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ENHANCING FIREFIGHTER SAFETY: EVALUATING PPE FOR COMFORT AND EFFECTIVENESS

Tahira Ticlo [1], Roopa Rao [2]

[1] Student, College of Home Science Nirmala Niketan Affiliated to Mumbai University, Mumbai, Maharashtra, India
[2] Mentor, Associate Professor, Department of Community Resource Management, College of Home Science Nirmala Niketan, (Affiliated to the University of Mumbai), Mumbai, Maharashtra, India

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Corresponding Author

Tahira Ticlo, tahiraticlo25@gmail.com

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ABSTRACT

Exploratory research was conducted among 160 firefighters from two Indian states - Goa and Maharashtra, to evaluate the ergonomic aspects of Personal Protective Equipment (PPE) and Clothing, focusing on firefighter comfort and operational effectiveness. Using a validated self-constructed questionnaire, researchers conducted structured interviews with firefighters to gain insights into the strengths and limitations of current PPE designs. The study revealed critical gaps in PPE utilization, informing recommendations for precise improvements to enhance firefighter safety and operational efficiency during emergencies. These findings aim to improve training programs and protocols, ensuring firefighters are not exposed to high-risk temperatures without adequate PPE. The study's results can influence policy decisions and research resource allocation, ensuring optimal equipping of firefighters to handle diverse hazards safely and comfortably. The research has broader implications, aiming to drive advancements in PPE materials and technologies, focusing on ergonomics, thus benefiting firefighting practices globally. By prioritizing comfort and functionality in PPE design, the study seeks to enhance the overall well-being and performance of firefighters in hazardous environments. Ultimately, the study aspires to inform better training programs, strengthen disaster response capabilities, and shape policies that prioritize firefighter safety worldwide, contributing to improved public safety on a global scale.

Keywords: Comfort, Ergonomics, Firefighter Safety, Occupational Health, Personal Protective Equipment (PPE)

1. INTRODUCTION

Firefighters are frontline heroes who brave extreme conditions to protect lives and property. However, the limitations of their Personal Protective Equipment (PPE) can compromise their effectiveness and safety. Traditional firefighting gear often focuses solely on protection, neglecting crucial aspects of comfort and ergonomics. This paper delves into the critical importance of integrating ergonomic design principles into the development of firefighter PPE to enhance safety, comfort, and overall performance.

The occupational hazards faced by firefighters are multifaceted, ranging from heat stress and smoke inhalation to physical exertion and limited mobility. Conventional PPE, while effective in shielding against these hazards, can be bulky, restrictive, and uncomfortable. Such limitations not only impede firefighters' movements but also contribute to fatigue and reduced effectiveness during critical operations.

Ergonomics, the science of designing equipment and systems to optimize human performance and well-being, offers a promising framework for addressing these challenges Rao (2018). By prioritizing the ergonomic needs of firefighters, PPE designers can create gear that not only provides superior protection but also facilitates natural movements and minimizes physical strain. One key aspect of ergonomic PPE design is mobility. Firefighters often need to navigate through confined spaces, climb ladders, and perform various tasks requiring agility and flexibility. Therefore, PPE should allow for unrestricted movement without compromising protection. Innovative design features, such as articulated joints, stretch panels, and adjustable closures, can enhance mobility while maintaining structural integrity. Dexterity is another critical consideration in PPE design, as firefighters must be able to manipulate tools, operate equipment, and perform intricate tasks with precision Park et al. (2014). Traditional glove designs, while protective, can impede tactile sensitivity and fine motor skills. Ergonomic gloves with anatomical shaping, tactile materials, and touchscreen compatibility enable firefighters to maintain dexterity without sacrificing protection. Comfort is paramount for firefighters who often work long shifts in challenging environments. PPE that is excessively heavy, poorly ventilated, or abrasive can cause discomfort and distraction, undermining performance and increasing the risk of heat-related illnesses. Ergonomic PPE incorporates breathable fabrics, moisture-wicking liners, and strategic padding to enhance comfort and thermoregulation. Ventilation is a critical aspect of firefighter PPE, as excessive heat buildup inside the gear can lead to heat stress and dehydration. Ergonomic designs incorporate airflow channels, mesh panels, and moisture management systems to enhance breathability and reduce heat retention, thereby improving comfort and performance in high-temperature environments. In conclusion, optimizing PPE design for firefighters with ergonomics in mind is essential for ensuring their safety, comfort, and effectiveness on the front. By integrating ergonomic principles into the development process, designers can create gear that not only offers superior protection but also enhances mobility, dexterity, comfort, and ventilation. This research contributes to the ongoing efforts to improve firefighter well-being and performance, ultimately saving lives and preserving communities.

