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Comparison of three internationally certified firefighter protective ensembles: Physiological responses, mobility, and comfort

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ABSTRACT

Background: Fire protective ensembles (FPEs) are essential to safely perform firefighting job tasks; however, they are often burdensome to the workers. The aim of this study was to compare three internationally certified fire protective ensembles from the European Union (EU), South Korea (SK), and United States (US) on physiological responses, mobility, and comfort.

Methods: Ten male professional firefighters performed a battery of exercises in the laboratory following the ASTM F3031-17 standard to evaluate mobility, occupation-specific performance, and physiological responses (body weight, heart rate (HR), core temperature (T_c), breathing rate (BR), and rating of perceived exertion (RPE)) to 20 min of treadmill walking (3.2 mph, 5% incline). All participants carried out the evaluation wearing each FPE in a random order. Mixed effects models examined time (pre-vs. post-) by ensemble (EU, SK, US) interactions for all physiological variables and compared comfort, performance, and subjective variables across ensembles.

Results: No interaction effects were observed for body weight, HR, T_c, BR, or RPE ($p = 0.890$, $p = 0.994$, $p = 0.897$, $p = 0.435$, and $p = 0.221$; respectively). SK had greater trunk flexion than EU (78.4° vs. 74.6°, $p = 0.026$) and US had lower standing reach than EU (105.5 cm vs. 115.4 cm, $p = 0.004$). Agility circuit time was lower in US (9.3 s) compared to EU (9.8 s) or SK (9.9 s) ($p = 0.051$ and $p = 0.019$, respectively).

Conclusions: The findings suggest that physiological burden remained largely unchanged across the international FPEs. However, mobility, performance, and comfort may be significantly influenced across types. International stakeholders and end users should consider design implications when choosing fire protective ensembles.

1. Introduction

Firefighting requires specialized equipment and strategies to safely and effectively respond to fire emergencies. It is essential for this profession to wear firefighter protective ensembles (FPE) to provide barrier protection from the dermal contact of hazardous materials such as heat, flame, and combusted product (Kim et al., 2017). However, the mass and bulkiness of various types of FPEs has been consistently shown to negatively affect user mobility, performance, and comfort (Coca et al., 2008, 2010; Park et al., 2015; Orr et al., 2019; Ciesielska-Wróbel et al., 2017). Specifically, FPE limits the human body's ability to properly regulate homeostatic temperature which can lead to altered physiological responses, heat strain, and slips, trips, and falls (Kong et al., 2010, 2013; Chang et al., 2016). Additionally, the added weight of the FPE can increase the workload of occupational tasks, increasing heat production, compromising task performance, and decreasing mobility and balance (Coca et al., 2010; White and Hostler, 2017; Hu and Qu, 2016). Given these factors, it is vital that FPE be designed and constructed with the end users' protection as well as occupational task performance in mind to ensure the safety and health of the user.

While international certification standards exist to control the protection capability of FPEs, physiological responses and ergonomics may differ across various internationally certified FPEs due to variability in construction techniques, fabrics, and designs used (Orr et al., 2019). A

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previous study has worked to compare internationally certified FPE in terms of total heat loss (THL) and thermal protective performance (TPP) (Kim et al., 2017), however, a direct comparison of the physiological implications and ergonomics is still needed to provide comparative information for the end users as well as relevant stakeholders. Thus, the aim of this study was to compare the ergonomics, physiological responses, and subjective characteristics of three internationally certified FPEs from the European Union (EU), South Korea (SK), and the United States of America (US) during relevant occupational tasks and mobility assessments as outlined in ASTM International standard F3031-17 (ASTM International, 2017).

