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Physiological and psychological neck load imposed by ballistic helmets during simulated military activities

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Abstract

The wearing of ballistic helmets commonly coordinated with a night vision device (NVD) often imposes a load to the neck of a soldier. A lighter ballistic helmet promises comfort and enhanced combat performance, but technological developments have not provided a complete solution satisfying all the requirements, including cost. Moreover, the change in munition has led to increasing demand for the attachment of more accessories to the helmet, providing advanced functions but additional weight. Therefore, the current study quantified the neck muscle strain caused by the varying weight of a ballistic helmet, particularly during simulated infantry activities with moderate neck flexion and neck extension against a head-weight in the prone position. Eight healthy males participated on four separate days. On each day, different loads were placed on the head: 0 kg (no helmet, NH) to 2.07 kg (1.5 kg helmet with a 0.5 kg night vision device, HH&NVD). The results showed that prone shooting imposed substantial muscular strain on the splenius capitis (neck extensor), resulting in a 7–9% maximal voluntary contraction depending on the overall helmet loads. In addition, a gradual increase in the subjective neck load and pain in proportion to the overall weight of the helmet assembly was noted, and the heaviest loads caused severe complaints for muscular discomfort. This paper recommends strategies for designing and developing ballistic helmets as well as further methodological issues on evaluating neck muscle strain caused by the helmet weight.

Keyword: Ballistic helmet, Night vision device, Surface electromyography, Muscle fatigue, Subjective neck load, Neck pain, Prone position, Sternocleidomastoid, Splenius capitis

Introduction

Ballistic helmets are protective equipment that provides head protection from shrapnel and ballistic threats. A lower weight ballistic helmet always promises better comfort and enhanced combat capability, but the technology required to provide a perfect solution satisfying all factors, including weight, performance, and even cost, is still under development. Moreover, the change in munition has increased the requirements for more accessories attached to the helmet giving advanced capabilities to individuals. In the United States, the advanced combat helmet (ACH), which was developed in 2002 and

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still in widespread use, weighs 1.22 – 1.67 kg. With additional devices that help enhance an individual's combat capability, the final weight can easily exceed 3 kg. The weight of the helmet depends basically on the shell thickness and its material, where the expense of material is also sensitively involved (Kulkarni et al. 2013). In a development process, compromise among conflicting factors, such as weight, ballistic protection requirement, and cost, is difficult to accomplish. Quantitative evidence regarding the advantages and disadvantages of a concession for each factor is needed.

Musculoskeletal discomfort in the neck has been reported in association with loading the helmet with its additional accessories, mostly toward pilots and helicopter aircrew (Harrison et al. 2015). Electromyography has been a useful method to assess the muscle activities during head movement and stabilization in a variation of the helmet weight and motions (Sommerich et al. 2000; Sovelius et al. 2008). Sovelius et al. (2008) examined the effects of a 1.5 kg helmet and 0.9 kg night-vision goggles during the simulated acceleration of gravity for helicopter aircrews. The results showed that a helmet caused a 13% increase in the sternocleidomastoid (STM) and an 18.7% increase in cervical erector spinae (CES). In addition, a night vision goggles (NVG) resulted in an 11.9 and 11.1% increase in STM and CES, respectively.

On the other hand, the majority of the available literature related to neck pain focused on aircrew. The research topics were muscular strain during flight (Oksa 1996; Sovelius et al. 2008; Harrison et al. 2015), the prevalence of neck injury and pain (Äng and Harms-Ringdahl 2006; Posch et al. 2019), and neck muscle strength and endurance training program to reduce discomfort and injuries (Alricsson et al. 2004). In comparison, there have been fewer evaluations of the neck muscle strain of a ballistic helmet specifically for an infantryman. Infantrymen, which comprise the largest population of ground troop forces, participate in warfare at a closer distance to the enemy and undertake various missions, such as searching, fighting, and attacking, using firearms and weapons while protecting themselves. Therefore, the neck load may be caused by various neck movements in the case of infantrymen, which differs from pilots, whose neck needs to be stabilized against the acceleration of gravity and be rotated occasionally during communication to other crew members. The prone shooting position is a representative posture of an infantryman, and it can cause substantial neck load and pain on the posterior neck because the posture requires not only neck extension but also the resistance of head-helmet weights, which imposes loads on the cervical spine.

Therefore, this study examined neck muscular strain during ground troop duties caused by varying helmet weights: 0–2.1 kg. Surface electromyography (sEMG) was used to assess the muscle activities quantitatively, and the subjective neck load was rated to access the level of musculoskeletal discomfort. This study hypothesized that (1) the neck muscle loads evaluated by the sEMG signals and subjective ratings would present gradual increases by increasing the overall loads on the head. (2) A prone shooting posture would impose the greatest muscle loads in both sEMG and subjective ratings.

