Special Correspondence

Unpowered Sensorimotor-Enhancing Suit Reduces Muscle Activation and Improves Force Perception

Yuichi Kurita, Jumpei Sato, Takayuki Tanaka, Minoru Shinohara, and Toshio Tsuji

***Abstract*—Studies suggest that the level of muscle activation may influence force reproduction. The purpose of this study was to develop a sensorimotor-enhancing suit (SEnS)—unpowered assistive clothing without actuators or electrical devices—and to examine its efficacy for reducing voluntary muscle activation and improving force reproduction in the upper limb in healthy young adults. The SEnS was made of elastic fabric and designed to produce assistive shoulder flexion moment that can partially mitigate the required activation of the user's shoulder flexor muscles. A series of human experiments were then conducted in healthy young adults. As a proof of concept, reduction in force reproduction performance of the shoulder moment was confirmed with mitigation of the shoulder moment by using an external string. To examine the efficacy of the SEnS, voluntary muscle activation and force reproduction performance was examined with and without using the SEnS, by comparing the amount of activation in the shoulder flexor muscles and the error in force reproduction in the upper limb. The results showed that wearing SEnS reduced muscle activation and force reproduction error. These results suggest that the accuracy of force reproduction can be improved substantially by partially mitigating the shoulder moment and associated voluntary muscle activation, using the SEnS.**

***Index Terms*—Force reproduction, sensorimotor performance, unpowered assistive clothing.**

I. Introduction

A number of assistive devices have been designed and developed for improving quality of life in various populations, including disabled people, and healthy young and older individuals. Assistive devices for supporting physical movement are often powered with electric or pneumatic actuators [1]–[5]. However, not all assistive devices are easily accepted or used by people in need because most of the actuators in the assistive devices are bulky and heavy, and many devices are expensive to purchase and maintain. To help resolve this problem, unpowered assistive clothing made of elastic fabric has been developed. Unpowered assistive clothing is designed to produce assistive force and reduce the required muscle activation of the user to accomplish the intended physical movement. The efficacy of unpowered assistive clothing has been demonstrated with electromyography (EMG) for simply attenuating muscle fatigue during a prolonged motor task [6], [7]. Human motor performance is often influenced by proprioceptive sensory performance, especially when individuals hold and move an object with their upper limb. It is unknown whether proprioceptive sensory performance can be improved using unpowered assistive clothing.

The potential efficacy of unpowered assistive clothing may be inferred from the relationship between the amount of voluntary muscle activation and proprioceptive sensory performance. For example, the sense of force is overestimated with muscle fatigue, with which increased voluntary muscle activation is required [8]–[10]. With the finger force, perception of force is reduced when individuals actively produce force by voluntarily activating their muscles compared with passively receiving force without muscle activation [11]. Compared with the direction of lower stiffness and higher manipulability in the upper limb, perception of force is smaller when applied in the direction of higher stiffness and lower manipulability, toward which greater voluntary muscle activation is required [12]. In our preliminary study that examined the relationship between tested force perception and estimated requirement of muscle activation using a 3-D musculoskeletal model, force perception was more accurate when the estimated requirement of muscle activation was lower [13]. Collectively, it was expected that the development of assistive wear that reduces voluntary muscle activation of the upper limb would help to enhance force perception and reproduction. Such assistive wears would help individuals to perceive and produce force more accurately, identify potential overweight objects more accurately by perception, increase work efficiency, avoid potential musculoskeletal disorders, and improve the degraded force perception and reproduction. The reduction in fatigue would also help to maintain the accuracy of force perception and reproduction.

In this paper as technical correspondence, we describe our development of a sensorimotor-enhancing suit (SEnS), human experiment on a proof of concept for improving force perception and reproduction by mitigating the shoulder moment, and experimental demonstration about the efficacy of wearing the SEnS. The SEnS is an unpowered wearable suit for reducing upper limb activity. When one of the upper limbs is raised forward and trunk posture is maintained in an upright position, the shoulder muscles need to be activated against the mass of the upper limb. The SEnS was designed to partially mitigate the shoulder flexion moment and associated voluntary muscle activation in such positions. The study shows that wearing the SEnS reduces voluntary muscle activation and improves force reproduction in the upper limb in healthy young adults.

