Forensic Science International 355 (2024) 111942

Contents lists available at ScienceDirect

Forensic Science International

journal homepage: www.elsevier.com/locate/forsciint

Examining thermally induced movement of the fatal fire victim

Mary-Jane Harding *, Nicholas Márquez-Grant, Mike Williams

Cranfield Forensic Institute, Cranfield University, Bedford, United Kingdom

ARTICLE INFO

Keywords:
Fatal fire
Fire investigation
Fire victim
Thermal Alteration
Pugilism

ABSTRACT

Investigating a fatal fire scene comprises analysis not only of the fire's development to identify the point of fire origin and ignition source, but analysis of a victim's position and their relationship within the scene. This work presents both qualitative and quantitative results from experimentation investigating the effect of a real fire environment on the human body, and how the position of a victim at the post burn investigation stage may be significantly different to the position at fire ignition. Qualitative observations were undertaken on the burning of 39 compartment and vehicle scenes from ignition through to suppression, each containing a human cadaver. The results of analysis question the validity of previous work based on cremation observations. Quantitative results were produced by recording 13 points on the body on the X, Y and Z axis, both pre and post burn on a smaller dataset of ten compartment burns. Results have enabled a more robust assessment of thermally induced movement of the body within the scene along each axis, evidencing that pugilism is not the universal reaction of the fatal victim to thermal exposure, with extension of the upper limbs far more common than has been previously reported.

1. Introduction

Understanding the effect of thermal penetration on human remains is key to the analysis of the fatal fire scene, with the recording of a victim's position and their relationship to the immediate surroundings a vital process in the investigation [1–6].

Most fire deaths are not the result of burning but are the result of inhalation of toxic chemicals present within the fire scene [7–11]. The thermal environment of fire is not only high in temperature but also very noxious due to complex and variable chemical release. As heat strikes the surface of objects within the scene, chemicals such as carbon monoxide are released and the atmosphere usually becomes toxic. Carbon Monoxide (CO) is a colourless, odourless and tasteless gas, and can be lethal. Upon inhalation the CO molecule binds with the haemoglobin found in blood with an affinity in excess of 200 times more than oxygen, producing Carboxyhaemoglobin (COHb). The formation of COHb reduces the oxygen level in the body with the level of 50 % within the blood considered lethal concentration. Post-mortem investigation of fatal fire victims include (where possible) blood analysis with CHOb levels which are widely used to indicate victim vitality [12–17].

The presence of other highly toxic gases may also be identified within the bloodstream, such as Hydrogen Cyanide (HCN). HCN is the by-product of heating combustible materials, for example paper, nylon, and products made from polymers and polyurethanes such as carpets and furniture [18]. Victim's clothing of natural fibres like silk and wool can also produce HCN which can explain its presence in an outdoor fatal fire environment [19]. The highly irritant gas Hydrogen Chloride (HCL), a by-product of heating polymeric materials such as Polyvinyl Chlorides (PVC) can also be present within the highly noxious environment [20], with these extremely toxic gases causing incapacitation, anoxia and in a high enough dose can lead to death [21,22]. Following incapacitation or death through toxic inhalation, the victim will continue to be subjected to thermal environment until suppression.

The growth of a fire is dependent of fuel, oxygen, heat and an uninhibited chemical reaction with thermal energy transferred predominantly by radiated and convected heat to the body. As oxygen is entrained at the base of the fire it creates a convective flow cycle due to buoyancy. Heated air rises and thermal energy transfers to the surface of cooler objects in its path [23] with the cooler air then falling. This process of convection is important for promoting the growth of fire in its early stages at $<c.150$–200 °C [24–26]. As fire grows and temperatures rise, the higher heat release rate facilitates the mechanism of heat transfer transitioning from convection to radiation at $c400$ °C [23].

