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Zubieta Pérez, Mikel

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Effect of Firefighters' Protective Gear on Physiological Performance: a Systematic Review

Authors:
Mikel Zubieta Pérez[1*], Jesús Cámara Tobalina[2]

Affiliations:
1. Faculty of Education and Sport, University of the Basque Country, Vitoria-Gasteiz, Spain
2. Physical Education and Sport Department, Faculty of Education and Sport, University of the Basque Country, Vitoria-Gasteiz, Spain

***Corresponding author:** Mikel Zubieta Pérez, Faculty of Physical Activity and Sports Science, University of the Basque Country, UPV/EHU, Lasarte 71, 01007, Vitoria-Gasteiz, Spain,
Phone: +34 622213579. E-mail: mikelzubieta.ehu@gmail.com. ORCID: 0000-0002-8105-9594

ABSTRACT

Purpose: This systematic review aims to examine the current research in professional firefighters' physiological response related to their personal protective equipment (PPE), during exercise. **Methods:** PubMed, ScienceDirect, and Web of Science were searched to gather all the studies published in peer-reviewed journals up to December 2020. **Results:** Both the use of personal protective clothing (PPC) or the self-contained breathing apparatus (SCBA) significantly reduce work tolerance and increase HR and RPE, with a greater effect when combined. Core temperature shows higher values while wearing the PPC, increasing heat strain. Ventilatory parameters, sweat, and parasympathetic reactivation do not show any clear evidence and require further research. **Conclusion:** Current evidence points that PPC increases thermal strain by preventing thermoregulation. Additionally, the further a garment is located from the body's center of mass, the greater physiological demand it creates, relative to its weight, making the SCBA relatively comfortable despite its considerable mass.

KEYWORDS

Firefighter, Physiology, Protective Equipment

1. **INTRODUCTION**

Firefighters are exposed to several different hazardous environments such as structural or wildland fires, accidents involving chemicals and hazardous materials, road accidents, or rescues at high altitudes. For instance, Foster and Roberts (1994) measured ambient temperatures of over 235 °C with thermal radiations as high as 10 $kW \cdot m^{-2}$ during the flashover stages of structural firefighting interventions and stated that no firefighter should be expected to work in such conditions. However, they also defined temperatures up to 100 °C and 1 $kW \cdot m^{-2}$ as routinary conditions, and they set a time limit of 25 min at those conditions. Given the extreme environment, most of these duties require personal protective equipment (PPE), which enables them to safely expose themselves to such adversities (Mcentire, Suyama, & Hostler, 2013; Morel, Bedek, Salaün, & Dupont, 2014). This PPE consists of personal protective clothing (PPC) and a self-contained breathing apparatus (SCBA).

Generally, an urban firefighters' PPC is composed of undergarment clothing worn in the fire-station, turn-out coat and pants (also known as bunker coat and pants), a helmet, fire-resistant gloves, a hood and intervention boots (or bunker boots) (Louhevaara, Ilmarinen, Griefahn, Künemund, & Mäkinen, 1995; Son, Bakri, Muraki, & Tochihara, 2014). The total weight of this PPC ranges between 10 and 12 kg (Marcel-Millet, Ravier, & Groslambert, 2020; Marcel-Millet et al., 2018; M. K. White & Hodous, 1987).

An essential part of this PPC is the turn-out gear, which is produced from multilayer textile materials to ensure proper protection. One of the main goals of the layers is to protect the wearer from heat. There are three types of heat transfer towards the firefighter: 1) conduction, heat transfer through the collision between neighbor atoms or molecules (mainly solid materials in contact); 2) convection, a fluid flow created by the difference in material density, therefore transferring hot fluids through the atmosphere (mainly gases); and 3) radiation, electromagnetic waves (energy transfer trough space or material medium) coming from hot surfaces (Bajaj & Sengupta, 1992).

Therefore, fire protective gear (turn-out gear) is designed to counter the three means of heat transfer, and for that, it normally includes three layers: an outer shell fabric (normally Nomex®), a moisture barrier (normally Gore-Tex®), and a thermal insulation layer (e.g. Isomex®, Iso air®) (Eryuruk, 2019). The outer shell offers protection from threats such as ultra-violet radiation, sparks or molten-metal splashes (Bajaj & Sengupta, 1992). The moisture barrier prevents vapor from getting to the thermal insulation layer, as humidity favors heat transfer by conduction (Morel et al., 2014), making it easier to absorb the ambient air temperature. However, sweat can still get to the thermal layer (there is no moisture barrier between the undergarment and the thermal layer) and it has been reported to alter the thermoregulation, creating unavoidable heat stress (Mcentire et al., 2013; Morel et al., 2014). The presence of air between the layers also enhances thermal insulation, thus, decreasing convective and conductive heat transfer through the PPC (Morel et al., 2014). When firefighters make contact with any surface at high temperature (e.g., rest their knee on the ground) the air between the layers vanishes, favoring conduction. For that reason, the turn-out gear also includes extra padding in knees and shoulders (Louhevaara et al., 1995), which help avoiding heat transfer by conduction when touching hot surfaces (Morel et al., 2014).

In special circumstances, it is mandatory that firefighters also wear an SCBA, in life and health-threatening environments (Wilkinson et al., 2020). This apparatus consists of a back frame with a supportive waist belt and straps to hold a cylinder containing compressed air at up to 300 bar. The cylinder, along with additional components, makes it possible for the firefighter to breathe air close to the atmospheric pressure (slightly over 1 bar) through a full-face mask. This equipment is essential for firefighters when they enter atmospheres containing hazardous components or harmful gases, making them able to breathe for around 30 min (less, as oxygen intake goes higher). However, all of these components that constitute the SCBA imply an additional weight of around 11-12 kg (Son et al., 2014; M. K. White & Hodous, 1987).