2. Methods

Ten male career EU firefighters (age=39.9±7.1 years, height=180.0±2.8 cm, weight=79.4±4.3 kg, and BMI=23.67±2.74 kg/m^2) reported to the laboratory on separate days during which each was informed about all study procedures, signed informed consent on all tests performed, and completed all study procedures. All study procedures were completed indoors in normal room environmental conditions (21 °C). The study design employed a within-subjects repeated measures design where each participant was tested while wearing each of the three FPEs (EU, SK, and US) all on the same day in a randomized order with at least a 20-min rest period between ensembles to ensure all physiological measurements returned to baseline values. The randomized order was used to reduce the influence of testing order on the measured outcomes. All study procedures were reviewed and approved by the Committee of Ethics in Investigation at the University of Deusto (Ref: ETK-13/17-18).

Following informed consent, the InBody bioelectrical impedance body composition analyzer (InBody 770, InBody Co., LTD, Seoul, South Korea) was used to obtain baseline body composition values and weight. After the first weigh-in, each participant drank 500 ml of water while being familiarized with the first randomized ensemble. After familiarization and water intake, a pre-ensemble weighing was carried out. Once the weighing was finished, the first ensemble was donned as would be normally completed during a fire station emergency. Following the donning of the ensemble, a gross range of motion (ROM) assessment was completed as outlined in ASTM F3031-17 (ASTM International, 2017). Measurements were taken using the Kinovea motion capture software (Kinovea v0.8.15) (Elwardany et al., 2015; Puig-Diví et al., 2019; Abd Elrahim et al., 2016). ROM measurements taken were as follows 1) Trunk flexion (Start: participant standing in standard anatomical position, End: the trunk is flexed forward to the limit of motion); 2) Lateral trunk flexion (Start: participant standing in standard anatomical position, End: participant in lateral trunk flexion to the limit of motion); 3) Standing reach (Start: participant standing with feet shoulder width apart and dorsal surface of the body in contact with a wall. Subject's arms at the side with palms facing inward, End: participant reaching forward as far as possible, without waist rotation). ROM was measured using the standard method involved with the Kinovea motion capture software by obtaining a still image of the end of each movement, manually choosing an axis of rotation and movement starting point (anatomical position), and digitally measuring the angular change of the body part around that axis (Elwardany et al., 2015; Puig-Diví et al., 2019; Abd Elrahim et al., 2016).

Following all ROM measurements, each participant completed an agility circuit for time. The agility circuit consisted of stepping over a 40 cm high step, crawling under an 80 cm high rope, turning around, and repeating the course back to the start (Fig. 1a). Next, each participant was asked to step onto a 40 cm high step for 5-min continuously at a participant chosen speed. The number of steps completed in the 5-min was recorded. Next, the participant completed the timed search task that simulated real-world firefighter tracking. The participant was asked to crawl back and forth along a 6-m straight wall as fast as possible without compromising technique (Fig. 1b). Lastly, each participant was asked to walk on a treadmill for 20-min at a speed of 3.2 miles/hour and incline of 5% which simulates the average work rate of firefighting tasks (Cheung et al., 2010). During the entire testing protocol, heart rate (HR, beats per minute), breathing rate (BR, breaths per minute), and estimated internal temperature (T_c. degrees Celsius) were continuously measured using the Zephyr BioHarness 3 (Zephyr Technology Corp. Annapolis, MD). The BioHarness 3 estimates T_c using HR, skin temperature, and proprietary algorithms and has been validated previously while wearing FPEs. (Buller et al., 2015; Seo et al., 2016) The pre-activity measurement was defined as the 1-min average directly before the start of the treadmill exercise. The post-exercise measurement was defined as the last-minute average during the treadmill walking task. Rating of perceived exertion (RPE) was also assessed using a Borg RPE scale where 0 = rest and 10 = maximum exertion before and after the 20 min walk (Borg, 1998).