Methods

Subjects

Eight healthy males with no history of known diseases or chronic neck pain were recruited (age = 24 ± 3 years; body weight = 73.0 ± 6.8 kg, height = 177.3 ± 6.8 cm, body

Table 1 Helmets and a night vision device used under each experimental condition

Conditions	NH	LH	HH	HH and NVD
Total weight on the head	0 kg	1.15 kg	1.50 kg	2.07 kg
				
Helmet				
Model	Not used	PASGT type	ACH type (side rail and front NVD mount included)	ACH type (side rail, front NVD mount, and NVD included)
Weight	N/A	1.15 kg	1.50 kg	1.50 kg
Material	N/A	Ultra high molecular weight polyethylene (UHMWPE)	Aramid	Aramid
Night Vision Device (NVD)				
Model	N/A	N/A	N/A	PVS-04 K, EO System co., Ltd, South Korea
Weight	N/A	N/A	N/A	573 g (a mount bracket included)

N/A not applicable

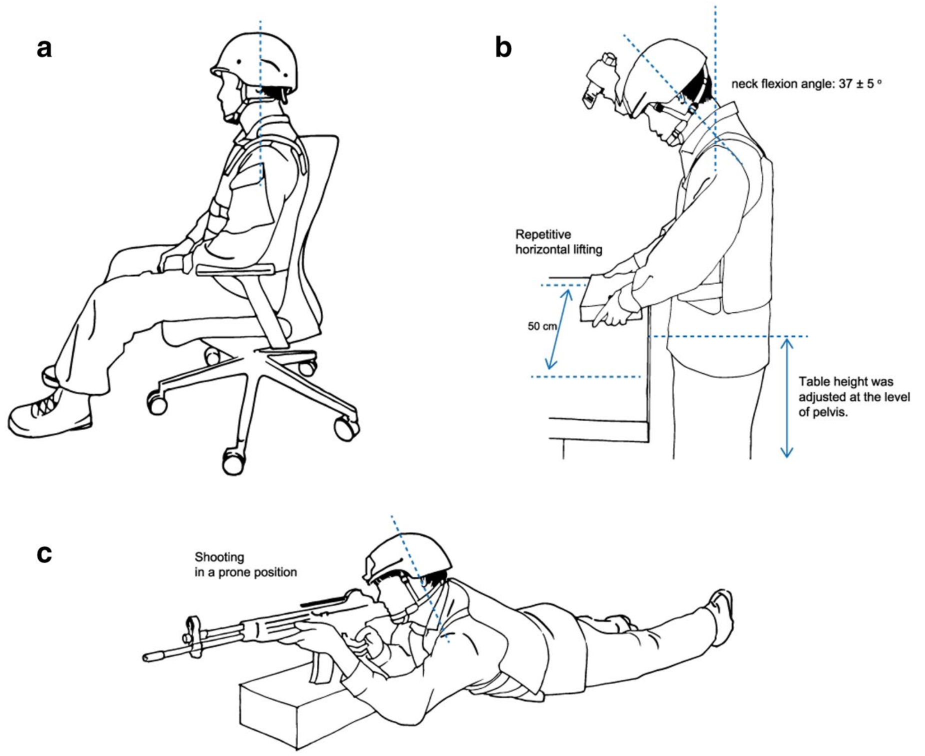

Fig. 1 Schematic diagram of simulated military activities and postures: Sitting in a chair looking in the forward direction (**a**), horizontal lifting on a table (**b**), and shooting in the prone position (**c**)

mass index (BMI) = 23.2 ± 1.4 kgm^{-2}, body fat (%BF) = 15.4 ± 5.4%). Body fat was calculated by using the formula of Garcia et al. (2005). All participants were familiar with military activities, such as shooting in the prone position, which was included in the experimental protocol, as in South Korea, which has compulsory national service to men. One subject was during his military duties at the time of the experiment, and the other seven had already completed their military services within the recent five years and were participating in a reserve force drill every year. All participants were informed of the experimental procedures and provided informed consent prior to participation. All procedures were fully approved by the Public Institutional Review Board designated by the Ministry of Health and Welfare (P01-201,812-11-003).