However, even though the firefighters' PPE protects from potential dangers, it has often been reported that it causes an added physiological burden (Eryuruk, 2019; Kesler, Ensari, et al., 2018; Lesniak, Bergstrom, Clasey, Stromberg, & Abel, 2020; M. K. White & Hodous, 1988; S. C. White & Hostler, 2017) and alters the working mechanics of the wearers (Brown, Char, Henry, Tanigawa, & Yasui, 2019; Ciesielska-Wróbel, DenHartog, & Barker, 2017; Kesler, Bradley, et al., 2018; Kong, Beauchamp, Suyama, & Hostler, 2010; Winkelmann, Rogers, Eberman, & Games, 2019). The goal of the present study is to characterize the effects of the firefighters' PPE during exercise and learn about the physiological response of the wearer.

2. METHODS

2.1. Search

This systematic review was performed following the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) guidelines (Moher, Liberati, Tetzlaff, Altman, & Grp, 2009). Searches were made in PubMed, ScienceDirect, and Web of Science databases to identify original research articles published by peer-reviewed journals. Searches were conducted to find the studies that described the physiological performance effects caused by wearing the firefighters' PPE while doing exercise. The following terms were included in the searches, to find those articles that met our criteria: "firefight*", "effect", "perform*", "physiology*" and "gear", "garment", or "breathing apparatus". All inclusion criteria missing in the search (e.g., "professional", "career", "exercise") were later filtered manually. Searches were adapted to each of the databases to adapt to the singularities of the search engines (Table 1). In addition, the "research article" filter was used in ScienceDirect to avoid the different types of publications that met the search criteria (e.g., books).

…(Table 1)…

The search was not limited to any language, but English terms were used to conduct the search. The only articles in foreign languages (2 in total) were later excluded, as the authors were not able to understand them. Both PubMed and ScienceDirect searches were made on the 12th of December, 2020 and the Web of Science search was made on the 17th of December 2020 due to a technical issue. All the research articles published to the respective dates were selected for the later exclusion process.

2.2. Inclusion process

Studies with professional firefighters or experienced emergency personnel in which PPE and no-PPE (control) trials were compared were included. The goal was to compare the physiological differences between the two conditions while performing any type of physical activity. Therefore, any outcome considered as physiological by the authors was analyzed. These outcomes included, among other measurements, heart rate (HR), rate of perceived exertion (RPE), oxygen consumption (VO_2), rectal temperature (T_{re}), and different calculations of the exercise workload.

…(Table 2)…

All studies with non-professional subjects and those that did not include a controlled trial were excluded. Studies conducted with wildland firefighters were also excluded, as the characteristics of the

PPE used in wildland fires differ from the PPE used in urban interventions, as they require unlike characteristics (Havenith & Heus, 2004). Lastly, studies that used the self-contained breathing apparatus (SCBA) alone (independent of the PPE), as an intervention, were included and reviewed separately (Marcel-Millet et al., 2020, 2018; M. K. White & Hodous, 1987).

All searches were conducted by (Z.M.) and the advice of (C.J.). All the search results were then uploaded to the Rayyan software (Ouzzani, Hammady, Fedorowicz, & Elmagarmid, 2016), where duplicates were removed using the same software. Based on the inclusion criteria explained above, a first filter was conducted by evaluating the titles. The same process was carried out with the abstracts, at which point, the full texts of the remaining articles were gathered. The full texts were assessed for eligibility by (Z.M.) and any doubt that resulted in the process was then talked over, and resolved, along with (C.J.).

2.3. Scientific quality

Once the inclusion process was finished, The Oxford 2011 Levels of Evidence (Howick, 2009) and the PEDro scale (de Morton, 2009) were used to evaluate the quality of every included article. The Oxford Level of Evidence aims to alert about the possible flaws of the evidence by classifying the investigations in 5 levels (with grades) depending on their characteristics, 1a being the maximum level in terms of scientific quality. PEDro scale consists of a maximum sum of 11 points, each one awarded for meeting the criteria of a specific question related to the methods of the article. The results of the evaluations are included in table 3.

…(Table 3)…

3. RESULTS

3.1. Search results

A total of 312 citations were gathered from the search results of PubMed, ScienceDirect and Web of Science, with 56, 95 and 161 articles, respectively. All the citations were uploaded to Rayyan (Ouzzani et al., 2016) for the selection process. The software Rayyan was used for duplicate detection and exclusion criteria labeling. All detected duplicate articles were checked one by one, and removed, leaving 257 non-duplicates remaining. After the succeeding title and abstract screening, 168 articles were discarded for not meeting the inclusion criteria detailed in the flow-chart (Figure 1). The full texts of 78 of the 89 remaining articles were obtained and the rest of them were requested to the respective authors via *ResearchGate*, indicating the goal of the review in the petition message. To the present date, one of the authors granted the full text of their study. Out of the 79 papers, after the final screening, 8 made through the exclusion process, and one last article was excluded on a further data extraction process. The whole process left 7 included articles. The screening process is shown in the PRISMA flowchart, with a more detailed list of exclusion criteria (Figure 1).

…(Figure 1)…

The included articles were limited to those that analyzed urban or structural firefighters' PPEs (Table 4). Those studies that used wildland firefighters' PPE were excluded as the characteristics of both PPEs differ (Carballo-Leyeda, Villa, López-Satué, & Rodríguez-Marroyo, 2017) and, consequently, could deviate the conclusions of this review. Likewise, the included studies were limited to those that included professional or career firefighters, to ensure that the studied subjects were experienced and the pertinent population to whom this review could come helpful.

…(Table 4)…

3.2. Description of included articles

The included studies varied significantly in terms of the tasks the subjects underwent for the experimental protocols. Three of the studies involved a treadmill protocol, with two of them being maximal efforts (Louhevaara et al., 1995; M. K. White & Hodous, 1987) and the remaining one a submaximal walk on the treadmill (D. L. Smith et al., 1995). A re-analysis of this last study (Petruzzello et al., 2009), along with the remaining three (Marcel-Millet et al., 2020, 2018; Son et al., 2014), made the participants complete a set of tasks, simulating firefighting interventions or common tasks that firefighters undertake in their regular day to day operations. Those tasks included: ascending a stairwell while carrying a pack, carrying hoses, discharging a pump can, chopping, dummy dragging, crawling back and forth, going over and under obstacles, or completing a labyrinth in a dark chamber. They also included tasks unrelated to the firefighting job, such as side jumping or a step-up task (Son et al., 2014).