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Y. Kurita, J. Sato, and T. Tsuji are with the Graduate School of Engineering, Hiroshima University, Hiroshima 739-8527, Japan (e-mail: ykurita@hiroshima-u.ac.jp; sato@bsys.hiroshima-u.ac.jp; tsuji@bsys.hiroshima-u.ac.jp).

T. Tanaka is with the Graduate School of Information Science and Technology, Hokkaido University, Hokkaido 060-8628, Japan (e-mail: ttanaka@ssi.ist.hokudai.ac.jp).

M. Shinohara is with Georgia Institute of Technology, Atlanta, GA 30332 USA (e-mail: minoru.shinohara@ap.gatech.edu).

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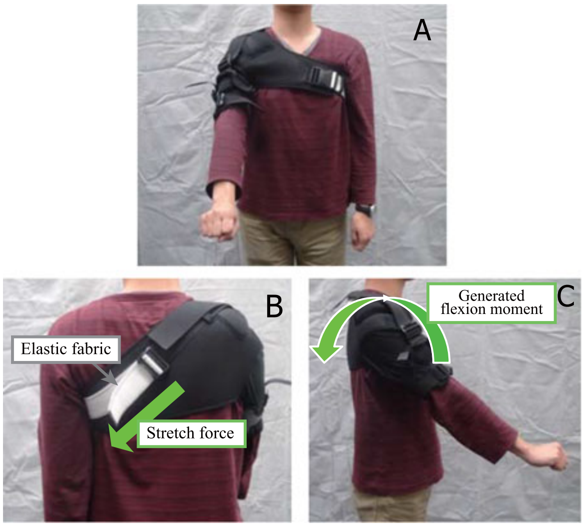

Fig. 1. SEnS. Elastic fabric generates the shoulder flexion moment shown as the arrows. One side of the elastic fabric is fixed at wearer's breast by a harness wrapping around the breast. (a) Front view. (b) Back view. (c) Side view.

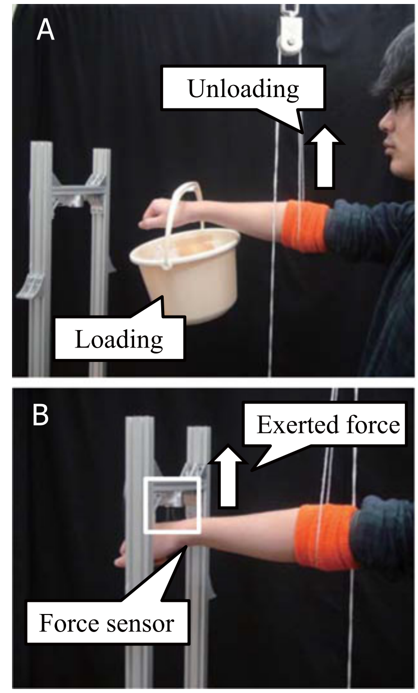

Fig. 2. Tasks with and without mitigation of the passive shoulder extension moment using an external string (Experiment 1). The pictures show the condition with mitigation. (a) Application of load using a plastic container with weights. The upward arrow indicates the direction of force that mitigates the passive shoulder extension moment (unloading). (b) Reproduction of perceived force against a force sensor (in a rectangle). The arrow indicates the direction of force caused by voluntary muscle activation (exerted force).

II. Method

A. Unpowered SEnS

The SEnS was developed to potentially enhance sensorimotor performance related to shoulder flexion by partially mitigating the shoulder moment caused by the mass of the arm (see Fig. 1). Made of elastic fabric, the SEnS is free of actuators or electrical devices and just contains a pad to support the upper limb. When the shoulder extension moment due to the mass of the arm is applied, the elastic fabric generates the larger stretch force depending on the stretch length. The elastic fabric is sewn up to fit the back part of the wearer from the upper limb to the shoulder, like a sleeve. Since one side of the elastic fabric is fixed at wearer's breast by the harness, which wraps around the breast, the stretch force is converted to the compression force around the wearer's breast. The harness was designed to make uniform pressure distribution on the wearer's body as possible as we can. The stretch fabric has a spring constant of 392 N/m. Wearing the SEnS generates shoulder flexion moment (see the arrow in see Fig. 1) when the upper limb is raised forward (i.e., when the shoulder is flexed from the neutral position), and the flexion moment caused by the SEnS partially mitigates the shoulder extension moment generated by the mass of the arm (i.e., passive shoulder extension moment).

