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Original scientific paper

Impact of PPE on the Field of Vision of Stretcher Bearers Based on Eye Tracking Technology and Biomechanical Testing

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Abstract: To evaluate the impact of wearing personal protective equipment (PPE) on stretcher bearers' dynamic visual field and the neck and trunk joint mobility required for environmental observation. Wearing PPE has been shown to restrict the visual field of healthcare workers, which may affect task performance, especially for stretcher bearers who perform dynamic tasks in varied environments. Twenty trained non-professional participants underwent dynamic visual field testing and performed simulated patient transfer and transport tasks, during which their eye movement data and the mobility data of their neck and trunk joints were recorded. The use of goggles significantly reduced the participants' dynamic visual field, while the use of protective clothing severely restricted the average and peak axial rotation angles of the neck joints (T_1-C_7, C_1) during stretcher-carrying. Subjective evaluations revealed that wearing PPE led participants to perceive restricted dynamic visual fields, worsened overall visual conditions, reduced neck and head mobility and declines in task performance and satisfaction. Wearing PPE severely impairs stretcher bearers' dynamic visual field and axial neck rotation, thereby reducing their ability to observe the surrounding environment. These findings provide a basis and direction for the improved design of medical PPE goggles and protective clothing, offering insights into changing the work model of stretcher bearers using PPE. This study evaluates the impact of PPE on stretcher bearers' dynamic visual field and neck joint mobility. Results show that PPE significantly reduces dynamic visual field and restricts neck rotation, leading to increased task difficulty and a higher risk of incidents. This study proposes recommendations from three aspects to improve these conditions.

Keywords: dynamic visual field; neck joint mobility; personal protective equipment; stretcher bearers

1 INTRODUCTION

In the period of viral pandemic like COVID-19, health care workers (HCWs) face a significantly higher risk of infection compared to the general population [1], thus the use of personal protective equipment (PPE) is essential. However, HCWs reported that wearing PPE worsened their visual field condition [2], which directly led to decreased movement speed, reduced task quality, and even resulted in medical accidents [3, 4].

[5] defined stretcher bearers as clinical assistants among HCWs, who are essential members in the pre-hospital care phase. The principal responsibility of stretcher bearers is lifting and transferring patients while assisting emergency physicians [6, 7]. Pre-hospital care occurs in urban, rural, and mountainous areas, as well as under complex lighting and weather conditions [8, 9]. Therefore, stretcher bearers require optimal visual field condition to prevent injury and medical accidents during patient transport. In a pandemic, the workload of pre-hospital care surges [10], imposing unprecedented physical and psychological pressure on stretcher bearers [11, 12], which necessitates optimal visual field condition to reduce cognitive burden [13]. Consequently, it is necessary to investigate whether wearing PPE will have a negative impact on the field of vision of stretcher bearers.

Dynamic visual field is an important category of the visual field. It refers to the spatial range visible when the head remains fixed while the eyes rotate [14, 15], representing the maximum visual range of a person, and is a subject of considerable attention in ergonomics research [16]. Studies by [17] and [18] have confirmed that the use of PPE restricts surgeons' dynamic visual field when performing operations under a microscope. In addition, stretcher bearers' routine tasks mainly involve lifting and transferring patients, with the dynamic visual field playing a primary role during these activities. Therefore, this study uses the dynamic visual field as a measurement indicator to examine the impact of PPE on stretcher bearers' visual conditions. Meanwhile, during tasks involving lifting and walking, the axial rotation capability of the neck and trunk is an important indicator for evaluating personnel mobility and environmental observation ability [19-21]. Therefore, the range of motion of the neck and trunk should likewise be considered an important measurement indicator for assessing the impact of PPE on stretcher bearers' dynamic observation ability.

Previous studies have shown that personal protective equipment (PPE) may significantly affect task performance in medical and emergency contexts. For instance, studies have demonstrated that wearing protective goggles and face shields can reduce visual acuity and peripheral vision, thereby impairing situational awareness during clinical tasks [22]. Furthermore, wearing full-body protective suits may restrict neck mobility and upper body movement, increasing physical workload and reducing task efficiency during patient handling and emergency transport. These factors can compromise the safety and performance of healthcare workers, particularly in emergency settings where rapid and precise movements are crucial.

In high-risk medical environments, these visual and movement-related constraints may increase the likelihood of operational errors and occupational injuries [23]. However, existing studies have primarily focused on subjective discomfort or general workload assessments, while quantitative evidence linking PPE-induced visual limitations to dynamic medical tasks remains limited. This gap highlights the need for further investigation into how PPE affects visual behavior and movement performance during stretcher-bearing tasks, which provides the motivation for the present study.

Ultimately, the purpose of this study is to evaluate the dynamic visual field and the joint mobility of the neck and trunk in stretcher bearers performing routine tasks while wearing PPE, and to propose targeted recommendations for PPE design improvements based on the test results.

2 MATERIALS AND METHODS

2.1 Participants

This study recruited a total of 20 participants (10 males and 10 females) from Beijing Institute of Graphic Communication. The participant's mean (SD) age was 23.6 (1.4) years. The mean (SD) height and weight of male participants were 177.7 (2.9) cm and 75.1 (6.5) kg, respectively, while the mean (SD) height and weight of female participants were 165.1 (3.3) cm and 63.9 (6.9) kg, respectively. The eligibility criteria included: 1) trained in emergency rescue knowledge, 2) with normal vision and not wearing glasses, 3) no restrictions in physical activities. All participants underwent a two-week training on daily stretcher-bearing tasks, completing at least 10 simulated patient transfer tasks during the training period. Although none of the participants were professional stretcher bearers, they all had some experience with stretcher handling. Therefore, their task proficiency was at a beginner level. This study was approved by the Institutional Review Board of Beijing Institute of Graphic Communication. One research assistant was designated to act as the simulated patient (age: 23; height: 162 cm; weight: 60 kg) throughout the experiment for all the participants.