All included studies performed a controlled trial with light clothing, though two of the researches' (published by the same authors) "light" assemble trial followed a different exercise protocol of that carried out in the experimental trials (Marcel-Millet et al., 2020, 2018). The rest of the investigations included the same exercise protocol for both the control and all experimental trials. All of the studies also incorporated an experimental trial involving a complete firefighting assembly (PPC + SCBA) comprised of firefighting coveralls (turn-out coat and pants), boots, helmet and an SCBA. Four of the studies also incorporated fire-resistant gloves in the PPE (Louhevaara et al., 1995; Petruzzello et al., 2009; Son et al., 2014; M. K. White & Hodous, 1987) and five of them also included a fire-retardant hood (Louhevaara et al., 1995; Marcel-Millet et al., 2020, 2018; Petruzzello et al., 2009; M. K. White & Hodous, 1987). The whole PPC + SCBA weight ranged around 19.2 - 25.9 kg.

In addition, two of the studies analyzed more than one whole PPE trial. One of them compared a 'traditional' hip-boot assemble, consisting of three-quarter hip boots and a full-length turnout coat, to a gear configuration based on the NFPA (National Fire Protection Association) 1500 standards (D. L. Smith et al., 1995). The other study compared two firefighting assembles developed in Japan, with one of them having an additional aluminum coating, and a third PPE based on the European standards (EN 469, 2005) (Son et al., 2014).

Another study also incorporated an experimental trial consisting of the light assemble with the SCBA, but no PPC (M. K. White & Hodous, 1987). Lastly, the two articles published by the same authors examined two additional assemblies: one consisting of just the PPC (no SCBA) and the other one incorporated the whole PPE (*SCBA* group) but the participants were able to breathe freely, not through the respirator (*SCBAc* group).

…(Table 5)…

3.3. **Physiological response of wearing PPE during exercise**

3.3.1. *Tolerance time and work performance*

In a study (M. K. White & Hodous, 1987), subjects carried out two different treadmill protocols to exhaustion with each assemble, one consisting of 25 min low-intensity efforts (5.3 $km \cdot h^{-1}$ at an incline of 0.67 %) followed by 5 min of rest and the other one consisted of 10 min high-intensity efforts (5.6 $km \cdot h^{-1}$ at an incline of 8.5 %) followed by 5 min rests. The maximum time limit was 180 min. When they compared the variance between the time to exhaustion of each assemble, they found significant ($p < 0.01$) time-reductions of 22.2 % originated by carrying the SCBA over the *light* assemble (11.8 kg) and an 84.4 % reduction with the complete PPE (23.1 kg) in the low-intensity trials. The high-intensity trials presented significant ($p < 0.01$) 74.7 % and 95.6 % time-reductions caused by the SCBA and the PPE, respectively.

Louhevaara et al. (1995) also found significant reductions in time to exhaustion when following another treadmill protocol. The protocol consisted of an incremental test, starting at 4.5 $km \cdot h^{-1}$ and 2°.

Initially, the incline increased by 2° every 2 min with a constant velocity, until it hit 10°. Then, the gradient stayed at 10° and the speed increased by 0.5 km·h^{-1} every 2 min, until the subjects were not able to continue the test. In this case, the time to exhaustion presented a 27 % reduction for the PPE (25.9 kg) trial and a 22 % reduction on the maximal walking speed at 10°, compared to the control trial.

Son et al. (2014) compared the performance of firefighters wearing three different PPEs: two Japanese standards (types A and B) and a third European one (type C), to a controlled trial. The exercise protocol was comprised of different tasks: step up (number/60s), side jump (number/20s), crawl (sec), object dragging (sec) and obstacle striding (sec). The performance of all the tasks decreased significantly ($p < 0.05$) with the PPEs, except for the object dragging task for PPE *type B*, which took an overall longer time to complete but did not differ significantly.

3.3.2. *Heat strain*

In one investigation, they re-analyzed the results obtained from two previous studies published by the same authors (D. L. Smith et al., 1995, 2001), to calculate the perceptual and physiological heat strain of the firefighters wearing the PPC (Petruzzello et al., 2009). They calculated the physiological strain index (PhSI) of the 15 min submaximal treadmill efforts (3.5 km·h^{-1}, at a 10 % incline) from a previous study (D. L. Smith et al., 1995), based on a formula that had been proposed in 1998 and is based on rectal temperature (T_{re}) and heart rate (HR) (Moran, Shitzer, & Pandolf, 1998).

They also calculated the perceptual strain index (PeSI) proposed (Tikuisis, McLellan, & Selkirk, 2002) in an attempt to provide a more practical tool to assess the heat strain, based on the thermal sensation (TS) scale (Young, Sawka, Epstein, Decristofano, & Pandolf, 1987) and rate of perceived exertion (RPE) (Borg, 1997).

The results showed a significant time main effect ($p < 0.001$) for PhSI, meaning that, in every condition, the strain had a significant upward tendency over the course of the protocol (submaximal treadmill). It also showed a significant gear main effect ($p < 0.001$), meaning that the control, hip-boot and 1500 trials were significantly different from one another, with values of 2.7 ± 0.10, 4.3 ± 0.13 and 4.9 ± 0.06 (arbitrary units), respectively. When the gear-time interaction was analyzed, the PhSI values also showed significant differences ($p < 0.001$), meaning that, not only does the 1500 standard assemble cause more strain, but it also increases significantly faster over the course of the exercise. Likewise, the repeated measures ANOVA showed a significant time main effect ($p < 0.001$) and main gear effect ($p < 0.001$) for the PeSI, but the gear-time interaction did not show significant differences ($p = 0.081$). This means that, unlike the PhSI values, PeSI does not increase at a significantly greater rate in any of the three assembles.