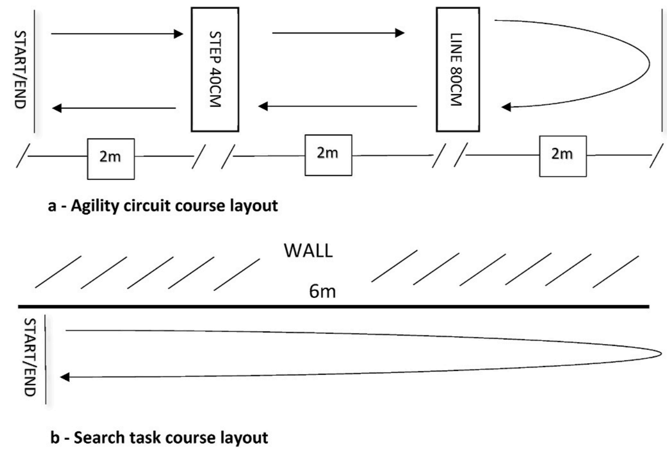

Fig. 1. Course layout for firefighter task drills.

After completing all the tasks and doffing the ensemble, a second body composition measurement was performed. Then each participant was asked to complete a participant questionnaire rating their overall impression of the ensemble, overall RPE across all exercises (overall-RPE), wearing comfort, thermal sensation, and perceived mobility. The overall ensemble rating was assessed on a 0 (worst) to 10 (best) scale. Overall-RPE was assessed using a Borg RPE scale (Borg, 1998). Wearing comfort was assessed on a 0-4 scale where 0 = comfortable and 4 = extremely uncomfortable (ISO 10551, 1995). Thermal sensation was assessed using a 4 to −4 scale where 4 = extremely hot, 0 = neither hot nor cold, and −4 = extremely cold (ISO 10551, 1995). Perceived mobility was assessed on a 3 to −3 scale where 3 = much mobility and −3 = much restriction (Parsons, 2014). Following all subjective questionnaires and a 20-min resting period, another 500 ml of water was ingested and the protocol was started again with the second randomized ensemble and the same with the randomly chosen third ensemble. Prior to beginning subsequent tests, researchers also ensured that heart rate and core temperature returned to values similar to baseline measurements (no specific criteria were used, just visual inspection).

2.1. Fire protection clothing ensembles

Three representative FPEs for structural firefighters, certified and widely used in the EU, SK, and US were worn by the participants. These three countries of origin were chosen to represent a wide range of geographic area around the world. Each international ensemble included jacket, pants, balaclava, helmet, gloves, and boots, worn together with a universal set of underwear (100% cotton, t-shirt and briefs). Mass of the total ensembles were as follows: US=10.41 kg, EU=7.98 kg, and SK=7.86 kg. Because the garments were purchased originally for testing on a thermal manikin, only one size of each of the three garments were available for this testing. Therefore, participants were only included in the study if they had a height and weight in the ranges of 175–185 cm and 75-85 kg, respectively. Additionally, all participants were screened for proper size to the garments prior to enrollment in the study. Participants were excluded if the garments did not fit properly based on the respective manufacturer's sizing guidelines. The sizes of the garments were as follows: US: coat=4232R, pants=38L, EU: coat and pants=large, SK: coat=6, pants=5. We have described the details of the FPEs including TPP, THL, and other thermal properties of the garments in a previous publication (Kim et al., 2017). No self-contained breathing apparatus (SCBA) was worn by the participants during the testing. Fig. 2 presents images of each ensemble.

2.2. Analytic approach

Mixed effects models were used to examine differences in physiological parameters (body weight, HR, BR, T_c, and RPE) across the three ensemble types (ensemble: EU, SK, and US) and two time periods (time: pre-versus post-exercise) and to detect ensemble by time interactions (interaction). Mixed effects models were further used to compare the continuous mobility, task performance, and subjective variables assessed at a single time point across the three ensemble types. All models accounted for within participant variability and utilized an unstructured covariance structure. All analyses were performed in Stata v.16 (StataCorp, College Station, Texas) with alpha level set at 0.05.

Fig. 2. International fire protective ensembles.