2.2 Personal Protective Equipment Tested

As shown in Fig. 1, four different PPE conditions were tested in this study: (a) Standard clothing, (b) Goggles (The goggles are constructed from transparent plastic material, featuring an anti-fog function for clear vision. However, the design of the goggles can obstruct peripheral vision, particularly when the wearer needs to frequently turn his head, thereby limiting the visual field.), (c) Non-integral foot cover type PPE (Made from SS non-woven fabric and breathable PE composite film, this protective suit offers effective barrier properties, blocking liquids and particles. The design, however, limits shoulder and neck mobility, which increases resistance to movement and affects the flexibility of stretcher bearers.), (d) Integral foot cover type PPE. As shown in Fig. 1, both types of disposable medical PPE tested included disposable protective suits, KN95 masks, protective goggles, face shields, gloves and foot covers, all complying with China's standard [22]. [22] clearly categorizes disposable protective suits into one-piece and two-piece design. Through on-site investigations at various hospitals, we found that the protective suits worn by HCWs are primarily one-piece designs, categorized into two types: with or without integral foot coverings. Therefore, this study selected Non-integral foot cover type and Integral foot cover type PPE for testing. In the control group, participants wore standard clothing for testing. In the three experimental groups, participants were required to wear goggles and two types of PPE over their standard clothing for testing. And the selection of all clothing sizes was based solely on height. Tab. 1 provides detailed information on the clothing used in this study. For all subsequent experimental conditions involving PPE, participants followed a standardized donning procedure prior to task execution the same PPE wearing protocol was applied across all relevant tasks.

Figure 1 Non-integral foot cover type PPE (left) and Integral foot cover type PPE (right)

Table 1 Detailed information for testing clothing

Tested clothing	Material composition	Clothing quality / g/m^2	size	Suitable for height / cm
Lined clothing	95% polyester fiber + 5% cotton	272.5-293.2	M	160-170
			L	165-175
			XL	170-180
Non-integral foot cover type PPE	SS non-woven fabric and breathable PE composite film	234.5-261.5	M	160-170
			L	165-175
			XL	170-180
Integral foot cover type PPE	SS non-woven fabric and breathable PE composite film	253.5-256	M	160-170
			L	165-175
			XL	170-180

2.3 Experimental Task Setting

This study measured the dynamic visual field and the range of motion angles in the neck and trunk joints of participants under four conditions. All experimental tasks were performed within an unobstructed laboratory environment, with the room temperature maintained at 20 °C. Prior to measuring, each participant engaged in multiple practice tasks to ensure they could proficiently complete the experimental tasks.

Prior to each experimental condition, participants were instructed to don the assigned personal protective equipment under the supervision of the research staff to ensure consistent and correct usage. All PPE was worn over standard clothing, and sizes were selected based solely on participants' height according to the manufacturer's recommendations. The four experimental conditions were conducted as follows:

(1) No PPE condition: participants wore only standard clothing without any additional protective equipment.

(2) Goggles condition: participants wore protective goggles in addition to standard clothing, ensuring a proper seal around the eye area.

(3) Non-integral foot cover type PPE condition: participants wore a disposable protective suit without integrated foot covers, along with KN95 masks, goggles, face shields, gloves, and foot covers.

(4) Integral foot cover type PPE condition: participants wore a disposable protective suit with integrated foot

covers, combined with KN95 masks, goggles, face shields, and gloves.

For each condition, participants wore the assigned equipment continuously for approximately 20 minutes, during which they completed both the dynamic visual field test and the simulated patient transfer task. Before data collection, standardized verbal instructions and demonstrations were provided to ensure participants clearly understood the task requirements, including the lifting, carrying, and lowering phases of the patient transfer task. Adequate rest time was allowed between conditions to minimize fatigue effects.

2.3.1 Dynamic Visual Field Test

The perimetry device can effectively assess the visual field range in the naked eye condition [23]. However, in this study, participants in the experimental group were required to wear protective goggles and other equipment, which conflicted with the physical structure of the perimetry device and prevented its use. Furthermore, visual field testing conducted using traditional methods requires participants to provide feedback by manually pressing a button after perceiving light stimuli, which increases the risk of measurement bias due to subjective factors. Therefore, this study aims to explore alternative devices or testing methods. Eye-tracking technology can capture pupil changes and corneal movement data to quantify the visual field [24]. When combined with external light source stimulation, it enables the evaluation of the visual field by analyzing key parameters such as pupil diameter and saccade frequency. Therefore, this study employed an eye tracker in conjunction with light stimulation units to quantify [25-27] the participants' dynamic visual field. Finally, the testing procedure is as follows:

The testing environment was a controlled dimly lit room of 9 m², with all four walls covered in light-absorbing black velvet fabric (light absorption rate > 95%) to minimize external light interference and ensure clear visibility of the stimulus light source [28]. Participants were seated in a neutral position on a specially designed test chair. Eye-tracking data, including pupil diameter, saccade frequency, and fixation point coordinates, were recorded to quantitatively evaluate the dynamic visual field of participants under four different conditions.

As shown in Fig. 2, the participants sat in the testing chair (50 cm high and adjustable) with their back against the backrest, maintaining a neutral position. Curved LED panels (size: 700 × 200 mm, curvature radius: 1500 mm) were symmetrically placed 40 cm on both sides of the participants. Each panel contained 20LED stimulus units (Φ5 mm, 0.1 W) evenly distributed along the horizontal midline. The vertical height of the panels was dynamically adjusted based on the participant's seated eye level to ensure that the LED stimuli were aligned horizontally with the participant's eyes. A black curtain (3 m × 3 m) was positioned 1 m from the participant, with 39 LED stimulation units (Φ5 mm, 0.1 W) evenly distributed along its vertical midline. As shown in Fig. 3, the horizontal stimulation units on the light panel were illuminated sequentially from the rear to the front of the participant, while the vertical stimulation units on the curtain were alternately illuminated from the center upward and downward. Each stimulation lasted for 1 s, with an interval of 6 s between successive stimulations. The stimulation units on the light panel were numbered sequentially from 1 to 20 in the visual forward-to-rearward direction, with unit No. 16 positioned along the extension of the line connecting both eyes. On the curtain, the central stimulation unit was designated as No. 1 and aligned horizontally with the participant's eyes, while the remaining units in the upward and downward directions were numbered from 2 to 20. The horizontal stimulation test cycle lasted 130 s, and the vertical stimulation test cycle lasted 240 s. Throughout the test, head movement was restricted using a headrest support frame. However, the participants could rotate their eyes in response to changes in the light stimulus.