3.3.3. Heart rate

Heart rate is one of the parameters that has been analyzed the most. In the study with the low and high-intensity protocols (M. K. White & Hodous, 1987), the mean HR values for the low-intensity trials were 119, 136, 172 bpm for the light, SCBA and PPE, respectively, all of them being significantly different from each other. The authors found a 15 bpm increase in mean HR for the SCBA trial (+11.8 kg) and a further increment up to 45 bpm for the whole PPE trial (+23.1 kg). While light and SCBA trials did reach a steady-state HR value, the PPE trial HR rose significantly faster and did not reach steady values, nor did the HR decrease to near rest-values during the 5 min recovery periods. When looking at the high-intensity trials, they measured 161, 169, 169 bpm for light SCBA and PPE, respectively. The authors declared that the high-intensity HR values showed a similar trend to those found in the low intensity. When looking at the reasons for test termination, they found that out of the 36 high-intensity trials, 32 ended due to the attainment of the HR criterion (reaching 90 % of the maximal HR).

D. L. Smith et al. (1995) support the fact that PPE increases HR values at submaximal exercises. The research with the NFPA 1500 standard PPE found significant increments of 50.1 bpm (174.5 ± 8.8 bpm versus 124.04 ± 9.0 bpm) when comparing their *1500* PPE to the control trial during the treadmill protocol.

PPE does not seem to alter maximum HR values, even though the time to reach those maximum values reduces and the mean HR remains significantly higher ($p < 0.05$-0.001) during the submaximal exercises with the PPE. The same seems to apply to systolic blood pressure (Louhevaara et al., 1995). The study carried out with Japanese and European standard PPEs also found significantly ($p < 0.001$ or $p < 0.01$) higher HR values at the end-task for all of the PPEs when compared to the control trial, along with a greater ($p < 0.01$) rise of HR (ΔHR) (62 ± 12 bpm, 61 ± 16 bpm and 62 ± 24 bpm versus 30 ± 16 bpm) (Son et al., 2014).

Marcel-Millet et al. (2018) analyzed the use of the SCBA independently from the PPC and found that heart rate recovery (HRR) was initially smaller while wearing the SCBA (+14 kg) and breathing through the mask, after completing submaximal exercise tasks. This means that HR values decreased significantly ($p < 0.05$) less in the subsequent 60s to the completion of the tasks (31.4 ± 11.4 bpm versus 24.3 ± 11.1 bpm) when the participants were carrying the SCBA. It must be said that, when each task was analyzed independently, only 4 out of the 6 showed significant differences. Also, when looking at the extended recovery-time period of 300s, the overall difference was not significant, meaning that the differences might just prevail in the early moments of the recovery. Additionally, significant differences ($p < 0.001$) were found in HHR for the first 60s (HRR_{60s}) and 300s (HRR_{300s}) for both PPC and PPE groups when compared to the control trial. It must be said that these differences may not respond to the use of the equipment, as the exercise protocol for the control trial (light) and the experimental trials (PPC and PPE) differed reasonably.

3.3.4. Parasympathetic reactivation

Parallel to the HRR, the aforementioned article (Marcel-Millet et al., 2018) also assessed the parasympathetic reactivation of the participants during the 10 min recovery period after the completion of the exercise tasks. The formulas they used were the standard deviation of the normal-to-normal interval (SDNN) and the log-transformation of the root mean square of successive differences of normal R-R intervals ($LnRMSSD_{30s}$), for every 30s interval. No significant differences were found among the experimental groups (PPC, SCBA and SCBAc) but the ANOVA indicated that the $LnRMSSD_{30s}$ was significantly higher in the light assemble ($p < 0.001$). These differences, again, are hard to be attributed to the respective assemblies, as the exercise consisted of a completely unalike protocol.

3.3.5. Skin and core temperature

Two of the reviewed articles assessed the temperature of the subjects while they exercised in the respective assemblies. Both studies measured rectal temperature (T_{re}), as an indicator of core temperature, and skin temperature (T_{sk}), based on different temperatures taken from different points of the body surface (thigh, calf, arm, chest, back and cheek).

M. K. White and Hodous (1987) examined the SCBA and PPE independently. The researchers reported no significant difference in T_{re} increment between the *light* assembly and the SCBA assembly at low-intensity exercise (0.2 $°C \cdot h^{-1}$ and 0.41 $°C \cdot h^{-1}$, respectively). Furthermore, both assembles reached thermal equilibrium, with no further increase in temperature during the exercise. That would indicate no thermoregulatory alteration due to the sheer use of the SCBA. However, the complete PPE assemble did show a significantly higher T_{re} increment (1.85 $°C \cdot h^{-1}$) and it was estimated that 62 min exercise would be sufficient to reach 39 °C of core temperature at such intensity. When we look at the high-intensity trials, no assembly reached a thermal equilibrium for T_{re} and they all spike from the beginning of the exercise.

As mentioned previously, 32 of the 36 trials ended due to the HR criterion, so, likely, the highest recorded values of the T_{re} (37.9 °C, 37.9 °C, 37.2 °C, for the light, SCBA and PPE, respectively) were not representative of those that could be reached in real circumstances.

If we look at the T_{sk}, the most notable difference is that it tends to decrease during the recovery periods, as opposed to T_{re}, although that decrease in T_{re} is not very notable in the PPE trial. The other study that examined temperature also came to the same conclusion (D. L. Smith et al., 1995). While T_{re} tends to change slower, T_{sk} increases and decreases rapidly, reacting faster to the ambient temperature. In the "NFPA standard" investigation, the subjects were tasked with a treadmill protocol to exhaustion, followed by a 10 min walking recovery. The 1500 standard PPE trial showed the significantly highest ($p < 0.001$) mean and maximum T_{re} and T_{sk}, and it was the only assemble to have a further increase in T_{re} during the whole recovery (10 min), while the other two assembles remained the same or started to gradually decrease. As for T_{sk}, it started to drop during the recovery in all trials. Not only does the 1500 standard assembly show the highest temperatures, but it also has a significantly greater ($p < 0.001$) increase rate than the hip-boot or light trials throughout the exercise period.

3.3.6. Sweat

The study with the high and low-intensity trials also measured the weight loss of the subjects between the pre-trial and post-trial, for the low-intensity efforts (M. K. White & Hodous, 1987). The total weight loss of the participants was 1.173 kg, 1.285 kg and 0.658 kg for the light, SCBA and PPE, respectively. However, if we look at the loss rate, the values turn over, showing a higher rate for the PPE trial (same order: 7.0 $g \cdot min^{-1}$, 9.9 $g \cdot min^{-1}$ and 25.3 $g \cdot min^{-1}$). However, the authors do not report whether these differences are statistically significant or not.