The rationale for conducting a study on firefighter personal protective equipment (PPE) in Maharashtra and Goa, India, is grounded in the need to address critical research gaps and enhance firefighter safety and performance. Existing studies, such as those conducted by the National Institute for Occupational Safety and Health (NIOSH), emphasize the importance of gathering data on firefighter body dimensions to support design changes that improve the ergonomic fit and effectiveness of PPE. By analyzing the physical characteristics of firefighters, NIOSH has contributed to the development of PPE that is snug, functional, and offers the required level of protection in hazardous environments Sadeghpour (2015).

Furthermore, a study by Nayak (2014) highlights the importance of balancing performance and comfort in firefighter protective clothing. While protective clothing must effectively shield firefighters from flames and heat, it should also be designed with ergonomic considerations to allow ease of movement and reduce physical strain during firefighting tasks. Multi-layered clothing systems have been

proposed as a solution to optimize both protection and comfort, offering flexibility for firefighters to adjust their attire based on the intensity of the situation Nayak (2014).

However, these two requirements are contradictory and for heat and flame protection this becomes more obvious. The clothing should protect from flame and prevent the external heat from entering the body. Protective clothing is being designed with ergonomic considerations to allow ease of movement and reduced physical strain during firefighting tasks. Multi-layered clothing systems offer flexibility by allowing firefighters to adjust their attire based on the intensity of the situation, optimizing both protection and comfort Nayak (2014).

Given the lack of studies on firefighter PPE design and safety specifically in Mumbai and Goa, India, and the importance of addressing ergonomic considerations and comfort without compromising protection, conducting a study in these locations is essential. By gathering data on firefighter body dimensions and assessing the performance and comfort of protective clothing in the unique environmental conditions of Mumbai and Goa, this study aims to contribute valuable insights that can inform the design and selection of PPE, ultimately enhancing the safety, well-being, and performance of firefighters in the field.

2. AIM

This study aims to comprehensively evaluate firefighter Personal Protective Equipment (PPE), with a specific focus on ergonomics, to ensure optimal safety and comfort during firefighting operations. By conducting a thorough assessment of PPE design and functionality, this study seeks to identify areas for improvement that will enhance the ergonomic fit, mobility, and overall effectiveness of protective gear. The ultimate goal is to provide firefighters with PPE that not only offers maximum protection against hazards but also minimizes physical strain and discomfort, thereby promoting their safety, well-being, and operational performance in challenging and hazardous environments.

3. METHODOLOGY

The research follows an exploratory study design aiming to understand firefighter experiences with their protective gear and identify any associated issues. A total of 160 firefighters from 15 fire stations across Goa and Maharashtra were randomly selected for participation. Inclusion criteria specified active firefighters aged between 21 and 50 years, while exclusion criteria excluded retired or inactive firefighters, as well as individuals with severe musculoskeletal conditions or disabilities that could influence the results. Informed consent was obtained from all participating firefighters before data collection. Rao (2015)

Data collection utilized multiple tools, including a self-constructed questionnaire designed to gather information on firefighters' ergonomic experiences and the personal protective equipment (PPE) they utilized. Additionally, an observation method was employed to supplement questionnaire responses, providing further insights into firefighters' interactions with their gear. Interviews were conducted with each firefighter, lasting approximately 20 to 25 minutes, to allow for in-depth exploration of their experiences and perspectives. Furthermore, a PPE Evaluation Checklist was utilized to systematically assess the condition and effectiveness of the protective equipment. Suman et al. (2024)

For data analysis, basic statistical measures such as frequency and percentage were employed using Microsoft Excel. This analysis aimed to identify any problems or limitations with the PPE and evaluate the impact of specific tasks firefighters undertook while using the gear. Based on the findings, recommendations were formulated to address any identified shortcomings in the current PPE, with a particular focus on improving ergonomic design features to better meet the needs and preferences of firefighters. These recommendations aimed to inform future improvements in PPE design and selection, ultimately enhancing the safety, comfort, and effectiveness of firefighters during operational tasks.

4. FINDINGS AND DISCUSSIONS

4.1. DEMOGRAPHIC PROFILE

The average age of the sample is 35.6 years, which shows they belong to the younger generation of firefighters. The firefighters have an average of 9.4 years of total work experience and about 8.4 years of related firefighting experience. 67942.1%) are graduates. 74.2% have permanent employment, whereas 42(26.4%) being employed temporarily. 124(78%) are designated firemen with 16(10%) leading firemen. The sample also had 2(1.3%) station officers.

