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RESEARCH

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Evaluation of an assistive exosuit for alleviating neck and shoulder muscle fatigue during prolonged flexed neck posture

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Abstract

Introduction Neck pain affects 203 million people globally and is prevalent in various settings due to factors like poor posture, lack of exercise, and occupational hazards. Therefore, addressing ergonomic issues with solutions like a wearable robotic device is crucial. This research presents a novel assistive exosuit, characterized by its slim and lightweight structure and intuitive control without the use of hands, designed to mitigate muscle fatigue in the neck and shoulders during prolonged flexed neck posture. The efficacy of the exosuit was confirmed through human experiments and user surveys.

Methods The preliminary feasibility experiment was conducted with five subjects for 15 min to verify the effect of supporting the weight of the head with a wire on reducing neck muscle fatigue. The prime experiment was conducted with 26 subjects for 15 min to quantitatively evaluate the reduction in muscle fatigue achieved by wearing the exosuit and to assess its qualitative usability from the user's perspective. For all experiments, surface electromyography (sEMG) data was measured from upper trapezius (UT) and splenius capitis (SC) muscles, the two representative superficial muscles responsible for sustaining flexed neck posture. The analysis of the device's efficiency utilized two parameters: the normalized root mean square value (nRMS), which was employed to assess muscle activity, and the normalized median frequency (nMDF), which was utilized to gauge the extent of muscle fatigue. These parameters were statistically analyzed with the IBM SPSS statistic program.

Results When wearing the exosuit, the nMDF of UT and SC increased by 7.18% ($p < 0.05$) and 5.38% ($p < 0.05$), respectively. For the nRMS, no significant differences were observed in either muscle. The nMDF slope of UT and SC increased by 0.63%/min ($p < 0.01$) and 0.34%/min (no significance). In the context of the nRMS slope, UT exhibited a reduction of 0.021% MVC/min ($p < 0.05$), while SC did not demonstrate any statistically significant outcomes. The exosuit received an average system usability scale score of 66.83.

Conclusions Based on both qualitative and quantitative evaluations, our proposed assistive exosuit demonstrated that it promises the significant reduction of muscle fatigue in the neck and shoulders.

Keywords Exosuit, Assistive wearable device, Clutch, Flexed neck posture, Surface EMG, Median frequency, Muscle fatigue, Splenius capitis muscle, Upper trapezoid muscle

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Introduction

Neck pain affects a staggering 203 million people worldwide with a prevalence of 2450 per 100,000 population, as reported by the Global Burden of Diseases, Injuries, and Risk Factors Study [1]. This symptom has multiple potential causes, including mental stress due to psychosocial factors, as well as physical factors like poor posture, lack of exercise, degenerative changes in the musculoskeletal system, and injury. While some psychosocial factors are the predominant causes of neck pain, it is also imperative to consider the physical risk factors as they are closely related to our daily and occupational lives [2–13]. Neck pain is particularly prevalent in less dynamic settings where maintaining a specific posture is required, particularly among office workers and surgeons who must maintain sedentary or static postures during their work [14–23]. These ergonomic risks can negatively impact working performance, reduce career longevity, and potentially contribute to a shortage of these workers.

Professions prone to neck pain require targeted interventions and preventive measures to minimize the risk. Conventional neck support devices were developed for patients with forward neck posture symptoms and typically feature a cervical collar structure made of rigid materials to support the head in a forward-facing position [24]. Due to the structural limitation of its static form for the single target posture, they cannot support various neck bending angles or head rotation. Adjustable neck supports, which improve upon previous limitations, have been developed to reduce muscle fatigue by alleviating the muscle effort required to maintain not only the forward-facing posture but also a flexed neck posture through manual adjustment of the chin support angle [25]. However, because they are manual devices, the support angle cannot be freely adjusted in situations where both hands are occupied. Additionally, it is difficult to have a conversation when the head is supported by the chin rest.

Recently, robotic exoskeletons have emerged as a game-changing solution to alleviate muscle fatigue in various industrial and healthcare applications [26, 27]. There are several robotic devices that can assist with maintaining static posture or moving various body parts, including the lower limbs, hips, back, and shoulders [28–31]. Unfortunately, there are limited options available to reduce muscle fatigue from head and neck movements. The cable-driven robotic platform for head-neck movement has shown significant reduction in neck muscle activity, but it was fixed to a grounded frame, restricting the wearer's mobility [32]. The passive neck orthosis with a variable stiffness mechanism was developed to support anterior and posterior flexion movements of the neck [33]. This device demonstrated a reduction in neck muscle activation in a neck flexed posture by using a passive actuator with elastic components that adjust bending stiffness proportional to the head flexion angle. However, the need for a vertical slider to support various neck flexion angles results in a bulky overall structure. Furthermore, the study has limitations, including the short experiment duration (5 min for measuring muscle activation) and the inability to analyze median frequency as a measure of muscle fatigue. Another passive neck orthosis was developed for patients with degenerative muscle diseases [34]. Although it was confirmed that upper trapezius activation decreased with the support of the fixed linkage frame in a neck flexed posture, the reduction in neck muscle activity and fatigue could not be verified. The passive neck assistive wearable device was developed to relieve neck muscle fatigue of surgeons [35]. However, the device was a prototype still in the developmental stage, and the effect of reducing muscle fatigue in the neck muscles was not confirmed to be statistically significant. According to the investigation of previous technologies, there is a need to develop a device that supports a flexed neck posture in various work environments for the general public. The requirements for this device should include: (1) a slim and lightweight structure, (2) intuitive control without the use of hands, and (3) a statistically proven effect in reducing muscle fatigue.

This study introduces a novel assistive exosuit as a promising solution to alleviate muscle fatigue of rear neck and shoulder during prolonged use under a neck-flexed posture, which is a common issue in various professions. Unlike existing solutions mentioned above, which are bulky, limited in mobility, or lacking statistical significance in its performance, this exosuit has a slim and lightweight structure with intuitive, hands-free control. The innovation behind this solution lies in its ability to support a flexed neck posture across different working environments, as is proventhrough extensive human subject experiments and user experience surveys. The primary focus of the study is to bridge the gap in current literature by developing a finalized product suitable for real-world applications, with a particular emphasis on achieving statistically significant outcomes. It hypothesizes that the proposed exosuit can reduce rear neck discomfort when maintaining a neck flexed posture, as evidenced by improved surface electromyography (sEMG) measures.

Materials and methods

This study conducted two distinct experiments on human subjects. The first experiment served as a feasibility test to verify whether simply supporting the weight of the head with a fixed wire could reduce muscle fatigue. The second experiment aimed to quantitatively evaluate the reduction in muscle fatigue achieved by wearing the exosuit and to assess its qualitative usability from the users' perspective.

sEMG measurement setup

The DELSYS® Trigno Research + system and Trigno Snap Lead sensors (Delsys Inc., MA, USA) were utilized to measure sEMG of muscles responsible for maintaining flexed neck posture or neck extension movement. The sensors were attached to the pairs of upper trapezius (UT) and splenius capitis (SC) muscles, as shown in Fig. 1. These two muscles are the two representative superficial muscles known to activate during neck extension [36]. SC originates from the spinous process of C7 vertebrae -T3 vertebrae and is inserted into the mastoid process of the temporal bone. The SC muscle is mostly located beneath the UT and sternocleidomastoid muscles, but is closest to the skin in a small exposed area on the side of the neck, as shown in Fig. 1a. The sEMG sensor for SC was located by palpating the muscle belly within the exposed area along the line between T1 vertebrae and the mastoid process, as can be seen in Fig. 1b. The reference electrodes for SC were attached to bilateral deltoid medial muscles. The placement of sEMG sensor for UT was done according to SENIAM recommendations [37]. The reference electrodes were placed on each infraspinatus muscles. After attaching the sEMG sensor, we checked whether the sensor was correctly located on the target muscle by observing the sEMG signal detected while the subjects tilted their head back or lifted their shoulders upward. The skins at the location of target muscle were shaved and sanitized with alcohol prior to attaching sEMG sensors. The EMG signals of each muscle were collected at a frequency of 1024 Hz.

Maximum voluntary contraction

Before experiments, maximum voluntary contraction (MVC) of each SC and UT muscle was measured to normalize muscle activity for each subject. Two distinct processes of MVC measurement were carried out for each SC and UT muscle (see Fig. 2). In the case of SC MVCs, subjects sat in a chair and lightly placed their chest against a chest support. Then they wore a headgear, which was connected to a load cell fixed on the stand via steel cable, restricting head extension at a neutral position. After preparation, subjects were instructed to extend their head against the resistance of the cable. For UT MVCs, subjects sat on a bench with fixed steel chain linkage on each side. They grasped the grip at the end of the chains and pulled them upward while maintaining a straight arm to ensure maximum contraction on UT. To encourage subjects to apply their maximum force in both processes of SC and UT MVC, we showed subjects real-time data from load cells that measured the force applied on the cable or chains. Three sets of 5-s long MVC measurements were completed for each body segment, and the highest value from the moving average of collected data with the 1-s window was chosen. EMG was simultaneously sampled from the relevant muscles at a frequency of 1024 Hz.