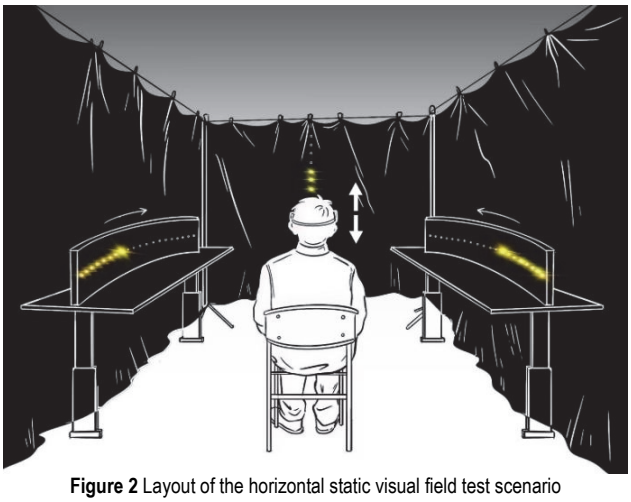

Figure 2 Layout of the horizontal static visual field test scenario

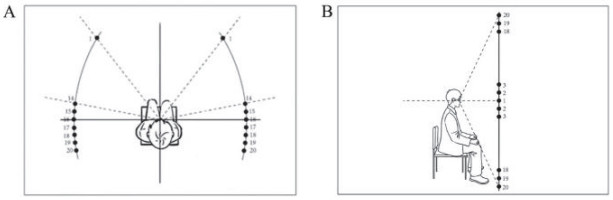

Figure 3 Arrangement of stimulus units

2.3.2 Assessment of Joint Range of Motion

Transferring patients with a stretcher is the primary task of stretcher bearers. In this study, the task was simplified to a joint range of motion testing task, namely the patient transfer movement. During the test, the range of motion data for the neck and trunk joints of the participants were collected. In addition, corneal movement data were also recorded during this test.

As shown in Fig. 4, an assistant simulated a patient lying supine on the stretcher. The participants, working in pairs, lifted the stretcher and walked a certain distance. In each experimental trial, both participants alternated positions to complete the task twice. At the start of the task, participants moved from a neutral standing position to a slow squat while keeping their backs straight, grasped the handles, lifted the stretcher, and walked 8 m in a straight line following the floor markings, then squatted down to place the load on the ground.

The processes of task can be divided into three phases: lift, hold, and down.

Lift: the process of transitioning the body from a

neutral standing position to a crouched posture, grasping the handle, and then returning to the neutral standing position.

Hold: the process of walking at a constant speed while carrying the stretcher.

Down: the process of the body transitioning from a neutral standing position to a crouched posture, lowering the handles after the stretcher lands, and then returning to the neutral standing position.

Figure 4 The procedure of the patient transfer task

2.4 Apparatus and Measures

2.4.1 Visual Behavior Data

An eye-tracking device (Tobii Pro Glasses 2; Tobii Tech; Sweden) with a sample rate of 100 Hz was utilized to measure the participants' pupil and eye movement data. The Tobii Pro Glasses 2 is a wearable binocular eye-tracking system designed for naturalistic task analysis. It records gaze data using infrared illumination and corneal reflection tracking, with a spatial accuracy of approximately 0.5° and a latency below 10 ms. The system allows unrestricted head movement and is suitable for dynamic task environments. Before each experimental session, a standard one-point calibration procedure was conducted for each participant according to the manufacturer's guidelines to ensure data accuracy.

All data were continuously recorded using the Tobii Pro Glasses Controller system, and up on completion of the tests, the data on pupil diameter, Saccade frequency, Saccade duration, and saccade distance of the gaze point were summarized. These data were selected because they represent the participants' physiological responses to horizontal light sources under different PPE conditions, indirectly demonstrating the impact of different PPE conditions on the stretcher bears' dynamic visual field. In addition, to determine the specific dynamic visual field angles under each PPE condition, continuous periods of stable pupil diameter lasting more than 14 seconds (during which more than two light stimuli did not cause abrupt changes in pupil diameter) were recorded and calculated as a proportion of the total duration. The dynamic visual field angles were then computed based on these results.

2.4.2 Kinematic Data

The inertial motion capture system (XsensMVN Analyze; Xsens; Netherlands) with a sample rate of 120 Hz was utilized to measure the participants' joint movement angles during the horizontal dynamic visual field test. A total of 17 inertial measurement units (IMU) were placed on the head, torso, arms, hands, legs, and feet. Each IMU integrates a 3D accelerometer, gyroscope, and magnetometer, transmitting data in real-time to a master receiver [29]. The IMU data is used as input to a 23-segment kinematic model, scaled to each participant based on manually measured body dimensions. The collected data were processed using the embedded tools in XsensMVN Analyze v. 2022.0.2. Before the start of data recording, the Xsens system was calibrated according to the manufacturer's guidelines. After data collection was completed, trunk and neck joint angle data, including L_5-S_1 (fifth lumbar vertebra to first sacral vertebra), L_3-L_4 (third lumbar vertebra to fourth lumbar vertebra), L_1-T_{12} (first lumbar vertebra to twelfth thoracic vertebra), T_8-T_9 (eighth thoracic vertebra to ninth thoracic vertebra), C_7-T_1 (seventh cervical vertebra to first thoracic vertebra), and C_1-Head (first cervical vertebra to head), were exported using the XsensMVN Analyze. Then, the mean and peak angles (95th percentile) of axial rotation, abduction, and flexion-extension of the trunk and neck joints were calculated.

2.4.3 Subjective Perception Data

After completing the two tasks with different PPE conditions, the participants were required to complete a subjective questionnaire to rate the dynamic visual field conditions for each task, including the horizontal and vertical visual fields. In addition, they rated their self-perceived physical flexibility, fatigue level, structural restrictions imposed by the equipment, weight restrictions, overall exertion level, and task performance during the patient transfer task. The questionnaire was designed based on the visual analogue scale (VAS), with the specific items shown in Tab. 2. For each question, a 7 cm line represented the measurement range of that item. Furthermore, after answering Question 6, participants were asked to specify in detail the specific body parts where they felt restricted.