3. Results

Fig. 3 presents the physiological variables across time by ensemble type, providing p-values for the main effects of ensemble and time as well as the interaction p-value. Body weight, HR, and BR all showed no significant effect of ensemble (p=0.781, p=0.269, and p=0.263, respectively). However, T_c and RPE had a significant ensemble effect (p=0.028 and p=0.039, respectively) with mean core temperature and RPE, independent of time, seeming to be higher in the US ensemble. All physiological variables showed a significant time effect, where the variable increased on average over time in HR, T_c, BR, and RPE ($p<0.001$ for all) and decreased over time for body weight ($p<0.001$). No interaction effects were observed for body weight, HR, T_c, BR, or RPE (p=0.890, p=0.994, p=0.897, p=0.435, and p=0.221; respectively) (Fig. 3).

Table 1 presents the comparison of mobility and task performance variables across the three ensemble types. Mean values of lateral trunk flexion were not significantly different across the three ensembles ($p>0.05$ for all comparisons). Trunk flexion in the SK ensemble (78.4° 95% CI:69.1–87.7°) was significantly higher than the EU ensemble (74.6° 95% CI:65.3–83.9°) (p=0.026). Trunk flexion for the US ensemble (75.8° 95% CI:66.5–85.1°) was not significantly different than the SK or EU ensembles (p=0.127 and p=0.481, respectively). Standing reach in the EU ensemble (115.4 cm 95% CI:106.3–124.5 cm) was significantly higher than the US ensemble (105.5 cm 95% CI:96.4–114.6 cm) (p=0.004). However, standing reach in the SK ensemble (110.1 cm 95% CI:101.0–119.2 cm) was not significantly different for the EU or US ensembles (p=0.124 and p=0.180, respectively) (Table 1).

Agility circuit time was significantly lower in the US ensemble (9.3 s 95% CI:8.5–10.1 s) than the EU ensemble (9.8 s 95% CI:9.0–10.6 s, p=0.051) and the SK ensemble (9.9 s 95% CI:9.1–10.7 s, p=0.019). Agility circuit time did not differ between the SK and EU ensembles (p=0.695). Search task time and steps in 5-min were not significantly different across the three ensemble types ($p>0.05$ for all comparisons) (Table 1).

Table 2 presents the comparison of subjective information across the three ensembles. The overall ensemble rating in the EU (7.2 95% CI:6.4–8.0) was significantly higher than US (6.0 95% CI:5.2–6.8, p=0.020) but not different than SK (6.5 95% CI:5.7–7.3, p=0.176). RPE score was significantly higher in the US ensemble (4.1 95% CI:3.5–4.7) compared to the SK ensemble (3.4 95% CI:2.8–4.0, p=0.006) and near significant for the EU ensemble (3.0 95% CI:2.4–3.6, p=0.078). Wearing comfort score was not significantly different across the three ensembles ($p>0.05$ for all comparisons). Perceived thermal sensation score was higher in US (2.5 95% CI:2.1–2.9) than EU (1.6 95% CI:1.2–2.0, $p<0.001$) and SK (1.7 95% CI:1.3–2.1, $p<0.001$). Perceived mobility score was higher in EU (1.3 95% CI:0.5–2.1) compared to SK (0.2 95% CI:0.6–1.0, p=0.047) but no different than US (0.5 95% CI:0.3–1.3, p=0.149).

4. Discussion

This study examined the physiological responses and ergonomics of three internationally certified FPEs (EU, SK, and US). Changes in the physiological parameters of HR, BR, T_c, and body weight before and after the occupationally specific testing battery did not differ significantly across the three ensemble types (no significant interactions were found). Mobility measurements remained relatively stable across all three ensembles; however, trunk flexion was higher in SK than EU and standing reach was lower in US than EU. Agility circuit time was significantly lower in US than the other two ensembles, but search and step task performance was not different across ensembles. Ensemble rating, wearing comfort, thermal sensation, and perceived mobility was the best in EU while RPE was the highest in US.