3.3.7. Rate of perceived exertion (RPE) and perceived muscle fatigue

One of the studies recorded RPE at maximal and submaximal intensities during incremental treadmill protocols to exhaustion (with and without PPE) (Louhevaara et al., 1995). The authors reported that there was no significant difference in maximal values between trials, meaning that carrying the PPE does not alter the ability to reach maximal exertion. However, the values up to a gradient of 10° and speed of 4.5 $km \cdot h^{-1}$, the RPE values of the PPE trials were significantly higher ($p < 0.001$).

The same results were obtained by D. L. Smith et al. (1995) when they measured RPE in a submaximal treadmill exercise. The 1500 standard PPE showed a significantly higher RPE ($p < 0.001$) than the hip-boot, which, synchronously, showed higher RPE values ($p < 0.001$) than the light assemble trial. However, there was no difference between the increase rates ($p = 0.12$). The authors reported similar results for the perception of respiration and the feeling scale, with the difference that these two perception scales did increase at a faster rate throughout the effort ($p < 0.01$).

The article with the Japanese and European PPEs used the RPE and muscle fatigue scales to determine the subjects' perception (Son et al., 2014). All PPEs showed a higher RPE and muscle fatigue during the tasks (mentioned previously) in comparison to the control trial ($p < 0.05$-0.001), but the PPEs were not significantly different from one another.

Marcel-Millet et al. (2018) analyzed different exercise tasks, but in this case, the assembles consisted of the PPC, SCBA and SCBAc (breathing freely). The results indicated differences in RPE among the PPC, SCBAc and SCBA trials ($p < 0.05$-0.001), with increasingly higher values in that order.

3.3.8. Ventilatory parameters

The study that compared the NFPA 1500 standard PPE to the hip-boot and light assembles also examined the absolute oxygen consumption (VO_2) of the subjects during the submaximal treadmill exercise (15 min at 3.5 $km \cdot h^{-1}$ and 10 % gradient) and the subsequent recovery walk (10 min) (D. L. Smith et al., 1995). The results showed a significantly higher ($p < 0.001$) VO_2 for the 1500 PPE throughout the whole protocol, but the differences decreased notably when the recovery started, meaning that the extent of the oxygen demand related to the PPE could depend on the exercise intensity. The same conclusions were drawn from the aforementioned respiratory distress values studied in the same article.

Another research compared the maximal values of the VO_2 (VO_2max) and the respiratory exchange ratio (RER) obtained at the end of an incremental treadmill protocol (Louhevaara et al., 1995). They found no significant differences in any of the two parameters, whatsoever. However, when the VO_2max was divided by the total weight (body + PPE), the differences were significant ($p < 0.001$), with mean values of 34.1 $ml \cdot min \cdot kg^{-1}$ (28.1 to 39.8 $ml \cdot min \cdot kg^{-1}$) for the PPE trial and 46.9 $ml \cdot min \cdot kg^{-1}$ (33.4 to 73.3 $ml \cdot min \cdot kg^{-1}$) for the light trial.

Lastly, the evidence is not clear on how the SCBA changes the respiration rate (or breathing frequency). Marcel-Millet et al. (2018) analyzed the respiration rate during different tasks and found out that the mean and maximum frequency decreased with the use of the SCBA when compared to the SCBAc and PPC conditions. The differences remained significant ($p < 0.0001$) in the overall values, as well as in each task independently ($p < 0.0001$). However, during the most strenuous tasks, the breathing frequency increased (reaching values of 55 $breaths \cdot min^{-1}$).

On the other hand, another study examined the respiration rate in both high and low-intensity treadmill exercises to exhaustion, with and without SCBA, and came to differing conclusions (Louhevaara et al., 1995). The breathing frequency remained significantly higher in the PPE (38.2 ± 7.0 $breaths \cdot min^{-1}$) and SCBA (37.7 ± 7.4 $breaths \cdot min^{-1}$) conditions when compared to the light trial (breathing freely at 32.6 ± 5.0 $breaths \cdot min^{-1}$). Nonetheless, the values reverted at high intensity, with an increased light condition (41.0 ± 8.2 $breaths \cdot min^{-1}$) and decreased SCBA (35.5 ± 3.7 $breaths \cdot min^{-1}$) and PPE conditions (33.9 ± 4.8 $breaths \cdot min^{-1}$).

3.3.9. Workload

Following a similar procedure as the SCBA and SCBAc investigation article (Marcel-Millet et al., 2018), the same authors made a research calculating different types of workload with data gathered from different tasks in the PPC, SCBA (PPC+SCBA) and SCBAc (PPC+SCBA, breathing freely) assembles (Marcel-Millet et al., 2020).

They calculated both Banister's (bTRIMP) and Edward's (eTRIMP) workloads, based on HR; Foster's workload (sRPE), based on RPE; and different types of external loads based on 3-axis accelerations (ExL). All of the workload types showed significant differences ($p < 0.001$) between the PPE trial and the other two assemblies. However, while the internal workload of the firefighters was higher with the SCBA and SCBAc assembles, the external workload showed opposite results, with a higher acceleration-based workload in the PPC assemble. This may result from the extra load carriage of the breathing apparatus, limiting the movement of the wearers. Lastly, the only workload that showed significant differences ($p < 0.01$) between the SCBA and SCBAc assembles was sRPE (66.2 ± 17.0, 89.5 ± 14.4 and 106.8 ± 21.5 (arbitrary units) for PPC, SCBA and SCBA, respectively).

4. **DISCUSSION**

The goal of this review was to analyze the existing scientific literature on the effects of the urban firefighters' PPE on physiological performance, to find out the adverse effects it may have and make any suggestions for future improvements. Son et al. (Son et al., 2014) concluded that professional firefighters are less affected by the PPE than non-professional subjects. As a result, it was decided to limit the review to those studies that included professional firefighters, to only study the pertinent population.

