EXOSKELETONS IN REDUCING PHYSICAL STRAIN ON FIREFIGHTERS. OUTLINE OF THE PROBLEM

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Abstract

Given the growing demands placed on firefighters during rescue operations, there is a growing need to explore modern technologies that could support their work. One promising solution in this field is the use of exoskeletons, biomechanical devices that reduce the physical load on the wearer.

The aim of this research was to outline the current state of knowledge on reducing the physical load of firefighters through the use of exoskeletons and to identify prospective directions for the continuation of this research. This paper sought to provide a comprehensive overview of the existing literature on the worldwide use of exoskeletons in the fire service, emphasising their potential impact on reducing the physical burden faced by firefighters. The focus was on design issues, principles of operation and conclusions regarding their practical application. Particular attention was paid to analyses of potential health benefits, such as reduced musculoskeletal load and improved ergonomics.

The study outlined a picture of the current state of knowledge on exoskeletons, as well as indicated directions for further research and development of technologies to assist firefighters during rescue operations.

Keywords: energy expenditure, exoskeleton, technical activities, firefighter, physical effort, fire service

1. Introduction

Firefighting is one of the most physically demanding professions in the world. It is not uncommon for firefighters to be subjected to extreme physical and mental stresses due to the nature of their work in extinguishing fires, saving lives, responding to the effects of natural hazards and dealing with a range of emergencies and disasters (Smith et al., 2024, Zahari et al., 2024). This requires firefighters to have not only the appropriate knowledge and skills, but also often the above-average strength and high physical capacity (Wejman, 2013).

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The specific nature of a firefighter's job translates into a relatively high risk of accidents in the line of duty (Szubert & Sobala, 2002; Pawlak et al., 2016). The Information Bulletin of the Fire State Service for the year 2022 indicated that accidents on duty most frequently occurred during sports activities (40.13% of all accidents), rescue operations (28.75% of all accidents), other duty (15.72% of all accidents) and 'training, drills and inspections' (7.66% of all accidents). The main causes of accidents were as follows (State Fire Service Information Bulletin, 2022):

- "incorrect behaviour, carelessness, own inattention and that of third parties – 53.08% of all incidents",
- "difficult, uneven, slippery passage, ground – 20.14% of all incidents",
- "medical emergencies and other causes (external and internal factors) – 7.35% of all incidents".

The following were noted as the most commonly observed in the period preceding accidents (State Fire Service Information Bulletin, 2022):

- "tripping, slipping, loss of balance – 41.07%",
- "physical dynamic load" (the use of multiple major muscle groups during work, often associated with lifting and transporting heavy materials) – 24.8%",
- "contact with or impact against immovable material agents – 10.43%",
- "coming into contact with, being struck, caught, crushed by material agents in motion – 9.32%".

Such an analysis of accident status is produced periodically, once a year, by the Office of Personnel and Organisation of the State Fire Service of Poland (SFS). The process is based on detailed data provided by individual units of the State Fire Service, including the accident severity rate, defined as the number of days off duty divided by the number of injured persons, and the accident rate, which is the number of injured persons in accidents per 1,000 officers employed (National Headquarters of the State Fire Service of Poland).

In the reported year, fire protection units handled 608,818 incidents, including 135,965 fires (22.33% of all actions), 424,958 local dangers (69.80% of all actions) and 37,895 false alarms (7.87% of all incidents. A total of more than 1,372,000 firefighters of the SFS took part in all rescue operations. This shows the scale of possible circumstances in which firefighters are exposed to above-average physical exertion. As a result of the above incidents, firefighters suffered injuries mainly related to fractures, dislocations, joint sprains, strains, contusions or tendon and muscle injuries. Physical dynamic loads compared to 2021 increased by six incidents (State Fire Service Information Bulletin, 2022).

The various hazards that may be encountered in the course of duty involve the risk of accidents. The use of modern technology can significantly reduce relevant occupational risks by reducing the physical burden of the activities performed. One possible solution is the use of exoskeletons, which are mechanical devices worn outside the wearer's body. They are designed to support or enhance natural human movement. The exoskeleton's operation is based on the use of actuators, sensors and controllers that interact with the wearer, with the aim of enabling him or her to perform tasks that are normally too strenuous or even impossible to perform (Dollar, 2008). For this reason, they can be applied in the fire service, reducing the physical strain on firefighters during rescue operations and reducing the risk of accidents on duty.

