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Combined effect of facial sweating and mounting a night vision device on helmet stability

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Abstract

A night vision device (NVD) equipped on a ballistic helmet violates the locational stability of a helmet, and sweating remaining inside a helmet can also reduce helmet stability. This study aimed to investigate the combined effect of sweating and mounting a NVD on helmet stability. Nine healthy males participated in the experiments which consisted of military simulated tasks and 20 min walking. Subjective evaluations containing helmet stability and comfort along with physiological measurements such as microclimate inside a helmet and sweating rate were obtained. Local sweat rate on the forehead was predicted by sweat rate on the upper back and forearm. The results showed that (1) mounting a NVD did not significantly influence on helmet stability per se before onset of sweating, however, (2) when it is combined with sweating, helmet stability reduced 50% during shooting in a prone position ($P < 0.05$). (3) There was a significant correlation with helmet overall comfort and helmet stability ($r = 0.762$, $P < 0.05$), and between helmet stability and helmet pressure ($\rho = 0.701$, $P < 0.05$). The present study demonstrated that mounting additional devices on the helmet violates helmet stability when accompanied by sweating, even when optimized fit provided and that just tightening bands cannot be an absolute solution. This study emphasized the importance of helmet stability as a variable for evaluating helmet comfort.

Keyword: Ballistic helmet, Sweating, Helmet stability, Helmet comfort, Pressing pain, Night vision device

Introduction

Ballistic helmets are worn in the battlefield to protect military personnel from shrapnel and ballistic threats. The ballistic performance is often the primary focus when developing a ballistic helmet, but comfort is emphasized in that it strongly relates to maintaining soldiers' physical capabilities, which assures their safety and even survival. These days, along with progression in the protective performance of ballistic materials (Kulkarni et al. 2013), helmets have been developed as "mounting platforms for various combat-essential devices" (Harrison et al. 2015) to expand their combat capability and to free both hands. A night vision device (NVD) is one of the most commonly used devices for enhancing the capability to operate under low light.

However, such devices can increase the muscle fatigue by increasing the head-supported weight and shifting the center-of-gravity (Äng 2008; Phillips and Petrofsky 1983; Verona and Rash 1989). The increased moment due to the NVD mounting can also make the helmet glide over the head too easily and thereby degrade combat capabilities by obstructing the view and consequently altering the weight distribution.

Helmet stability (antonym: helmet gliding) is a critical element of helmet performance to sustain adequate head coverage and positioning (Thai et al. 2015; Van den Oord et al. 2012). As documented in a study of military helicopter aircrews' helmets (Van den Oord et al. 2012), greater helmet stability improves helmet comfort, and poor helmet stability is related to increased neck load and neck pain. Various methods have been applied to test helmet stability, especially for motorcycle helmets (AS/NZS 1698, (2006); Snell Memorial Foundation, Inc. 2008). However, to the best of our knowledge, little research has investigated the helmet stability of military ballistic helmets for the ground troop soldiers. Different types of helmet postulate different users' motions and postures and thermal environments. Sweating can be a critical factor to ground troop soldiers as they are often exposed to excessive heat strain by hot environments and demanding physical loads. Profuse sweating on the head can be more problematic especially when the head is encapsulated by a ballistic helmet, as it can be hardly evaporated and remains inside the helmet (Bogerd et al. 2015).

Sweating plays a critical role in thermoregulation when it is efficiently evaporated by activating heat loss, but when it is partly retained within the textile layers adjacent to the skin, it can cause negative subjective feelings such as stickiness, irritation and discomfort. When the textile is fully saturated by water, the stickiness disappears because the lubricating layer that is created within the skin-textile interface makes it much easier to slide over the skin surface than a dry surface (Tang et al. 2018). This phenomenon can be beneficial when it occurs at the interface of the skin and clothing where the textile that is adhered to the skin interrupts the body motion. In contrast, it can be problematic when it occurs at the interface of the skin and helmet, where positional stability is rather beneficial. Moreover, the forehead experiences a greater sweating rate than other body regions during thermal loading independent of exercise intensity (Machado-Moreira et al. 2008; Smith and Havenith 2011). Therefore, we focused on whether the gliding phenomenon caused by sweating arises when a ballistic helmet is worn during simulated military postures. Maintaining helmet stability is expected to be even more challenging when an NVD is mounted on the frontal part of the helmet. The current study focuses on the ballistic helmet worn by ground army troops, who are frequently exposed to thermal loads and for whom the postures and motions in the battlefield can vary according to the circumferences and duties, in contrast to other helmets generally donned in typical riding or operating postures. The evaluation of human trials that mimic the user's environment will generate data on helmet stability similar to that found in the real-world and its influence on the overall helmet comfort. This study hypothesized that (1) the NVD-induced shift of the center-of-gravity significantly reduces helmet stability, and (2) the reduction of helmet stability caused by an NVD is greatly aggravated by sweating. In this context, the local sweat rate on the forehead ($LSR_{forehead}$) was predicted and compared with the water absorbent capacity of the inner pads covering the forehead.