B. Participants

Three experiments were conducted with human participants. In Experiment 1, changes in force perception was examined using a string as a proof of concept for improving force perception due to mitigation of the shoulder moment. In Experiment 2, changes in the amount of voluntary muscle activation were examined following the partial mitigation of the passive shoulder extension moment with the SEnS. In Experiments 3, changes in force perception were examined following the mitigation of the passive shoulder extension moment with the SEnS. Ten, six, and twelve healthy young men (aged 22–24 years) participated in Experiments 1–3, respectively. All participants were right-handed, and the experiments were conducted on their right arm. Informed consent was obtained from all participants before the experiments based on the Declaration of Helsinki.

C. Experiment 1: Force Reproduction With and Without Mitigation of the Shoulder Moment Using an External String

Experiment 1 was performed to examine the influence of the mitigation of the passive shoulder extension moment on force reproduction using an external string as a proof of concept. In the upright standing posture, the ten participants raised their extended and pronated right arm forward horizontally and closed their eyes to block visual cues (see Fig. 2). The horizontal position was used for simplicity in a fully mitigating passive shoulder extension moment caused by the mass of the arm. Full mitigation was employed to elicit maximal effect on force reproduction. Under one condition, the passive shoulder moment was mitigated by suspending the arm from an external string at the elbow that created a counterweight with the same weight as the arm. Under another condition, the passive shoulder moment was not mitigated. Under both conditions, participants maintained their arm position while holding the plastic container (same as in Experiment 1) at the dorsal aspect of their wrist [see Fig. 2(a)]. A load of 500, 1000, 1500, or 2000 g was placed in the container in random order. Without being informed of the load, participants perceived the force by focusing on their shoulder muscles and remembered the perceived force without moving the wrist or the arm. The experimenter asked the participants not to use information about impact, visual, or auditory cues to feel the force. The container was then gently removed and participants reproduced the perceived force with the contraction of the shoulder muscles by pressing on a force sensor (CFS018CA101U, Leptrino Co. Ltd., Saku, Japan) that was attached to the dorsal aspect of their wrist [see Fig. 2(b)]. The knowledge of applied or exerted force was not provided to the participants. This protocol was employed based on the method by Walsh *et al.* [14] to evaluate sensorimotor performance.

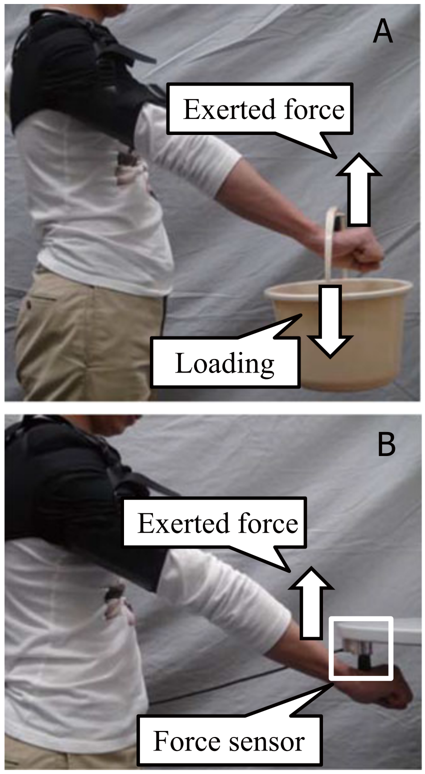

Fig. 3. Tasks with and without partial mitigation of passive shoulder extension moment using the SEnS (Experiments 1 and 3). The pictures show the condition with the SEnS. (a) Application of load using a plastic container with weights in Experiments 2 and 3. The downward arrow indicates the direction of force based on the weight (loading). (b) Reproduction of perceived force against a force sensor (in a rectangle) in Experiment 3. The arrow indicates the direction of force caused by voluntary muscle activation (exerted force).

Five trials were conducted for each load, and a rest period of 30 s was provided between trials. The order of the mitigation condition was randomized.