Experimental setup and protocols

A commercialized ballistic helmet (lighter helmet, LH; 1.15 kg) and a recently developed prototype helmet (heavier helmet, HH; 1.50 kg) were used. LH has been supplied to the army since 1995 and is in widespread use in South Korea. On the other hand, HH has been developed with the aim of supply them to the army within the next few years. They differ in various aspects, including covering area, material, head suspension system, as well as weight, which are summarized in Table 1. LH is similar in appearance to a Personnel Armor System for Ground Troops (PASGT) helmet, while HH is much closer to an Advanced Combat Helmet (ACH) (Kulkarni et al. 2013). On the other hand, other factors except for weights, were assumed to be relatively negligible regarding the effects on the neck load, particularly during static and semi-static tasks, where rapid movement is not required. Four conditions with varying overall helmet weights (including helmet and additional accessories) were assigned in randomized order: (1) [NH]: No Helmet (overall weight = 0 kg), (2) [LH]: overall weight = 1.15 kg, (3) [HH]: overall weight = 1.5 kg (side rail and front NVD mount included),(4) [HH&NVD]: overall weight = 2.1 kg (Table 1). In HH&NVD, an NVD (370 g, PVS-04 K, EO System co., Ltd, South Korea) was mounted on the frontal part of the ballistic helmet using a mounting bracket (203 g). This increased the overall weight of the helmet to 2.07 kg. The participants wore military uniforms with a flexible ballistic vest, weighing 5.5 kg.

Horizontal lifting work and shooting in the prone posture were selected as reference activities of infantrymen (Fig. 1). First, the horizontal lifting required moving 2.5 kg loads (size = 210 × 297 × 50 mm) at the level of the pelvis while holding with both hands from left to right for 10 min. The loads were transferred repetitively and horizontally on the table. The distance of both ends was 50 cm. The subjects stood still and kept their eyes on the loads they were moving, which allowed the range of neck flexion and rotation to be maintained. The participants moved the box to the identical pace of an electrical metronome, which was set to 45 rpm. Photograph analysis showed that the average neck-flexion angle of all subjects during horizontal lifting was 37 ± 5°. Secondly, shooting in the prone position was chosen because it is a representative military posture requiring substantial neck extension. To simulate a shooting posture, an authentic replica of a rifle, which has an identical size and shape to an actual one, was used. The subjects laid down prone on the floor and stared forward. The rifle was always supported by the ground or boxes so that the muscle fatigue from factors other the helmet loads could be minimized. The subjects were placed at a 10 m distance, and the target height was set to the eye height of each subject. This posture was maintained for 10 min. All experimental trials were carried out at a room at 22.3 ± 0.8 °C and 22.3 ± 3.1% relative humidity (RH) with a wind speed of $< 0.2\ \text{ms}^{-1}$.

Outcome measures

Ag–AgCl electrodes were placed over two pairs of neck muscles: sternocleidomastoid (SCM) and splenius capitis (SPL). Bipolar EMG recordings were obtained via pregelled surface electrodes (EMG Electrode 246H, SEED Technology, South Korea). They were attached longitudinally to each muscle, 2 cm apart (Sovelius et al. 2008). The placements of the electrodes were determined, according to Keshner et al. (1989). The electrodes for SCM were attached to the palpated muscle belly approximately one-third of its length rostral to its sternal attachment with their head laterally rotated. The SPL electrodes were placed on the palpated muscle belly at approximately 6–8 cm lateral to the median line at the C4 level (Keshner et al. 1989). The ground electrodes were placed on the bony prominence at C7. The skin surface at each electrode location was shaved and scrubbed vigorously with an alcohol wipe to remove oil and slightly debride the skin. Once the electrodes were placed, they were secured to the skin with a strip of surgical tape.

The subjects performed a maximal voluntary contraction (MVC) of the cervical muscles by pushing against a fixed surface for 5 s in the anterior, posterior, left, and right directions (lateral bending), respectively. They were asked to reach the maximum exertion within 3 s and maintain the maximum force for the last 2 s. A 1 min rest was offered to minimize muscle fatigue, and subjects repeated the test three times for each direction. Verbal encouragement was provided to draw greater exertion. Among the measured outcomes, the greatest 30 s values were extracted as the MVC of each muscle and used as the reference muscle activity to normalize every measurement. After 5 min of recovery, the subjects performed experimental trials composed of sitting gazing forward (neutral position), horizontal lifting on a table (moderate neck flexion), and prone shooting (severe neck extension). The muscle strain was represented as a percentage of the MVC (%MVC).

The recordings were amplified and filtered (20–500 Hz) in analog (MP160, BIOPAC systems, Inc., US) and then digitally filtered using AcqKnowledge® 5.0.1 Software (BIOPAC systems, Inc.) using an FIR bandpass filter (20–500 Hz). The data were then full-wave rectified and averaged with a 100 ms time constant to draw the amplitude of the sEMG signals. The muscle activities representing the neck load of each posture was obtained from the averaged value for 7 min during each posture, where the first 1 min and last 2 min were removed to obtain clearer outcomes.

The subjective neck load and neck pain were rated using a Visual Analogue Scales (VASs) at the end of every phase. The VAS scales have 100 mm lines with verbal anchors on each side. The subjects chose a number between 0 and 10, denoting “no neck load (0)” and “intolerable neck load (10)” in the case of neck load and “no pain (0)” and “intolerable neck pain (10)” in the case of neck pain.