Table 2 The subjective questionnaire

Number	Question	
1	I can clearly see the surroundings on both sides without turning my head	
	Very clear	Very blurry
2	I can clearly perceive obstacles appearing above or below without turning my head.	
	Very clear	Very blurry
3	I need to frequently turn my head to observe the surrounding environment during patient transport tasks.	
	Never	Always
4	During patient transport tasks, I need to frequently turn my head to observe the surrounding environment.	
	Never	Always
5	I feel that my visual field during this task is…	
	Very satisfied	Very dissatisfied
6	The degree to which I feel physically restricted during patient transport tasks	
	Not at all	Completely restricted

Table 2 The subjective questionnaire - continuation

Number	Question	
7	The degree to which I feel increased fatigue during patient transport tasks	
	Not at all	Very severe
8	During patient transport tasks, the equipment's restriction on my mobility affected my performance.	
	Not at all	Very severe
9	During patient transport tasks, the weight of the equipment affected my performance.	
	Not at all	Very severe
10	My overall perceived exertion.	
	No effort	Maximum effort
11	Overall, I feel about my performance in the task that...	
	Very satisfied	Very dissatisfied

2.5 Statistical Analysis

This study implemented a repeated measures approach to analyze each dependent variable of participants under three varying levels of independent variables. The independent variables were the personal protective equipment conditions (no PPE, goggles, non-integral foot cover type PPE, and integral foot cover type PPE). The dependent variables included the visual behavior data; joint movement angles of the neck and trunk; scores of subjective perceptions. All data were statistically analyzed using SPSS version 26 (IBM Corp, Armonk, NY). PPE was treated as the independent factor, with joint angles, eye movement data, and subjective evaluation data as the dependent variables. The Shapiro-Wilk test was first applied to assess the normality of the dependent variables under each PPE condition. If the normality assumption was met, a repeated measures ANOVA was conducted to examine the effects of PPE conditions. Dependent variable data sets that failed to meet the normality assumption were transformed using either logarithm, Johnson, or square root transformations, and the transformed data were analyzed in the same manner as the normally distributed data described previously. The post-hoc pairwise tests (Tukey HSD or Wilcoxon signed rank) were further conducted when statistical significance was found ($p < 0.05$). The effect sizes (Cohen's d) were calculated to evaluate the pairwise differences in dependent variables among PPE conditions.

3 RESULT

3.1 Eye Movement Parameters

Eye movement parameters were collected and analyzed while participants performed the dynamic visual field test and the joint range of motion test under four PPE conditions to assess whether PPE affected their visual field. As shown in Fig. 5 and Tab. 3, during the seated horizontal light stimulation task, wearing goggles or either of the two PPE types significantly affected mean pupil diameter, mean saccade frequency, total saccade duration, and the proportion of time with stable pupil diameter ($p < 0.05$).

During the horizontal and vertical light stimulation tests, as shown in Fig. 5a , Tab. 3 and Tab. 4, wearing goggles and the two types of PPE significantly increased participants' mean pupil diameter (horizontal: mean difference up to 0.92, $p < 0.01$; effect size = −0.91 to −1.69; vertical: mean difference up to 0.61, $p < 0.05$; effect size = −0.67 to −0.85). As shown in Fig. 5b, Tab. 3 and Tab. 4, wearing goggles and the two types of PPE significantly decreased participants' mean saccade frequency (horizontal: mean difference up to 0.27, $p < 0.05$; effect size = 1.00 to 1.10; vertical: mean difference up to 0.31, $p < 0.05$; effect size = 0.88 to 0.94). As shown in Fig. 5c, Tab. 3 and Tab. 4, wearing goggles and the two types of PPE significantly decreased participants' total saccade duration (horizontal: mean difference up to 10.78, $p < 0.05$; effect size =1.02 to 1.11; vertical: mean difference up to 19.09, $p < 0.05$; effect size = 0.89 to 1.01). Finally, as shown in Fig. 5d, Tab. 3 and Tab. 4, wearing goggles and the two types of PPE significantly increased the proportion of time during which pupil diameter remained stable (horizontal: mean difference up to 14.44, $p < 0.05$; effect size = 1.01 to 1.08; vertical: mean difference up to 16.15, $p < 0.05$; effect size =1.02 to 1.06).

Additionally, as shown in Tab. 3, wearing goggles and the two types of PPE did not have a significant effect on the movement distance of participants' gaze point coordinates under the two stretcher-carrying positions (front and rear) ($p > 0.05$).

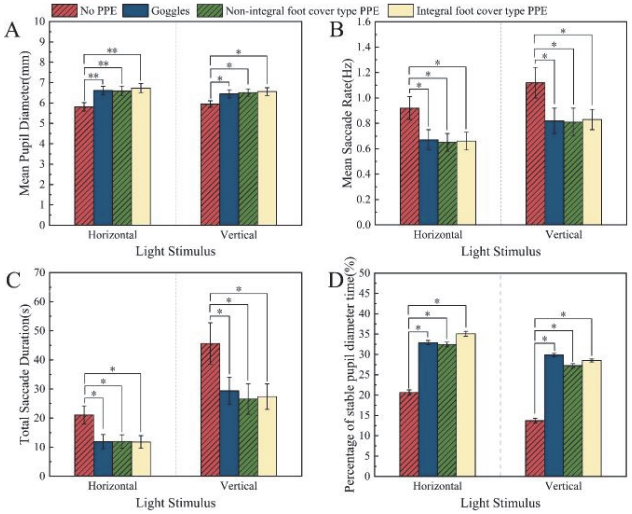

Figure 5 The mean values of each eye movement parameter under the four PPE conditions (No PPE, Goggles, Non-integral Foot Cover Type PPE, Integral Foot Cover Type PPE) in the dynamic visual field test. An asterisk (*) indicates a significant difference between two groups with a p-value < 0.05, while two asterisks (**) denote a significant difference with a p-value < 0.01

Table 3 Mean (standard error) and p-values for visual behavior data under four different PPE conditions

Measure	Goggles	No PPE	Non-integral foot cover type PPE	Integral foot cover type PPE	p-values
Horizontal light stimulus					
Mean Pupil Diameter	5.81(0.21)	6.61(0.21)	6.59(0.24)	6.73(0.22)	0.009
Mean Saccade Frequency	0.92(0.09)	0.67(0.08)	0.65(0.07)	0.66(0.07)	0.042
Total Saccade Duration	21.09(3.08)	11.89(2.47)	11.97(2.28)	11.78(2.17)	0.032
Proportion of time with stable pupil diameter	20.64(0.66)	32.91(0.52)	32.45(0.58)	35.08(0.61)	0.032
Vertical light stimulus					
Mean Pupil Diameter	5.95(0.16)	6.45(0.20)	6.51(0.18)	6.56(0.19)	0.042
Mean Saccade Frequency	1.12(0.12)	0.82(0.10)	0.81(0.11)	0.83(0.08)	0.049

Table 3 Mean (standard error) and p-values for visual behavior data under four different PPE conditions - continuation