The average value of the reproduced force was determined for the steady 3-s period on each trial. The absolute difference between the average reproduced force and applied load was determined on each trial. The mean value across five trials of each load was used in statistical analysis for each variable. The average reproduced force and the absolute error were tested with two-factor analysis of variance (ANOVA) (factors: mitigation condition and load) with repeated measures. An alpha value of 0.05 was used for determining statistical significance.

D. Experiment 2: Voluntary Muscle Activation With and Without Partial Mitigation of the Shoulder Moment Using the SEnS

To determine the extent to which the SEnS may reduce voluntary muscle activation of the upper limb, the amplitude of the surface EMG was examined in muscles related to the active generation of the shoulder flexion moment by the participants when wearing the SEnS. In an upright standing posture, the six participants raised their pronated right upper limb forward to yield a position of 40° shoulder flexion [see Fig. 3(a)]. Participants held a plastic container (250 g) at the dorsal aspect of their wrist while maintaining the posture for 10 s. There was a round-surfaced stiff attachment (diameter: 40 mm) as an interface between the container and the wrist. A load of 0, 500, 1500, or 2000 g was included in the container in random order. Knowledge of the load was not provided to the participants. Participants performed the task with and without wearing the SEnS. They performed three trials per load, and a rest period of 15 s was provided between trials. The order of the SEnS condition was randomized. Surface EMG was recorded from the anterior deltoid, posterior deltoid, and biceps brachii (long head) muscles in the right limb in a bipolar configuration (P-EMG plus bioamplifier, Oisaka Electronic Equipment Ltd, Fukuyama, Japan). EMG was full-wave rectified and low-pass filtered at 4.8 Hz. The average EMG amplitude (AEMG) in the middle 5 s was calculated on each trial and normalized to the maximal AEMG during maximum voluntary contraction (MVC) performed in the same posture. The mean value of normalized AEMGs across three trials was used in statistical analysis. AEMG was tested with two-factor ANOVA (factors: SEnS condition and load) with repeated measures in each muscle. An alpha value of 0.05 was used to determine statistical significance.

E. Experiment 3: Force Perception With and Without Partial Mitigation of the Shoulder Moment Using the SEnS

Experiment 3 was conducted to examine whether partial mitigation of the passive shoulder moment with the SEnS improves the perception of force. Twelve participants were tested for their force perception with and without wearing the SEnS. Participants raised their arm forward with the arm extended and pronated and closed their eyes to block visual cues. The procedure of the force perception/reproduction task, determination of dependent variables, and their statistical testing were the same as in Experiment 1. In brief, by pressing on the force transducer [see Fig. 3(b)], participants reproduced the perceived force caused by various applied loads [see Fig. 3(a)], and mean reproduced force and error were compared between the conditions with and without the SEnS using two-factor ANOVA (factors: SEnS condition and load) with repeated measures.

III. Results

A. Force Perception With and Without Mitigation

In Experiment 1, the effect of mitigation on force perception was examined by participants reproducing the perceived force immediately after the application of 500–2000 g weights with and without the mitigation of passive shoulder extension moment. Perceived force increased with the increases in the applied load in both mitigation conditions ($F(3, 72) = 20.8, p \leq 0.001, \eta^2 = 0.46$) [see Fig. 4(a)]. Perceived force was greater with the mitigation, on average, but no significant difference was found between the mitigation conditions. The difference between the perceived force and the applied load was determined as the error in perceived force in each participant. In the grouped results, the error in perceived force was reduced with the mitigation across loads, by 29% on average, as supported by a main effect of mitigation ($F(1, 72) = 4.07, p = 0.047, \eta^2 = 0.053$) without a significant interaction of mitigation and load [see Fig. 4(b)].