The significant time effects observed across all physiological

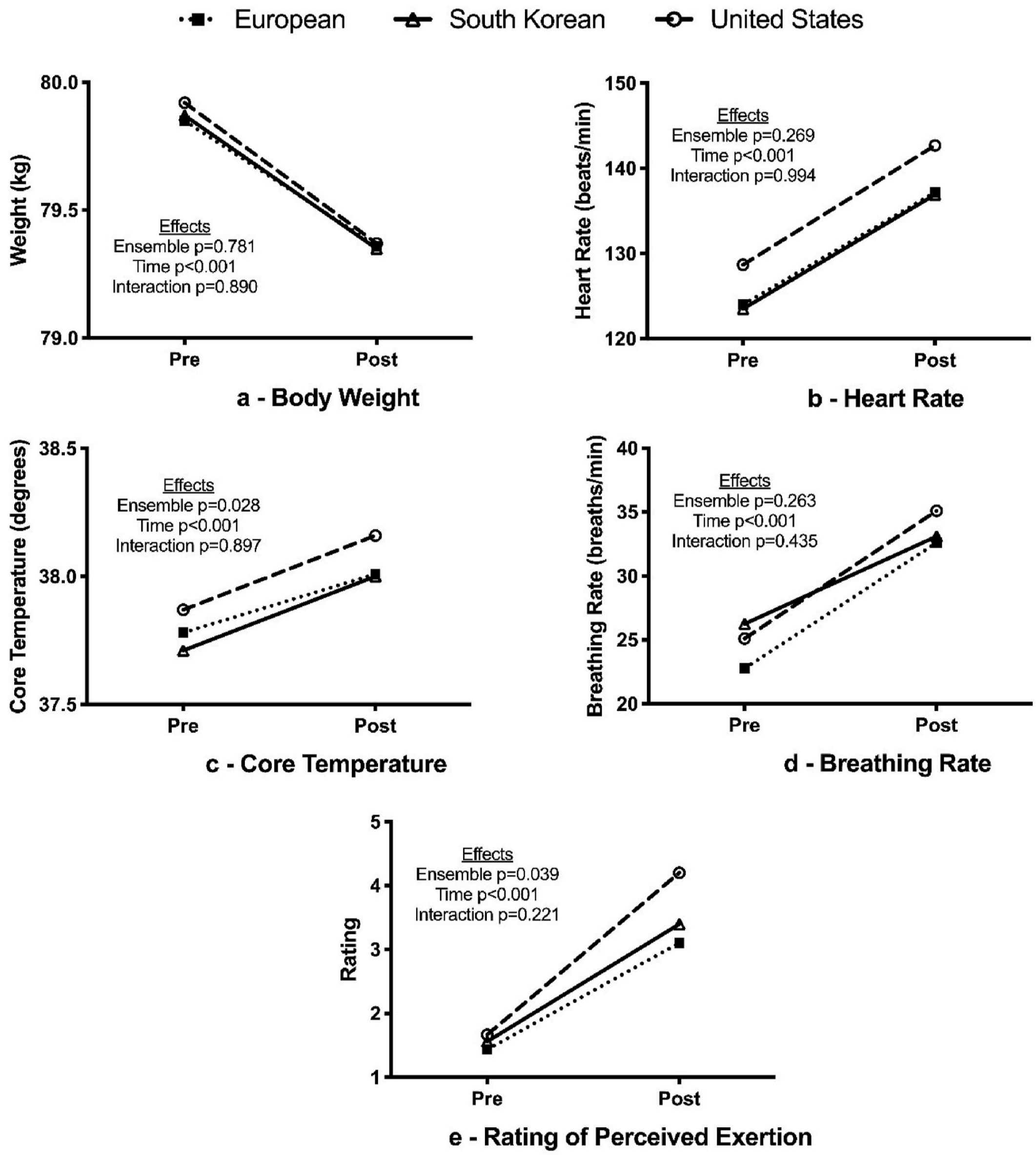

Fig. 3. Physiological comparison across ensembles.