Once heat rises in an enclosed area it is trapped within the ceiling layer radiating heat to the surfaces below. The increase in surface temperature of objects below, results in the release of gases such as CO,

* Corresponding author.
E-mail address: m.harding@cranfield.ac.uk (M.-J. Harding).

https://doi.org/10.1016/j.forsciint.2024.111942
Received 7 May 2023; Received in revised form 2 November 2023; Accepted 14 January 2024
Available online 17 January 2024

HCN and HCL by pyrolysis which then rise mixing with the uncombusted carbon products (smoke) in the ceiling layer. This cycle of increased heat eventually reaches an optimal point of autoignition at ~600 °C or heat flux ~20 kW/m^2 [23,27–29], resulting in a phenomenon termed flashover, with the increased radiated temperatures promoting ignition of all surfaces within the scene [25,29–31]. Flashover occurs predominantly in compartment/room environments where the temperatures of the post flashover environment can reach in excess of 1000 °C, and can be maintained for several minutes making survival of the fire victim untenable [25,30,32].

As the human body continues to be exposed to high temperatures, thermal onslaught can initiate movement of the limbs into the pugilistic position [33,34]. This is achieved by heat penetrating into the soft tissue resulting in the denaturing and shrinking of muscles, ligaments and tendons [2,4,14,35,36]. As both extensor and flexor muscles retract, flexor muscles dominate resulting in the movement of limbs into the pugilistic position [37–39]. It is suggested that this process follows a predictable pattern [4] where all the external variables are similar [40], with posture change presenting in deeply charred remains [27]. Additionally, it is proposed that the absence of pugilism is indicative of body restriction with Symes and colleagues [40] suggesting that as the human body is essentially the same anatomy for all fatal fire victims, it will therefore undergo the same physical reaction of posture change through fire modification if all external variables are similar. Their study contained minimal discussion around the variation of body positioning within the fire environment other than observing that a victim was discovered face down (prone) under vehicle wreckage or within the vehicle and how this position restricted movement to pugilism. There is limited scene discussion around fire dynamics, exposure times or fuel loads that victims were exposed to other than their presence in stairwells or in vehicles . This lack of data instigates a level of ambiguity when proposing these examples as being indicative of predictable burn patterns found on the fatal fire victim.

Investigations of thermally induced movement leading to pugilism have been undertaken retrospectively utilising case work data [1,4,36,41]. These studies provide insight from a post fire perspective whilst identifying the requirement of real time fire experimentation. Further examination of this movement phenomenon has been conducted via observation through a crematoria retort window and door [42,43]. While cremation temperatures are equivalent to the high temperatures reached in real fires, each cremation is undertaken on an individual basis with technicians altering the activation of both the burners and oxygen intake to make the cremation process efficient [44]. Furthermore, a crematoria retort does not replicate real fire in either scene dynamics or duration time [45–47].

A study by Bohnert et al. (1998) recorded that a body exposed to temperatures between 670 °C and 810 °C will show pugilism after approximately 10 min. Recognising that the presence of the coffin hindered early observations they proposed reservation in applying their findings in forensic investigations [43]. Symes et al. (2012) report a more perceptive observation into pugilism transition by observing individuals cremated without coffins [42]. Whilst their study produced a detailed sequence of alteration to the human body by fire, their data lacks time frames and specific temperatures with the research methodology stating that of the eight cremations used for data collection, only the first two were observed from start to finish implying that the further six were not. No further discussion on observation was undertaken other than video being recorded intermittently by opening the retort door. In both of the above data sets there is no reference to whether the individuals were embalmed.

Modern techniques of embalming involve the removal of blood and gases from the body followed by the insertion of a preserving agent. Formaldehyde is the most widely used chemical in embalming due to its bactericidal, fungicidal and insecticidal antiseptic properties which prevent decay [48]. It is also generally associated with extreme rigidity, which can be counteracted through modification of the key component of sodium pyrophosphate, enabling limbs to be more pliable with joints moving more freely [49].

Understanding the thermal environment and its role in the alteration of human remains is an area of experimentation hindered by the difficulty in acquiring research subjects, creating obstacles in forensic analysis [47,50]. This is now being addressed with experimental studies involving the burning of donated cadavers in a real fire setting by both Pope [35,51], and DeHaan [2,52]. Pope focused research on the effects of fire on trauma, and the thermal alteration of soft tissue and bone with no correlation to temperature undertaken. Where the focus was on transitional movement into pugilism it is discussed as an experimental overview, rather specific to an individual. DeHaan focused on individuals including both temperature and time observations, with the fires produced in his experimentation a mixture of full size compartment scenes and smaller scenes big enough to hold a mattress with a wall removed for observation. Where assessment and discussion regarding the repositioning of the remains was undertaken it is on observational and qualitative data with no quantitative measurements discussed.