Measure	Goggles	No PPE	Non-integral foot cover type PPE	Integral foot cover type PPE	*p*-values
Total Saccade Duration	45.65(7.09)	29.37(4.70)	26.56(5.21)	27.38(4.38)	0.049
Proportion of time with stable pupil diameter	13.72(0.58)	29.87(0.41)	27.24(0.50)	28.51(0.38)	0.028
Patient transfer task (front)					
Mean gaze point coordinate displacement (*X*-axis)	0.42(0.03)	0.47(0.04)	0.44(0.04)	0.42(0.03)	0.300
Mean gaze point coordinate displacement (*Y*-axis)	0.36(0.05)	0.46(0.06)	0.43(0.04)	0.38(0.06)	0.177
Patient transfer task (rear)					
Mean gaze point coordinate displacement (*X*-axis)	0.53(0.04)	0.47(0.03)	0.51(0.03)	0.44(0.05)	0.258
Mean gaze point coordinate displacement (*Y*-axis)	0.34(0.03)	0.42(0.05)	0.43(0.05)	0.39(0.02)	0.170

Table 4 Effect sizes (Cohen's *d*) of eye movement data of goggles and two PPE relative to no PPE condition

Measure	No PPE-Goggles	No PPE- Non-integral foot cover type PPE	No PPE-Integral foot cover type PPE
Horizontal light stimulus			
Mean Pupil Diameter	−0.908	−1.462	−1.685
Mean Saccade Frequency	0.995	1.098	1.037
Total Saccade Duration	1.022	1.059	1.107
Proportion of time with stable pupil diameter	1.014	1.083	1.046
Vertical light stimulus			
Mean Pupil Diameter	−0.666	−0.824	−0.846
Mean Saccade Frequency	0.923	0.880	0.936
Total Saccade Duration	0.886	0.951	1.010
Proportion of time with stable pupil diameter	1.056	1.029	1.015

3.2 Joint Range of Motion

3.2.1 Average Joint Movement Angle

In this study, data from the front stance and rear stance were analyzed separately to clarify the effects of four PPE conditions on the neck and trunk joint movements of stretcher bearers. Analysis of the experimental data revealed that wearing goggles did not have a significant effect on the mean range of motion of the neck and trunk joints across three planes in either the front stance or the rear stance ($p > 0.05$).

Interestingly, as shown in Fig. 6, Tab. 5, and data from this study, wearing either of the two PPE types had a significant effect on participants' neck joint axial rotation in both the front and rear stances ($p < 0.05$). Front stance analysis showed that wearing the two PPE types significantly reduced the mean axial rotation angles of the T_1-C_7 joint (up to 1.83°) and the C_1-Head joint (up to 3.81°) ($p < 0.05$; effect size = 1.16 to 1.29 and 1.19 to 1.38, respectively). Similarly, analysis of the rear stance data showed significant reductions in the mean axial rotation angles of the T_1-C_7 joint (up to 1.83°) and the C_1-Head joint (up to 3.71°) when wearing the two PPE types ($p < 0.05$; effect size =1.05 to 1.08 and 1.09 to 1.14, respectively). Moreover, no significant differences were observed in other joint angle data under both stance conditions ($p > 0.05$).

To investigate the specific periods during which wearing the two types of PPE restricts participants' neck axial rotation, data from the three steps at each stance were analyzed separately. As shown in Analysis of the experimental data revealed that wearing the two PPE types did not have a significant effect on neck axial rotation during the lift and down phases in either stance ($p > 0.05$). However, as presented in Fig. 7, Tab. 5 and data from this study, during the hold phase, wearing both PPE types significantly affected neck axial rotation in both stances ($p < 0.05$), with the integral foot cover type PPE causing a highly significant reduction ($p < 0.001$). In the front stance, wearing either PPE significantly decreased the mean axial rotation angles of the T_1-C_7 joint (up to 2.25°) and the C_1-head joint (up to 4.50°) ($p < 0.05$; effect size =1.32, 1.37 to 1.43). Similarly, in the rear stance, both PPE types significantly reduced the mean axial rotation angles of the T_1-C_7 joint (up to 1.33°) and the C_1-head joint (up to 2.68°) ($p < 0.05$; effect size = 0.60 to 0.85, 0.59 to 0.79).

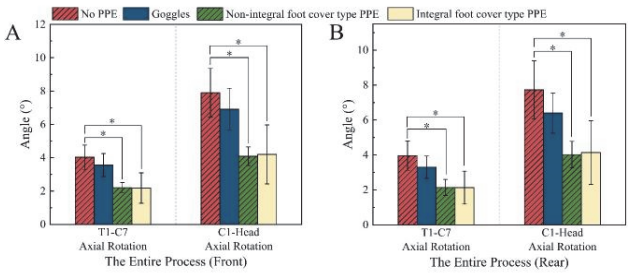

Figure 6 Average axial rotation angles of the T_1-C_7 and C_1-Head joints under the four PPE conditions (No PPE, Goggles, Non-integral foot cover type PPE, Integral foot cover type PPE) in the entire process. An asterisk (*) indicates a significant difference between two groups with a *p*-value < 0.05

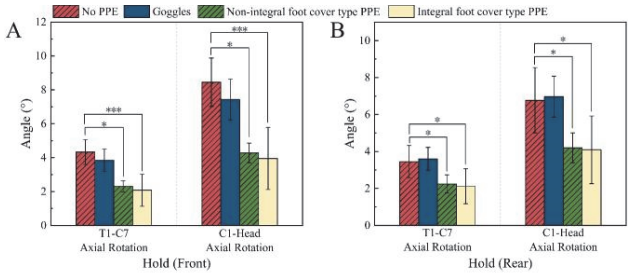

Figure 7 Average axial rotation angles of the T_1-C_7 and C_1-Head joints under the four PPE conditions (No PPE, Goggles, Non-integral foot cover type PPE, Integral foot cover type PPE) in the hold phase. An asterisk (*) indicates a significant difference between two groups with a *p*-value < 0.05, while three asterisks (***) denote a significant difference with a *p*-value < 0.001.