Figure 1

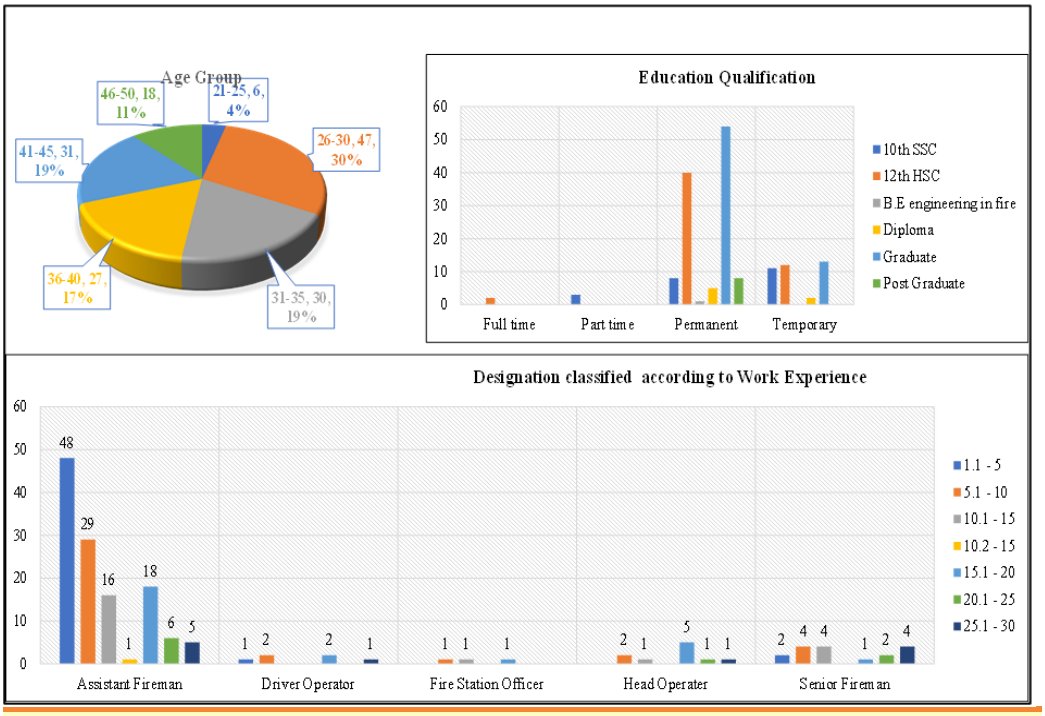

Figure 1 Demographic Profile

4.2. PERSONAL PROTECTIVE EQUIPMENT (PPE)

Personal Protective Equipment (PPE) is of utmost importance to firefighters as it serves as a critical line of defense against various hazards encountered during firefighting operations. Some main reasons for its importance Global Threat Report (2024) are:

- PPE, such as fire-resistant clothing and helmets, shields firefighters from extreme temperatures and flames encountered during firefighting tasks, reducing the risk of burns and heat-related injuries.

- Respiratory PPE, including masks and self-contained breathing apparatus (SCBA), safeguards firefighters against smoke, toxic gases, and airborne contaminants, ensuring they can breathe safely in hazardous environments.
- Helmets, gloves, and boots protect against falling debris, sharp objects, and other physical hazards, reducing the risk of head injuries, cuts, and punctures.
- PPE equipped with specialized materials and coatings offers protection against chemical spills, biological contaminants, and other hazardous substances encountered during emergency response activities.
- High-visibility PPE, such as reflective vests and clothing, improves firefighters' visibility in low-light conditions, reducing the risk of accidents and improving overall safety on the scene.
- Comfortable and well-fitted PPE can boost firefighters' confidence and psychological well-being, allowing them to focus on their tasks effectively without distractions or discomfort.

Adhering to PPE guidelines and standards ensures compliance with regulatory requirements and industry best practices, and promotes a culture of safety within firefighting organizations. The importance of PPE to firefighters cannot be overstated, as it plays a vital role in safeguarding their health, safety, and well-being during emergency response operations.

The PPEs were evaluated for Comfort, Uncomfortable components, Restriction caused, Design, and Overall effectiveness.