Statistics

Before commencing statistical analysis to identify the effects of the helmet weights on the psychological and subjective neck load, this study examined whether the distribution of data was normal using a Kolmogorov-Sminor normality test. Non-parametric statistics were performed on the data that did not satisfy a normal distribution. A Friedman test was performed to conduct a comparison between four conditions. Thereafter, a Wilcoxon test was performed to clarify the two groups, which showed a significant difference. A Bonferroni correction was used to examine the effects of the overall helmet weights and postures. Statistical differences were accepted at $P < 0.05$.

Results

Muscular demands

Figure 2 shows the mean muscle activities of all four muscles described as %MVC. Generally, the muscle strain of NH tended to be lower than the other helmet conditions, but the differences among LH, HH, and HH&NVD were not significant. The only significant difference was found in the left and right SPL during horizontal lifting between HH&NVD and NH ($P < 0.05$, Fig. 2). When the %MVC of SPL was again recalculated in ΔHEL, an increasing tendency by the overall helmet weight was observed, particularly during horizontal lifting. In LH, the HH, HH&NVD, and ΔHEL of SPL were 1.19, 1.25, and 1.57 times greater than NH, respectively (Table 2). Posture differences were obtained. Horizontal shooting caused a 2.4 to 3.3 times higher neck load than the sitting posture, while prone shooting produced a 5.1 to 6.3 times greater muscle load than

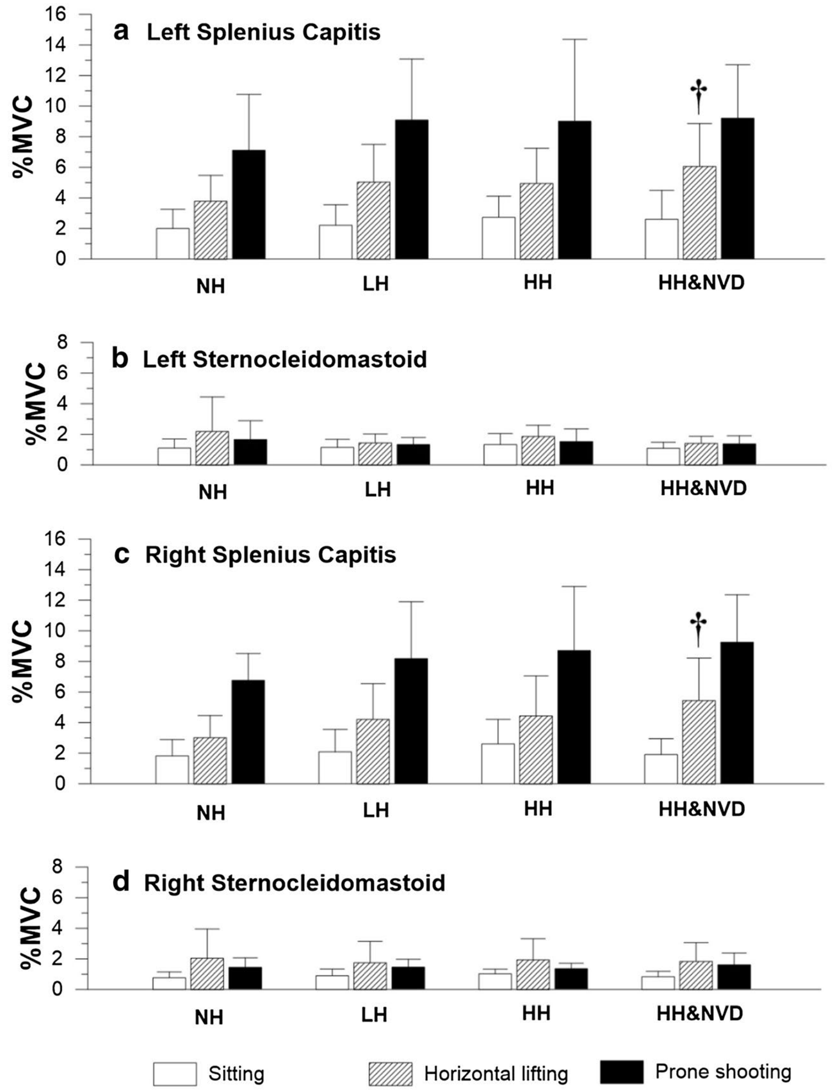

Fig. 2 Effect of total helmet weight on the muscle strain of the four neck muscles during sitting, horizontal lifting, and prone shooting described as changes in %MVC (*N* = 8) (mean ± SD): The values were averaged for 5 min during each posture. NH = No Helmet; LH = 1.15 kg helmet; HH = 1.5 kg helmet, HH&NVD = 1.5 kg helmet with a night vision device (total weight = 2.1 kg). $^{\dagger}P < 0.05$ indicates the helmet effects versus NH; Friedman test used for identifying the group differences with a Wilcoxon test as a post-hoc test

sitting (Table 2). On average, horizontal lifting imposed 3.81%MVC [NH] to 6.09%MVC [HH&NVD], and prone shooting imposed 7.07%MVC [NH] to 9.17%MVC [HH&NVD] (Table 2).