Methods

Design

A randomized counterbalanced measures design was used to evaluate the effect of an NVD on helmet stability and the sweating effect on the relationship between the mounted NVD and helmet stability. The study consisted of two conditions distinguished by the existence of an NVD (370 g) mounted on the frontal part of the ballistic helmet with a mount bracket (203 g): (1) BH: Ballistic Helmet (total helmet weight = 1.5 kg), (2) BH-NVD: Ballistic Helmet with an NVD (total helmet weight = 2.1 kg). Testing sessions were separated by at least 48 h to minimize any effects of fatigue arising from the previous trial. Also, all participants visited the laboratory in advance on a separate day from the testing session to familiarize with the laboratory environment and experimental protocol and to provide anthropometric information.

Subjects

Nine participants with no history of any known diseases or neck pain were recruited (age = 24 ± 3 year; body weight = 73.0 ± 6.8 kg, height = 177.3 ± 6.8 cm, body mass index (BMI) = 23.2 ± 1.4 kg m^{-2}, body fat = 15.4 ± 5.4%). Eight of them had completed military services and were taking part in a reserve force drill once in a year. One participant was serving his military duties in the army. Their head circumferences were previously measured and properly fitted helmets provided. Each participant was instructed to refrain from drinking any alcohol and excessive training that could induce muscle fatigue for the previous 24 h and any food intake and caffeine drinks for the previous 2 h before each trial. All participants were informed of all 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 protocols and procedures

Among various postures and motions that are commonly conducted during military duties, the following postures and motions in which a heavier helmet can provide a greater physical burden on the neck were chosen. At first, the participants moved boxes on a table at a controlled speed. During this task, the participants stood still in the front of the table and repeatedly moved boxes (size = 210 * 297 * 50 mm, weight of each box = 2.5 kg) from side to side. The speed of moving boxes was controlled by an electrical metronome (45 rpm). The distance between the boxes was identically set at 50 cm and the subjects were instructed to keep their eyes on the boxes which they were moving to maintain their neck flexed. Photograph analysis showed that the average neck-flexion angle of all subjects during horizontal lifting was 37 ± 5 degrees. The height of the table was individually adjusted to the level of the subject's pelvis. The second task, shooting in a prone position, was chosen because it is a representative posture of shooting that is also included in basic military training. Instead of using an actual rifle, a sophisticated replica of an M2 rifle was used. Subjects lay prone, stared forward, and held the rifle while the magazine of the rifle was touching the ground. The target was located at a 10 m distance. The subjects were therefore instructed to just take aim at the target with