1) **PPE Evaluation for Comfort:** The provided data presents the evaluation of various Personal Protective Equipment (PPE) items based on comfort, rated on a scale of 1 to 5. The summary of the findings is as follows:
   - **Fire Helmets:** Most respondents (44.4%) rated fire helmets with a comfort score of 10, indicating high satisfaction in terms of comfort. Additionally, 34.4% rated them at 8, further demonstrating positive feedback.
   - **Hoods & Face Protection:** The majority of respondents (60%) rated hoods and face protection with a comfort score of 9, indicating a high level of comfort. A significant portion (18.8%) rated them at 10 as well.
   - **Safety Glasses/Goggles:** Comfort ratings for safety glasses/goggles were distributed across various scores, with 37.5% rating them at 9 and 19.4% at 10, suggesting generally positive feedback regarding comfort.
   - **Gloves**: A considerable majority (62.5%) rated gloves with a comfort score of 9, indicating high satisfaction in this aspect. Additionally, 25.6% rated them at 10.
   - **Firefighting Boots:** Firefighting boots received predominantly high comfort ratings, with 75.6% of respondents giving them a score of 10. Another 15.6% rated them at 9.
   - **Belts & Harness:** Comfort ratings for belts and harnesses were distributed across various scores, with 36.3% rating them at 9 and 25% at 10, indicating generally positive feedback.
   - **Breathing Apparatus:** Although the comfort ratings for breathing apparatus were not as high as other items, a substantial portion of respondents (50.6%) rated them with a comfort score of 9, with an additional 23.8% rating them at 10.

The data suggests that the majority of respondents expressed high levels of satisfaction with the comfort of the evaluated PPE items, particularly fire helmets, hoods & face protection, gloves, firefighting boots, and belts & harnesses. However, there may be opportunities for improvement in the comfort of safety glasses/goggles and breathing apparatus based on the distribution of ratings.

2) **Uncomfortable Component:** Analyzing the provided data on personal protective equipment (PPE) evaluations reveals insights into user satisfaction regarding both protection and comfort. This focuses on potential areas for improvement:
   - Firefighting Boots stand out for their high approval (75.6% rated 10), suggesting a successful balance between protection and comfort. However, continuous innovation to enhance comfort is advisable.
   - Gloves and Breathing Apparatus are well-regarded (62.5% and 50.6% rated 9, respectively), indicating effective protection. Enhancements in wearability and ergonomics could further increase user satisfaction.
   - Belts & Harness and Hoods & Face Protection present opportunities for improvement in adjustability and breathability, respectively, to better meet user needs for comfort and functionality.
   - Safety Glasses/Goggles are praised for their protection but could benefit from anti-fogging innovations and reduced pressure points to increase wearability.
   - Fire Helmets, while highly rated, could see benefits from reductions in weight and better integration with communication devices.

3) **Restriction Caused:** The data in the above graph indicates the restriction caused due to different types of personal protective equipment (PPE) among the firefighters:
   - **Fire Helmets:** Approximately 4.3% of respondents approved of fire helmets, while 95.6% did not.
   - **Hoods & Face Protection:** Only 1.2% of respondents approved of hoods and face protection, while 98.8% did not.
   - **Safety Glasses & Goggles:** A low approval rate of 3.1% was observed for safety glasses and goggles, with 96.8% of respondents not approving.
   - **Gloves:** Similarly, only 1.2% of respondents approved of gloves, while 98.7% did not.
   - **Firefighting Boots:** Approval for firefighting boots was slightly higher at 1.8%, with 98.1% of respondents not approving.
   - **Belts & Harness:** Approximately 2.5% of respondents approved of belts and harnesses, while 97.5% did not.
   - **Breathing Apparatus:** The lowest approval rate was for breathing apparatus, with only 0.6% of respondents indicating approval, while 99.3% did not approve.

Results suggest a general lack of satisfaction for most types of PPE among the respondents. This indicates potential areas for improvement in terms of design, comfort, and functionality to meet the needs and preferences of the firefighters.

4) **Design:** The data provided offers insights into the acceptance or approval rates for different types of personal protective equipment (PPE) among respondents in terms of its design. The summary of findings is as follows:
   - **Fire Helmets:** Approximately 23.1% of respondents indicated approval, while 76.8% did not approve of fire helmets.
   - **Hoods & Face Protection:** Approval for hoods and face protection was slightly higher, with 26.2% of respondents indicating approval, while 73.7% did not approve.
   - **Safety Glasses & Goggles:** Only 3.1% of respondents approved of safety glasses and goggles, while a significant majority (96.9%) did not approve.
   - **Gloves:** A mere 1.8% of respondents approved of gloves, while 98.1% did not approve.
   - **Firefighting Boots:** Approval for firefighting boots was very low, with only 0.6% of respondents indicating approval, while 99.3% did not approve.
   - **Belts & Harness:** Similar to firefighting boots, only 0.6% of respondents approved of belts and harnesses, while 99.3% did not approve.
   - **Breathing Apparatus:** None of the respondents approved of the breathing apparatus, with 100% indicating disapproval.