Relatively lower strain was observed in STM throughout the protocols. Horizontal lifting tended to impose greater strain, but the values were approximately 2%MVC under all conditions (Fig. 2).

Table 2 Effect of the total helmet weight on the muscle strain of the left splenius capitis during sitting, horizontal lifting and prone shooting described as changes in %MVC ($N=8$)

Movements	NH	LH	HH	HH and NVD	*P* value
Sitting					
%MVC	1.99 ± 1.26	2.21 ± 1.34	2.73 ± 1.38	2.60 ± 1.90	
ΔHEL	1.0 ± 0.0	1.24 ± 0.91	1.70 ± 1.67	1.42 ± 0.88	
ΔMOV	1.0 ± 0.0	1.0 ± 0.0	1.0 ± 0.0	1.0 ± 0.0	
Horizontal lifting					
%MVC	3.81 ± 1.69	5.06 ± 2.46	4.97 ± 2.30	6.09 ± 2.80†	0.014
ΔHEL	1.0 ± 0.0	1.19 ± 0.25	1.25 ± 0.29	1.57 ± 0.34	
ΔMOV	2.7 ± 1.5	2.8 ± 1.5	2.4 ± 1.3	3.3 ± 2.2	
Prone shooting					
%MVC	7.07 ± 3.67	9.05 ± 3.98	8.97 ± 5.36	9.17 ± 3.50	0.919
ΔHEL	1.0 ± 0.0	1.20 ± 0.58	1.29 ± 0.47	1.33 ± 0.60	
ΔMOV	6.3 ± 5.4	5.4 ± 4.8	5.8 ± 5.9	5.1 ± 4.1	
P					–

%MVC muscle strain normalized by its maximal voluntary contraction activity, *ΔHEL* a mean of individual changes in %MVC in comparison with NH (in times), *ΔMOV* a mean of individual changes in %MVC compared to the sitting posture (in times), *NH* No Helmet, *LH* 1.15 kg helmet, *HH* 1.5 kg helmet, *HH and NVD* 1.5 kg helmet with a night vision device (total weight = 2.1 kg)

The values represent the neck pain when each posture lasted for 8 min. Data are shown as the mean ± SD

† $P<0.05$ indicates the helmet effects versus NH; Friedman test used for identifying the group differences using a Wilcoxon test as a post-hoc test

Subjective neck load and pain

The effects of the helmet weight were detected in the subjective neck loads and pain by showing gradual increases in the total helmet weight (Fig. 3) ($P<0.001$ in all phases for both the neck load and pain except for the pain during sitting). In HH&NVD, the subjects expressed severe neck load (7.0 ± 2.7) and substantial neck pain (6.0 ± 2.9) during prone shooting. The post-doc test results revealed differences even during the sitting position (Fig. 3): [neck load] NH, 0 ± 0; LH, 0.6 ± 0.5; HH, 1.4 ± 1.5; HH&NVD, 3.9 ± 3.0 ($P=0.012$, HH&NVD versus. LH). Statistical differences regarding movements were observed in the neck load (LH, HH) and neck pain (all conditions, except NH) ($P<0.001$, Fig. 3). In particular, during the prone position, the subjects rated up to 7.0 ± 2.7 (HH&NVD) of the neck load and 6.0 ± 2.9 of neck pain in the heaviest overall weight imposed on the head (HH&NVD).

Discussion

The current study highlights the need for a quantitative evaluation of the neck load and pain that infantrymen may experience during their actual military duties in relation to the helmet weight. The muscle activities of the neck extensor and flexor accessible via sEMG were of primary interest to this investigation. The results showed that the helmet weight alone had a significant effect on muscular strain, particularly on the SPL rather than STM, but the effects of the helmet weight on the sEMG outcomes were less distinguishable than the subjectively rated neck load and pain. The hypothesis that different helmet loads from a 1.15 to 2.07 kg helmet can cause an increase in neck load was rejected statistically by sEMG in the current experimental settings. Nevertheless,