Table 5 Effect sizes (Cohen's d) of neck joint angles of two PPE relative to no PPE condition

Measure	No PPE- Non-integral foot cover type PPE	No PPE- Integral foot cover type PPE
The Entire Process (Front)		
T_1-C_7 Axial Rotation	1.290	1.162
C_1-Head Axial Rotation	1.380	1.186
The Entire Process (Rear)		
T_1-C_7 Axial Rotation	1.046	1.075
C_1-Head Axial Rotation	1.142	1.089
Hold (Front)		
T_1-C_7 Axial Rotation	1.324	1.327
C_1-Head Axial Rotation	1.434	1.367
Hold (Rear)		
T_1-C_7 Axial Rotation	0.597	0.848
C_1-Head Axial Rotation	0.587	0.794

3.2.2 Peak Joint Movement Angle

As shown in Analysis of the experimental data it was revealed that wearing goggles did not have a significant effect on participants' mean peak range of motion of the neck and trunk joints across three planes in either of the two stance positions ($p > 0.05$). However, we found that wearing either of the two PPE types had a highly significant effect on participants' peak axial rotation angles of the neck joints regardless of stance position ($p < 0.001$). As presented in Fig. 8, Tab. 6, and data from this study, in the front stance, wearing the two PPE types significantly reduced the peak axial rotation angles of the T_1-C_7 joint (up to 7.96°) and the C_1-Head joint (up to 15.21°) ($p < 0.001$; effect size = 1.47 to 1.80 and 1.41 to 1.79). Similarly, in the rear stance, wearing the two PPE types also significantly reduced the peak axial rotation angles of the T_1-C_7 joint (up to 8.58°) and the C_1-Head joint (up to 16.00°) ($p = 0.001$; effect size = 1.31 to 2.04 and 1.33 to 1.95).

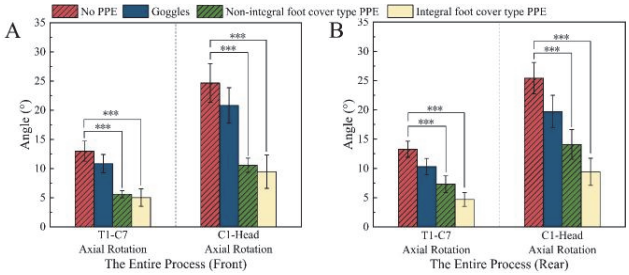

Figure 8 Peak axial rotation angles of the T_1-C_7 and C_1-Head joints under the four PPE conditions (No PPE, Goggles, Non-integral foot cover type PPE, Integral foot cover type PPE) in the entire process. Three asterisks (***) indicate a significant difference between two groups with a p-value < 0.001

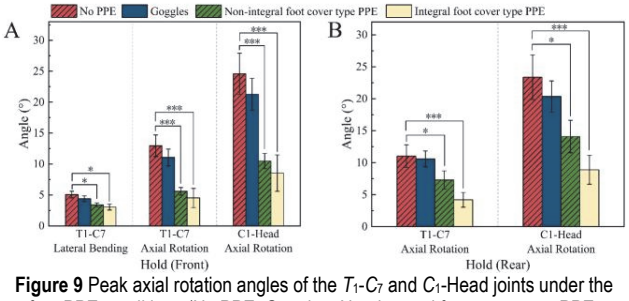

Figure 9 Peak axial rotation angles of the T_1-C_7 and C_1-Head joints under the four PPE conditions (No PPE, Goggles, Non-integral foot cover type PPE, Integral foot cover type PPE) in the hold phase. An asterisk (*) indicates a significant difference between two groups with a p-value < 0.05, while three asterisks (***) denote a significant difference with a p-value < 0.001

Consistent with Section 3.2.1, this study continued to analyze the mean peak angle data of the three steps in both stances to identify the specific periods subject to significant restriction. Experimental data analysis showed that, during the lift and down phases, wearing either of the two PPE types had no significant effect on participants' peak axial rotation angles of the neck in either stance ($p > 0.05$). However, as presented in Fig. 9, Tab. 6, and data from this study, during the hold step in the front stance, wearing the two PPE types exerted a highly significant restrictive effect on the peak axial rotation angles of the T_1-C_7 joint (up to 8.44°) and the C_1-Head joint (up to 20.40°) ($p < 0.001$; effect size = 1.84 to 1.91 and 1.84 to 1.93). Additionally, wearing the two PPE types significantly restricted the peak lateral bending angle of the T_1-C_7 joint (up to 2.02°) ($p < 0.05$; effect size = 1.02 to 1.20). In the hold step of the rear stance, the two PPE types similarly exerted a highly significant restrictive effect on the peak axial rotation angles of the T_1-C_7 joint (up to 6.82°) and the C_1-Head joint (up to 12.47°) ($p < 0.05$; effect size = 0.58 to 1.36 and 0.52 to 1.29).

Table 6 Effect sizes (Cohen's *d*) of neck joint peak angles of two PPE relative to no PPE condition

Measure	No PPE- Non-integral foot cover type PPE	No PPE- Integral foot cover type PPE
The Entire Process (Front)		
T_1-C_7 Axial Rotation	1.795	1.473
C_1-Head Axial Rotation	1.787	1.411
The Entire Process (Rear)		
T_1-C_7 Axial Rotation	1.308	2.039
C_1-Head Axial Rotation	1.332	1.950
Hold (Front)		
T_1-C_7 Lateral Bending	1.017	1.196
T_1-C_7 Axial Rotation	1.905	1.838
C_1-Head Axial Rotation	1.927	1.835
Hold (Rear)		
T_1-C_7 Axial Rotation	0.576	1.358
C_1-Head Axial Rotation	0.522	1.285

3.3 Subjective Perception Data

As shown in Tab. 7, wearing goggles and the two types of PPE had a significant impact on self-perceived scores for horizontal visual field, vertical visual field, overall visual field, bodily restriction, task performance, and task satisfaction ($p < 0.05$). Compared with the No PPE control group, participants wearing goggles or either type of PPE reported higher scores for horizontal, vertical, and overall visual field restriction, as well as increased ratings for worsened task performance due to bodily restriction and equipment weight, and decreased task satisfaction. Almost all participants indicated that wearing either PPE type restricted neck and head mobility during task execution, and 20% reported perceived restrictions in shoulder and chest mobility. No significant differences between PPE conditions were found for the remaining questionnaire items.