The objective of this paper was the investigation of thermally induced movement of human remains in a range of positions placed within real time fire scenes. Temperature and duration were recorded in addition to measurements of the bodies' position both pre and post fire, enabling quantitative analysis of thermally induced movement. It is anticipated that empirical studies such as these will enable a fuller quantitative comprehension of how bodies react naturally to fire [47] with the volume of recovered remains increased by research into the movement of remains in fires [53].

2. Materials and methods

Experimentation was undertaken under the auspices of San Luis Obispo Fire Investigation Strike Team (SLOFIST) on their annual Forensic Fire Death Investigation Course (FFDIC) in years 2017 to 2019 inclusive. The FFDIC is a unique course for the education of professional practitioners in fatal fire scene investigation. Following a classroom element, students are then assigned to a multi-disciplinary team and tasked with investigating a real fire scene and recovering a fatal fire victim. In total twelve scenes are burnt all containing human cadavers. Ten scenes are recreated from casework experience of the SLOFIST Executive Board which is compiled from Law Enforcement, Bureau of Alcohol Tobacco and Firearms (ATF), Coroners, Forensic Science and Fire Investigators.

Human remains were acquired for the FFDIC by SLOFIST through the Medical Education and Research Institute (MERI) and the Genesis program. Entire bodies are donated for education and research purposes with all remains in the FFDIC utilised within one year following death. Experimental studies at the facility are an addendum to education with medical ethics acquired by San Luis Obispo Sheriff-Coroner Office and experimental ethics approved by the Cranfield University Research Ethics System. Personal biological demographics were recorded for each body including age-at-death, biological sex, date of death, cause of death, any medical procedures undergone, height, weight and BMI. All cadavers remained unembalmed and were frozen following death. When requisitioned for training, remains were loaded into a refrigerated lorry with internal temperature set to 6.7 °C (40 ℉), slowly rising and thawing to 12.8 °C (55℉) during transit. Studies analysing the effect of freezing on human tissues have identified that cells dead prior to freezing will not return to their previous volume once thawed [54,55].

On the day of burning the deceased individuals were dressed in cotton clothing and placed within the relevant scene early morning to allow time to acclimatise to the environmental temperature. Thermocouples were placed within the scenes with initial temperatures recorded at time of ignition. Attempts were made to record thermal penetration into muscle tissue by insertion of thermocouple directly into the biceps. Unfortunately, this compromised the integrity of the epidermis and dermis, which resulted in skin retracting producing a skin split with the thermocouples becoming expelled. Dynamic review of body thermocouple placement resulted in amending insertion into the thoracic cavity by MERI personnel via an intubation tube, with length of thermocouple measured to mitigate ambiguity on depth. Whilst it is recognised that this positioning does not directly reflect thermal penetration into the soft tissue of the limbs, it does provide quantifiable data of internal body temperature.

Both qualitative and quantitative analysis were undertaken in the assessment of body movement from the pre burn to the post burn position. Reviewing both still and video photography enabled identification of position modification initiated by thermal penetration for all scenes comprising of compartments, vehicles and external radiative demonstration scenes. These observations facilitated the documentation of subtle changes to both the hands and feet which were not recorded in the quantitative 3D movement data capture.

Various methods of recording body position were investigated in order to identify a procedure for accurately recording the body in a 3-dimensional format. Markers were placed within the scene at various intervals with location recorded pre burn. Regrettably the markers became compromised through thermal alteration, loss of structural integrity or fire suppression.

Photographic recording of the position of the body was undertaken using a single DSLR Cannon EDS 100D camera, as well as recording images of the overall scene. Varying the heights of camera angles allowed digital depth elevation, facilitating both volumetric and distance calculations to be extrapolated from the created models. Photogrammetry software Photoscan© Professional Edition (Agisoft LLC. St. Petersburg) was used which aligned and overlapped individual images creating a 3D image. When undertaking measurements of the body and its position it was identified that the presence of clothing, and variation in body orientation did not facilitate accurate quantitative data to be recorded.

