel at the start of the snow-shoveling movement were specified to be same for each participant. To perform the actual snow shoveling work, they moved sideways with each snow-shoveling movement and scooped up as much snow as they could every time. Repetition of the snow-shoveling movement was as fast as possible. They repeated snow shoveling until they were fatigued. The first snow-shoveling trial was performed without HAL for Care Support (Video 1), then the participants took a rest for five minutes. When their pulse and blood pressure had recovered as confirmed after rest, a second snow-shoveling trial was performed with HAL for Care Support (Video 2). The participants simulated the snow-shoveling movement at nonload before the trial, so that the snow-shoveling movement of each subject was constant.

Video 1.

Video 2.

2.3. Outcome measures

Lumbar load was assessed using a visual analog scale (VAS 100 mm as a full-scale score) of lumber fatigue after the

Fig. 2. A study participant shoveling snow using the HAL for Care SupportCare Support.

Table 1
Descriptive statistics for snow shoveling with and without HAL for Care Support.

Variable	Units	Without HAL Mean (SD)	With HAL Mean (SD)
Heart rate (pre)	Beats/min	78.9 (10.0)	87.0 (14.9)
Heart rate (post)	Beats/min	112 (24.5)	123 (32.6)
Systolic blood pressure (pre)	mmHg	143 (37.3)	152 (28.3)
Systolic blood pressure (post)	mmHg	174 (22.2)	163 (28.6)
VAS of lumbar fatigue		75.4 (8.9)	39.8 (15.0)
Number of scoops		50.3 (19.9)	144 (44.9)
Snow-shoveling time	s	147 (57.1)	366 (106)
Snow-shoveling distance	m	9.6 (2.5)	35.4 (11.7)

snow-shoveling trial with and without HAL for Care Support. To evaluate the snow-shoveling performance, we measured the number of scoops, and snow-shoveling distance and time of each trial.

Obtained measured values were defined as follows: the number of scoops was the number of times snow was thrown in succession as measured by a counter, snow-shoveling time was the time that the participants could keep shoveling snow as measured by a stopwatch, and snow-shoveling distance was the distance that snow was thrown as measured by a tape measure. The pulse and blood pressure of all participants was measured before and after each trial. All obtained data are expressed as mean with SD. A paired *t* test was used to evaluate differences between shoveling with and without HAL for Care Support. All statistical calculations were performed using SPSS Statistics (version 24; SPSS Inc, Chicago, IL, USA) and differences with $P < .05$ were considered significant.

3. Results

The results are summarized in Table 1 and Fig. 3. The mean of VAS of the lumbar fatigue of all participants without HAL for Care Support was 75.4 ± 8.9 mm (range, 61–89 mm), while that with HAL for Care Support was 39.8 ± 15.0 mm (range 20–77 mm). With lumbar support of HAL for Care Support, subjective lumbar fatigue after repetitive snow-shoveling movements decreased significantly ($P < .001$). The mean number of scoops without HAL for Care Support was 50.3 ± 19.9 (range 22–82), while that with HAL was 144 ± 44.9 (range 67–215) ($P < .001$). The mean snow shoveling time without HAL for Care Support was 145 ± 57.1 s (range 66–255 s), while that with HAL for Care Support was 366 ± 106 s (range 167–503 s) ($P < .01$). The mean snow shoveling distance without HAL for Care Support was 9.6 ± 2.5 m (range 5.3–13.7 m), while that with HAL for Care Support was 35.4 ± 11.7 m (range 23.3–57.6 m) ($P < .001$). The snow-shoveling performance, including the number of scoops, and snow-shoveling time and distance, significantly improved with HAL for Care Support. A power analysis showed that there was sufficient statistical power for VAS of lumbar fatigue (0.99), the number of scoops (0.99), and shoveling time (0.99) and distance (0.99). By contrast, no significant difference in pulse and blood pressure was found between shoveling with or without HAL for Care Support. All participants completed their snow-shoveling trials safely. There was no adverse event during snow-shoveling with HAL for Care Support.

4. Discussion

Snow shoveling is often performed in freezing temperatures. Energy expenditure for snow-shoveling reaches approximately 6 metabolic equivalents of task [10,11]. Thus, the snow-shoveling work has a risk to harm health, including musculoskeletal injury and cardiovascular disorder, especially in the elderly [1,2]. In particular, low back pain is associated with snow-shoveling movements because of the need to lift heavy snow in a lumbar flexion position. The most common snow-shoveling related medical