parameters were as expected with any aerobic exercise, especially while wearing a FPE which can limit human thermoregulation and exaggerate physiological responses (Barr et al., 2010). However, no significant interaction effect was observed for any of the four physiological variables measured. This result indicates that the ensemble type did not have a significant effect on how the physiological parameters changed from pre-to post-activity measurements. While slight differences across the ensembles do exist (fabric type, design, fit, mass, etc.) and previous literature has demonstrated that THL and TPP vary across these three specific ensembles (Kim et al., 2017) as well as other FPEs (Młynarczyk and Zielińska, 2020), it is unsurprising that these differences did not result in significant physiological effects. It does appear that the US ensemble had a slightly higher overall T_c, HR, and RPE compared to the other ensembles which could have been explained by the higher mass of the overall ensemble. Additionally, the US ensemble seemed to have a higher starting HR at the onset of the treadmill walk. One previous study demonstrated that the SK ensemble has the highest TPP and lowest THL of the three ensembles indicating higher metabolic heat stress while the EU is the opposite with the lowest TPP and highest THL indicating the lowest heat stress (Kim et al., 2017). Despite these variations in ensemble thermal characteristics, they are all still internationally certified, requiring relatively high thermal burden across the ensembles, resulting in no physiological differences being observed in the current study. It may be that the differences in the thermal characteristics of the ensembles only become evident at high environmental temperatures and high activity intensities which were not examined in the current study. Furthermore, 2-dimensional textile characteristics may not always be reflected in the 3-dimensional ensemble testing. Lastly, higher physiological metrics in the US ensemble during the treadmill walk could have been indicative of higher ensemble weight or higher occupational task speed and associated workload.

While, no previous study has compared physiological responses across the ensembles examined in the current study, our results do agree with one previous study that compared the physiological effects (HR and T_c) between standard ensemble and prototype FPEs, concluding that the physiological responses were largely unchanged between the two (Williams et al., 2011). Some evidence does suggest that different configurations of FPEs, such as wearing 3/4 hip boots or helmets of varying mass does significantly impact body temperature during activity compared to standard ensembles (Smith and Petruzzello, 1998; Smith

Table 1
Mobility and task performance compared across ensembles.

	Mean	95% CI	Comparison p-values	
Lateral trunk flexion				
European	141.0°	130.3–151.7	reference	
South Korean	143.8°	133.1–154.5	0.120	reference
United States	141.9°	131.2–152.6	0.617	0.292
Trunk flexion				
European	74.6°	65.3–83.9	reference	
South Korean	78.4°	69.1–87.7	0.026	reference
United States	75.8°	66.5–85.1	0.481	0.127
Standing reach				
European	115.4 cm	106.3–124.5	reference	
South Korean	110.1 cm	101.0–119.2	0.124	reference
United States	105.5 cm	96.4–114.6	0.004	0.180
Agility circuit time				
European	9.8 s	9.0–10.6	reference	
South Korean	9.9 s	9.1–10.7	0.695	reference
United States	9.3 s	8.5–10.1	0.051	0.019
Search task time				
European	19.7 s	16.2–23.2	reference	
South Korean	18.4 s	14.9–21.9	0.538	reference
United States	16.6 s	13.1–20.1	0.140	0.391
Steps in 5-min				
European	140.0	132.9–147.1	reference	
South Korean	139.3	132.2–146.4	0.814	reference
United States	141.6	134.5–148.7	0.590	0.438

Higher lateral trunk flexion, trunk flexion, standing reach, and step values represent greater mobility and performance; lower agility circuit and search task times represents greater performance.

Table 2
Subjective perceptions compared across ensembles.

	Mean	95% CI	Comparison p-values	
Ensemble Rating				
European	7.2	6.4–8.0	reference	
South Korean	6.5	5.7–7.3	0.176	reference
United States	6.0	5.2–6.8	0.020	0.334
Overall-RPE				
European	3.0	2.4–3.6	reference	
South Korean	3.4	2.8–4.0	0.314	reference
United States	4.1	3.5–4.7	0.006	0.078
Wearing Comfort				
European	0.3	−0.2–0.8	reference	
South Korean	0.8	0.3–1.3	0.141	reference
United States	0.8	0.3–1.3	0.141	1.000
Thermal Sensation				
European	1.6	1.2–2.0	reference	
South Korean	1.7	1.3–2.1	0.608	reference
United States	2.5	2.1–2.9	<0.001	<0.001
Perceived Mobility				
European	1.3	0.5–2.1	reference	
South Korean	0.2	−0.6–1.0	0.047	reference
United States	0.5	−0.3–1.3	0.149	0.589