Hand held measurements were undertaken on each body at 13 points on the X Y and Z axis using the Suaoki D8 40 m Laser Distance Meter, both before and following the burns. The meter was utilised in the metric unit rear reference point mode for all measurements, with the LCD backlight enabling recording to be undertaken in the darkened fire environment. Small spirit levels were attached on each axis to facilitate accurate recording. Where elements of the structure had been compromised, such as walls, a sheet of drywall plasterboard was inserted to facilitate measurements. Where ceiling measurements were not able to be conducted post burn, reverse measurements to the floor were undertaken with manual calculation establishing the measurement to ceiling.

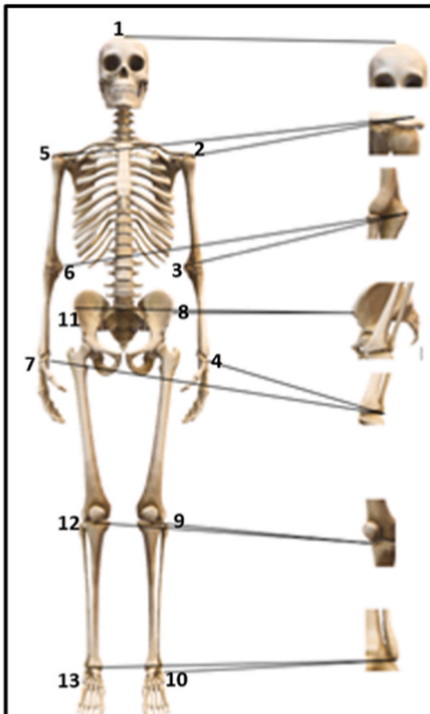
Measurement 1 was taken at the top of the head in order to incorporate individuals in the prone position (face down). Further measurements were taken from prominent and robust elements on the body (Fig. 1) that were identifiable through clothing and soft tissue by physical touch in order to maintain continuity in measurements both pre and post burn.

Where the prone position (face down) measurements did not allow for direct access such as the pelvic region, measurement was made adjacent to the position recorded with a metal rule and manually calculated to the digital measurement. Body XYZ points were plotted using IBM SPSS 28 package in the 3D scatter graph mode both pre and post burn.

Body point data was recorded for cadavers within compartment burns which were isolated constructions built of wood and chipboard with the internal walls and ceiling lined with plasterboard. Each compartment was fitted with a standard residential door and functioning window. Each scene unit contained relevant furniture to reflect the scene scenario such as bedroom, bathroom, living room or bedsit (bedroom with cooking facilities), with furniture acquired through donations and sourced locally through second hand shops.

The duration of each burn was independently assessed at the discretion of SLOFIST staff and were variable from three and a half minutes through to total burnout where the fire was left to self-extinguish.

Suppression was performed though the application of water into the scene in a fine mist format known as gas cooling or fogging. By introducing small separated droplets into a fire scene the increased surface area exposed to the fire results in an expediated absorption of thermal



Number	Skeletal Position
1	Top of skull
2	Left side Scapula acromion
3	Left side Ulna olecranon
4	Left side Ulna styloid process
5	Right side Scapula acromion
6	Right side Ulna olecranon
7	Right side Ulna styloid process
8	Left side Pelvic anterior superior iliac spine
9	Left side Patella apex
10	Left side Fibula malleolus
11	Right side Pelvic anterior superior iliac spine
12	Right side Patella apex
13	Right side Fibula malleolus

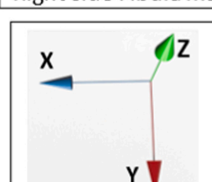


Fig. 1. Body measurement placement.

energy and reduction in temperature [56–58]. This format for firefighting is preferred over the high pressure of straight streaming due to the rapid reduction of temperature, in addition to reducing the potential of disturbing evidence within the scene. This is especially pertinent in this study where straight streaming had potential to influence the post burn position of the body through direct force.

3. Results

Qualitative observational analysis catalogued both major and subtle changes of the body between the pre burn and post burn positions (Figs. 2 and 3 below).

Fire duration for scene 2018/9 was 6.5 min from ignition to suppression with the phenomenon of flashover happening at 4 min exposing the body to a full flame environment for 2.5 min. Thermal penetration did not transition the body into the pugilistic pose but resulted in limb movement of both arms to an outstretched position, and movement of the right leg to the edge of the mattress with flexion at the right knee. Extremities were most effected with fingers retracting the hands into fists, and the foot of the right leg transitioning into a pointed position.