Research on the use of exoskeletons in the fire service is presently in its early stage. It is a relatively new area of safety engineering. No publications have been found in the literature that could provide a compendium of knowledge on the subject or even point to the most promising research directions. This may be considered a significant knowledge gap. To address this, a study was designed and implemented to outline the current state of knowledge on reducing the physical burden on firefighters through the use of exoskeletons.

2. Research Assumptions

The purpose of the research was to outline the current state of knowledge on the reduction of physical strain on firefighters through the use of exoskeletons, as well as to identify prospective directions for the continuation of this research.

The main research problem formulated for this research assumed the form of the question: *What is the current state of knowledge regarding reducing physical strain on firefighters through the use of exoskeletons, and what are the resulting prospective directions for the continuation of this research?*

The main research problem was broken down into specific research problems as listed below.

1) How does physical strain affect the safety of firefighters during their service?
2) How is the idea of using exoskeletons to reduce the physical strain on firefighters expressed?
3) What are the solutions to date for using exoskeletons to reduce the physical burden on firefighters?
4) What are the prospective directions for continuing research on the use of exoskeletons in reducing the physical burden on firefighters?

Specific research problems were addressed selectively in individual subsections in chapter 3.

It was assumed that the exoskeleton might help reduce the physical strain on firefighters during rescue operations and the risk of in-service accidents by increasing their strength and endurance in their services, improving operational efficiency, maintaining freedom of movement and increasing the safety of the wearer. An empirical research method of literature review was employed to verify the above research hypothesis and to address the formulated research problems (main research problem and specific research problems). Scientific articles published in the ScienceDirect database (www.sciencedirect.com) and materials available on the Internet (www.google.com) were reviewed. In both cases the phrases, 'exoskeleton

AND fire service', 'exoskeleton AND fire brigade' and 'exoskeleton AND firefighter' were used to select the research material. The review of the research material was carried out until sufficient information had been compiled to answer the formulated research problems, to verify the research hypothesis and to clearly establish whether the research objective had been achieved.

3. Results

3.1. Impact of physical strain on firefighter safety

Energy expenditure, that is the amount of energy consumed by the body during various activities, is the key indicator influencing the effectiveness and safety of the rescue operations carried out (Heil, 2002; Acharya et al., 2024). High physical strain can lead to rapid physical exhaustion, which in turn can increase the risk of tactical errors, injuries and an impairment of firefighters' health (Garner et al., 2013; Park et al., 2015). During rescue operations, firefighters have to cope with a variety of stresses, such as carrying heavy and/or uncomfortable PPE, moving through difficult terrain, and carrying out demanding activities such as administering firefighting currents or emergency evacuation of casualties. The weight of items carried, the restriction of freedom of movement and the respiratory resistance due to the use of respiratory protection equipment can lead to relatively faster fatigue (SGSP, 2020). The additional risk is poorly fitted or designed protective equipment, which can cause discomfort and affect the firefighters' ability to operate effectively. Firefighters' personal protection includes a variety of equipment, from special clothing to breathing apparatus to specialised gloves and footwear. All are aimed at protecting against hazardous, harmful and/or nuisance factors. In the dynamically changing operational conditions at the rescue site, the implementation of innovative solutions plays a key role. When developing and implementing modern protective equipment, it is essential that ergonomic principles are taken into account so that their size, weight and other characteristics are properly adapted to the user (SGSP, 2020).

Ergonomics is the process of designing a working environment that not only ensures safety, but also improves efficiency for workers performing a given task. As regards rescue operations, often carried out under difficult and stressful conditions, it is crucial to improve the comfort and safety of firefighters. General ergonomic hazards at the scene of rescue operations comprise the following (Fire and Emergency Medical Services Ergonomics, 1996):

a) intense physical exertion (e.g. when lifting or carrying heavy equipment, ladders or injured persons),
b) uncomfortable body positions (e.g. when operating a fire extinguishing station),
c) environmental conditions (e.g. heat - heat stress).