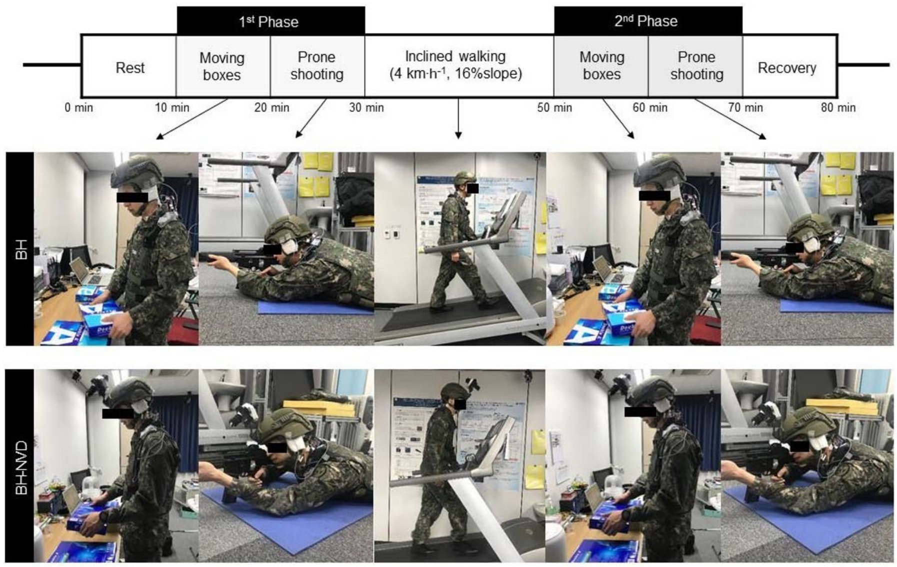


Fig. 1 Experimental protocol and subjects in each phase and condition

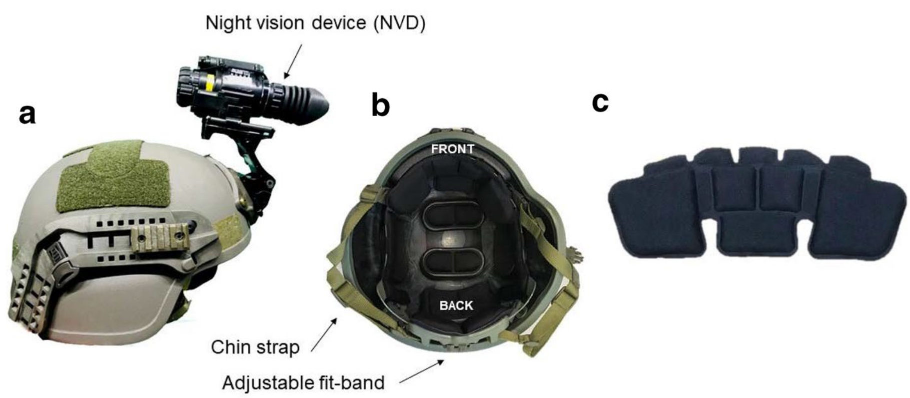


Fig. 2 External view of the ballistic helmet equipped with a night vision device (**a**), and internal view of the ballistic helmet (**b**) and the inner pad covering the forehead (**c**)

the rifle. Each participant shot in their accustomed postures as all subjects had regularly participated in rifle instruction during their military service. After shooting, they walked on a treadmill for 20 min at a speed of 4 km h^{-1} at a slope of 16% to increase the body core temperature and to make them wet with perspiration. Thereafter, the two experimental tasks were repeated to observe the difference caused by profuse sweating. The entire protocol was began with initial stabilization for 10 min and ended with 10 min recovery. All experimental sessions were conducted in a room at 22.3 ± 0.8 °C, 22.3 ± 3.1% relative humidity (RH) and wind speed < 0.2 m·s^{-1}. Before each test, 300 ml water was provided, after which the subjects wore a combat uniform including ballistic helmet and bulletproof vest (5.5 kg, Soft body armor for NIJ Standard Level III). Each subject adjusted a fit-band inside the helmet by themselves to make the helmet optimally fit on their head Figs. 1, 2.

Outcome measures

The following dependent variables were surveyed at the end of each posture: helmet stability (or helmet gliding), perceived neck load and neck pain, helmet pressure and pressing pain, and perceived helmet weight. Separate Visual Analogue Scales (VASs) were used, following the procedure of Van den Oord et al. (2012). The VAS scales have 100 mm lines with verbal anchors on each side indicating extreme experiences (e.g., "no suffering from helmet gliding" vs. "extreme suffering from helmet gliding"). Ear-canal temperature was continuously measured every 1 s (MP 160, Biopac systems, US). Probes to measure ear-canal temperature were inserted in the left ear-canal and fully insulated by cotton pads (40 * 40 * 15 mm) at least 1 h before the tests started. To monitor the course of saturation inside the helmet, the microclimate temperature and humidity inside the helmet were also recorded every 5 s using a microclimate sensor (TR-72wf, T&D recorder, Japan). The sensor was attached on the inner surface of the helmet at a position 5 cm above the temple. The location was confirmed not to cause any irritation or discomfort (e.g., directly touching and pressing the scalp) in the pilot tests. The local sweat rate was measured by absorbent patches (30 * 30 mm) on the ventral side of the forearm (glabrous surface) and upper back (scapula). They were weighed inside their sealed bags before and after each protocol with an electronic microbalance (HR-200, A&D Weighing, Japan). Although the local sweat rate on the forehead is critical for analyzing the effect of sweating on helmet stability, it was not directly collected because covering the skin of the forehead with insulating film or capsules can violate the interface property between skin and helmet inner pads, leading to variation in helmet stability measurement. Therefore, instead of measuring the local sweat rate on the forehead, the sweating rate was predicted using other regional sweating rates based on the sweating sensitivity reported by Smith and Havenith (2011). The water absorbency capacity of the forehead pads of the helmet was also measured. It was separated from the helmet, completely submerged in a water tank for 5 min, taken out and vertically hung until water dripping was not observed within a 30 s interval. The increase in weight was measured and it was expressed as the mass of water gain per unit area of fabric (g cm^{-2}) (Tang et al. 2015) by dividing the covering area of the inner pad. Body fat was calculated by using the formula of Garcia et al. (2005) derived from skinfold thickness and waist circumferences. Skinfold thickness was measured on the 3 regions (triceps, subscapular, and abdominal) with a skinfold caliper (TKK 5011a, Beta Technology Inc., USA).