Data processing

The Delsys EMGWorks software was used to process all EMG data analysis. DC offsets were eliminated by removing the mean of each signal. The offset signal was

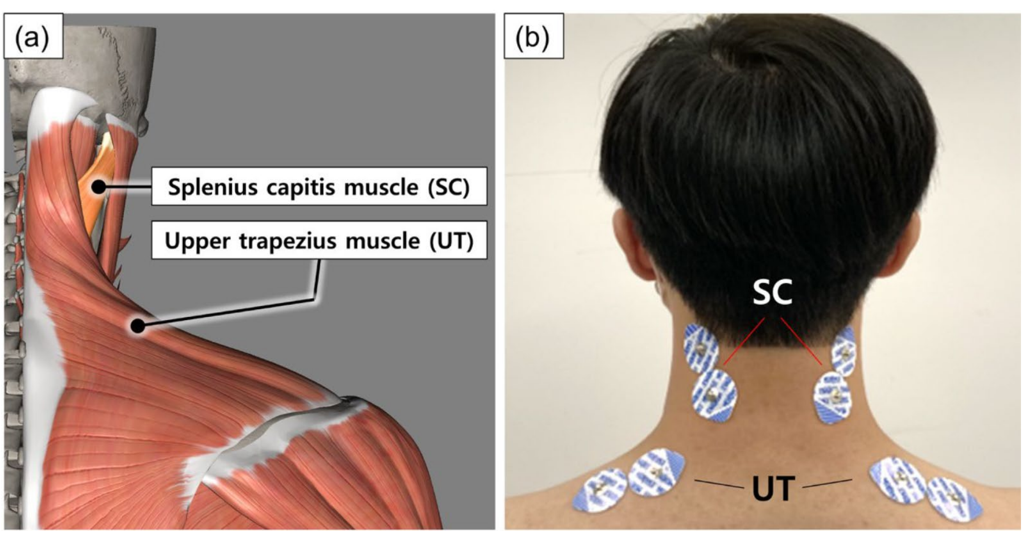

Fig. 1 Positions of target muscles and sEMG sensors. **a** Anatomical positions of the SC and UT muscle. **b** Placement of sEMG sensors on the subject

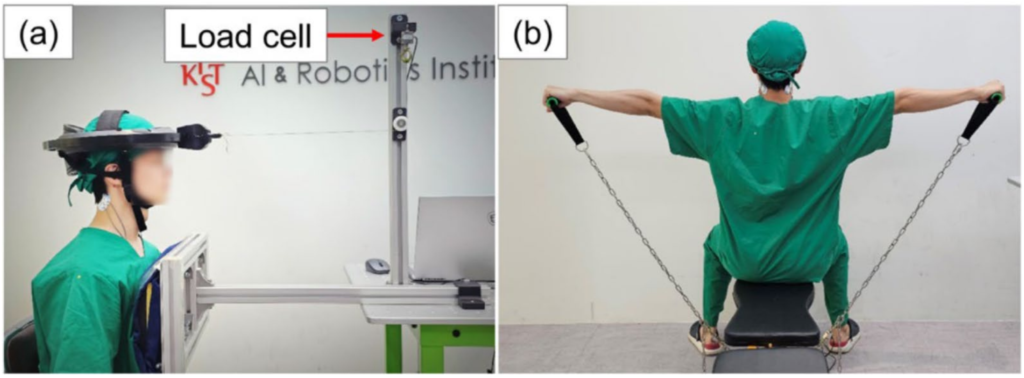

Fig. 2 Measurement of MVC for **a** SC muscle and **b** UT muscle

band-pass filtered (4th-order Butterworth) at frequencies between 20 and 450 Hz, a typical filter range for SC and UT muscles. The median frequency (MDF) was determined with a fixed window of 125 ms. The moving average with a window size of 1 min was used, option, and the signals were normalized by the average MDF value during the first 1 min of neutral posture during the experiment.

For root mean square EMG (RMS) data, the DC offsets were eliminated by removing the mean of each signal, and the signal was band-pass filtered at frequencies below 20 and above 450 Hz. The RMS data of this signal was then obtained. Similar to MDF, the moving average with a window size of 1 min was used, and the signals were normalized by the largest value recorded during MVCs.

For both MDF and RMS data, the change of value between the neutral posture and the final minute of the experiment was considered as the change in fatigue while performing the task. Also, the linear regression slope for the data collected over 15 min was observed to measure the degree of muscle fatigue change over time. These values were used as indices for comparing w/ and w/o cases. An increase in MDF value signifies a decrease in muscle fatigue, whereas an increase in RMS value denotes an increase in muscle fatigue.

Participants

The first experiment was conducted on four healthy subjects (three males and one female) to verify whether simply supporting the head's weight with a wire could reduce muscle fatigue. The subjects' ages, weight, height, and body mass index (BMI) reported as mean and standard deviation were 25.75 ± 1.89 years, 69.50 ± 13.87 kg, 1.76 ± 0.11 m, and 22.13 ± 2.11 kg/m^2, respectively. Individual information can be found at Table S1 in Supplementary information. Individuals who are overweight (those with a BMI over 25) and those with any history of musculoskeletal disorders or chronic pain in the back, shoulder, and neck were ineligible to participate. Prior to the experiment, all participants provided written informed consent approved by the Korea Institute of Science and Technology Institutional Review Board (KIST-202303-HR-011).

The second experiment for exosuit evaluation was conducted on 26 healthy subjects (13 males and 13 females). The subjects' ages, weight, height, and BMI reported as means and standard deviations were 24.81 ± 3.28 years, 1.69 ± 0.08 m, 59.64 ± 10.16 kg, and 20.64 ± 2.16 kg/m^2, respectively. Individual information can be found at Table S2 in Supplementary information. The eligibility to participate in the experiment was identical to the previous participant recruitment. Prior to the experiment, all participants provided written informed consent approved by the Korea Institute of Science and Technology Institutional Review Board (KIST-202303-HR-004).

Feasibility test

The sEMG sensors were attached to the subjects' bilateral upper trapezius (UT) and splenius capitis (SC) muscles. The subject's head flexion angle was measured with a headgear, which had an integrated inertial measurement unit (IMU) (Biscuit™, WITHROBOT, South Korea) and a laser pointer (see Fig. 3a). The IMU was located at the forehead of the headgear to measure head angle. The laser pointer provided visual feedback to ensure the maintenance of the neck bending posture over the experiment, as the subjects were asked to aim the laser spot within a designated marked area on the desk in front of the subjects. Each subject measured the angle of their neutral posture, and the head flexion angles were measured with respect to this neutral posture angle. The wire tension assist apparatus comprised a load cell and an aluminum frame vertically fixed on a

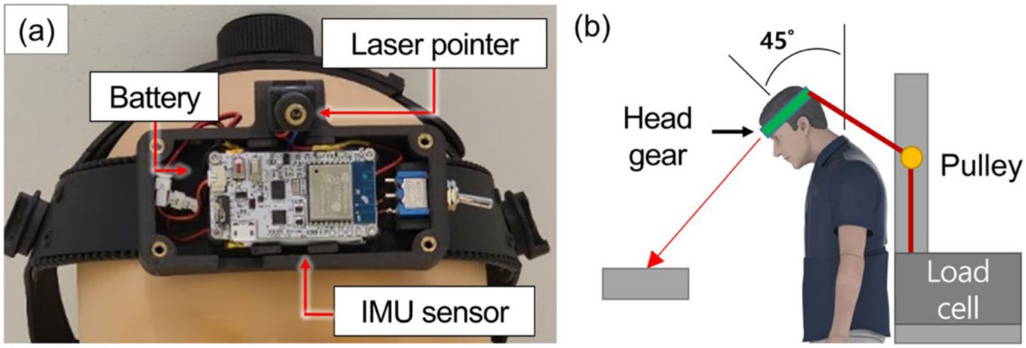

Fig. 3 Experimental setup of feasibility test. **a** Detailed view of headgear components and **b** experimental setup

table (see Fig. 3b). A pulley was mounted on the frame, with a wire passing through it to connect between the headgear and the load cell. The subjects were instructed to stand in front of the wire tension apparatus and tilt their heads downward by 45 degrees, maintaining this position for 15 min under two different conditions: one with the wire support (w/) and the other without(w/o). The flexion angle value and the force exerted on the load cell were continuously monitored and recorded during these experiments. The RMS and MDF data from the experiment were normalized by MVC and averaged MDF for the initial 30 s in a neutral head posture, respectively.

A 45-degree head tilt may seem substantial, but it is a common angle seen in many occupational and everyday tasks that involve extended neck flexion. For instance, during open surgery, surgeons typically maintain an average neck flexion of 37.8 degrees, with a standard deviation of 11.4 degrees [38]. Also, it is also found that people tend to maintain head flexion angle of 33–45 degrees while using smartphones [39]. An angle value that is at the upper limit of the ranges suggested in the above studies was chosen. Such angle value would allow us to assess the exosuit's performance under conditions that impose considerable, yet endurable, strain on the neck muscles. This approach enabled us to better understand the upper limits of the exosuit's effectiveness and ensure its reliability across various usage scenarios. It was also important to avoid the Flexion Relaxation Phenomenon (FRP) during the experiment [40]. The FRP is the phenomenon where Erector Spinae activity decreases once full trunk flexion is reached. An occurrence of the FRP could distort the EMG signal, leading to inaccurate measurements during the experiment. Based on these studies, 45-degree angle turned out to be a suitable angle along the upper limit of the frequent neck flexion angle range in various activities while avoiding an occurrence of the FRP.

Simple wire support helps reduce muscle fatigue

The feasibility test involved four participants and focused on determining whether the results supported the hypothesis that using a fixed wire to support the weight of the head could reduce fatigue in the neck and shoulder muscles. The emphasis was on this determination rather than a statistical analysis.