Noteworthy here are the results of a study on the biomechanical analysis of the effect of PPE on the mobility of firefighters during lifting activities. The purpose of the study was to assess the effect of personal protective equipment on firefighters' mobility during weightlifting tasks. The study included 10 Malaysian firefighters, divided into age groups and differentiated by the body mass index (BMI). The firefighters were equipped with a motion capture system (Rokoko Smarsuit Pro) that enabled precise recording of kinematic parameters such as chest angle deflection and angular acceleration during lifting (Yunus, 2022). The sensor layout and hardware configuration of the Rokoko Smartsuit Pro are shown in Figure 1.

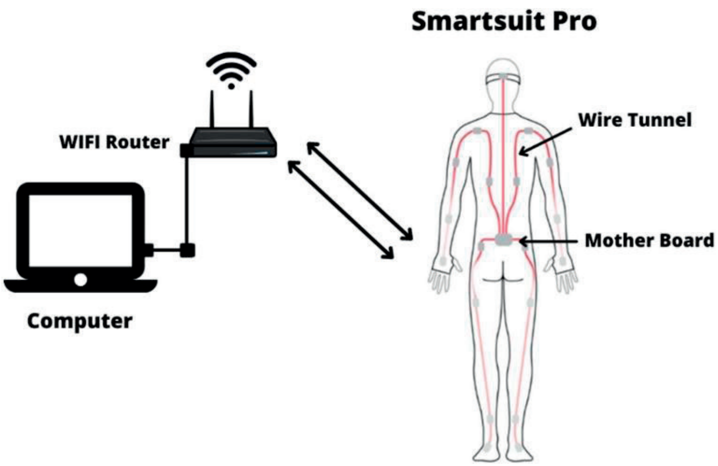

Figure 1. Sensor layout and configuration of Rokoko Smartsuit Pro
Source: (Yunus, 2022)

The results of the study have shown that the use of PPE significantly reduces the mobility of firefighters, which is particularly evident in older respondents and those whose BMI was higher. This limitation can lead to an increased risk of musculoskeletal injury, especially in the spine, due to reduced flexibility and increased strain from carrying heavy equipment such as an air brace. In addition, this study suggested the need for further work on the ergonomic optimisation of firefighters' PPE and the modification of their lifting techniques to reduce the risk of injury and thereby increase operational efficiency (Yunus, 2022).

Failure to follow ergonomic principles during rescue operations can lead to a number of adverse consequences, both for the firefighter and the effectiveness of rescue operations. These include (Piec, 2016; Yunus, 2022; Hanses, Horwath, 2022):

a) **increased risk of injury** (injuries to the spine, joints, muscles, prolonged work in awkward positions, especially pressure on the knees and shoulders),
b) **reduced physical fitness and fatigue** (non-ergonomic performance techniques, reduced physical endurance can affect the ability of firefighters to perform effectively in intense and prolonged rescue operations),

c) **increased energy expenditure** (non-ergonomic activities requiring more energy consumption, thus a faster depletion of strength),
d) **increased risk of errors and accidents** (physical fatigue and pain can affect concentration and quick reactions, increasing the risk of error),
e) **long-term health problems** (chronic stresses resulting from non-compliance with ergonomic principles can lead to long-term health problems such as arthritis or spinal disorders).

Following ergonomic principles, including the reduction of physical strain, is of paramount importance for the enhancement of firefighter safety, particularly during rescue operations. The utilisation of innovative technologies, such as exoskeletons, can offer substantial support in this regard.

3.2. Concept of using exoskeletons to reduce the physical strain on firefighters

The human skeleton (endoskeleton) is inside the body, surrounded by other tissues, and carries loads associated with lifting and carrying objects. The strain on the musculoskeletal system during physical work can lead to dysfunction when the working conditions differ from natural ones. One potential solution in this context is the implementation of an additional external exoskeleton, which has the potential of reducing the load on both the endoskeleton and muscles. The appropriate combination of actuators, sensors and controllers can assist the user in performing tasks specific to rescue operations. Exoskeletons can be classified according to their purpose, range of operation, type of power supply and method of control. This division has been shown in Figure 2.