Data analysis

Descriptive statistics were shown as means and standard deviations. Ear-canal temperature and microclimate data were sampled from the 8th to 9th min in each phase. $LSR_{forehead}$ was predicted by the following equation:

$$LSR_{forehead} = LSR_{upper\ back} \times \left(SS_{forehead}/SS_{upper\ back}\right) \quad (1)$$

where $LSR_{upper\ back}$ was measured by absorbent patches (mg cm^{-2}). $SS_{forehead}$ and $SS_{upper\ back}$ indicate the overall sudomotor sensitivity of the forehead and upper back, respectively. For the calculation, the values of sudomotor sensitivity reported in Smith and Havenith (2011) were used. Because overall sudomotor sensitivity indicates a relative increase of sweating rate divided by an increase of core body temperature (unit: mg cm^{-2} min^{-1} °C^{-1}), to calculate predicted $LSR_{upper\ back}$ and $LSR_{forehead}$, ear-canal temperature measured with insulating cottons was used as an alternative of body core temperature (Taylor et al. 2014). To verify the validity and reliability of the prediction, $LSR_{forearm}$ was firstly calculated from $LSR_{upper\ back}$ which was measured by absorbent patches to compare the predicted and measured $LSR_{upper\ arm}$. As a first step in the statistical analysis, Kolmogorov–Smirnov normality test was conducted to verify each sampling data distribution. Then non-parametric statistics were used with the data of which normality was not accepted. Wilcoxon signed rank test was used to compare two groups of measured data and subjective ratings on the sweating and helmet conditions. To identify the within-subjects correlation coefficient between subjective parameters, including helmet comfort, helmet stability, helmet pressure, pressing pain, and perceived helmet weight, repeated measures correlation was analyzed using the rmcorr package in the software package R (Bakdash and Marusich 2017). The outcomes were presented by a repeated measured correlation coefficient (r_{rm}). On the other hand, between-subjects correlation was analyzed with Spearman's rank correlation test and the correlation coefficient (ρ) was used. Among the results, the data measured while moving boxes in the BH condition at the first phase were reported. Statistical analyses identifying sweating effect were conducted based on eight subjects except a subject who could not complete the experiment due to pressing pain on the lateral part of the head, especially near the temple during the second section of moving boxes. The significance was set at $P < 0.05$. Statistical analyses were performed with IBM SPSS Statistics 21.0, except for the repeated measures correlation analysis which was carried out using R.

Results

Microclimate inside a helmet and body temperature

Ear-canal temperature significantly increased between the 1st and 2nd phases in both helmet conditions and both tasks without differences between BH and BH-NVD, which indicates that the heat strain was increased in the second phases ($P < 0.05$, Table 1). Microclimate humidity inside the helmet was significantly increased during inclined walking (Fig. 3): from 39.9 ± 9.5 to 77.1 ± 11.8%RH while moving boxes, and from

Table 1 Ear-canal temperature and microclimate inside a helmet (Mean ± SD)

Measured outcomes	Condition	A. moving boxes side to side		B. shooting in a prone position	
		1st phase [No Sweating]	2nd phase [Sweating]	1st phase [No Sweating]	2nd phase [Sweating]
Ear-canal temperature (°C)	BH	35.65 ± 0.43	36.40 ± 0.39†	35.92 ± 0.52	36.37 ± 0.41†
	BH–NVD	35.60 ± 0.56	36.35 ± 0.60†	35.74 ± 0.58	36.29 ± 0.60†
Temperature inside a helmet (°C)	BH	25.61 ± 0.65	28.81 ± 1.03†	26.11 ± 0.54	29.00 ± 0.93†
	BH–NVD	26.30 ± 0.59	29.50 ± 0.48†	26.95 ± 0.69*	29.56 ± 0.38†
Humidity inside a helmet (%RH)	BH	39.9 ± 9.5	77.1 ± 11.8†	48.4 ± 8.5	84.7 ± 10.1†
	BH–NVD	42.6 ± 6.2	84.2 ± 3.4†	53.1 ± 13.4	89.1 ± 8.9†

BH ballistic helmet, *BH-NVD* ballistic helmet with a night vision device

[*] Significantly different from BH ($P < 0.05$); [†] Significantly different from the 1st phase ($P < 0.05$)