Overall, the data suggests a lack of satisfaction or approval for most types of PPE among the respondents, particularly for safety glasses & goggles, gloves, firefighting boots, belts & harnesses, and breathing apparatus. This indicates potential areas for improvement in terms of design, comfort, and functionality to better meet the needs and preferences of users.

5) **Overall effectiveness:** The data provided indicates the overall effectiveness ratings for different types of personal protective equipment (PPE) among respondents:
   - **Fire Helmets:** Approximately 11.8% of respondents rated fire helmets as effective, while 13.1% did not consider them effective.
   - **Hoods & Face Protection:** A very low effectiveness rating was observed for hoods and face protection, with only 1.2% of respondents considering them effective, while 73.7% did not.
   - **Safety Glasses & Goggles:** Safety glasses and goggles received a relatively high effectiveness rating, with 67.5% of respondents considering them effective, while 32.5% did not.
   - **Gloves:** Gloves had a split effectiveness rating, with 50% of respondents considering them effective and 50% not.
   - **Firefighting Boots:** Similar to safety glasses and goggles, firefighting boots received a relatively high effectiveness rating, with 67.5% of respondents considering them effective, while 31.8% did not.
   - **Belts & Harness:** Belts and harnesses had a moderate effectiveness rating, with 38.1% of respondents considering them effective, while 11.8% did not.

- **Breathing Apparatus:** The breathing apparatus also had a split effectiveness rating, with 50% of respondents considering them effective and 50% not.

Results suggest varying perceptions of effectiveness for different types of PPE among respondents. While safety glasses and goggles, firefighting boots, and breathing apparatus received relatively higher effectiveness ratings, hoods, and face protection had a very low effectiveness rating. This highlights the importance of addressing concerns and improving the design and functionality of PPE to enhance overall effectiveness and user satisfaction.

5. SUGGESTIONS

Based on the evaluation of various aspects of Personal Protective Equipment (PPE) for firefighters, several recommendations can be made to enhance their effectiveness, comfort, and overall satisfaction:

1) **Comfort Improvement:**
   - The focus must be on enhancing the comfort of safety glasses/goggles and breathing apparatus, as indicated by the lower satisfaction scores compared to other PPE items.
   - Anti-fogging technologies for safety glasses/goggles to improve visibility and wearer comfort must be implemented.
   - Options to reduce pressure points and increase breathability in breathing apparatus to enhance comfort during prolonged use must be explored.
2) **Enhancing Wearability and Ergonomics:**
   - New designs of gloves and breathing apparatus to improve wearability and ergonomics, addressing user concerns and increasing overall satisfaction must be implemented.
   - Investing in continuous research and development to create lightweight and well-fitted fire helmets that integrate seamlessly with communication devices, reducing strain and discomfort during extended wear.
3) **Adjustability and Breathability:**
   - Improving the design of belts & harnesses and hoods & face protection to enhance adjustability and breathability, providing firefighters with greater flexibility and comfort during operations.
   - Incorporating breathable materials and adjustable features to optimize comfort while maintaining adequate protection levels.
4) **Anti-Restriction Measures:**
   - Concerns related to restriction caused by certain PPE items, such as fire helmets and hoods & face protection, by exploring innovative design solutions that balance protection and mobility must be addressed.
   - Prioritizing user feedback and ergonomic principles in the redesign process to minimize restriction without compromising safety.
5) **Design Enhancements:**
   - Revising the design of PPE items with low approval rates, such as firefighting boots, belts & harnesses, and breathing apparatus, to address user dissatisfaction and improve overall acceptance.

- Considering user-centric design approaches that prioritize functionality, comfort, and ease of use to create PPE solutions that better meet the needs and preferences of firefighters.

6) Overall Effectiveness Optimization:

- Enhancing the overall effectiveness of PPE items through continuous improvement initiatives and collaborative efforts between manufacturers, regulatory agencies, and end-users.
- Prioritizing investments in research and development to address performance gaps and optimize the protective capabilities of PPE while ensuring user comfort and satisfaction.

The recommendations outlined above aim to address the identified areas for improvement in PPE design, comfort, and effectiveness based on the evaluation results. By implementing these recommendations, firefighting organizations can enhance the safety, well-being, and performance of firefighters in the field, ultimately saving lives and reducing the risk of occupational hazards.

6. AUTHOR STATEMENTS

- **Informed Consent:** Before their participation, all participants provided written informed consent, demonstrating their understanding of the study's objectives, procedures, and potential risks.

CONFLICT OF INTERESTS

None.

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