For the biomechanical analysis of this experiment, the study conducted by Hasraj et al. [41] indicates that the load imposed on the cervical spine dramatically increases when flexing the head forward at varying degrees. An adult head typically weighs about 10 to 12 pounds in the neutral position. As the head tilts forward, the forces seen by the neck surge to 27 pounds at 15 degrees, 40 pounds at 30 degrees, 49 pounds at 45 degrees, and 60 pounds at 60 degrees. Figure 4a presents a static analysis using a free-body diagram of a human head, centered at G when the neck is flexed. This diagram is a simplified model of the human head-neck posture, illustrated as an inverted pendulum that rotates with respect to C7 vertebra. The moment balance equation of the free body diagram is given as:

$$\begin{aligned} &Rcos(10^\circ+\theta_1^\circ)\left\{mg + xsin(\theta_2^\circ)\right\} \\ &- Rsin(10^\circ+\theta_1^\circ)\{xcos(\theta_2^\circ)\} - ry = 0 \end{aligned} \tag{1}$$

where R is the distance between C7 and the center of mass of a human head, m is a mass of a human head, g is the gravitational acceleration, x is the tension of the cable, θ_1 is a head-tilt angle change from neutral configuration, θ_2 is an angle in which the cable is pulled, r is a moment arm of splenius capitis, and y is a muscle load to cervical spine. In our calculations, the value of R has been set to 160 mm, following the recommendation in ref. [41]. The weight, mg, is set to 60 N, which corresponds to the average mass of a human head. The variable x has been assigned a value of 4.9 N, representing the average force measured at the load cell during the feasibility test, as shown in Fig. 4b. θ_1 is given a value of 45°, which is

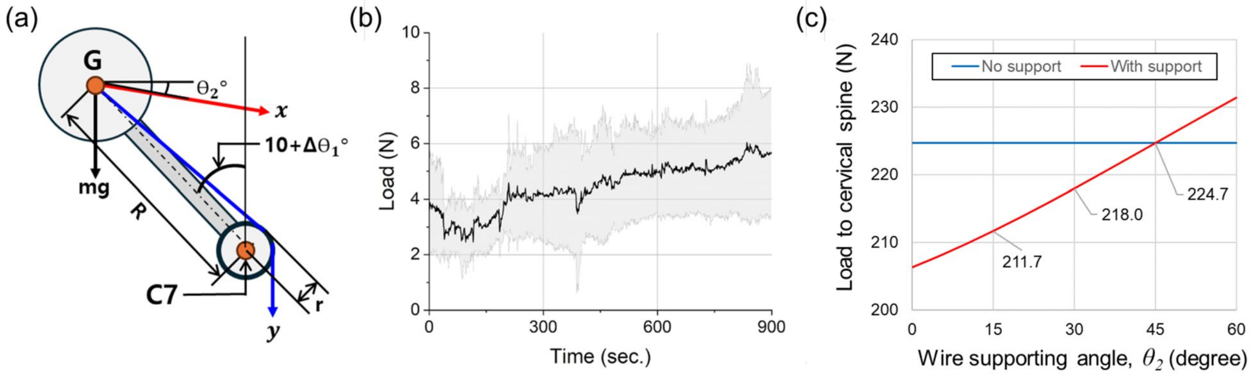

Fig. 4 Biomechanical analysis of the effects of wire support. **a** Free body diagram showing the wire support acting on the neck and head, **b** wire tension during the feasibility test, and **c** variation in cervical spine load with changes in the wire supporting angle

the head tilt angle. The extra angle of 10° was assigned to account for the natural angle of the cervical spine at a neutral configuration. This angle value also corresponds with the 10–12 pounds of weight on the spine at a neutral configuration, as mentioned in ref. [41]. θ_2 was between 15 and 30 degrees during the experiment. The value of r has been set to 35 mm, which is the average moment arm of the splenius capitis muscle with respect to C7, referring to ref. [42]. With values assigned to each variable, y has been derived from Eq. (1). For θ_2 less than 45° when the neck flexion angle is 45°, Fig. 4c suggests that the load on the cervical spine to maintain the flexed posture decreases as the angle θ_2, at which the direction of cable tension acts, approaches 0 degrees (horizontal direction). However, to set θ_2 in the horizontal direction, a long support is required to maintain the tension direction at a high position from the c7 vertebra, making it difficult for the wearable device to fit closely to the body. Therefore, if θ_2 is designed to be between 15 and 30 degrees based on these calculation results, it is expected that the load on the cervical spine will be reduced by about 6 to 13 N compared to the case where there is no assistive force from the wire.

Figure 5 presents two plots of moving averaged nRMS and nMDF over time in the feasibility test for UT and SC muscles, using a window size of one minute. The values were averaged from 4 subjects. The nRMS and nMDF at the initial state were calculated based on the average

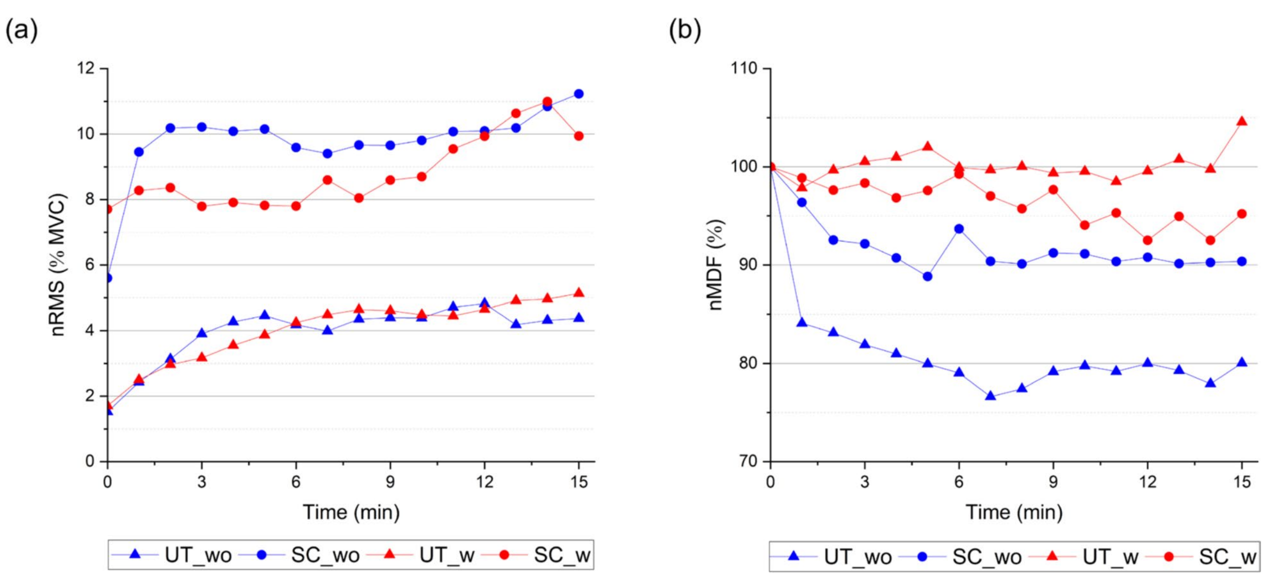

Fig. 5 Changes of neuromuscular parameters over time in the feasibility test for UT and SC muscles. **a** Normalized RMS and **b** normalized MDF. The values were averaged from 4 subjects

nRMS and nMDF of 30 s immediately before the start of the 15-min experiment in a neutral head posture. Data from left and right muscles were averaged since our experiment did not involve lateral bending of head-neck motion.

The results of Fig. 5a show that the nRMS (% MVC) for both the UT and SC muscles exhibit similar trends regardless of the presence or absence of wire support. At the endpoint (15 min), the nRMS for UT and SC muscles were 4.37 ± 5.19% MVC and 11.23 ± 12.21% MVC in the case without wire support and 5.13 ± 5.83% MVC and 9.94 ± 8.64% MVC in the case with wire support, respectively. On the other hand, Fig. 5b clearly shows the substantial improvement in the nMDF (%) for the UT and SC muscles when wire support was used. At the endpoint, the nMDF for the UT and SC muscles were 80.04 ± 12.82% and 90.36 ± 2.14% in the case without wire support and 104.56 ± 22.37% and 95.20 ± 6.45% in the case with wire support, respectively. This significant increase in nMDF indicates that the wire support effectively mitigates muscle fatigue, underscoring its potential benefits for ergonomic improvements.

Design of the neck supporting exosuit

Building on the results of the feasibility test, where the wire support effectively reduced muscle fatigue, a new exosuit has been designed to incorporate this support method in a more wearable and intuitive form. As shown in Fig. 6, the exosuit primarily consists of four main components: a clutch, a vest, a neck brace, and the same headgear used in the feasibility test. The clutch is employed as a locking mechanism to hold a wire connected to the headgear, enabling the maintenance of a flexed neck posture [43]. The mechanism consists of a spool with wire wound around it, a ratchet, and a tape spring, all of which share the same concentric axis and are connected to the spool. Additionally, there is a pawl that can engage with the ratchet, a push–pull solenoid actuator (ROB-11015, Sparkfun, USA) that can drive the pawl, and an incremental rotary magnetic encoder (RMB20, RLS®, Slovenia) that is positioned at the top of the clutch to detect the spool's rotation, allowing for the measurement of the change in wire length. The clutch is attached to the backside of the vest, which is made of non-stretchable fabric to prevent undesired movement caused by wire tension. The 3D-printed rigid neck brace has been meticulously designed to precisely conform to the contours of the neck and shoulders. Its primary function is to prevent the shift of vest around the shoulder axis caused by the tension from the wire. The wire connected to the clutch is linked to a moving pulley, while another wire, with its ends anchored to the left and right sides of the head via magnet holders, passes through a wire separator and is connected to the moving pulley. This functionality allows users to turn their head left and right even when the clutch locks the wire in a flexed neck position. The clutch is controlled by an STM32 microcontroller (NUCLEO-L432KC, STM Microelectronics, Denmark) and powered by a 7.4 V, 900 mAh battery, enabling the device to operate for 9 h. The total weight of the exosuit, including the head gear and battery, is 975.5 g, and the time required to wear the exosuit alone is less than 30 s (see Supplementary Movie 1).