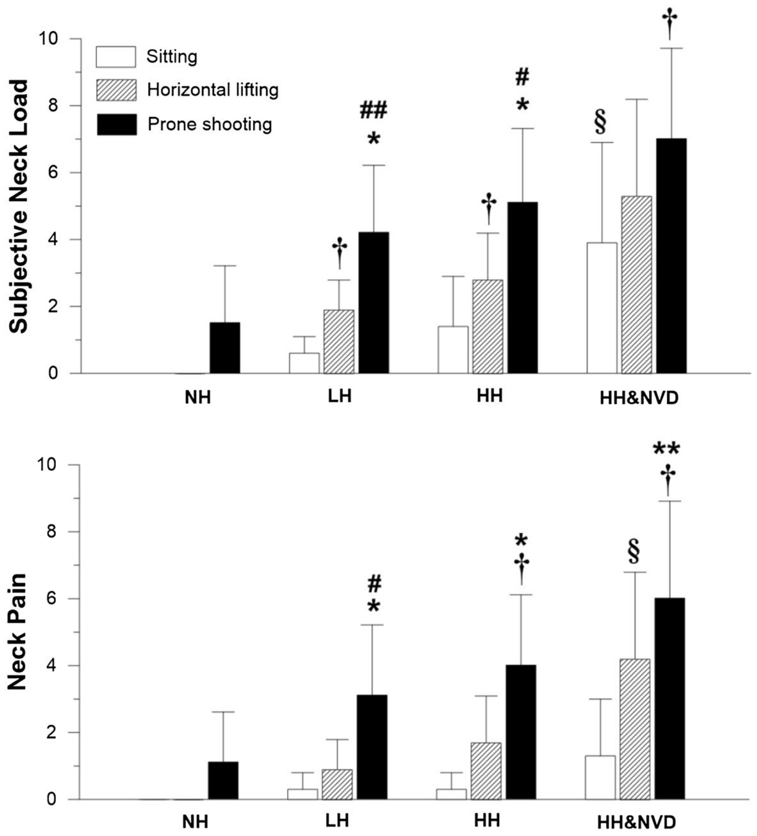

Fig. 3 Effects of helmets and postures (resting, moving boxes, prone shooting) on the subjective neck load and neck pain. They were rated with a visual analogue scale from 0 (no neck load), to 10 (intolerable neck load) or a scale from 0 (no pain) to 10 (intolerable neck pain). $^{*}P < 0.05$ and $^{**}P < 0.01$ indicate the posture effects versus sitting; $^{\#}P < 0.05$ and $^{\#}P < 0.01$ indicate the posture effects versus horizontal lifting; $^{\dagger}P < 0.05$ indicates the helmet effects versus NH; $^{\S}p < 0.05$ indicates the helmet effects versus LH. All significances were verified by non-parametric statistics: Friedman test was used to identify the group differences with a Wilcoxon test as a post-hoc test

the hypothesis was explicitly supported by the subjective ratings on neck load and pain. Among the simulated tasks, the prone shooting posture imposed a much greater load on the SPL as well as subjective outcomes. In contrast, a relatively lower load was reported during horizontal lifting with moderate neck flexion.

This study used horizontal lifting requiring neck flexion with an angle of approximately 30° and prone shooting resulting in neck extension against the head-weight. Musculoskeletal discomfort in the neck is closely associated with the working postures commonly described by the joint angle and occasionally external moments (e.g., G forces in case of flight situation). Twenty-three neck muscles composed of several layers are involved in head stabilization as well as movement, including head and neck extension, flexion, lateral bending, and rotation. Different types of work employ differently characterized muscle activation. Most of the concerns have been toward the neck load of pilots during flight. Although there have been numerous findings and implications on the muscle loads imposed by the helmet weight (Van Dijke et al. 1993; Sovelius et al. 2008), infantrymen engage in a range of tasks that are different from aircrew.

Among them, prone shooting, a typical posture of infantryman to target enemies from a concealed position, was evaluated as a vulnerable posture to overall helmet loads. In addition, the postures led to 8 ~ 9%MVC on the SPL with 1 ~ 2 kg loads on the head without noticeable changes by the overall loads. The values coincide with the activation level during neck extension reported by Cheug et al. (2016), who calculated the activation level of each muscle using a musculoskeletal model during neck movement with various angles. In their study, the muscle strain of SPL was 6.2 ~ 6.5%MVC in 20% neck extension and 7.3 – 8.3%MVC in 30% neck extension, which is comparable to 6.7%MVC in NH. According to Ng et al. (2014), such intensities can be categorized as a substantial neck load because smaller muscles, such as STM and SPL, are more prone to be fatigued compared to larger muscles, such as the trapezius (Harrison et al. 2015). In the study, the severity of the neck load represented in 8 ~ 9%MVC of SPL was also supported by the subjective neck load denoting 7.0 ± 2.7 evaluated on a scale from 0 (no neck load) to 10 (intolerable neck load). One subject also complained of difficulty in correctly aiming a target caused by severe neck load, causing collapses of a stable shooting posture. In this context, although the current study did not measure the shooting performance according to the varying helmet loads, the example suggests that a lighter helmet may contribute strongly to the combat capability and individual survival. When considering that the physical, physiological, and subjective strains are often aggravated by other factors in the field such as heat stress, characteristics of ground (e.g. sand, mud, graveled) and additional weights on the back and shoulders, the 2 kg load on the head in this study, which approximately corresponds to 3% of body weight (mean body weight of subjects = 73 kg), can be a conservative upper limit to avoid intolerable neck load and pain during prone position.