We need to understand that the primary purpose of the firefighters' PPC is to protect the rescue personnel from hazardous environments, such as high ambient temperatures, exposure to intense thermal radiation, abrasion and molten metal splashes, as well as to protect from possible burns (Wieczorek & Dembsey, 2001). On the other hand, the SCBA is necessary to get into environments with low oxygen levels and contain hazardous chemicals or smoke. It lets firefighters breathe fresh air, with an autonomy of 30min with a standard one-cylinder unit, or even longer with two-cylinder units or bigger size units (Kesler, Ensari, et al., 2018).

However, that protection does not come without a reduction of performance. As seen in some reviewed studies (Louhevaara et al., 1995; Son et al., 2014; M. K. White & Hodous, 1987), the work tolerance and time to exhaustion decreased while wearing protective gear, whether it is a constant (M. K. White & Hodous, 1987) or increasing (Louhevaara et al., 1995) intensity. Even with recovery periods, the SCBA seems to decrease work tolerance time by almost 75 % in high intensities and 22 % in lower intensities, most likely due to the added weight (around 12 kg). As seen in other studies, the added weight can decrease the performance time in submaximal intensities (Phillips et al., 2018). Nonetheless, it has been reported that the physiological burden of the weight carriage is not equivalent in every part of the body. Indeed, it has been found that one kilogram located on the feet (footwear) is equivalent to an 8.7 times greater mass in the form of an SCBA (Taylor, Lewis, Notley, & Peoples, 2012), meaning that, the fractional burden of carrying the SCBA may not be that significant compared to the different PPC garments, especially boots. As seen in this review, in low intensities, the whole PPE represents almost a 4 times greater time reduction than the SCBA alone (84.4 % versus 22.2 %) (M. K. White & Hodous, 1987). The explanation seems to be that, the further a load is carried from the body's center of mass, the more inertia it accumulates during the swing phase of the movement (walking, running…) and, thus, increases the muscular work needed to initiate and terminate every motion (Cavagna & Kaneko, 1977). The requirement to lift the feet with extra weight also creates an additional energy demand (Taylor et al., 2012).

Another explanation for the decreased performance with the PPC is that the friction between the different protective layers creates a resistance when sliding one over the other (Lee, Bakri, Kim, Son, & Tochihara, 2013), demanding a higher power to complete the same tasks. Decreases in performance of up to 7 % have been reported (while cycling) (Holmér, Kuklane, & Gao, 2006).

A clear increase in HR has been found among the experimental trials of the reviewed studies (Louhevaara et al., 1995; Son et al., 2014; M. K. White & Hodous, 1987). Waring the SCBA alone (over the light clothing), an increase of 15 bpm has been reported throughout the submaximal intensity treadmill exercise (M. K. White & Hodous, 1987). However, this additional stress is not as substantial as the stress caused by the whole PPE, which has been reported to increase HR from 32 bpm to 50 bpm when compared to the light assembly. Different authors have attributed this additional stress to a decrease in central blood flow and cardiac stroke volume due to a reduction of blood plasma volume (Barr, Gregson, & Reilly, 2010; M. K. White & Hodous, 1987). This reduction in plasma volume seems to be related to sweat loss (Barr et al., 2010), even though it might not explain the whole HR increase (Jon Williams et al., 2011). Only one of the 7 studies analyzed in this review included weight loss (sweat loss), but the authors did not report any significant difference among trials (M. K. White & Hodous, 1987), making it difficult to associate the increase in HR to the sweat loss. In addition, HR seems to be the best indicator for physiological strain, as it shows a notable increase before the T_{re} and offers reliable insight about the firefighters' physiological condition before any other variable (M. K. White & Hodous, 1987). What is more, it is a relatively easy variable to assess, making it a useful tool for real-time monitoring.

Body temperature measured as T_{re} also shows higher values with PPE in the reviewed studies (Louhevaara et al., 1995; Son et al., 2014; M. K. White & Hodous, 1987), even though the increase during the exercise was not as sharp as HR (M. K. White & Hodous, 1987). SCBA alone (with no PPC) does not seem to cause any change in T_{re}, making it clear that the responsible for the temperature increase is mainly the PPC. It is already some kind of a consensus in the scientific literature that PPC does alter the thermoregulation of the firefighters (Barr et al., 2010; Mcentire et al., 2013; Morel et al., 2014). The firefighters' PPC is very effective in insulating the wearer from ambient heat exposure, whether it is radiation or convection (by gases). However, it seems that the moisture barrier prevents sweat from evaporating, restricting heat dissipation and making it impossible to decrease the T_{sk} and, as a result, T_{re}. T_{re} even continues to increase slightly after 10 min of recovery (D. L. Smith et al., 1995) after treadmill exercise. Likewise, PhSI also shows an increasing trend throughout 15 min of submaximal exercise, more so than the equivalent light trial (Petruzzello et al., 2009). Therefore, a future improvement for moisture barriers should look into developing a layer that allows sweat evaporation, while still restricting the moisture penetration from the outside: an "inwards-only" vapor barrier. Cooling methods have already been investigated in scientific literature, and some of them have been proven effective, although the most effective methods require dedicated recovery in a cool environment (Hostler, Reis, Bednez, Kerin, & Suyama, 2010; Mcentire et al., 2013; Walker, Driller, Brearley, & Argus, 2014).

The literature also indicates that wearing firefighters' PPE while exercising has a clear increase in the perceived scales. RPE shows higher values while wearing the PPE in treadmill exercise or tasks (Son et al., 2014; M. K. White & Hodous, 1987). Part of the perceived exertion is attributable to breathing through the SCBA mask, and additionally, to the SCBA carriage (Marcel-Millet et al., 2018). Breathing through the mask alone can make the subject perceive a higher exertion, even though variables such as HR or T_{re} do not show any differences. The explanation for this rise in RPE in the SCBA versus SCBAc trial could be related to the breathing frequency, which showed a significant decrease with respirator usage (Marcel-Millet et al., 2018). Nonetheless, the evidence in this matter is confronting (Marcel-Millet et al., 2018; M. K. White & Hodous, 1987) and requires further investigation. Other variables based on RPE, such as PeSI (Petruzzello et al., 2009) and sRPE (Marcel-Millet et al., 2020) also seem to show higher values while wearing the whole PPE.