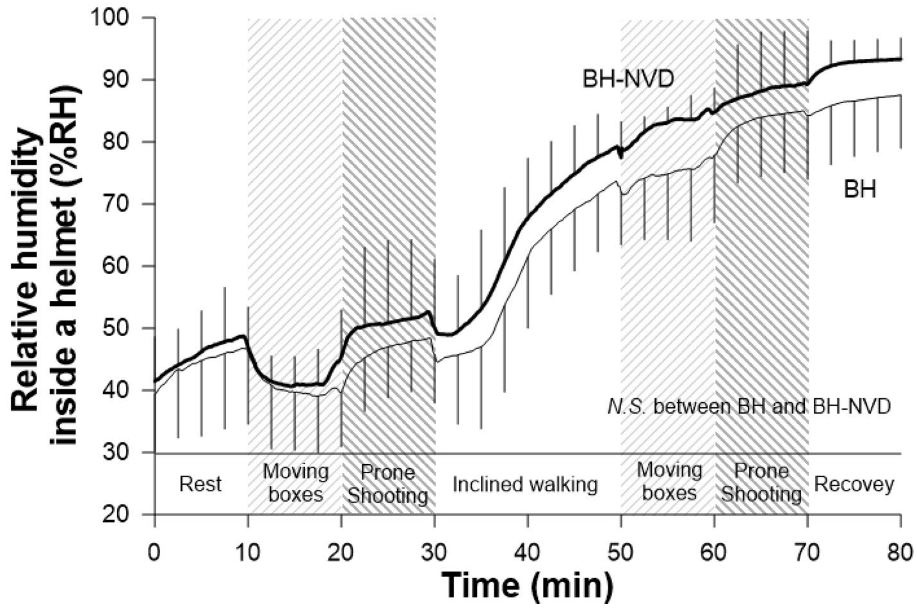


Fig. 3 Changes in the relative humidity inside a helmet in both conditions during entire protocol. No significance (N.S.) was found between BH and BH_NVD by Wilcoxon signed rank test (N=8)

Table 2 Comparison of local sweat rate between measured outcomes and predicted values (Mean ± SD)

Condition	Local sweat rate (LSR) during entire protocol (mg cm^{-2})		
	$LSR_{forearm}$		
	Observation	Prediction	*P*-value
BH	17.3 ± 3.9	20.5 ± 6.3	0.167
BH–NVD	26.2 ± 10.8	23.3 ± 10.0	0.641

Prediction of $LSR_{upper\ back}$ was conducted based on measured $LSR_{forearm}$ and the ratio of sudomotor sensitivity of the forearm and upper back. In this way, prediction of $LSR_{forearm}$ was based on the measured $LSR_{upper\ back}$. Regional sudomotor sensitivity was brought from Smith and Havenith (2011)

BH ballistic helmet, *BH-NVD* ballistic helmet with a night vision device, *LSR* local sweat rate, $LSR_{upper\ back}$ local sweat rate on the upper back, $LSR_{forearms}$ local sweat rate on the forearm

P-value was drawn from the paired sample t-test (*N* = 8)

53.1 ± 13.4%RH to 89.1 ± 8.9%RH during the shooting phases. Significant differences were found between the 1st and 2nd phases in both conditions ($P < 0.05$), whereas no significant difference between helmet conditions was observed (Table 1).

Predicted $LSR_{forehead}$ and water absorbent capacity of the inner pads

Predicted $LSR_{forearm}$ was 20.5 ± 6.3 and 23.3 ± 10.0 mg·cm^{-2} in BH and BH-NVD, respectively, while the measured values were 17.3 ± 3.9 and 26.2 ± 10.8 mg·cm^{-2}. In both conditions, there was no significant difference between observation and prediction ($P > 0.05$,

Table 2). Since no significant difference in the predicted and observed $LSR_{forearm}$ was observed, the $LSR_{forehead}$ was further calculated. As a result of calculation, the predicted $LSR_{forehead}$ was 135.0 ± 41.5 mg·cm^{-2} in BH and 153.4 ± 66.0 mg·cm^{-2} in BH-NVD. On the other hand, the water absorbent capacity of the inner pads covering the forehead was 112.2 mg·cm^{-2}.

Effect of a night vision head mounted assembly

The effect of an NVD was consistently presented in the perceived helmet weight by showing greater ratings in BH-NVD than in BH during all phases of both postures ($P < 0.05$, #9 and #10 in Fig. 3). On the other hand, helmet stability and overall comfort demonstrated significant effects of an NVD only in the 2nd phase of shooting posture ($P < 0.05$, #6 and #8 in Fig. 3). In contrast, no significant effect of an NVD was found in helmet pressure and pressing pain during all phases, despite an increasing tendency displayed in the figure #1 to #4 in Fig. 3 especially in case of pressing pain ($P > 0.05$).