RPE = Rating of Perceived Exertion; higher ensemble rating represents better rating, higher RPE score represents more exertion; higher wearing comfort score represents less comfort; higher thermal sensation score represents higher thermal stress; higher perceived mobility score represents better mobility.

et al., 1995; Lee et al., 2014). However, the differences in design between the current ensembles tested were likely not drastic enough to illicit significant physiological impact, especially given the relatively low intensity and thermal load of the activities performed. Some evidence does suggest that the thermal burden of FPEs is more exaggerated at high environmental temperatures (Smith et al., 1997; Windisch et al., 2017) and activity intensities (Horn et al., 2019). Therefore, future comparisons of internationally certified FPEs may consider conducting physiological comparisons in high environmental temperatures and activity intensities as would be seen during real-world firefighting activities.

The current study results indicate some differences in mobility measures across the ensemble types where SK seemed to have the most favorable trunk flexion and US had the least favorable standing reach performance. Furthermore, the US ensemble has significantly better agility circuit time. No other performance task differences were observed. It has been previously demonstrated that firefighting tasks, even in the absence of heat stress, can lead to muscular fatigue of the trunk muscles, diminished posture, and increasing spinal flexion (Gregory et al., 2008; Quinn et al., 2018). However, importantly, it is also clear that just the FPE itself reduces mobility characterized by decreased shoulder flexion, trunk flexion, trunk lateral flexion, and standing reach as compared to standard shorts and t-shirt (Coca et al., 2010). However, little evidence exists comparing the mobility and performance implications across various types of FPEs. One previous study compared mobility across different types of FPEs (chem/bio prototype vs. standard) finding that no mobility differences existed though differences in subjective wearing comfort did (Coca et al., 2008). Another study compared variation in task performance and mobility across three different types of FPEs made of different materials and designs, concluding that FPE design has a significant impact on performance tasks such as stepping and vertical jump (Orr et al., 2019). Overall, the current study results and the previous literature suggest that FPE design may have a small impact on mobility and performance of the user and should be considered during the design of the ensemble. Importantly, some differences in mobility and performance exist even among internationally certified FPEs from different countries. These implications, albeit relatively small in the current study results, could be exaggerated during more intense activities in higher heat environments. These activity characteristics should be explored further to fully understand the implications of FPE choice on firefighter safety and task performance.

Lastly, implications on comfort and subjective effort across varying internationally certified FPEs should be considered. In the current study, the overall ensemble rating, overall-RPE, comfort scales, and perceived mobility were all the best in the EU ensemble and mainly the worst in the US ensemble (except for mobility where SK was worst). It is unsurprising that differences in perceptions exist as it is well known that FPE material, design, and mass can significantly impact perceptions of comfort and effort despite no changes in physiological responses or performance metrics (Coca et al., 2008; Smith et al., 1995, 2014). The previously published THL and TPP values of the currently studied ensembles would predict that the metabolic heat stress and consequently the perceived exertion and thermal sensation would be the worst in SK (highest TPP and lowest THL) and best in EU (lowest TPP and highest THL) (Kim et al., 2017). These assumptions held in the current analysis where EU was perceived as the least burdensome and most comfortable. While the current evidence supports the implications of THL and TPP on comfort and thermal sensation among the subjective results, the same differences across FPEs were not seen among the physiological results. It may be that the assumptive effect of TPP and THL on thermal burden only become evident in high heat environments where physiological and thermal burden is exaggerated. This hypothesis warrants further investigation to understand the implications of ensemble thermal characteristics (THL and TPP), as required by international standards, on effort and comfort under various environmental conditions.