The parasympathetic reactivation and sweat rate do not show any clear results. Even though the authors do not specifically report significant differences (M. K. White & Hodous, 1987), it could be thought that the sweat rate increases with the use of the PPC, as the values are higher, and T_{re} does show greater values. As for the parasympathetic reactivation, even though the values of $LnRMSSD_{30s}$ and SDNN show significant differences in the only study that assessed them (Marcel-Millet et al., 2018), the exercise protocol of the light (control) assemble is not the same. The *intermittent fitness test* may be much more intense than the tasks carried out in the experimental trials, making the comparison not valid.

Same as HR, RPE and T_{re}, absolute VO_2 also increases with the PPE usage, although it is more responsive to exercise than the rest of the parameters, decreasing notably as the exercise intensity goes down (active recovery) (D. L. Smith et al., 1995). If we look at peak absolute VO_2 values, no differences have been found regarding the assembly. Notwithstanding, when normalized with the whole carriage weight (body + PPE), VO_2max does seem to show 26 % lower values in the PPE trials (Louhevaara et al., 1995). Finally, ventilation (V_E) seems to be higher while wearing the SCBA, even when respiration rate has been found to drop, therefore, the V_E retention in high intensities is accounted entirely to tidal volume (M. K. White & Hodous, 1987). Nevertheless, ventilatory parameters are complex variables to assess and were hardly investigated in the reviewed articles, hence, more research is required to cover this gap in scientific literature.

5. CONCLUSION

Firefighters' PPE implies a considerable extra weight carriage for the user (23 kg). This additional weight creates physiological stress to the firefighters, decreasing performance reasonably. However, the different garments have their peculiarities. The SCBA, even though it is the heaviest equipment of the PPE, causes a minimal strain to the firefighters in comparison to the PPC. The close location from the center of mass makes the SCBA a comfortable component to carry, causing a minimal strain relative to its weight. Nonetheless, the SCBA's respirator increases the wearers' perceived exertion and there is some unclear evidence indicating that it also alters the breathing pattern.

On the other hand, the different components of the PPC seem to significantly increase the physiological strain of the firefighters. The garments that are located the furthest from the firefighter's center of mass (e.j. boots) seem to have a bigger impact on the energy demand while exercising. On the other hand, turn-out gear seems to prevent the thermoregulation of the wearer, increasing the thermal strain and restricting the available working time. Enhancing thermoregulation by allowing sweat evaporation may be the most interesting aspect to consider for future technological advancements.

HR, RPE and T_{re} show a clear rise due to the PPE. Submaximal VO_2 and sweat rate also seem to increase with PPE but need more research, as few studies have assessed them. Parasympathetic reactivation and breathing frequency show unclear results and also require further investigation.

6. HIGHLIGHTS

·Firefighters' PPE significantly increases the physiological burden of professionals while doing exercise, limiting their performance by almost 92 % in high intensities.

·The further a weight is carried from the center of mass (e.g., boots), the more energy it requires, relative to their weight, for the same work.

·Future technological advancements should focus on the moisture barrier, letting sweat evaporation to and allowing the wearer to thermoregulate.

7. CONFLICTS OF INTEREST

The authors declare there are no conflicts of interest.

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9. APPENDIX (TABLES AND FIGURES)

Table 1: Specific search text	
PubMed	firefight* AND effect AND perform* AND (gear OR garment* OR "breathing apparatus")
ScienceDirect	firefight AND effect AND perform AND (gear OR garment OR "breathing apparatus") AND physiology
Web of Science	firefight* AND effect AND perform* AND (gear OR garment* OR "breathing apparatus")

Table 2: Inclusion criteria
All articles were required to meet the following characteristics to be included
·The subjects: they needed to be professional or career firefighters (rescue personnel), familiar with the PPE. ·Intervention: a controlled trial without the PPE (or a specific garment, e.g., SCBA). ·Intervention: an experimental trial with structural firefighter PPE (not wildland). ·An exercise protocol for the experimental and control trials. ·Outcome: physiological parameter measurements for both trials (experimental and control). ·Statistical comparisons between the physiological values of the experimental and control trials.

Table 3: Scientific quality of the included studies													
Article	**PEDro scale criteria**												**Level of evidence**
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**Total**	
(M. K. White & Hodous, 1987)	0	1	0	1	0	0	0	1	1	1	1	6	1b
(Louhevaara et al., 1995)	0	0	0	1	0	0	0	1	1	1	1	5	1b
(Smith et al., 1995)	0	0	0	1	0	0	0	1	1	1	1	5	1b
(Smith et al., 2001)	0	0	0	1	0	0	0	1	1	1	1	5	1b
(Petruzzello et al., 2009)	0	0	0	1	0	0	0	1	1	1	1	5	1b
(Son et al., 2014)	0	0	0	1	0	0	0	1	1	1	1	5	1b
(Marcel-Millet et al., 2018)	0	1	0	1	0	0	0	1	1	1	1	6	1b
(Marcel-Millet et al., 2020)	0	1	0	1	0	0	0	1	1	1	1	6	1b

Table 4: Description of the participants					
Article	**n**	**Experience / occupation**	**Age (years)**	**Weight (kg)**	**Height (cm)**
(M. K. White & Hodous, 1987)	9	firefighter and emergency personnel	24.8	75.3	177
(Louhevaara et al., 1995)	12	Pro firefighters	32 (26-46)	85.6 (69.1-101)	180 (174-187)
(Smith et al., 1995)	10	Career firefighters	29.8±4.2	85.7±11.3	198.9±6.3
(Petruzzello et al., 2009)	21	Career firefighters	-	-	-
(Son et al., 2014)	9	9 professional firefighters	28.6±2.4	69.4±5.1	172.4±5.9
(Marcel-Millet et al., 2018)	32+2 F:6, M:28	32 professional + 2 volunteer firefighters	M: 37±7 F: 29±3	M: 76±9 F: 64±3	M:179±6 F: 171±4
(Marcel-Millet et al., 2020)	22	firefighters	36±7	75±9	178±6