Within vehicles, visual recording of the upper body was undertaken when the cadavers were positioned seated as no photographic evidence of leg position was available. Full body observation was conducted when the body was positioned along the rear seat and external to the vehicle. Recording of body position was undertaken on all burns for years 2017 to 2019 inclusive.

Analysis of the qualitative data set out in Table 1 below identified thermal alteration in the functional anatomy of the body. The absence of post fire observational data for compartment scene 2017/3, and three vehicle scenes is due to structural debris restricting line of sight, in addition to a single recording failure (2019/10) reduced the overall post burn data set to 35 scenes.

Within the vehicle fires the pre burn positioning of remains was substantially maintained post burn with subtle alteration in the hand positioning in 8 scenes. The largest movement observed in the vehicle fires was the transitioning of the individual from lying supine on back seat moving into a prone position within the footwell in scene 2018/2, and the movement from seated to lying supine of the body sat external to the vehicle (2017/5).

Hand flexion into fists was observed in 4 of the vehicle scenes, with the presence of both hand flexion into fist and the pointing of feet observed together in 13 compartment and demonstration scenes (Table 2). Post fire hand disassociation was identified in six individuals with burn duration ranging from 5 min in 2019/DemS through to scene 2018/3 burning for 27.5 min.

The outstretching of arms from the torso was recorded in all types of scenes, with arm flexion into pugilism identified in a single individual

Fig. 2. Scene 2018/9 supine body pre burn.

Fig. 3. Scene 2018/9 supine body post burn.

(2018/7). The pre burn position recorded arm flexion with hands in lap, transitioning post burn to hands disassociated with arms flexed into pugilism. The scene was the only scene left to burn out by natural suppression, with thermocouple recording stopped at 23 min.

The data set for quantitative analysis was limited to the subset of fourteen compartment burns as vehicles did not provide suitable dynamics for body point data acquisition. The study was further limited by the early burning of two scenes prior to data collection, and a scene that was left to progress to total burn out with post burn data point collection unobtainable. Recording of XYZ body point data on all 13 data points of the body before and following the burn enabled analysis of thermally induced body movement on each axis (Table 3).

Analysis of overall mean movement by data point on each individual axis identified the greatest movement was across the body on the X axis. Points one to four evidenced the largest movement due to the transition of individuals off furniture onto the floor, with the individual in scene 2018/6 transitioning from supine on bed to prone on floor resulting in the largest recorded movement of the left arm.

Analysis of Y axis data (length of body) confirms observations of greater thermally induced movement of the upper body of the elbows and wrists, with the Z axis (height) indicating that the right hand exhibited the greatest movement in the burns.

Fig. 4 below demonstrates the precision recording between pre and post burn data points. Analysis identified greatest movement to be that of the lower arms at points 4 (left wrist) and 7 (right wrist) on both the X and Y axis.

The greatest movement on the Z axis (height) is with point 4, with the hand transitioning off the mattress towards the floor and not hands raising to the pugilism stance. Total movement on each axis for each data point was calculated, with Scene 2018/9 represented in Fig. 5 below identifying point 4 on the Y axis exhibited the greatest movement. These heat induced positional changes can be observed in Figs. 2 and 3 above.

With pugilism defined by the repositioning of the arms into the boxing stance in front of the torso, analysis of the movement difference between pre and post body points of both wrists on both the X and Y axis was undertaken (see Table 4 below).

Using the IBM SPSS 28 statistical package, analysis of correlation between upper body element movement and both exposure duration, and maximum exposure temperature identified no statistical significance relationship present.

IBM SPSS 28 enabled 3D analysis on each of the X,Y and Z axis for each body point plotted for both pre and post burn. This enabled quantitative visual representation of body point movement (Figs. 6 and 7 below).

Presenting data in this format enabled observational clarity of the movement of each body point simultaneously on the XY and Z axis.

Table 1
Observations of thermal induced movement.