Given that the FPE comfort and effort scores ranked in parallel where the ensembles with the best comfort also had the lowest effort (EU), it may be that these two scores are related where perceived wearing comfort can negatively influence perceived exertion and vice versa. Because perceived effort is known to be an important independent factor in optimizing physical performance (Lin and Lu, 2013), it may be that FPE design which enhances comfort can reduce perceived effort and increase performance. This hypothesis was untested in this study; however, future research should consider the relationship between comfort, perceived effort, and performance among firefighters. Again, these subjective factors may change in the context of heat or higher intensity activity so future examinations should consider these variables further.

4.1. Strengths and weaknesses

This study was most notably strengthened by its ability to complete a novel comparison of ergonomics and physiological responses across three internationally certified FPEs. This comparison can provide valuable information to international stakeholders and end users about the implications of FPE choice on firefighter performance. This study was also strengthened by using career firefighters rather than a general healthy sample population. Previous literature suggests that career firefighters provide more reliable mobility and performance measurements while wearing FPEs than non-firefighters (Son et al., 2014). However, it must also be considered that the firefighters were from the EU which could have influenced their perceptions of the EU FPEs compared to the others. The within participant design allowed comparisons which were uninfluenced by demographic, body type, and gender factors. However, such factors may interact with the comparisons made and future studies should include a larger, more diverse sample to study these possible interactions. This study was also limited by the controlled environmental conditions used for activity performance (room temperature). While these environmental conditions were chosen to allow for clean comparisons of physiological responses, mobility, and performance characteristics, the conditions were not necessarily representative of what a firefighter would experience in the field. Because the characteristics described here may be influenced by variations in environmental conditions, future studies should include various environmental conditions to further expand on the current comparisons made. The current study was limited by the estimation of T_c rather than direct measurement of esophageal or rectal temperature. However, the method used (Zephyr BioHarness) has been validated previously to estimate T_c accurately in a variety of environmental conditions (Seo et al., 2016). The study was limited by not including a “no PPE” control condition. However, previous studies have demonstrated significant differences in the same tests between no PPE and PPE conditions which justified comparisons only across the various FPE’s (Coca et al., 2010). Finally, all of the tests were completed without an SCBA which somewhat limits the generalizability of the results. However, because the international SCBA standards are so vastly different, the design and weight of the SCBAs vary quite drastically. Thus, comparison of FPEs including SCBAs would be largely comparative of the SCBA design rather than the ensemble properties themselves which was the goal of the study.

5. Conclusions

This study provided a novel comparison of three internationally certified FPEs from EU, SK, and US. No significant physiological differences were observed across the three ensemble types before and after activity. Some small differences in mobility and performance metrics were observed where SK had the most trunk flexion while US had the shortest standing reach and agility circuit time. Subjective perceptions of effort and comfort scores were positively related where the ensemble with the lowest RPE (EU) also had the best perceived comfort and mobility. It appears that previously described differences in TPP and THL across the ensembles did not impact the physiological responses in the current study as would be predicted but did align with the subjective findings well. It may be that the implications of ensemble thermal characteristics on physiological parameters do not become evident until the thermal and physiological burden is exaggerated as is experienced in high heat environments.

FPE choice, even among internationally certified ensembles, must consider specific design implications that may positively or negatively impact mobility, performance, comfort, and effort. Often, optimization in one metric results in a compromise in another making comparisons such as this across ensemble types important to international stakeholders and end users’ decision-making processes. Future studies should consider larger, more diverse samples as well as making comparisons within varying environmental conditions that represent more realistic occupational environments to confirm and expand upon these results.

Disclaimer

The findings and conclusions in this report are those of the author(s) and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention. Mention of any company or product does not constitute endorsement by the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention.

Author’s statement

AC, BS, IS, JK, and JL participated in initial project development. BS, IS, AS, and AC participated in data collection. TQ and AC conducted statistical analyses. TQ, BS, IS, AS, JL, JK, and AC contributed to critical manuscript review and authorship.

Declaration of competing interest

The authors have no conflicts of interest to report.

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