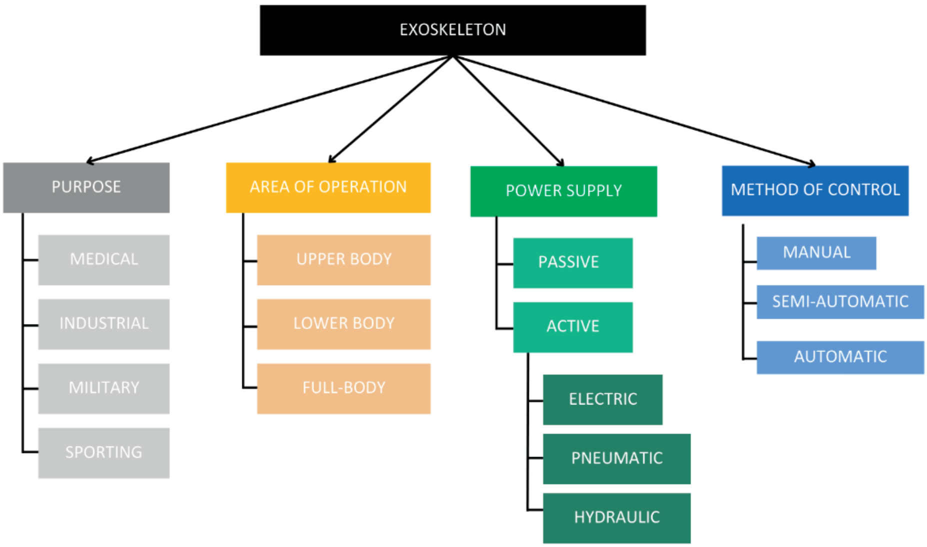

Figure 2. Classification of exoskeletons

Source: (Pons, 2008)

This classification can be further clarified as follows (Pons, 2008):

1) **medical exoskeletons:**
   a) Rehabilitation – used in the rehabilitation process of patients following injury, surgery or suffering from neurological conditions such as stroke. They help to restore motor function and enable them to perform movements they cannot perform on their own.
   b) Strengthening – designed for people with limited mobility, such as the elderly, to help them with daily activities;
2) **industrial exoskeletons:**
   a) job aids – these aim to support workers who have to perform heavy or repetitive tasks, such as heavy lifting or prolonged standing,
   b) strength-enhancing – increases the user's strength, allowing them to lift and carry heavier loads (Golabchi, 2023);
3) **military exoskeletons:**
   a) strengthening – used to increase the strength and endurance of soldiers, enabling them to carry a heavier load and move through difficult terrain;
   b) protective – equipped with additional shields and armour to increase safety in combat conditions;
4) **sports exoskeletons:**
   a) performance-enhancing – used to improve performance or speed up rehabilitation after injury.

The presented detailed breakdown draws attention to branches in which exoskeleton technologies are currently most widely used. They can also be helpful in outlining the issue of using exoskeletons in fire services and pointing out the prospective directions of their development. The division of exoskeletons by area of operation covers different parts of the body. Upper limb exoskeletons allow support for the arms, forearms and hands, assisting activities that require precise movements and strength. Lower limb exoskeletons are designed to support the legs, helping users to walk, stand up, sit down and recover from falls. Full-body exoskeletons, on the other hand, cover the user's entire body, providing support for both upper and lower limbs and full-body.

It is possible to differentiate between various categories of power supply. The first is passive power, which relies on mechanical spring systems and other elements to support movement without the use of external energy. Active power supply, on the other hand, allows the user's movements to be supported by providing additional energy (e.g. electricity). There are three main types of energy used in active exoskeletons, and on this basis the appropriate power modes are classified:

a) **electric** – battery-powered, using electric motors to propel movement,
b) **pneumatic** – using compressed air to generate force to assist movement,
c) **hydraulic** – using pressurised fluid to drive actuators.

The division by method of control comprises three principal categories of exoskeleton. Manual exoskeletons are devices whose movements are controlled directly by the user, without the use of sophisticated automation. Semi-automatic exoskeletons combine manual control with some level of automation, for example through assistance with basic sensor systems. Automatic exoskeletons, on the other hand, are equipped with advanced control systems. A preliminary analysis of types of exoskeletons identifies the idea of using exoskeletons to reduce the physical burden on firefighters. It is expressed in mechanical supporting of a firefighter performing rescue operations by relieving the movements of his arms, legs and even the whole body, based on platforms powered by electrical, pneumatic and/or hydraulic energy or not requiring such power.