B. Voluntary Muscle Activation With and Without the SEnS

In Experiment 2, the effect of wearing the SEnS on voluntary muscle activation was examined by testing AEMG in the anterior deltoid, posterior deltoid, and biceps brachii muscles (see Fig. 5). In the anterior deltoid, AEMG ranged 7.9–11.7% MVC across loads without the SEnS. With the SEnS, AEMG in the anterior deltoid was reduced across loads by 34%, on average, as supported by a main effect of the SEnS condition ($F(1, 50) = 12.78, p = 0.0008, \eta^2 = 0.20$). In the biceps brachii, AEMG ranged 9.7–12.5% MVC across loads without the SEnS. With the SEnS, AEMG in the biceps brachii was reduced across loads by

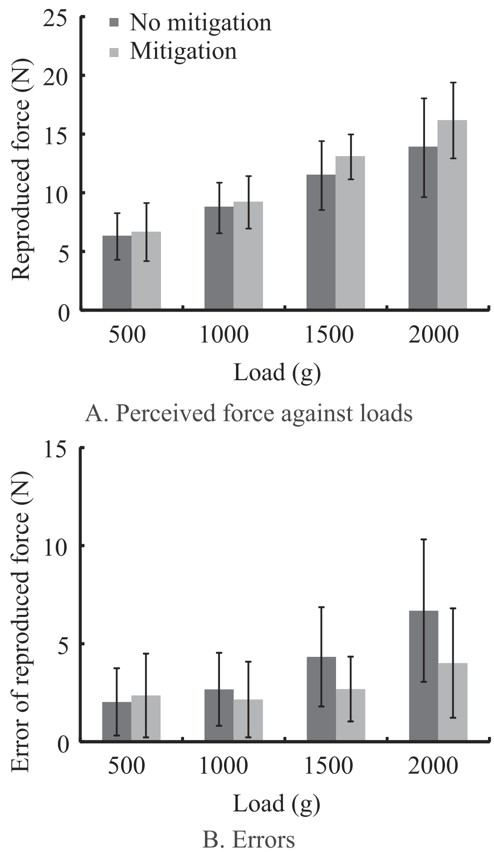

Fig. 4. (a) Reproduced force against various loads with and without the mitigation of passive shoulder extension moment using an external string. (b). Errors (absolute differences) between the reproduced forces and applied loads with and without the mitigation using an external string. Data are means and SDs.

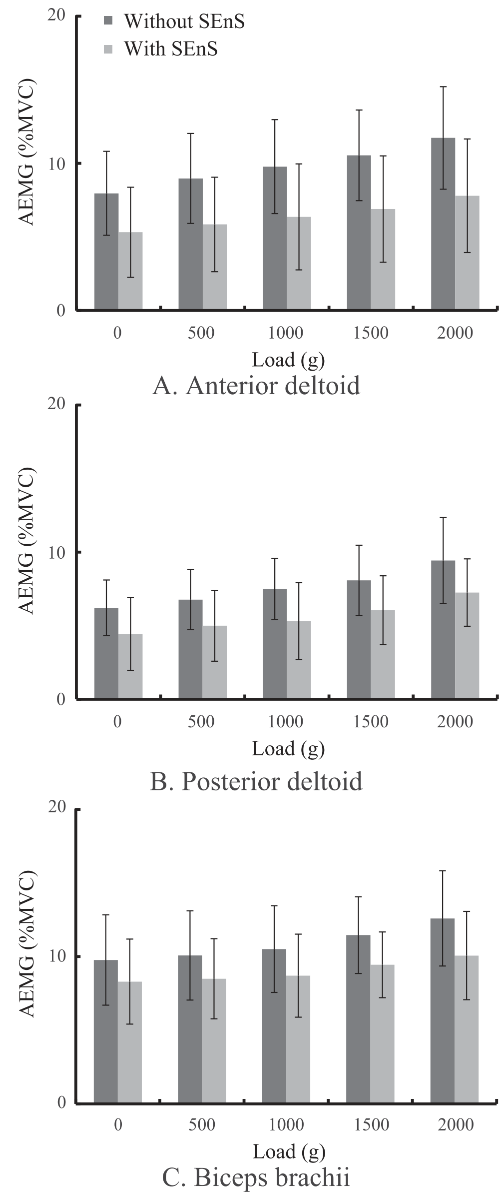

Fig. 5. Magnitude of voluntary activation in the upper-limb muscles for holding various loads with and without wearing the SEnS. (a) Anterior deltoid. (b) Posterior deltoid. (c) Biceps brachii. AEMG, amplitude of electromyogram; MVC, maximal voluntary contraction.