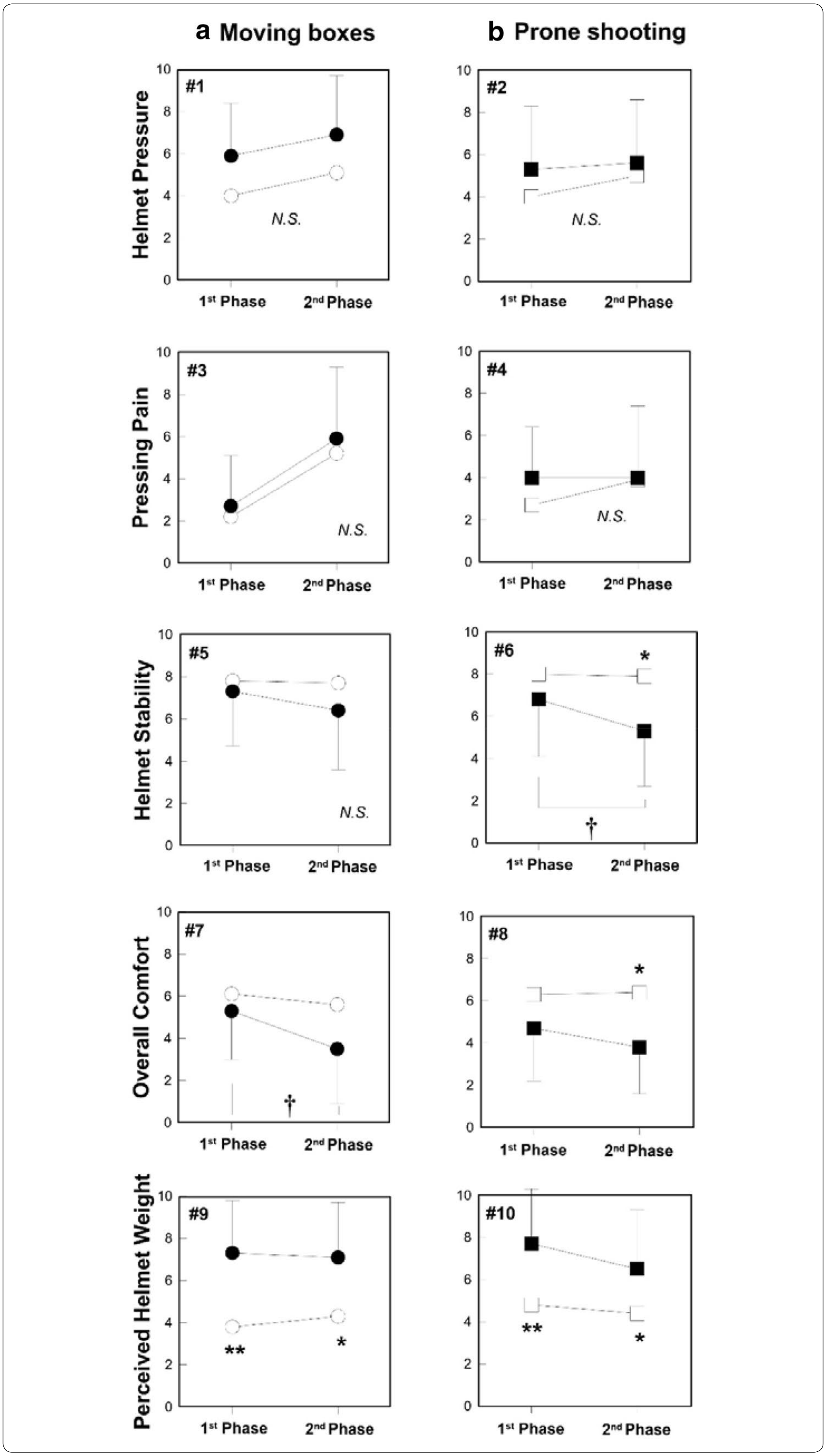
Effect of sweating

Sweating exerted an effect only in helmet stability in the BH-NVD while shooting in a prone position. Without an NVD, helmet stability was stably maintained during identical tasks (#6 in Fig. 4), but with an NVD, helmet stability was significantly decreased in the 2nd phase ($P < 0.05$). Compared with BH-NVD in the 1st phase, it decreased by 28.3%, but compared with BH in the 2nd phase, it decreased by 49.0%. Overall comfort during moving boxes also significantly decreased in the 2nd phase ($P < 0.05$, #8 in Fig. 4).