The exosuit can control the clutch lock based on the user's head movement (see Supplementary Movie 2 and 3). If users flex their head and remain still, with no change in wire length for 3 s, the encoder detects this stationary state as a triggering signal. The solenoid actuator then pushes the pawl, engaging the ratchet and locking the wire spool connected to it. This action limits wire movement, and users can relax their posterior neck muscles by relying on the wire tension for support. To release

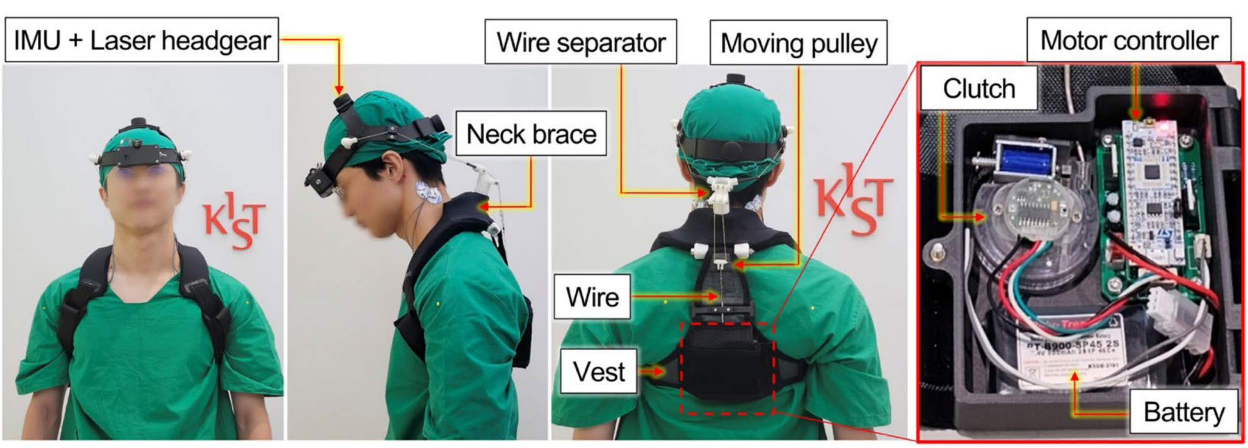

Fig. 6 Exosuit system components

the locking mode, the user only needs to raise their head to loosen the wire tension. The ratchet will rotate in the opposite direction due to the restoring force of the tape spring, disengaging the pawl. As a result, the wire can move freely again.

Experimental setup

Experimental design

The independent variable for the static posture task was the exosuit intervention, which had two conditions: performing the task (1) with (w) the exosuit, and (2) without (wo) the exosuit. The dependent variables were the change in the normalized median frequency (nMDF), root mean square EMG normalized by MVC (nRMS), and their change over time throughout the experiment. In addition, we conducted a qualitative evaluation of the exosuit based on participant feedback according to the system usability scale (SUS). The SUS, developed by John Brooke in 1986, is a widely-used, simple, and reliable tool for evaluating the usability of a wide range of products, offering quick and clear insights with minimal resources [44]. Its versatility, ease of use, and standardized evaluation make it invaluable in usability research worldwide [45].

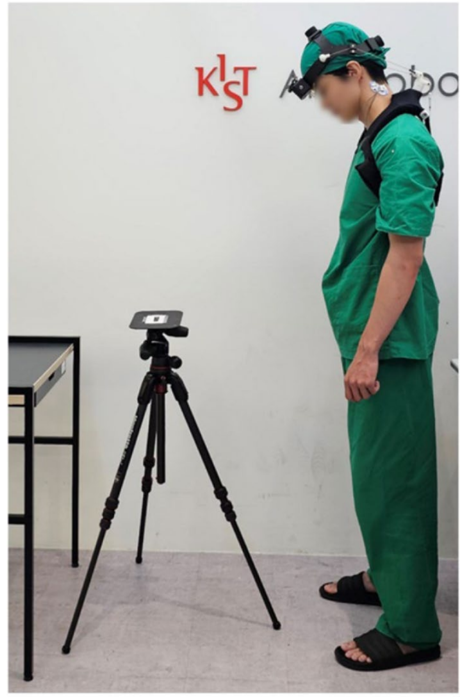

Fig. 7 Experimental setup with the participant wearing the exosuit

Experimental protocol

The experimental tasks were composed of three distinct tasks: (1) MVC measurement to normalize muscle activities, (2) a static neck-flexed posture task for 15 min to evaluate fatigue alleviation, and (3) the same task as (2) after a 3-h intermediate break. The 15-min duration set for this experiment was determined based on the consideration of whether participants, equivalent to the general public, could complete the experiment without giving up due to physical fatigue. For tasks (2) and (3), participants were randomly assigned to wear the exosuit during one task (w) and to perform the other task without it (wo). Prior to the "w" task, a 5-min training session was conducted to familiarize the subjects with the exosuit. Following this training, a 30-min break was implemented to prevent the accumulation of muscle fatigue before the "w" case. In tasks (2) and (3), participants were instructed to stand in front of the desk at a designated location, as can be seen in Fig. 7. Subsequently, the angle measured by the IMU sensor in the headgear was initialized to zero while the subject's head was in a neutral posture. After the zero-angle calibration, the laser pointer in the headgear was turned on, and subjects flexed their neck at a 45-degree angle. The 1.5 (width) × 5 (length) cm sized tape was attached to the location where the laser was pointing on the table.

After the preparation, subjects were asked to stand still with a neutral head posture for one minute to ensure stable sEMG sensor attachment and to measure the average EMG data at neutral position. Then, the subjects flexed their neck at a 45-degree angle and were verbally reminded to keep their backs and shoulders straight while only flexing their head. Subjects were then asked not to move and to keep the laser point within the tape for 15 min. During the experiment, the real-time output of the neck flexion angle was monitored. If a subject tried to deviate from the 45-degree angle, the experimental assistant guided the subject to return.

Study description

A brief description of the study was provided, and informed consent was obtained from participants upon arrival at the lab. This step was followed by researchers gathering anthropometric data (age, weight, stature, and BMI). Subjects were then asked to change into the provided clothing for ease of sEMG sensor attachment. Subsequently, they were seated on a chair while their skin, on which the target muscles were located, was shaved and sanitized with alcohol for sEMG sensor attachment. Following the sEMG sensor attachment, task (1), measuring MVCs for the muscles of interest, was performed. If task (2) was a "w" case, subjects were trained to use the exosuit before a 5-min break. If it was a "wo" case, subjects were given a break immediately after the task (1). After task (2), a 3-h break was given before task (3). If task (3) was a "w" case, the exosuit training was conducted during the break, at least one hour before the break ended, with a duration of 5 min. Upon completion of task (3), subjects carried out the SUS evaluation and a user experience survey to assess the neck assist exosuit's usability.

Statistical analysis

Statistical analyses were conducted using the IBM SPSS Statics program to compare and evaluate the changes of nMDF and nRMS in the UT and SC muscles with and without the exosuit. The RMS and MDF data from the experiment were normalized by MVC and averaged MDF for an initial 1 min in a neutral head posture, respectively. The normality of each normalized dataset was assessed using the Shapiro–Wilk test. Since each comparison was made using measurements from the same subject ("w" and "wo"), the paired samples t-test was utilized to evaluate the effect of the exosuit for data satisfying normality. In contrast, the Non-parametric Wilcoxon signed-rank test was used for data violating normality. The significance threshold was set at $\alpha = 0.05$, indicating that a p-value below this threshold was considered statistically significant.

Results

Effectiveness of the exosuit for maintaining the neck flexed posture

Figure 8 shows two plots of moving averaged nMDF and nRMS over time for UT and SC muscles, with and without exosuit, using a window size of one minute. The nMDF and nRMS at the initial state were calculated based on the average nMDF and nRMS of the first 60 s immediately before the start of the 15-min experiment in a neutral head posture. Data from left and right muscles were averaged since our experiment did not involve lateral bending of head-neck motion.

For the UT muscle, as shown in Fig. 8a, the nRMS values for both conditions (with and without the exosuit) are very similar, leading to overlapping lines in the plot. The activation level is minimal, around 1% of MVC, indicating negligible muscle activation. For the SC muscle, the nRMS initially starts at about 3% of MVC. Upon flexing the head, it increases to approximately 5% of MVC and then rises steadily. This trend is observed for both conditions, with the lines overlapping, indicating similar levels of muscle activation regardless of the exosuit usage. For both UT and SC muscles in "wo" case, as shown in Fig. 8b, nMDF shows a sharp initial drop followed by a more gradual decline. For "w" case, the nMDF shows a more moderate initial decline and then levels off, maintaining higher values compared to without the exosuit. This result suggests that while the exosuit does not significantly impact the nRMS values for UT and SC muscles, it helps maintain higher nMDF values, indicating reduced muscle fatigue.