Scene	Type	Body position Pre burn	Body position post burn	Burn time minutes	XYZ recorded
2017/1	Car	Driver seat slumped to side. Left hand on steering wheel, right hand towards passenger footwell.	Sitting more upright with left arm at side although hand seen rising during burn.	13	No
2017/2	Car	Supine back seat. Left arm straight down body. Right arm footwell. Legs both bent knees towards front seat.	Same position with hand in fists, arms same position. Legs bent at knees but splayed.	11.5	No
2017/3	Sitting Room	Body supine on floor under furniture. Legs straight, arms outstretched.	No line of sight to limb position.	9	No
2017/4	RV	Sat on floor bent forward with head on right knee. Arms at sides.	Body leaning back with arms outstretched. Hands in fists. Lower limbs under debris.	15	No
2017/5	Car	Sat external to driver side wheel. Left arm at side, right arm slightly away from body. Legs straight.	Body laying down with arms outstretched and legs straight and open.	53	No
2017/6	Bedsit	Body prone with torso on bed, legs straight on floor. Left arm on bed slighty bent at elbow. Right arm on floor slightly bent at elbow.	Body now on floor. Right arm flexed, left arm outstretched on bed, hand in fist. Right leg straight, left leg flexed at knee.Both feet pointed.	7.5	Yes
2017/7	Bathroom	Lying on right side with legs flexed at the knee. Arms across torso.	On back with right knee raised upright. Hands and lower legs disassociated. Arms flexed.	9	No
2017/8	Sitting room	In chair bent to the right with head on chair arm. Right lower arm on seat, left arm stretched across body. Legs straight out with feet raised on stool.	Body sitting up with head back and arms bent next to torso with hands in fists. Legs straight with feet pointed.	6.5	Yes
2017/9	Bedroom	Supine on bed. Arms bent at elbow with hands in lap. Left leg straight, right leg slightly bent.	Arms both outstretched with hands in fists. Both legs bent at the knee, feet pointed.	7	Yes
2017/10	Car	Sat in driver's seat with both hands in lap.	Maintained position, hands now in fists.	22.5	No
2017/DemS	Bedroom	Supine on bed with arms straight, palms up. Legs straight.	Arms outstretched with hands loosely in fists. Legs bent at the knees with both feet pointed.	4.5	No
2017/DemP	Bedroom	Prone on bed with arms straight, palms up. Legs straight.	Arms out bent at the elbow with hands in fists. Legs straight and open wide with feet pointed.	4.5	No
2017/DemR	Chair	Sat in chair with arms down the outside. Legs slightly flexed at knee.	Arms raised flexed at elbow still at side of chair, hands remain splayed, feet pointed.	8	No
2018/1	Car	Sat in driver seat. Left hand in lap, right hand on steering wheel.	Remained seated. Left arm still flexed at elbow, and right hand still in lap. Both hands in fists.	12.5	No
2018/2	Car	Supine on back seat. Right arm under body.	Prone in back footwell. Right arm bent on seat, left arm straight in footwell.	19.5	No
2018/3	Bedsit	Supine on floor beneath furniture. Both arms outstretched. Legs straight and angled to the left.	Similar position. Left arm not under furniture, hand disassociated. Legs straight, feet pointed.	27.5	Yes
2018/4	Car	Sat in driver seat. Right hand across stomach. Left hand in groin area.	Similar position. Left hand moved to thigh area. Debris restricted observation of right arm.	22	No
2018/5	Car	Sat in driver seat holding shotgun balanced in footwell. Head forward.	Similar position. Right arm disassociated below elbow. Left arm straight, hand disassociated.	22	No
2018/6	Bedroom	Torso supine on bed. Left arm flexed hand in lap. Right arm and both legs off bed with feet on floor.	Body prone on floor. Arms outstretched, left hand in fist. Legs straight and splayed.	11	No
2018/7	Bathroom	Sat in bath, legs flexed at knee. Left arm flexed, hand in lap. Right arm flexed, arm down body side.	Body supine. Left arm flexed into pugilism. Lower arm and leg bones exposed.	(23) Total Burnout	No
2018/8	Sitting room	Supine on floor. Left arm outstretched, right arm down side of body. Legs straight.	Arms outstretched, left hand in fist, right hand disassociated. Left leg flexed foot pointed. Right leg straight, foot disassociated.	14	Yes
2018/9	Bedroom	Supine on bed. Arms straight by torso, palms up. Legs straight.	Arms outstretched, both hands in fists. Left leg straight, right flexed at knee, both feet pointed.	6.5	Yes
2018/10	Car	Driver side. Left hand in lap. Right arm flexed at elbow on arm rest.	No line of sight due to interior structure collapse.	41.5	No
2018/DemS	Bedroom	Supine on bed. Arms straight by torso, palms down. Legs straight.	Arms outstretched, hand in fists. Left leg straight, right leg flexed at knee. Both feet disassociated.	5.5	No
2018/DemP	Bedroom	Prone on bed. Arms straight by torso, palms up. Legs straight.	Body fallen through furniture. Right leg straight, left flexed. Both feet pointed. Elbows flexed, hands in fists.	5.5	No
2018/DemR	Chair	Seated with arms resting on chair arms.	Arms flexed and outside of chair, hands in fists. Feet disassociated.	13	No
Scene	**Type**	**Body position pre burn**	**Body position post burn**	**Burn time minutes**	**XYZ recorded**
2019/1	Car	Sat in passenger seat hands in lap.	Similar position.	10.5	No
2019/2	Car	Supine on back seat.	Structural garage collapse. No sight of body.	12	No
2019/3	Bedsit	Prone on floor. Right arm flexed above head. Left arm flexed next to torso. Legs straight.	Right arm straight above head. Left arm flexed with hand now by head. Legs straight.	5	Yes
2019/4	Car	Driver seat with both hands on the steering wheel.	Arms flexed, hands in lap.	14	No
2019/5	Car	Driver seat. Left hand in lap, right hand on passenger seat.	Arms straight down by torso with hands disassociated.	14	No
2019/6	Bedroom	Prone on floor. Arms flexed with hands above head, palms down. Left leg slightly flexed. Right leg flexed at knee with foot resting on stool.	Arms flexed with elbows moved down in line with shoulders and hands wider apart. Left leg straight and splayed. Right leg still flexed.	6.5	Yes
2019/7	Bathroom	Sat in bath with arms flexed, hands in lap. Straight legs with feet on end of bath.	Body moved down into bath. Hands still in lap, fingers splayed. Legs straight but splayed. Toes on right foot starting to point.	3.5	Yes
2019/8	Sitting room	Sat on sofa. Right arm on sofa arm. Left arm flexed with hand in lap.	Right arm still on sofa arm. Left arm splayed out. Both hands in fists. Legs further apart.	3.5	Yes