Associations between subjective variables

As a result of a repeated measured correlation test, helmet comfort showed a significant positive correlation with helmet stability ($r_{rm} = 0.762$, $P < 0.05$) and negative correlations with helmet pressure ($r_{rm} = -0.783$, $P < 0.05$) and pressing pain ($r_{rm} = -0.748$, $P < 0.05$). Perceived helmet weight was significantly correlated with helmet pressure ($r_{rm} = 0.740$, $P < 0.05$) and pressing pain ($r_{rm} = 0.913$, $P < 0.05$). In the inter-individual correlation with a spearman rank correlation test, helmet stability showed a significant correlation with helmet pressure ($\rho = 0.701$, $P < 0.05$), while all other correlations that showed in the repeated measures correlation test were also verified, except for the relationship between helmet stability and helmet comfort: helmet comfort and pressing pain ($\rho = -0.824$, $P < 0.05$), helmet pressure and pressing pain ($\rho = 0.743$, $P < 0.05$), helmet pressure and perceived helmet weight ($\rho = 0.673$, $P < 0.05$), and pressing pain and helmet perceived weight ($\rho = 0.716$, $P < 0.05$).

(See figure on next page.)
Fig. 4 Helmet pressure, pressing pain, helmet stability, helmet overall comfort and perceived helmet weight during both phases of moving boxes and prone shooting (N = 8). Closed circles and squares represent BH-NVD, and opened circles and squares represent BH. During prone shooting, helmet stability did not change, regardless of sweating, in BH, but it significantly decreased in BH-NVD. N.S. = Not significant. *P < 0.05; **P < 0.01 versus BH-NVD; †P < 0.05 significant difference between the 1st and 2nd phases tested by Wilcoxon signed rank test


a Moving boxes
b Prone shooting
Helmet Pressure
Pressing Pain
Helmet Stability
Overall Comfort
Perceived Helmet Weight
#1
#2
#3
#4
#5
#6
#7
#8
#9
#10
N.S.
*
**
†
1st Phase
2nd Phase
10
8
6
4
2
0

Discussion

Main results

In the current study, helmet stability decreased when an NVD was mounted on the helmet and sweating on the head occurred. Results by a repeated measures correlation analysis showed that increased helmet stability is strongly correlated with helmet comfort ($r_{rm}=0.762$), which was not revealed in the within-subjects analyses, Spearman's correlation test in this study. Helmet comfort was also strongly linked to helmet pressure and pressing pain, but they were not directly correlated with helmet stability. The series of results imply that the reduced helmet stability can be caused by sweating, rather than by changes in helmet pressure. Considering that even when the helmet was properly fitted, helmet stability and comfort were significantly reduced by sweating and mounting an NVD, we suggest that optimized helmet fit cannot fully maintain helmet stability.

Sweating which plays a critical role in thermoregulation was associated to the reduced helmet stability. This result may relates to the reduced drag force to move the fabric on the skin by lubricating layer within the skin-textile interface (Tang et al. 2018). Generally, greater stickiness is often linked to deteriorated comfort (Tang et al. 2018), but, for a ballistic helmet, greater stickiness may be rather beneficial by resulting in a stably located helmet on the head. It would be recommended to further investigate the relationship between textile properties such as textile stickiness or drag force and helmet stability and comfort in future studies.

With regard to the prediction of local sweat rate, it should be noted that the validity and acceptability of prediction of local sweating rate using the results of Smith and Havenith (2011) is disputable. The reason is that, to our knowledge, the prediction of local sweating rate using the results of Smith and Havenith (2011) has been rarely attempted, and also experimental conditions including the aerobic physical capacities of subjects (athletes and non-athletes), exercise conditions (running at 55% & 75%$\dot{V}O_{2max}$ versus inclined walking at 4 km h^{-1} at a slope of 16%), and clothing (sportswear with a direct attachment of absorbent pads on the skin versus military uniform with helmets and a ballistic vest) differed from the current study. Despite such differences in experimental conditions, predictions using Smith and Havenith (2011) have been used in this study to provide a supplementary data for grasping the local sweating rate, based on following considerations: (1) The $LSR_{forehead}$ was supposed to be an important factor closely related to helmet stability. (2) Direct measurement of the forehead local sweat rate was not considered in this study because the attachment of sensors or patches can distort the level of helmet stability per se. (3) an assessment of the preliminary validation of the prediction was conducted with $LSR_{forearm}$ in both BH and BH-NVD by comparing predicted values with patch test results. There was no significant difference between them in both condition ($P>0.05$, Table 2). However, cautions are needed in interpretation of the results. In particular, peripheral sudomotor sensitivity can be influenced by the endurance and non-endurance training (Shin and Lee 2014).