3.3. Solutions to date on the use of exoskeletons in reducing the physical burden on firefighters

In the global initiative to enhance the efficiency and safety of firefighters during rescue operations, exoskeletons are becoming an increasingly prevalent tool to facilitate their work. These sophisticated devices are currently undergoing evaluation in a number of countries.

As regards growing demands and challenges, exoskeletons present a promising avenue for providing support, thereby alleviating the burden on the musculoskeletal system. In Australia, exoskeletons are available in a variety of forms, including lightweight structures designed to support the upper and lower body, such as the legs, arms, or shoulders. It is worthy of particular note that the Advanced Firefighting Apparatuses (AFA) merit further consideration. The exoskeleton was developed by Ken Chen at Monash University in Melbourne and has the capacity to markedly diminish the physical burden generated by the equipment being handled and the components being lifted and secured (e.g. structural components of machinery and equipment). Figure 3 illustrates the Advanced Firefighting Exoskeleton, which was developed at Monash University by Ken Chen. In accordance with the technical specifications of the aforementioned design, the exoskeleton weighs 23 kilograms yet enables the user to lift weights of up to 91 kilograms. The exoskeleton is affixed to the user's belt and operated via joysticks. The device is powered by two electric batteries, which provide continuous operation for a period of two hours. At the time of writing, the exoskeleton is undergoing testing.

In China, exoskeleton technology for firefighters is being developed to support firefighting operations during large-scale forest fires. Researchers from the Research Centre for Human Functional Enhancement Technology (https://www.globaltimes.cn/page/202104/1221691.shtml), operating within the China Aerospace and Industry Corp (CASIC), have developed a system used to increase firefighters' weight-carrying capacity to 50 kilograms, as well as making it easier to navigate difficult mountainous terrain and forests. The exoskeleton weighs 5 kilograms and can save more than 50% of the energy used in walking, climbing and carrying loads. The process of donning and doffing the exoskeleton is completed in a time frame of less than 60 seconds.

Prototypes of the exoskeleton described above are shown in Figure 4.

Figure 3. Advanced Firefighting Exoskeleton developed in Monah University by Ken Chen
Source: (https://betterfutureawards.com/MEL14/project.asp?ID=12906)

Figure 4. Exoskeleton designed by CASIC
Source: https://www.globaltimes.cn/page/202104/1221691.shtml

Another example of an exoskeleton is the Auberon model being tested by firefighters in Singapore. The Auberon exoskeleton, developed by Hope Technik, is the country's first air-powered exoskeleton and was developed in collaboration with the Singapore Civil Defence Force (SCDF) and the Office of the Director of Science and Technology under the Ministry of Home Affairs (MHA). It is designed to increase the strength and endurance of firefighters during rescue operations. The device is equipped with a pneumatic drive, which utilises compressed air in a 6.8-litre cylinder to provide support for the user's movements. The lightweight yet robust design is intended to facilitate the performance of tasks over extended periods without undue physical exertion. (https://toyhaven.blogspot.com/2018/04/scdf-exoskeleton-to-be-worn-by.html). The exoskeleton by the Singaporean researchers is shown in Figure 5.

Figure 5. The Auberon Pneumatic Exoskeleton is designed to provide relief for firefighters carrying up to 40 kg of firefighting equipment up the stairs of burning high-rise buildings

Source: (https://toyhaven.blogspot.com/2018/04/scdf-exoskeleton-to-be-worn-by.html)

The device is designed to assist the user in transporting heavy loads over multiple floors, utilising pistons mounted at leg height. The firefighter is able to carry up to 40 kilograms of equipment, including breathing apparatus, fire hoses and power tools. It is anticipated that the firefighter will experience reduced muscle strain when carrying firefighting equipment, particularly in the shoulder region, owing to the design of the device. Ng Kiang Loong, the programme director of Hope Technik, elucidated the operational mechanics of the exoskeleton, which entails the distribution of the equipment's weight through the exoskeleton frame and its subsequent transfer to the ground via specialized footrests. In emergency situations, the firefighter is able to rapidly disengage the exoskeleton with a dedicated button.