Table 7 Mean (Standard error) and *p*-values of subjective question scores under the four different PPE conditions

Measure	No PPE	Goggles	Non-integral foot cover type PPE	Integral foot cover type PPE	*p*-values
1	1.57(0.44)	3.06(0.53)	3.19(0.60)	3.72(0.58)	0.047
2	1.45(0.34)	3.06(0.50)	3.38(0.54)	3.39(0.52)	0.027
3	1.19(0.15)	2.88(0.48)	2.70(0.64)	3.22(0.59)	0.063

Table 7 Mean (Standard error) and *p*-values of subjective question scores under the four different PPE conditions - continuation

Measure	No PPE	Goggles	Non-integral foot cover type PPE	Integral foot cover type PPE	*p*-values
4	1.45(0.34)	2.44(0.44)	3.07(0.59)	3.06(0.57)	0.114
5	1.33(0.34)	3.00(0.47)	3.31(0.64)	3.83(0.65)	0.034
6	1.45(0.33)	2.15(0.69)	3.56(0.56)	4.00(0.52)	0.005
7	1.88(0.34)	2.56(0.41)	3.38(0.50)	3.55(0.50)	0.051
8	1.57(0.29)	2.31(0.40)	3.06(0.49)	3.61(0.52)	0.023
9	1.25(0.15)	1.70(0.42)	1.94(0.42)	2.78(0.37)	0.038
10	3.38(00.47)	3.91(0.57)	4.51(0.78)	4.78(0.79)	0.443
11	1.81(0.20)	2.44(0.39)	3.31(0.46)	3.11(0.50)	0.039

4 DISCUSSION

This study evaluated the effects of wearing goggles and two types of PPE on participants' dynamic visual field range and the range of motion of neck and trunk joints during the performance of dynamic tasks simulating patient transport. The objective experimental results showed that wearing goggles and the two types of PPE significantly reduced participants' dynamic visual field and wearing the two PPE types also significantly restricted the axial rotation angle of the neck joints. The subjective evaluation results indicated that, during dynamic tasks, wearing either type of PPE had a significant negative impact on perceived neck and trunk flexibility, garment comfort, visual field range, task difficulty, and task performance quality.

Currently, international standards lack a clear definition of the lower limit for the safety threshold of the visual field for stretcher bearers. However, studies have confirmed a significant negative correlation between the extent of visual field restriction and human movement coordination performance [30]. This highlights the urgent need for stretcher bearers to have a clear visual field. We compared eye movement data across four PPE conditions and found that, in both horizontal and vertical visual field tests, the groups wearing goggles and the two full PPE sets showed significantly increased mean pupil diameter, significantly decreased mean saccade frequency, and significantly reduced total saccade duration compared to the No PPE control group. These signals indicate that the amount of light stimulation received by participants' eyes was significantly reduced. Additionally, compared to the No PPE group, the proportion of pupil stability duration significantly increased in the other three groups. Based on the data calculations, wearing goggles and the two PPE types significantly reduced participants' horizontal dynamic visual field from 179.3° (±1.5°) to 151.6° (±1.2°), 152.6°(±1.3°) and 146.6° (±1.4°), respectively ($p < 0.001$), and similarly reduced the vertical dynamic visual field from 123.5°(±0.8°) to 100.4°(±0.6°), 104.2°(±0.7°) and 102.3°(±0.5°). However, no significant differences were found among these three groups in the above data ($p > 0.05$). Considering that the goggles are the only equipment obstructing the participant's visual field, it is inferred that they are the primary factor causing the visual field restriction.

This inference aligns with the findings of [31] and [32] whose studies demonstrated that traditional goggles (similar to those in PPE) often obstruct the peripheral areas of eyes, particularly the temporal side, significantly impairing participants' ability to perceive peripheral visual stimuli. Therefore, this study proposes an improved design for the goggles, as shown in Fig. 10. While ensuring protective performance, we propose extending the transparent lens towards the front of the ears, increasing the temporal side of the goggles by 12-15 mm, and moderately reducing the edge height to achieve a smooth transition or adopting a fully transparent material. Additionally, the strap design has been made adjustable to ensure the goggles are universally adaptable.

Figure 10 Design of redesigned goggles for stretcher bearers

When visual field impairment occurs, individuals compensate by increasing the range of axial rotation in the neck, torso, and lower limb joints [33, 34]. However, the test results of this study revealed an opposite trend. Compared with the baseline data of the control group, wearing the two types of PPE in the front-carrying position reduced the participants' mean axial neck rotation angles by 32.9% and 36.3% ($p < 0.05$), and peak rotation angles by 57.1% and 61.6% ($p < 0.001$). In the rear-carrying position, the two types of PPE reduced the mean axial neck rotation angles by 47.3% and 46.4% ($p < 0.05$), and peak rotation angles by 44.7% and 63.5% ($p < 0.001$). By dividing the task into three steps for segmented analysis, we found that, in both stances, the restriction of neck joint motion caused by wearing PPE occurred primarily during the walking phase while carrying the stretcher, with no significant impact observed during the lifting and lowering phases. This indicates that the use of PPE limits the stretcher bearers' ability to observe the environment through axial neck rotation during walking. Meanwhile, analysis of the eye-tracking data showed no significant differences in the displacement of gaze coordinates among the groups during patient transfer ($p > 0.05$). This suggests that, even though goggles restricted the dynamic visual field and PPE limited axial neck rotation, the stretcher bearers may not have been aware of these restrictions and therefore did not compensate by increasing eye movements.

Restriction of axial neck rotation will directly reduce the visual information input, which in turn may impair the stretcher bearers' balance and spatial awareness [35]. In fact, findings from some clinical observational studies have shown that wearing PPE can cause dizziness and a sense of imbalance in healthcare workers [37, 38], which may be related to abnormal functioning of the visual system resulting from limitations in axial neck rotation and dynamic visual field. Notably, [39] and [40] have both demonstrated that ill-protective clothing can lead to a significant reduction in the range of motion of the relevant

joints, thereby impairing occupational performance. According to the data analysis results of this study, PPE did not have a significant effect to thoracic and spinal mobility or their perception of back restriction ($p > 0.05$), but significantly restricted the perception of freedom in the neck and shoulders ($p < 0.001$). Therefore, this study suggests that insufficient looseness or inadequate material elasticity of the protective suit at the neck and shoulders may be the primary cause of the restriction in neck joint axial rotation.

Based on the above findings, this study recommends developing an ergonomic assessment system for medical PPE, which includes a standardized framework with key indicators such as joint mobility and visual field range, to provide scientific evidence for design Optimization. During the transitional phase before establishing a standardized system, targeted improvements should be implemented in existing products to mitigate the issue of restricted neck joint rotation. A survey conducted by [41] revealed that over 67% of healthcare workers expressed dissatisfaction with the fit of existing PPE. Despite selecting equipment based on standardized sizes, it often failed to meet individualized ergonomic requirements. Therefore, this study proposes the following solution (as shown in Fig. 11): 1) Based on the [5] standard, moderately loosen the shoulder structure of the suit and incorporate adjustable features to enable personalized adjustments. 2) Improve the material fabrication. Studies have shown that fabric elasticity typically decreases after surface coating treatment [42]. Therefore, we recommend adopting a more elastic weaving technique in the neck and shoulder areas of the protective suit to better preserve elasticity [43] or directly replacing the materials with one that has superior elasticity.