The results of the study are summarized in Table 1, which compares the neuromuscular parameters between "w" and "wo" cases for UT and SC muscles. The neuromuscular parameters include nRMS (% MVC) and nMDF (%) at the 15-min state in the 45-degree neck flexed posture, and their respective linear regression slopes over time (% MVC/min for nRMS and %/min for nMDF). The normality test results in SPSS showed that normality was

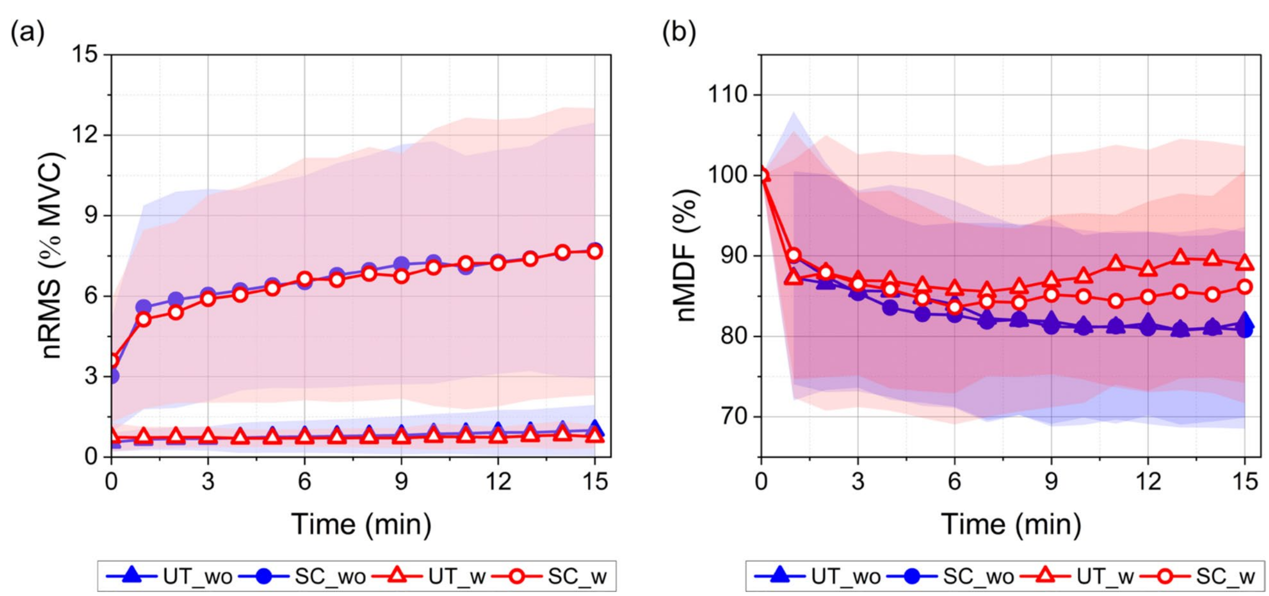

Fig. 8 Changes of neuromuscular parameters over time while maintaining the 45-degree neck flexed posture for UT and SC muscles. **a** Normalized RMS and **b** normalized MDF. The solid lines with symbols are averages and the shaded areas are standard deviations

Table 1 Comparison of neuromuscular parameters between the conditions with and without the exosuit

Outcome measure	Muscle	Without exosuit		With exosuit		p-value
		Average	SD	Average	SD	
nRMS (% MVC)	UT	1.00	0.95	0.76	0.42	0.395[a]
	SC	7.71	4.77	7.66	5.35	0.829[a]
nMDF (%)	UT	81.76	11.86	88.94	14.71	0.048[b]
	SC	80.79	12.24	86.17	14.47	0.032[a]
Slope of nRMS (% MVC/min)	UT	0.025	0.057	0.004	0.021	0.016[a]
	SC	0.202	0.164	0.206	0.216	0.849[a]
Slope of nMDF (%/min)	UT	– 0.75	0.62	– 0.12	0.73	0.002[b]
	SC	– 0.80	0.82	– 0.46	0.77	0.118[a]

[a] Two-sided Wilcoxon signed-rank test

[b] Two-sided paired samples t-test

satisfied for the nMDF in the UT muscle, while nMDF in the SC muscle and nRMS in both UT and SC muscles violated normality. For the UT muscle, as shown in Fig. 9a, the average nRMS without the exosuit was 1.00 ± 0.95% MVC, whereas with the exosuit, it decreased slightly to 0.76 ± 0.42% MVC. This difference was not statistically significant (p = 0.395). For the SC muscle in Fig. 9b, the average nRMS was 7.71 ± 4.47% MVC without the exosuit and 7.66 ± 5.35% MVC with the exosuit, also showing no significant difference (p = 0.829). The nMDF for the UT muscle in Fig. 10a showed a significant increase with the exosuit, rising from 81.76 ± 11.86% to 88.94 ± 14.71% with a mean difference of 7.18 ± 17.64% (p = 0.048) among all subjects. Similarly, for the SC muscle in Fig. 10b, nMDF increased from 80.79 ± 12.24% without the exosuit to 86.17 ± 14.47% with the exosuit (p = 0.032), indicating a significant difference.

The slope of nRMS for the UT muscle showed a significant decrease in "w" case, from 0.025 ± 0.057%MVC/min without the exosuit to 0.004 ± 0.021%MVC/min with the exosuit (p = 0.016), as can be seen in Fig. 11a. However, for the SC muscle, there was no significant difference between conditions, with values of 0.202 ± 0.164%MVC/min without the exosuit and 0.206 ± 0.216%MVC/min with the exosuit (p = 0.849). In Fig. 11b, the slope of nMDF for the UT muscle significantly decreased from – 0.75 ± 0.62%/min without the exosuit to – 0.12 ± 0.73%/min with the exosuit (p = 0.002). For the SC muscle, the slope of nMDF showed a decrease from – 0.80 ± 0.82%/min without the exosuit to – 0.46 ± 0.77%/min with the exosuit, but the change was not statistically significant (p = 0.118).

Survey on usability

After human subject experiments, two surveys were carried out to gauge user experience. The participants assessed the passive neck assist exosuit's usability with the system usability scale (SUS) and shared their personal

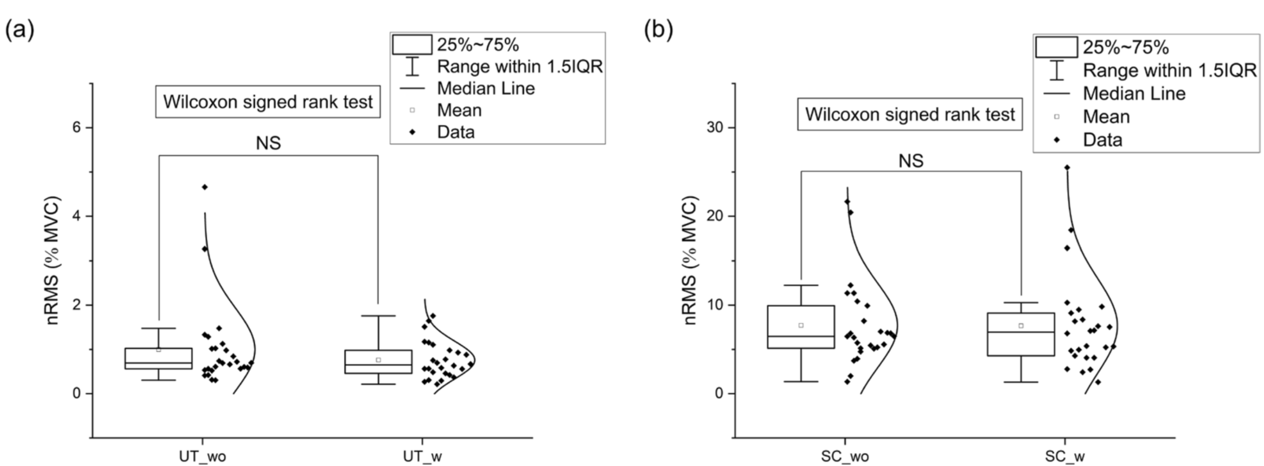

Fig. 9 Normalized RMS (% MVC) for **a** UT muscle and **b** SC muscle after 15 min