17%, on average, as supported by a main effect of the SEnS condition ($F(1, 50) = 5.37, p = 0.025, \eta^2 = 0.097$). In the posterior deltoid, the apparent reductions of AEMG with the SEnS across loads did not reach statistical significance ($F(1, 50) = 3.37, p = 0.072, \eta^2 = 0.063$). There was no significant interaction of the SEnS condition and load.

C. Force Perception With and Without the SEnS

In Experiment 3, the effect of the SEnS condition on force perception and reproduction was examined by participants reproducing the perceived force immediately after the application of various loads with and without wearing the SEnS. The perceived force increased with the increases in the applied load in both conditions ($F(1, 88) = 15.32, p < 0.001, \eta^2 = 0.34$) [see Fig. 6(a)]. To assess the error in the perceived force, the absolute difference between the perceived force and the applied load was determined for each participant. In the grouped results, the error in the perceived force increased with the applied load under both SEnS conditions, but decreased when wearing the SEnS across loads by 24%, on average [see Fig. 6(b)]. These differences were supported by main effects of the SEnS condition ($F(1, 88) = 4.93, p < 0.029, \eta^2 = 0.053$) without a significant interaction of the SEnS condition and load.

IV. Discussion

We have described the basic structure of the SEnS and provided the experimental results on the proof of concept and the efficacy of the SEnS. The major experimental results are that the error in force reproduction in the upper limb was reduced with mitigation of the shoulder extension moment (Experiment 1), AEMG of the shoulder flexor muscles when holding a load was reduced by wearing the SEnS (Experiment 2), and the error in force reproduction was reduced by wearing the SEnS (Experiment 3).

The SEnS was designed and developed as an unpowered assistive clothing device for the primary purpose of partially mitigating the passive shoulder extension moment and thus reducing the required flexor muscle activity. The anterior deltoid and the biceps brachii are the major muscles producing the shoulder flexion moment. The 17–34% reduction of AEMG in these flexor muscles with the SEnS (Experiment 2) supports the idea that wearing the SEnS reduces the flexor muscle activity when holding a load because of the partial mitigation of the shoulder extension moment. The absence of significant interaction

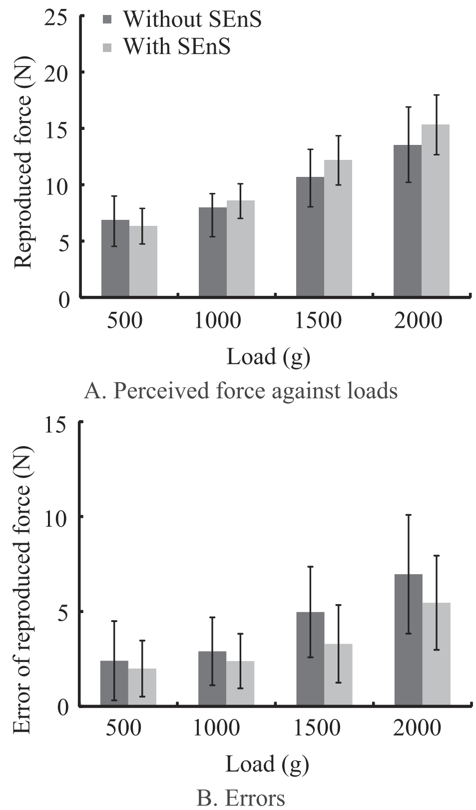

Fig. 6. (a) Reproduced force against various loads with and without partial mitigation using the SEnS. (b) Errors (absolute differences) between the reproduced forces and applied loads with and without the partial mitigation using the SEnS. Data are means and SDs.

between the SEnS condition and applied load indicates that the capability of the SEnS for reducing muscle activation is comparable across loads at least up to the tested load of 2000 g, corresponding to AEMG of 12% MVC without the SEnS in the shoulder flexor muscles. Hence, the current findings confirm the efficacy of the SEnS for reducing voluntary flexor muscle activity.