(*continued on next page*)

Table 1 (*continued*)

2019/9	Bedroom	Supine with legs together, slightly flexed to left hand side. Right arm slightly flexed next to torso. Left arm flexed with hand in lap.	Arms straight and splayed. Hands in fists. Legs splayed with left leg slightly flexed and right leg straight. Both feet pointed.	6	Yes
2019/10	Car	Burn recording failure.	Burn recording failure.	7	No
2019/DemS	Bedroom	Supine with arms straight, palms down. Legs straight.	Arms outstretched with hands disassociated. Legs both flexed at the knee with feet pointed.	5	No
2019/DemP	Bedroom	Prone with arms straight, palms up. Legs straight.	Arms flexed at elbow and hands in fists. Legs straight and splayed with feet pointed.	5	No
2019/DemR	Chair	Sitting with both arms and hands on chair arms.	Slumped forward with left arm moved to legs and right arm on outside of chair. Hands in loose fist and feet pointed.	16	No

Table 2
Observed thermal alteration to body.

Scene type	Hands in fists (*n* = 35)	Feet pointed (*n* = 24)	Hands disassociated (*n* = 35)	Feet disassociated (*n* = 24)	Arms outstretched (*n* = 35)	Legs Splayed (*n* = 24)
Compartment	8	8	4	2	6	5
Vehicle	4	0	1	0	1	1
Demonstration	6	5	1	3	3	2

Table 3
Mean body point movement on XYZ axis.