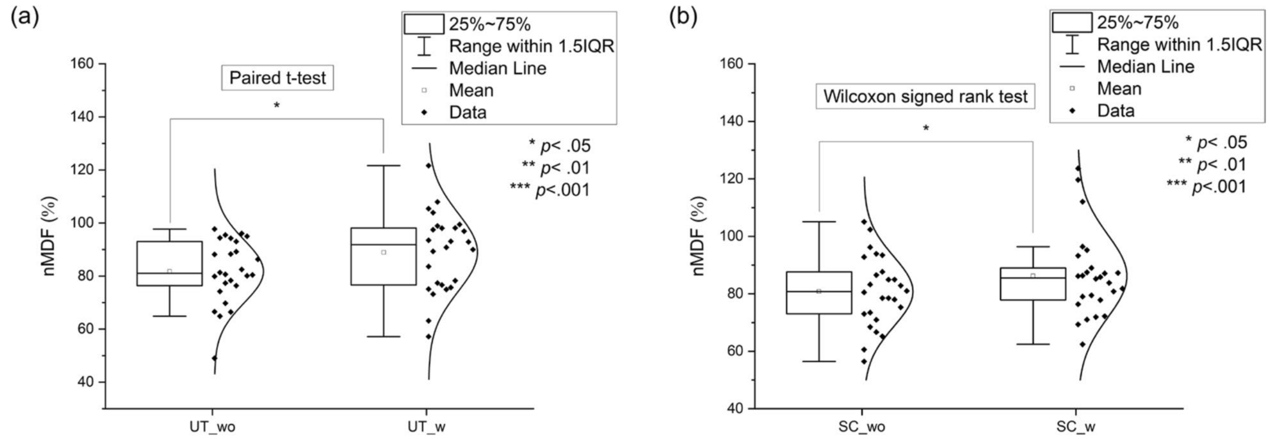

Fig. 10 Normalized MDF (%) for **a** UT muscle and **b** SC muscle after 15 min

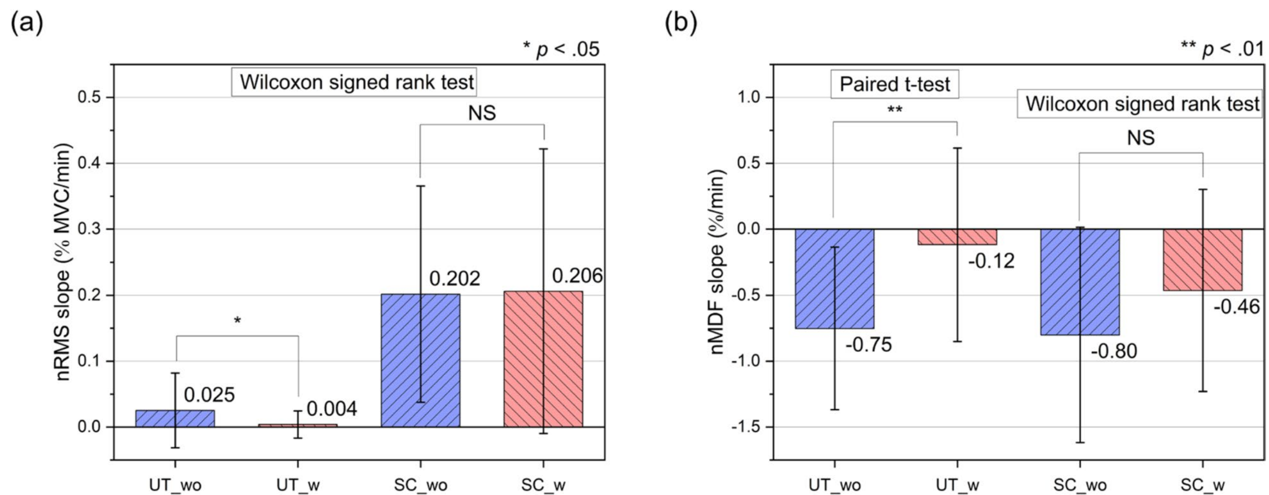

Fig. 11 Linear regression slope changes in UT and SC muscle over 15 min. **a** nRMS (% MVC/min) and **b** nMDF (%/min)

opinions with a custom-made qualitative survey. According to the responses from 10 questions in SUS, as shown in Fig. 12, the exosuit received an average usability score of 66.83 from 26 subjects, corresponding to the 46-percentile rank. The qualitative survey yielded positive feedback about the device, including comments such as "I experienced relief in my muscles" and "the system was intuitive and easy to use." Conversely, negative comments were also noted, such as "I felt excessive pressure around shoulders" and "my arms felt numb."

Discussion

The results from the feasibility test confirmed that providing support for the head's weight through fixed wire tension in a flexed posture can reduce fatigue in the SC and UT muscles. Based on these findings, the exosuit that provides neck flexion assistance through wire tension with the clutch was developed. Human trials with this exosuit similarly confirmed the muscle fatigue reduction effect observed in the earlier feasibility test. However, while the feasibility test's nMDF results indicated a considerable reduction in muscle fatigue due to the assistive force, the reduction effect observed with the exosuit was not as pronounced. The differences of nMDF at the endpoint between the non-wire-support and wire-support cases in the feasibility test were 24.52% for UT and 4.84% for SC. In comparison, the differences between "w" and "wo" cases in the exosuit test were 7.18% for UT and 5.38% for SC. This discrepancy might be attributed to the differences in how the assistance was provided. In the feasibility test, the assistive device was part of a fixed system separate from the participant's body, offering external support without interfering with the body. In contrast, the exosuit is mounted on the subject's shoulder, and it is highly likely that the load applied on the cable transmitted to reaction forces that the upper

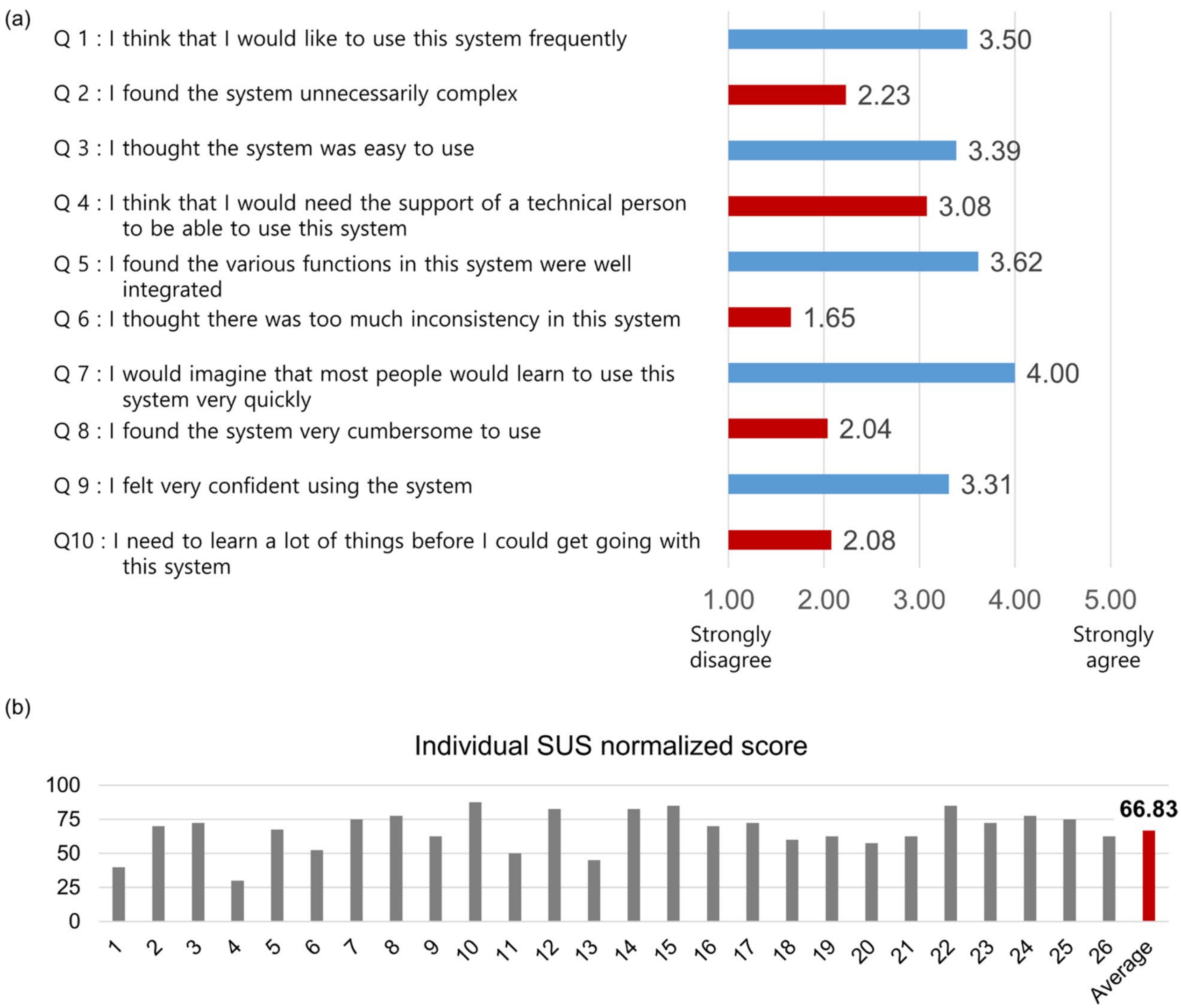

Fig. 12 User experience evaluation of the exosuit system according to SUS. **a** Average SUS scores for each questionnaire item and **b** individual SUS normalized scores for each subject

cervical and trunk muscles had to endure, thereby causing additional muscle fatigue. Also, as indicated by qualitative survey responses, the exosuit occasionally exerted excessive pressure on the muscles due to its high degree of fixation on the body. Additionally, psychosocial factors such as the tension and anxiety associated with wearing the device might have intervened during the experiment. These discomfort factors are presumed to have led to a relatively lower perceived fatigue reduction effect by users.

Among the 26 participants, regarding nMDF at the endpoint, 14 participants showed absolute advantages in utilizing the exosuit, 9 participants showed partial advantages (with positive changes in nMDF for either UT or SC muscles only), and 3 participants (subjects 10, 13, and 23) experienced entirely negative impacts on both UT and SC muscles. In the case of the maximum positive effect from the exosuit (see Fig. 13a), the participant observed differences in nMDF for UT and SC muscles of 49.86% and 19.78%, respectively. Conversely, as shown in Fig. 13b, the participants who experienced the maximum negative effect from the exosuit showed differences in nMDF for UT and SC muscles of − 26.07% and − 25.19%, respectively.

To understand these conflicting results, we examined the nRMS values. As shown in Fig. 14a, subject 6, who exhibited a positive assistance effect, had lower nRMS values when wearing the exosuit. On the other hand, subject 10, who showed a negative assistance effect, had higher nRMS values when wearing the exosuit as shown

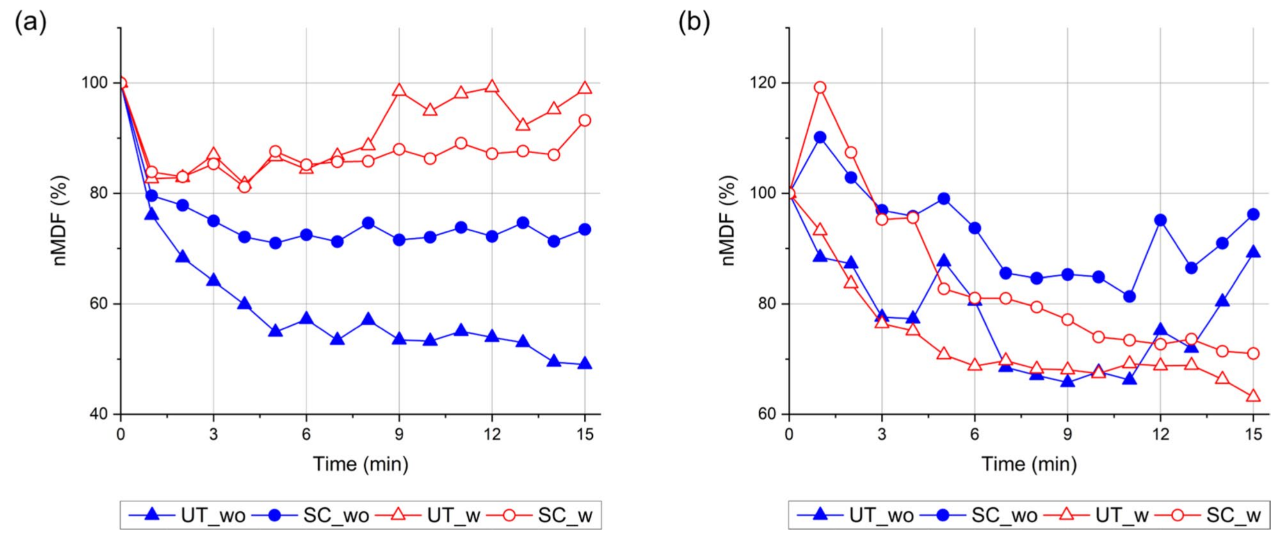

Fig. 13 Results of nMDF in the exosuit experiment for **a** the maximum positive effect case (subject 6) and **b** the maximum negative effect case (subject 10)