Generally, neck muscle pain is most common in the posterior region of the neck (Joines et al. 2006). In most occupational settings, neck flexion is problematic, even though it is very slight but prolonged. In the back neck musculature, the semispinalis capitis is located more in the inner layer than the SPL, and it is involved primarily in neck flexion, which is in contrast to the SPL, which is involved in varied neck movement, including extension, rotation, and lateral movement (Takebe et al. 1974; Keshner et al. 1989; Sommerich et al. 2000). The restricted number of neck muscles investigated is one limitation considering that the semispinalis capitis can contribute to neck flexion along with SPL. Muscle activation may occur on the other neck flexor due to the loading. Sustained postures might encourage the participation of other muscles. Huge individual differences in muscle use also exist. Keshner et al. (1989) reported that the SPL did not show 100% consistency between subjects, and it was activated preferentially during neck flexion in half and during neck extension in the other half.

Regarding the loads on the head, Thuresson et al. (2005) reported an increase in muscle activation with increasing weight added to the helmets (a night vision goggle weighing 0.755 kg, a CW weighing 0.325 kg and a helmet weighing 1.417 kg) during 20° neck flexion on the upper neck (C2 level). In addition, the activities of those muscles did not exceed 2% of the reference voluntary contraction (RVC). They also showed statistical differences between helmet only and helmet with a night vision goggle attached. In the current study, SPL (C4 level) showed 3.8%MVC (NH) to 6.09%MVC (HH&NVD) with a statistical difference only between NH and HH&NVD. The authors reported that the less-sensitive statistical results, despite the larger %MVC, could be related to the duration of neck flexion as well as a smaller number of subjects (8 versus 14). Thuresson et al. (2005) also used each posture maintained for approximately five seconds while the current study requested the posture be maintained for 10 min, and data were analyzed based on the 5 min averaged values.

Nevertheless, a steady increase in the SPL activities by the overall helmet weights was observed, particularly during horizontal lifting (Table 2), showing a 21, 30, and 67% increase in LH, HH, and HH&NVD, respectively. Sovelius et al. (2008) reported that the helmet increased muscle strain by 18, 28, and 18% in the SCM, cervical erector spinae (CES), and trapezius, and a night vision google produced a further increase of 11 and 6% in the SCM and CES, respectively. Nevertheless, a comparison with the current results is difficult owing to the different experimental settings, such as trampoline-induced acceleration and the few muscles of common interest, but this study still suggests a meaningful implication in that only postures and helmet loads caused a gradual increasing neck load without any G forces.

Several methodological issues may be considered, including non-parametric statistics, probably resulting from the insufficient sample size and the restricted number of muscles and military activities. Another limitation could be that the current study only considered the overall helmet weight, and the shifting center of gravity was not considered. The higher center of gravity can cause greater strain on the neck (Phillips and Petrofskyss 1983). The muscular loads caused by the additional weight of HH&NVD can be overestimated when an NVD shifts the center-of-gravity.

Nevertheless, the following meaningful implications can be suggested. (1) In addition to the heavy load carriage, ballistic helmets causing neck extreme neck extension can be most strenuous during military duties when a heavier ballistic helmet and equipment is loaded on the head, particularly in the prone position. (2) Activities with different neck postures showed huge changes in the subjective neck load, suggesting that an evaluation of the neck load in a simple sitting posture distorts the actual discomfort severely. (3) The effects of the ballistic helmet weight through subjective ratings can provide useful and sometimes distinguishable results, even compared to sEMG, when actual occupational postures with a prolonged duration time are considered together. (4) In the perspective of design, priority should be given to reducing the helmet weight when developing a ballistic helmet, its accessories, and the connecting components between them. Any strategy reducing the neck load, especially focused on the prone position, will be beneficial.

Conclusion

A ballistic helmet imposed a substantial neck load during military activities. The subjective neck load proportionally increased the total weight of a helmet and its accessories. In particular, shooting in the prone position imposed a severe neck load to the neck extensor muscles. Along with the technological progression of military equipment, a larger number of components have been designed as a form attached to the ballistic helmet to enhance the individuals' physical capability. On the other hand, the current results recommended lowering the total helmet weight in the perspective of ergonomics when considering that the subjective neck load and pain showed a gradual increase in proportion to the total helmet weight. Considering that the technological limitations have barely allowed rapid innovation for a decrease in helmet weight while maintaining the ballistic performance, the authors propose the following considerations for a ballistic helmet design with a lower weight, its accessories, and the connecting components between them. The concerns on technologically developed helmets integrated with various equipment, enhancing an individual's combat capabilities have increased. On the other hand, finding the optimal balance between the ballistic or combat performance and comfort is important. Despite there being no upper limit to the gradual increase in helmet weight, an approximately 3% body weight on the head can have severe deleterious effects on soldiers in the prone position.