3.4. Prospective directions for continuing research into the use of exoskeletons in reducing the physical strain on firefighters

A review of the available technical solutions indicates that exoskeletons can offer firefighters a number of benefits in reducing the physical burden associated with rescue operations:

a) **increased strength and endurance** (with the support of external structure it is possible to lift weights of up to 100 kilograms with the exoskeletons' own weight of around 20 kilograms);
b) **improved operational efficiency** (firefighters can perform tasks faster and with less fatigue, resulting in higher operational efficiency during rescue operations);

c) **reducing the risk of injury** (reducing muscle and joint strain reduces the risk of injury and trauma associated with carrying heavy loads and prolonged physical exertion);
d) **preserving freedom of movement** (modern exoskeletons provide full freedom of movement, which is crucial in dynamic and unpredictable working environments. An example is the design of the Advanced Firefighting Apparatus (AFA), which integrates additional features such as a small fire hose mounted on the forearm);
e) **long-term health benefits** (regular use of the exoskeleton can contribute to long-term health improvements, reducing the frequency of injuries and chronic pain associated with heavy physical work);
f) **protection of the user from harm** (during an emergency they can be easily and quickly removed by pressing a button, an example of which is the Auberon exoskeleton).

Conclusions from an analysis of the use of exoskeletons in firefighter rescue operations indicate the significant potential of these technologies to improve operational efficiency and occupational safety. As an advanced biomechanical device, exoskeletons have the potential of becoming a crucial piece of equipment in the future, assisting firefighters in enhancing their strength and endurance during rescue operation.

Above all, exoskeletons offer the possibility to significantly reduce physical strain, which is particularly important in the context of performing prolonged and physically demanding tasks. Reducing musculoskeletal load can contribute to reducing injuries and prolonging operational capacity, which is key to maintaining their health and effectiveness for longer periods of time. Exoskeletons can enable firefighters to perform tasks that require a great deal of strength and endurance more precisely and efficiently, such as operating heavy rescue equipment or handling casualties in difficult terrain. With assisted movement technology, firefighters can complete these tasks with less effort, allowing them to perform their duties for longer and more efficiently. The insights formulated are the same as the prospective directions for continuing research into the use of exoskeletons in reducing the physical burden on firefighters. In addition, the implementation of exoskeletons also presents some challenges:

a) **adaptation to the specifics of the profession** – the need to optimise exoskeletons for the dynamic movements performed by the firefighter, so as not to restrict their mobility and dexterity during rescue operations;
b) **compatibility with existing protective equipment** – exoskeletons are required to be fully integrated with current PPEs, such as breathing apparatus;
c) **resistance to extreme conditions** – the construction of the exoskeletons should be fireproof, moisture-proof and resistant to contact with chemicals;
d) **training requirements** – to develop and implement training programmes to ensure that firefighters are adequately prepared to use the exoskeleton effectively and safely during rescue operations;

e) **cost implications** – to take into consideration the high costs associated with purchasing or maintenance.

Each of these challenges requires an in-depth analysis and implementation strategy to make the introduction of exoskeletons in the SFS safe, effective and economical. Further research is needed on their ergonomics and integration with current firefighter equipment. Comprehensive testing in real operational conditions is also needed to accurately assess their effectiveness and reliability.

4. Conclusion

Understanding and monitoring the energy expenditure of firefighters is key to ensuring their safety and performance. High levels of physical activity, combined with prolonged stress, can lead to rapid depletion of the body's energy resources, which in turn increases the risk of injury, reduces the ability to perform effectively and can ultimately lead to an accident.

The exoskeleton is a device that has the potential to significantly improve firefighters' working conditions, increasing their efficiency and safety and minimising the risk of injury during rescue operations. By supporting muscular strength and improving ergonomics of movements, they can significantly reduce the physical strain on firefighters allowing them to work more efficiently and for longer periods without excessive fatigue.

Internationally, exoskeletons are already being tested in a variety of rescue scenarios, showing positive results in increasing efficiency and safety. In China, exoskeletons help firefighters carry heavy equipment over difficult terrain, in Singapore they support ergonomics when lifting and carrying victims during rescue operations, and in Australia research is focused on improving operations in extreme conditions. Prospective research directions comprise further optimisation of ergonomics, enhanced autonomy and adaptation of exoskeletons to the dynamic working conditions of firefighters. Introducing them to the Polish market could benefit both the health of firefighters and the effectiveness of rescue operations.

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