On the other hand, the predicted $LSR_{forehead}$ was 135 mg cm^{-2} in BH and 153 mg cm^{-2} in BH-NVD, while the water absorbent capacity of the inner pads covering the forehead was 112 mg cm^{-2}. Thus, the excess sweat remaining on the interface between the skin surface and inner pads of the helmet may form a lubricant film at the interface (Tang et al. 2018).

In this context, it can be implied that any attempts to reduce sweating on the forehead or preventing the change in frictional properties due to sweat may be beneficial. For example, using textiles with greater stickiness or morphological variation can be applied to the surface of the inner pads to prevent the formation of a lubricant film in between them. In particular, it may be helpful to explore a similarity to the hydroplaning phenomenon. A layer of water between tires and the road makes the vehicle slide, and track morphology can influence the kinetic friction characteristics (Heinrich and Klüppel 2008).

Besides, ballistic helmets usually rigidly cover the head without any pores or slits to provide higher protection from shrapnel and ballistic threats. Such overall helmet design increases the head insulation and reduces ventilation (Bogerd et al. 2015). Activated ventilation is directly related to sweating evaporation because the difference of the water vapor pressure at the skin and the surrounding air is one of the driving forces of evaporation. In the current study, microclimate humidity was seemingly decreased during the first moving boxes phase in both conditions (Fig. 3), which is presumed to be caused by forced convection induced by the repetitive rotation of the head. But, during the 2nd phase, it was not observed a clearly as that observed during the 1st phase. Possibly, it could be contributed by greater amount of sweating generated despite the increase in ventilation. For a bicycle helmet, vents positions, shape and number, and the existence of an in-helmet channel influence the ventilation, and thus the cooling rate. However, the need for ballistic protection limits the application of these methods in the ballistic helmet. Any method to promote ventilation while maintaining protective performance would be useful because it would alleviate the heat strain of military personnel in hot environments and ensure their physical capabilities and safety.

In this study, two simulated working postures were used: moving boxes on the table and shooting in a prone position. Inclined walking was also performed, but its main purpose was to induce heat stress and thus high sweating rate. The two postures and motions differed mostly in terms of a continuous movement and gaze direction, as well as neck postures. Moving boxes was a less-static posture that required subjects to move their head from side to side continuously while staring downwards. On the contrary, prone shooting was a totally static posture. Subjects were asked not to move but just to aim at a target at their eyes' level. We presumed that helmet stability would be more affected during continuous movement. However, the results showed a significant deterioration in helmet stability resulting from sweating and an NVD during prone shooting, but not while moving boxes. We speculated that this difference was caused by the difference in gaze direction. Helmet sliding downwards may be less annoying when staring downwards because it rarely obscures the subjects' sights. On the other hand, in the case of the eyes staring at a target on the same horizontal line with the neck flexed, the eyesight can be partly blocked by the ballistic helmet if the frontal part of the helmet slides down. The experiments did not examine whether the visual field was obstructed by the ballistic helmet, but some subjects tried to raise their ballistic helmet when it obstructed their view of the target when they sweated. This experimental result implies that an appropriate experimental protocol using simulated working postures is needed to distinguish the discomfort and problems that exist in practice. The present experimental results are limited by the fact that simulated military postures and motions were selectively adopted in a modified form. Helmet stability may be decreased to a much greater extent during more dynamic military tasks, which needs to be further investigated in future research.

Conclusion

In this study, helmet stability was highlighted as an important factor influencing helmet comfort. Above all, it was demonstrated that sweat can impair helmet stability when combined with NVD based on empirical data obtained during simulated military tasks. To the ground-troop soldiers who often train and carry out an operation while wearing ballistic helmet with head sweats, tightening the fit-band in the helmet may not improve helmet stability when helmet stability is degraded by sweating and shifts of the center-of-gravity. Instead, any attempts to reduce sweating on the forehead or preventing the change in frictional properties due to sweat may be beneficial. Further researches are needed to investigate with a relevance to textile properties and morphology as well as strategies to promote ventilation inside helmet to secure better helmet stability as a way to improve the bulletproof helmet design.

Abbreviations

NVD: Night vision device; $LSR_{forearm}$: Local sweat rate on the forearm; $LSR_{forehead}$: Local sweat rate on the forehead; $LSR_{upperback}$: Local sweat rate on the upper back; RH: Relative humidity; $SS_{forehead}$: Overall sudomotor sensitivity on the forehead; $SS_{upper\ back}$: Overall sudomotor sensitivity of the upper back; VAS: Visual analogue scale.

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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