Abbreviations

ACH: Advanced combat helmet; CES: Cervical erector spinae; CW: Counter-weight; ΔHEL: Mean of individual changes in %MVC in comparison with NH; ΔMOV: Mean of individual changes in %MVC in comparison with sitting posture; MVC: Maximal voluntary contraction; NVD: Night vision device; PASGT: Personnel armor system for ground troops; sEMG: Surface electromyography; SPL: Splenius capitis, neck extensor muscle; STM: Sternocleidomastoid, neck flexor muscle; UHMWPE: Ultra high molecular weight polyethylene; VAS: Visual analogue scales.

Authors' contributions

SK and WJ contributed to the design and implementation of the research, to the analysis of the results and to the writing of the manuscript. Both authors read and approved the final manuscript.

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Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

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References

Alricsson M, Harms-Ringdahl K, Larsson B, Linder J, Werner S (2004) Neck muscle strength and endurance in fighter pilots: Effects of a supervised training program. Aviat Space Environ Med 75:23–28.

Äng, B., & Harms-Ringhahl, K. (2006). Neck pain and related disability in helicopter pilots: a survey of prevalence and risk-factors. *Aviation, Space, and Environmental Medicine, 77*(7), 713–719.

Cheng, C.-H., Chien, A., Hsu, W.-L., Chen, C. P.-C., & Cheng, H.-Y. K. (2016). Investigation of the differential contributions of superficial and deep muscles on cervical spinal loads with changing head postures. *PLoS Ones*. https://doi.org/10.1371/journal.pone.0150608.

Garcia, A. L., Wagner, K., Hothorn, T., Koebnick, C., Zunft, H.-J. F., & Trippo, U. (2005). Improved prediction of body fat by measuring skinfold thickness, circumferences, and bone breadths. *Obesity Research, 13*(3), 626–634.

Harrison, M. F., Coffey, B., Albert, W. J., & Fisher, S. L. (2015). Night vision goggle-induced neck pain in military helicopter aircrew: A literature review. *Aerospace Medicine and Human Performance, 86*(1), 46–55.

Keshner, E. A., Campbell, D., Katz, R. T., & Peterson, B. W. (1989). Neck muscle activation patterns in humans during isometric head stabilization. *Experimental Brain Research, 75*, 335–344.

Kulkarni, S. G., Gao, X.-L., Horner, S. E., Zheng, J. Q., & David, N. V. (2013). Ballistic helmets — their design, materials, and performance against traumatic brain injury. *Composite Structure, 101*, 313–331.

Ng, D., McNee, C., Kieser, J., & Farella, M. (2014). Neck and shoulder muscle activity during standardized work-related postural tasks. *Applied Ergonomics, 45*, 556–563.

Oksa, J., Hamalainen, O., Rissanen, S., Myllyniemi, J., & Kuronenen, P. (1996). Muscle strain during aerial combat maneuvering exercise. *Aviation, Space, and Environmental Medicine, 67*(12), 1138–1143.

Phillips, C. A., & Petrofsky, J. S. (1983). Neck muscle loading and fatigue: Systematic variation of headgear weight and center-of-gravity. *Aviation, Space, and Environmental Medicine, 54*(10), 901–905.

Posch, M., Schranz, A., Lener, M., Senn, W., Äng, B. O., Burtscher, M., et al. (2019). Prevalence and potential risk factors of flight-related neck, shoulder and low back pain among helicopter pilots and crewmembers: a questionnaire-based study. *BMC Musculoskeletal Disorder, 20*(1), 44. https://doi.org/10.1186/s12891-019-2421-7.

Sommerich, C. M., Joines, S. M. B., Hermans, V., & Moon, S. D. (2000). Use of surface electromyography to estimate neck muscle activity. *Journal of Electromyography and Kinesiology, 10*, 377–398.

Sovelius, R., Oksa, J., Rintala, H., Huhtala, H., & Siitonen, S. (2008). Neck muscle strain when wearing helmet and NVG during acceleration on a trampoline. *Aviation Space and Environmental Medicine, 79*(2), 112–116.

Takebe, K., Vitti, M., & Basmajian, J. V. (1974). The functions of semispinalis capitis and splenius capitis muscles: an electromyographic study. *The Anatomical Recordsss, 179*, 477–480.

Thuresson, M., Äng, B., Linder, J., & Harms-Ringdahl, K. (2005). Mechanical load and EMG activity in the neck induced by different head-worn equipment and neck postures. *International Journal of industrial Ergonomics, 35*, 13–18.

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