Reductions in voluntary muscle activation were expected to improve the accuracy of force perception because voluntary effort is known to alter force sensation in the index finger [11]. The current study confirms that the full mitigation of the shoulder flexion moment improves the accuracy of force perception in the upper limb as a proof of concept (Experiment 2). The reduction in the error in the perceived force (Experiment 3) and the muscle activity (Experiment 2) by wearing the SEnS supports the idea that the SEnS improves the accuracy of force perception and reproduction that is associated with reduced muscle activation. These findings are in line with our preliminary results, which use 3-D musculoskeletal modeling and human experiments, that suggest better accuracy in force perception when the required muscle activation is lower [15]. The absence of significant interaction between the SEnS condition and load indicates that the improvement of force perception and reproduction caused by the SEnS is comparable across loads, at least up to 2000 g. Thus, the partial mitigation of the shoulder flexion moment using the SEnS robustly and substantially improves the accuracy of force reproduction.

As a potential mechanism underlying the observed improvement in force perception and reproduction with reductions in voluntary muscle activation, suppression of sensation caused by central motor commands [11], [16], [17] can be considered. In [11], perception of force was attenuated when participants perceived force while their finger actively produced force compared with while their finger passively received force. Their research group subsequently found that this sensorimotor attenuation originates from central motor command signals [16], and that the activation of secondary somatosensory cortex is reduced when sensation is associated with motor action [17]. In the current study, the reductions of voluntary muscle activation by wearing the SEnS most likely reflect reductions in the amount of central motor command. It is likely that such a reduction in the central motor command with the SEnS may reduce sensorimotor attenuation and thus improve force perception during active force production. In this short technical correspondence, however, our research purpose was focusing on simply examining whether or not this new device can actually reduce muscle activity and improve force perception/reproduction. Detailed examination on the amount of reduction in muscle activity and improvement in force perception/reproduction with various approaches would be another important research purpose that should be examined systematically in future studies. The current study demonstrates the efficacy of the SEnS only for improving the accuracy of force reproduction by the shoulder. It implies that an individual would be able to perceive and produce force more accurately by wearing the SEnS. The potential direct application of this efficacy to the real world issues would include the assessment of weight without using scales. For example, when farmers want to assess and compare the ripeness of produces (e.g., water melons) by just lifting and holding them for classification purposes, wearing the SEnS would allow for more accurate assessment and comparison. Similarly, when agents receive packages or baggage for delivery or flight, wearing the SEnS would allow for better estimation whether they are close to the weight limit and need to be measured with scales. It is of note that the National Institute for Occupational Safety and Health of the USA has issued recommended weight limit for manual lifting tasks for preventing musculoskeletal disorders [18]. Manual lifting tasks include loading punch press stock, loading supply rolls, loading bags into a hopper, package inspection, dish-washing machine unloading, product packaging, depalletizing operation, handling cans of liquid, and warehouse order filling, to name a few [19]. In the actual working situation, weight of handling objects may not be measured with a scale every time, but could be reported if workers feel them overweight. Wearing the SEnS would help identify potential overweight objects more accurately by perception, increase work efficiency, and avoid potential musculoskeletal disorders in the long run. The SEnS may also help to improve the degraded force perception and reproduction that is often observed in older adults [20].

There are additional aspects of sensorimotor performance that may benefit when wearing the SEnS. For example, a reduction of the voluntary muscle activity with the SEnS is expected to attenuate neuromuscular fatigue during the activity that involves the prolonged or repeated use of unsupported upper limbs (e.g., harvesting fruits from trees). As a consequence, a greater amount of work may be completed for the same amount of fatigue, or fatigue-related symptoms may be prevented if the amount of work is maintained. Since neuromuscular fatigue alters the sense of force [8]–[10], the expected reduction in fatigue would also help to maintain the accuracy of force perception and reproduction. The finding would be possible to be used for the design of assistive devices for rehabilitation or exercises. Clarification of the listed potential functional significance warrants further systematic research.

V. Conclusion

We developed an unpowered SEnS for the purpose of partially mitigating shoulder flexor muscles when holding a load. Wearing the SEnS decreased the EMG amplitude of shoulder flexor muscles and reduced the error in perceived force. The results suggest that the accuracy of force reproduction can be improved substantially by partially mitigating passive moment and reducing voluntary muscle activation, using the SEnS.

Because the maximum generated stretch force is limited due to the limited stretchable length of the elastic fabric, an appropriate design of the spring constant and stretchable length of the elastic fabric is essential to improve the force reproduction capacity depending on the target weight. Future work includes improving the SEnS to be able to unload larger force on broader ranges of muscles. Continued research may lead to the development of equipment that helps individuals working in workplaces.

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