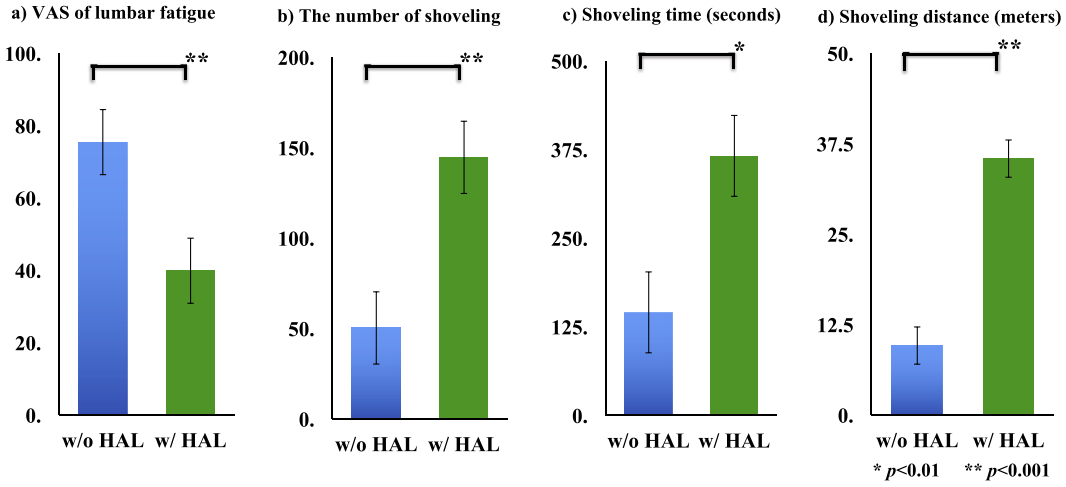

Fig. 3. Bar graphs showing mean data of (a) VAS of lumbar fatigue, (b) number of scoops, (c) shoveling time, and (d) shoveling distance. Error bars represent standard deviations. $^{*}P < .001$, $^{**}P < .0001$. w/o HAL, snow-shoveling trial without HAL for Care Support; w/HAL, snow-shoveling trial with HAL for Care Support.

emergency treated in U.S. emergency departments and body part injured as a result of snow shoveling is the lower back as reported by the U.S. National Electronic Injury Surveillance System from 1990 to 2006 [3].

Whether or not various improvements of shovel design can reduce the lumbar load during snow-shoveling has been investigated in North America. A bent-shaft shovel significantly reduces lumbar velocity and acceleration, resulting in a reduction of lower-back discomfort [12,13]. Furthermore, a bent-shaft shovel significantly reduces L5-S1 extension angular impulses by 16.5%, peak moments by 11.8%, and peak flexion by 13.0% compared with a regular straight-shaft shovel during a simulated snow-lifting task [14]. A bent-shaft design can reduce the lumbar load compared with a conventional straight-shaft shovel.

By contrast, very few studies have focused on attempts at snow-shoveling work using exoskeletal robots. In this study, we investigated whether the HAL for Care Support would reduce lumbar load in actual outdoor snow-shoveling work. The present results showed that the HAL for Care Support significantly reduced subjective lumbar fatigue to about half and improved the snow-shoveling performance, including the number of scoops, and snow shoveling time and distance.

A limitation of the present study is that the participants were not elderly or women with little strength, the main populations bearing the burden of snow-shoveling in northern Japan. An excessive physical load with snow-shoveling for the elderly is a serious problem. In future studies, the effect of the HAL for Care Support for the elderly and women should be considered. To our knowledge, the present study is the first to evaluate lumbar load using a wearable robot during snow-shoveling. HAL for Care Support has the potential to reduce lower-back discomfort during snow-shoveling work.

5. Conclusion

In conclusion, the HAL for Care Support significantly reduced subjective lumbar fatigue and improved the snow-shoveling performance in repetitive snow-shoveling movements by healthy male adults. The present study showed that the HAL for Care Support robot could potentially reduce lumbar load during repetitive snow-shoveling movements.

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Conflict of interest

A commercial party having a direct financial interest in the results of the research supported by this article has conferred or will confer a financial benefit on one or more of the authors. Yoshiyuki Sankai is a professor of University of Tsukuba, a founder, a shareholder, and the CEO of University venture company "CYBERDYNE Inc", Ibaraki, Japan. Hiroaki Kawamoto is an associate professor of University of Tsukuba, a co-founder, a shareholder, and an outside director of University venture company "CYBERDYNE Inc". They are managed according to the University rules and guideline. Cyberdyne is the manufacturer of the HAL. The present study was proposed by the authors. Cyberdyne was not directly involved in the study design; collection, analysis, or interpretation of data; writing the report; or the decision to submit the paper for publication. No commercial party having a direct financial interest in the results of the research supporting this article has or will confer a benefit on the authors or on any organization with which the authors are associated (Kousei Miura, Hideki Kadone, Masao Koda, Tetsuya Abe, Hirooki Endo, Hideki Murakami, Minoru Doita, Hiroshi Kumagai, Katsuya Nagashima, Kengo Fujii, Hiroshi Noguchi, Toru Funayama, Kenji Suzuki, Masashi Yamazaki).

Ethics approval

This study was conducted with approval of the Ethics Committee of the Iwate Medical University School of Medicine.

Authors' contributions

All authors read and approved the final manuscript.

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