Table 5: Article descriptions						
Article	**Dependent variables**	**Assemblies**	**Weight (kg)**	**Models (configuration)**	**Protocol**	**Relevant results**
(M. K. White & Hodous, 1987)	HR, T_{re}, T_{sk}, VE, VE_{rate}, weight loss (sweat)	Light (C) SCBA (E) FF (E)	3.8 11.8 23.1	-Chemklos II coverall + Servus boots -Light + SCBA (MSA model 401) -SCBA + Janesville NFPA turnout coat/pants, Nomex® hood, Firedraft gloves, Cairns 660C helmet, Servus bunker boots	Treadmill to max (each assemble): -Low intensity: 25/5 min at 5.3 km/h 0.67 % -High intensity: 10/5 min at 5.6 km/h 8.5 %	-HR of *SCBA* (sig.) higher than *light* (15 bpm) -*FF* HR rise (sig.) higher, with no steady-state. 14-45 bpm higher than *light* (sig.). -*SCBA* and *light* T_{sk} (sig.) similar, *FF* (sig.) higher. -Decrease in VE_{rate} in *SCBA*.
(Louhevaara et al., 1995)	VO_2, VCO_2, HR, RPE, BP	Light (C) PPE (E)	- 25.9	-Shorts + sneakers -Fire protective gear (EN 469; 1994) + SCBA (Dräger)	Treadmill to the max in a climatic chamber (each assemble): 5min warm-up, gradient increase by 2°/2 min to 10° (4.5 km/h). Then, +0.5 km/h/2min. Fin with 6 min walk	-No (sig.) difference in VO_2max, HRmax, RERmax systolic BP and RPE between assembles. -In sub max. exercise, HR, systolic BP and RPE were sig higher in *PPE* than *light*. -Most powerful individual predictors (92 % predicted) were body fat, height, RPEmax and RERmax.
(Smith et al., 1995)	HR, Thermal Sensation, T_{re}, T_{sk}, RPE, Perception of respiration, Feeling Scale, VO_2, VCO_2,	Light (C) Hip-Boot (E) 1500(E)	- 20.18 21.17	-Fire resist. pants + t-shirt + boots -Work uni. + three-quarter hip boot, Nomex® turnout coat + helmet + gloves + SCBA -Work uni. + bunker boots, bunker pants, turnout coat, hood, helmet, gloves + SCBA	-Treadmill: 15 min at 10 %, 3.5 km/h (each assemble)	-HR, VO_2, T_{re}, T_{sk}, Respiratory distress, RPE, Thermal sensation, Feeling scale (sig.) higher in *1500* than other two conditions
(Petruzzello et al., 2009)	PhSI (based on HR and T), PeSI (based on TS and RPE),	Light (C) Hip-Boot (E)	- 20.18	-Fire resist. pants + t-shirt + boots -Work uni. + three-quarter hip boot, Nomex® turnout	-Treadmill: 15 min at 10 %, 3.5 km/h (each assemble)	-PhSI increased (sig.) faster with *1500* than with the rest

		1500 (E)	21.17	coat + helmet + gloves + SCBA -Work uni. + bunker boots, bunker pants, turnout coat, hood, helmet, gloves + SCBA	-Simulated activities (each assemble): ·Ascend stairwell ·Hoist hose ·Discharge pump can ·Chopping task ·Dummy dragging	
(Son et al., 2014)	HR, RPE, perceived muscle fatigue	Control (C) Type A (E) Type B (E) Type C (E)	1 19.2 19.4 20.8	-T-shirt, shorts, running shoes -Japan type: Aromatic polyamide textiles + flame retardant + SCBA -*Type A* + aluminum coat -European type: Hainsworth TITAN, Gore-tex® + SCBA	-Grip test -Physical performance test: ·Step up ·Side jump ·Crawl ·Object dragging ·Obstacle stride	-*PPE* conditions had (sig.) lower grip strength than *control*, Type C the (sig.) lowest. -HR and ΔHR for end task were (sig.) higher in *PPE* than *control*. -RPE and muscle fatigue were (sig.) higher in *PPE* than *control*.
(Marcel-Millet et al., 2018)	HR (HRV, HRR), BF, RPE, air consumption (SCBA),	Control (C) PPC (E) PPC + SCBA (E) PPC + SCBAc (E)	- 9 23 22.5	-Shorts, T-shirt, running shoes -Boots, bunker coat and pants, hood, helmet -PPC + SCBA (breathing through it) -PPC + SCBA without the face mask (breathing freely)	-IFT (only control): intermittent fitness test (30/15 s, starting 8 km/h, +0.5 km/h every 45 s) -Rescue simulation (only experimental): ·Hose carry ·Tower 1 with hoses (8 stories) ·Dark chamber ·Stroop test ·Tower 2 (8 stories) ·Mannequin dragging	-HRR_{60s}, HRR_{300s}, $LnRMSSD_{5\text{-}10min}$ were (sig.) lower and T30 (sig.) higher in *all E trials* than *IFT (C)*. - $LnRMSSD_{30s}$ was (sig.) lower in *all E trials* than *IFT (C)*. -HR was (sig.) higher in *SCBA* and *SCBAc* than *PPC*. -BF (sig.) decreased in *SCBA* in comparison with *SCBAc* and *PPC*.

(Marcel-Millet et al., 2020)	HRV, RPE, workload (bTRIMP, eTRIMP, lnHF, sRPE, HRV-load, external-load)	Control (C) PPC (E) PPC + SCBA (E) PPC + SCBAc (E)	- 9 23 22.5	-Shorts, T-shirt, running shoes -Boots, bunker coat and pants, hood, helmet -PPC + SCBA (breathing through it) -PPC + SCBA without the face mask (breathing freely)	-IFT (only control): intermittent fitness test (30/15 s, starting 8 km/h, +0.5 km/h every 45 s) -Rescue simulation (only experimental ·Hose carry ·Tower 1 with hoses (8 stories) ·Dark chamber ·Stroop test ·Tower 2 (8 stories) ·Mannequin dragging	-HR and RPE were (sig.) lower for *PPC* than *SCBA* and *SCBAc*. -Only sRPE shows (sig.) differences between assembles (among workloads).
(sig.) = statistical significance (p < 0.05)						

Figure 1: Flow-chart (description of the study selection process)