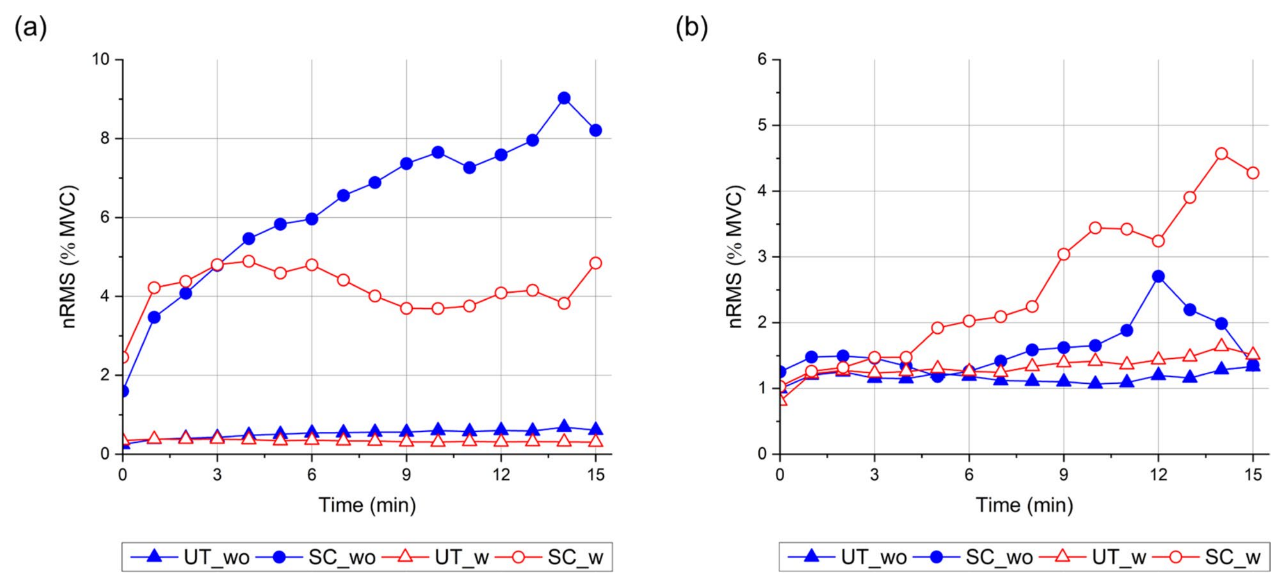

Fig. 14 Results of nRMS in the exosuit experiment for **a** the maximum positive effect case (subject 6) and **b** the maximum negative effect case (subject 10)

in Fig. 14b. One of the most significant factors contributing to higher nRMS in cases of negative assistance effect was likely the fit of the exosuit on the wearer. For the assistive force to be fully transferred to the headgear and maintain the head flexion posture, the endpoint of the assistive wire attached to the exosuit's vest must remain stationary when the wire is fixed. However, since the exosuit is not custom-designed for people with different body figures, it may not fit closely to the body in some cases, causing the clothing to move under wire tension. This movement prevents the wire from providing sufficient support at the fixed 45-degree head flexion angle. As a result, the participant had added weight of the device on his shoulder and head without getting sufficient support of the wire, leading to higher nRMS values despite wearing the exosuit.

Another factor to consider is that wearing the exosuit may have caused excessive pressure on the shoulder from its components, such as the 3D-printed neck brace and straps, leading to increased fatigue. According to the research on the effect of mechanical compression on shoulder muscle fatigue [46], excessive mechanical compression, such as from carrying a load, can impede blood flow in the shoulder muscles, leading to the accumulation of metabolite and decreased muscle efficiency. This results in an elevated rate of muscle fatigue, as indicated by changes in EMG readings during prolonged muscle contractions. For these reasons, the excessive pressure from the neck brace and straps of the exosuit on the shoulders likely caused the UT muscle's nMDF to be lower.

Other potential contributors include insufficient training time with the exosuit, and the subject's poor physical condition. Survey responses indicate that many participants perceived the duration of the training to be insufficient. Although they acknowledged the exosuit's user-friendliness, they preferred expert guidance during exosuit use.

Despite its statistically proven effect in this study, the device has some rooms for improvement. The exosuit's impact on laterally bent and axially rotated neck posture requires further investigation, as the current experiment exclusively focused on a flexed neck posture. Also, its performance has not been proven in real-life scenarios. Further experimentation is desired to comprehensively assess its effectiveness in a more realistic scenario with non-limited head postures, particularly within an authentic surgical context or an office, to gauge its performance when the user's arm is in motion. Other future work includes exploring its efficacy in assisting the user during frequent head-neck motion, not just a posture. There is a potential for enhanced functionality by incorporating a variable stiffness spring, working in tandem with the existing wire locking mechanism, to accommodate both static postures and dynamic motion.

Conclusions

This study confirmed that supporting the head's weight using wire tension in a flexed neck posture can reduce muscle fatigue in the SC and UT muscles. Based on these findings, the exosuit that provides assistance in maintaining flexed neck posture through wire tension with the clutch was developed. Human trials with 26 participants using this exosuit similarly confirmed the muscle fatigue reduction effect observed in the earlier feasibility test. The significant increase in nMDF for both UT and SC muscles when using the exosuit suggests reduced muscle fatigue in the neck flexed posture, while there is no significance in the change of nRMS for both UT and SC muscles. The reduction in the absolute value of the nMDF slope for both UT and SC muscles was observed, but statistical significance was found only for the UT muscle. The nRMS slope for the UT muscle showed a statistically significant decreasing trend, whereas the nRMS slope for the SC muscle exhibited minimal differences and did not reach statistical significance. Based on these results, the neck assistive exosuit has a promising potential to be utilized in many applications that require an alleviation of muscle fatigue while maintaining a flexed neck posture. Possible applications could be surgeons, office workers, and students who have to maintain their flexed neck posture for a long time.

Abbreviations

BMI	Body mass index
UT	Upper trapezius
SC	Splenius capitis
sEMG	Surface electromyography
MVC	Maximum voluntary contraction
RMS	Root mean square EMG
MDF	Median frequency
nRMS	Normalized root mean square EMG
nMDF	Normalized median frequency
w	With wire support or exosuit
wo	Without wire support or exosuit
IMU	Inertial measurement unit
SUS	System usability scale
NS	Not significant

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12984-024-01540-5.

Supplementary Material 1.

Supplementary Material 2.

Supplementary Material 3.

Supplementary Material 4.

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Author contributions

HMC and S.-W.K conceptualized the study. The design and fabrication of the exosuit were carried out by HMC, J.-H.M, J.-R.C, and S.-W.K, while the clutch mechanism design and fabrication were undertaken by J.-R.C, K.-J.C, and S.-W.K. The experiment design was developed by HMC, J.-H.M, and S.-W.K, who also conducted the experiments. HMC, J.-H.M, and S.-W.K analyzed and interpreted the data. Visualization with figures and movies was performed by HMC, J.-R.C, and S.-W.K. Funding for the project was acquired by K.-J.C and S.-W.K, who also managed the project and provided supervision. The original draft of the manuscript was written by HMC, J.-R.C, K.-J.C, and S.-W.K.

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Availability of data and materials
All relevant data is within the paper and supplementary information. Detailed information and raw data may be available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
All human experiments in this study were approved by the Korea Institute of Science and Technology Institutional Review Board (KIST-202303-HR-004, KIST-202303-HR-011), and all participants agreed to provide their information and have given consent to the publication of the data present in this manuscript.

Competing interests
The patents describing the exosuit and clutch documented in this manuscript have been filed with the K.R. patent office. HMC, J.-H.M, J.-R.C, K.-J.C, and S.-W.K are inventors of at least one of the following patent applications: K.R. 10-2023-0156983, US 18/432792, filed by Korea Institute of Science and Technology and Seoul National University. J.-R.C and K.-J.C are inventors of at least one of the following patent applications: K.R. 10-2022-0013914, filed by Seoul National University.