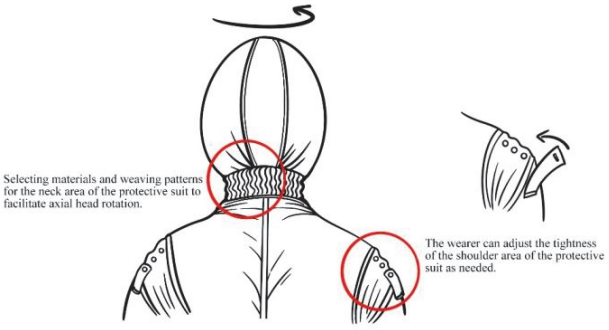

Figure 11 Improved neck and shoulder design for enhanced mobility in PPE

The psychological effects of PPE use on healthcare workers extend beyond physiological limitations, including elevated cognitive load [35], reduced attention, and increased anxiety levels [43, 44] demonstrated that cognitive load is strongly associated with healthcare workers' perceptions of self-efficacy and task load. Our analysis of the subjective assessment supports this finding, indicating that wearing goggles and both types of PPE had a significant negative impact on participants' self-perceived task performance and task satisfaction. Some ophthalmological studies have shown that loss of visual field is correlated with a decline in cognitive ability [45], and long-term loss of visual field may even increase the risk of cognitive impairment and depressive symptoms [46]. Although our subjective assessment results did not directly demonstrate this connection, they indicated that participants were able to perceive significant restrictions in their horizontal and vertical dynamic visual fields when performing tasks while wearing goggles and both types of PPE. Therefore, it is essential to pay close attention to the potential increase in cognitive load caused by the decline in environmental observation ability resulting from prolonged visual field restriction and limited neck mobility.

This study recognizes that it is unrealistic to make comprehensive improvements and widespread adoption of protective goggles and suits in the medical PPE system in the short term. This leads us to propose optimizing operational strategies to mitigate the cognitive load issues caused by PPE. Multiple studies have shown that compensatory sensory stimulation can effectively reduce the cognitive load of individuals with visual limitations. For example, [47] developed a navigation system integrating voice, haptic, and other feedback modalities to guide visually impaired individuals and alleviate their cognitive load. Based on such studies, this study proposes a 'collaborative guidance' work model, where an accompanying person is assigned as a route guide when stretcher bearers must wear PPE during tasks. The guide will assist the stretcher bearer in safety transporting the patient through verbal communication or physical guidance.

This study has several limitations worth noting. First, the PPE used in this study was developed in compliance with Chinese standards, which may limit the generalizability of the findings to PPE systems based on other regulatory frameworks. Second, due to limitations of the measurement equipment, the patient transfer task in this study was simplified. Third, it should be noted that the participants in this study were trained non-professional stretcher bearers; however, their movement strategies and risk perception may differ slightly from those of professional stretcher bearers. Fourth, the visual stimuli in this study were based on regular LED light sources under controlled laboratory conditions, which may not fully represent the complexity of real-world environments. Future research should conduct more rigorous field experiments to clarify the effects of goggles and PPE on stretcher bearers' task performance. Finally, the proposed modifications to goggles and protective clothing require further ergonomics testing to determine their practicality, as well as in-depth discussions on material costs and specific manufacturing processes.

The findings of this study have important implications for the occupational safety of stretcher bearers, particularly in emergency situations where rapid responses and precise movements are required. The observed reductions in dynamic visual field and changes in visual behavior when wearing PPE may compromise environmental awareness, increasing the risk of tripping, collisions, or missteps during patient transport. In addition, PPE-related restrictions in movement and visual perception may delay reaction times and reduce coordination between team members, which could further elevate safety risks in time-critical scenarios such as emergency evacuations or infectious disease outbreaks. These risks are especially relevant when stretcher bearers must navigate complex or unfamiliar environments under high physical and cognitive

demands. Therefore, while PPE is essential for infection control, its potential impact on operational safety should be carefully considered. Optimizing PPE design to balance protective performance with visual and motor functionality may help reduce injury risks and improve overall safety for stretcher bearers in emergency operations.

5 CONCLUSION

In this study, one type of goggles and two types of PPE were tested. The use of goggles significantly reduced the dynamic visual field of stretcher bearers in both horizontal and vertical directions. During the patient transfer task, wearing protective clothing significantly decreased the mean and peak axial rotation angles of the T_1-C_7 and C_1 cervical joints, with this restriction occurring entirely during the stretcher-carrying phase. However, the impact of goggles and protective clothing on the ability to visually scan the environment did not elicit compensatory increases in gaze shift distance. Subjective evaluations indicated that wearing goggles and PPE increased the perception of visual field restriction and limitations in neck and head mobility, negatively affecting task performance and task satisfaction. In conclusion, PPE markedly impaired the dynamic visual field and axial neck rotation of stretcher bearers during task execution, reducing their ability to monitor the surrounding environment and increasing the likelihood of hazardous events. We have proposed three targeted recommendations: expanding the temporal coverage area of the protective goggles and optimizing the edge structure, increasing the relaxation at the shoulder area of the protective suit, modifying the weaving process or material of the shoulder and neck regions, and establishing the 'collaborative guidance' work model. Future research should focus on the long-term effects of wearing different PPE configurations on stretcher bearers' visual performance, musculoskeletal load, and fatigue accumulation during prolonged and repeated tasks. In addition, longitudinal studies involving professional stretcher bearers in real-world emergency scenarios are needed to further validate and extend the findings of this study.

Key Points

·Goggle significantly reduced the stretcher bearer's dynamic static visual field.

·Protective suit significantly restricted the axial rotation of the neck joints (T_1-C_7 and C_1-Head) during patient transfer and transport tasks performed by stretcher bearers.

·Wearing PPE significantly increased stretcher bearers' perception of restricted mobility in their visual field, neck, and shoulder, while also reducing task performance and task satisfaction

·Optimizing the design of goggles and protective suit, along with establishing the 'collaborative guidance' work model, is expected to mitigate the horizontal visual field limitations imposed by PPE on stretcher bearers and alleviate the associated cognitive load.

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