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References
1. GBD 2021 Neck Pain Collaborators. Global, regional, and national burden of neck pain, 1990–2020, and projections to 2050: a systematic analysis of the Global Burden of Disease Study 2021. Lancet Rheumatol. 2024;6(3):e142–55.
2. Kanchanomai S, Janwantanakul P, Pensri P, et al. Risk factors for the onset and persistence of neck pain in undergraduate students: 1-year prospective cohort study. BMC Public Health. 2011;11:566.
3. Genebra CVDS, Maciel NM, Bento TPF, Simeão SFAP, Vitta A. Prevalence and factors associated with neck pain: a population-based study. Braz J Phys Ther. 2017;21(4):274–80.
4. Berolo S, Wells RP, Amick BC III. Musculoskeletal symptoms among mobile hand-held device users and their relationship to device use: a preliminary study in a Canadian university population. Appl Ergon. 2011;42(2):371–8.
5. Ning X, Huang Y, Hu B, Nimbarte AD. Neck kinematics and muscle activity during mobile device operations. Int J Ind Ergon. 2015;48:10–5.
6. Song D, Park D, Kim E, Shin G. Neck muscle fatigue due to sustained neck flexion during smartphone use. Int J Ind Ergon. 2024;100:103554.
7. Cheung MC, Lai JSK, Yip J, Cheung JPY. Increased computer use is associated with trunk asymmetry that negatively impacts health-related quality of life in early adolescents. Patient Prefer Adher. 2021;15:2289–302.
8. Lee S, Choi YH, Kim J. Effects of the cervical flexion angle during smartphone use on muscle fatigue and pain in the cervical erector spinae and upper trapezius in normal adults in their 20s. J Phys Ther Sci. 2017;29(5):921–3.
9. Aafreen A, Khan AR, Khan A, Ahmad A, Shaphe MA, Alzahrani A, Alhusayni A, Alameer AH, Alajam RA. Decoding the impact of driving postures: comparing neck pain, mobility, proprioception in car and bike drivers with and without Forward Head Posture. J Transp Health. 2023;33:101719.
10. Gerr F, Fethke NB, Merlino L, Anton D, Rosecrance J, Jones MP, Marcus M, Meyers AR. A prospective study of musculoskeletal outcomes among manufacturing workers: I. Effects of physical risk factors. Hum Factors. 2014;56(1):112–30.
11. Holmström EB, Lindell J, Moritz U. Low back and neck/shoulder pain in construction workers: occupational workload and psychosocial risk factors. Spine. 1992;17(6):672–7.
12. Negm A, MacDermid J, Sinden K, D'Amico R, Lomotan M, MacIntyre NJ. Prevalence and distribution of musculoskeletal disorders in firefighters are influenced by age and length of service. J Mil Vet Fam Health. 2017;3(2):33–41.
13. Koutras C, Buecking B, Jaeger M, Ruchholtz S, Heep H. Musculoskeletal injuries in auto racing: a retrospective study of 137 drivers. Phys Sportsmed. 2014;42(4):80–6.
14. Ariëns GA, Bongers PM, Douwes M, Miedema MC, Hoogendoorn WE, van der Wal G, Bouter LM, van Mechelen W. Are neck flexion, neck rotation, and sitting at work risk factors for neck pain? Results of a prospective cohort study. Occup Environ Med. 2001;58(3):200–7.
15. Szeto GPY, Straker L, Raine S. A field comparison of neck and shoulder postures in symptomatic and asymptomatic office workers. Appl Ergon. 2002;33(1):75–84.
16. Straker L, Mekhora K. An evaluation of visual display unit placement by electromyography, posture, discomfort and preference. Int J Ind Ergon. 2000;26(3):389–98.
17. Villanueva MBG, Sotoyama M, Jonai H, Takeuchi Y, Saito S. Adjustments of posture and viewing parameters of the eye to changes in the screen height of the visual display terminal. Ergonomics. 1996;39(7):933–45.
18. Morton J, Stewart GD. The burden of performing minimal access surgery: ergonomics survey results from 462 surgeons across Germany, the UK and the USA. J Robotic Surg. 2022;16(6):1347–54.
19. Welcker K, Kesieme EB, Internullo E, Kranenburg van Koppen LJC. Ergonomics in thoracoscopic surgery: results of a survey among thoracic surgeons. Interact Cardiovasc Thorac Surg. 2012;15(2):197–200.
20. Soueid A, Oudit D, Thiagarajah S, Laitung G. The pain of surgery: pain experienced by surgeons while operating. Int J Surg. 2010;8(2):118–20.
21. Aaron KA, Vaughan J, Gupta R, Ali NES, Beth AH, Moore JM, Ma Y, Ahmad I, Jackler RK, Vaisbuch Y. The risk of ergonomic injury across surgical specialties. PLoS ONE. 2021;16(2): e0244868.
22. Tran M, Kortz MW, Johnson B, Janis JE. Operation-related musculoskeletal injuries among United States surgeons: a gender-stratified national survey. Plast Reconstr Surg Glob Open. 2022;10(2): e4142.
23. Brandt ML. Sustaining a career in surgery. Am J Surg. 2017;214(4):707–14.
24. Russell LJ, Dodd T, Kendall D, Lazenbury A, Leggett A, Paytohn-Haines S, Jiang L, Filingeri D, Worsley PR. A bioengineering investigation of cervical collar design and fit: implications on skin health. Clin Biomech. 2024;112:106178.
25. Tescher AN, Rindflesch AB, Youdas JW, Terman RW, Jacobson TM, Douglas LL, Miers AG, Austin CM, Delgado AM, Zins SM, Lahr BD, Pichelmann MA, Heller SF, Huddleston PM III. Comparison of cervical range-of-motion restriction and craniofacial tissue-interface pressure with 2 adjustable and 2 standard cervical collars. Spine. 2016;41(6):E304–12.
26. Golabchi A, Chao A, Tavakoli M. A systematic review of industrial exoskeletons for injury prevention: efficacy evaluation metrics, target tasks, and supported body postures. Sensors. 2022;22(7):2714.
27. Siviy C, Baker LM, Quinlivan BT, Porciuncula F, Swaminathan K, Awad LN, Walsh CJ. Opportunities and challenges in the development of exoskeletons for locomotor assistance. Nat Biomed Eng. 2022;7:456–72.
28. Zhou YM, Hohimer CJ, Young HT, Mccann CM, Pont-Esteban D, Civici US, Jin Y, Murphy P, Wagner D, Cole T, Phipps N, Cho H, Bertacchi F, Pignataro I, Proietti T, Walsh CJ. A portable inflatable soft wearable robot to assist the shoulder during industrial work. Sci Rob. 2024;9: eadi2377.
29. Spada S, Ghibaudo L, Gilotta S, Gastaldi L, Cavatorta MP. Investigation into the applicability of a passive upper-limb exoskeleton in automotive industry. Proc Manuf. 2017;11:1255–62.
30. Aoki K, Kawahira H, Shimomura Y, Lefor AK. An exoskeleton upper extremity support for laparoscopic surgery: a pilot simulation study. J Jap Soc Comput Aided Surg. 2020;22(1):33–9.
31. Wang T, Norasi H, Tetteh E, Smith T, Mendes BC, Hallbeck MS. Examining the effectiveness of a lower back exoskeleton in reducing discomfort and workload in vascular surgery. Proc Hum Factors Ergon Soc Annu Meet. 2022;66(1):2153–7.
32. Bales I, Zhang H. A six degrees-of-freedom cable-driven robotic platform for head-neck movement. Sci Rep. 2024;14:8750.

33. Torrendell SP, Kadone H, Hassan M, Chen Y, Miura K, Suzuki K. A neck orthosis with multi-directional variable stiffness for persons with dropped head syndrome. IEEE RA-L. 2024;9(7):6224–31.
34. Mahmood MN, Tabasi A, Kingma I, van Dieën JH. A novel passive neck orthosis for patients with degenerative muscle diseases: development & evaluation. J Electromyogr Kinesiol. 2021;57:102515.
35. Tetteh E, Hallbeck MS, Mirka GA. Effects of passive exoskeleton support on EMG measures of the neck, shoulder and trunk muscles while holding simulated surgical postures and performing a simulated surgical procedure. Appl Ergon. 2022;100:103646.
36. Chang BC, Zhang H, Long S, Obayemi A, Troob SH, Agrawal SK. A novel neck brace to characterize neck mobility impairments following neck dissection in head and neck cancer patients. Wearable Tech. 2021;2: e8.
37. Hermens HJ, Freriks B, Disselhorst-Klug C, Rau G. Development of recommendations for SEMG sensors and sensor placement procedures. J Electromyogr Kinesiol. 2000;10(5):361–74.
38. Yang L, Money SR, Morrow MM, Lowndes BR, Weidner TK, Fortune E, Davila VJ, Meltzer AJ, Stone WM, Hallbeck MS. Impact of procedure type, case duration, and adjunctive equipment on surgeon intraoperative musculoskeletal discomfort. J Am Coll Surg. 2020;230(4):554–60.
39. Lee S, Kang H, Shin G. Head flexion angle while using a smartphone. Ergonomics. 2014;58:220–6.
40. Zabihhosseinian M, Holmes MW, Ferguson B, Murphy B. Neck muscle fatigue alters the cervical flexion relaxation ratio in sub-clinical neck pain patients. Clin Biomech. 2015;30(5):397–404.
41. Hansraj KK. Assessment of stresses in the cervical spine caused by posture and position of the head. Surg Technol Int. 2014;25:277–9.
42. Ackland DC, Merritt JS, Pandy MG. Moment arms of the human neck muscles in flexion, bending and rotation. J Biomech. 2011;44(3):475–86.
43. Choi JR, Kim SW, Cho KJ. Self-unlocking active clutch for quasi-passive wearable robots. IEEE/ASME Trans Mechatron. 2024. https://doi.org/10.1109/TMECH.2024.3509854.
44. Brooke J. SUS: a "quick and dirty" usability scale. In: Jordan PW, Thomas B, McClelland IL, Weerdmeester BM, editors. Usability evaluation in industry. London: Taylor & Francis Group; 1996. p. 189–94.
45. Lewis JR. The system usability scale: past, present, and future. Int J Hum-Comput Interact. 2018;34(7):577–90.
46. Piscione J, Gamet D. Effect of mechanical compression due to load carrying on shoulder muscle fatigue during sustained isometric arm abduction: an electromyographic study. Eur J Appl Physiol. 2006;97(5):573–81.