Data point	Body element	Mean movement X Axis (Metres)	Mean movement Y Axis (Metres)	Mean movement Z Axis (Metres)
1	Top of head	.266 Std ± .325	.222 Std ± .297	.096 Std ± .142
2	Left shoulder	.263 Std ± .342	.150 Std ± .210	.087 Std ± .133
3	Left elbow	.362 Std ± .402	.236 Std ± .273	.061 Std ± .114
4	Left wrist	.364 Std ± .431	.250 Std ± .216	.191 Std ± .253
5	Right shoulder	.241 Std ± .184	.146 Std ± .232	.105 Std ± .128
6	Right elbow	.198 Std ± .149	.139 Std ± .164	.073 Std ± .074
7	Right wrist	.248 Std ± .227	.259 Std ± .210	.078 Std ± .094
8	Left hip	.167 Std ± .219	.112 Std ± .117	.103 Std ± .156
9	Left knee	.168 Std ± .200	.101 Std ± .097	.108 Std ± .146
10	Left ankle	.231 Std ± .202	.100 Std ± .116	.035 Std ± .030
11	Right hip	.072 Std ± .081	.082 Std ± .081	.120 Std ± .142
12	Right knee	.160 Std ± .164	.116 Std ± .121	.122 Std ± .132
13	Right ankle	.247 Std ± .172	.163 Std ± .189	.082 Std ± .063

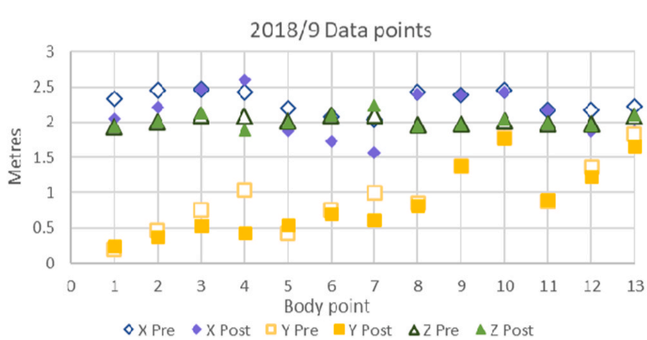


Fig. 4. Total data points for 2018/9.

4. Discussion

Understanding the transition of the human body into thermally induced pugilism is an important aspect, and key to fatal fire investigation. Not all fatal fire victims present as pugilistic post fire, with the absence of pugilistic posture proposed as indicative of potential homicide or restriction of the victim's limbs without discussion on scene dynamics, potential shielding of body elements during thermal exposure within the scene or the position of the victim [6,59,60].

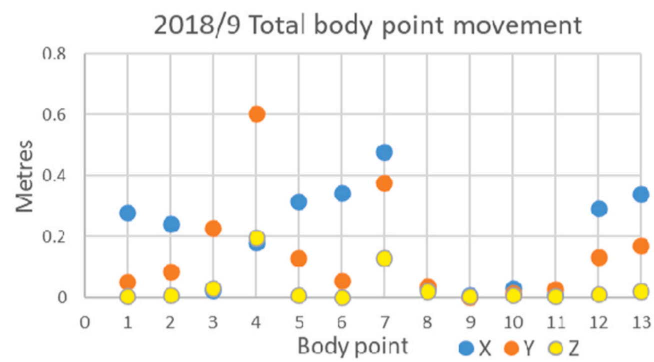


Fig. 5. Total body movement by body point for 2018/9.

Analysis of fatal fire autopsy reports has identified that inhalation of toxic gases produced within the fire environment is the leading cause of death, responsible for 60–80 % of the fatal fires [10,16]. The highly toxic gases present within the fire environment cause incapacitation through cardiovascular, neurological and respiratory functions of the body by affecting the respiratory centre in the brain [61–63]. In a compartment fire the burning of a polyurethane plastic mattress cushion producing HCN of 200 ppm is enough to incapacitate an individual in 2 min, with increased HCN of 250–400 ppm enough to cause death at 5 min [64]. In a well ventilated compartment fire it is considered that toxic gas inhalation can cause incapacitation in as little as 4 min post ignition [65], with continued inhalation increasing concentrations leading to death [10,66–68].

In the early stages of fire development voluntary movement of conscious individuals allows cognitive processing and decision making in response to the thermal environment by initiating evacuation or firefighting [69] [70]. Following an individual becoming incapacitated and unconscious this voluntary movement discontinues, with the body continuing to be exposed to the increasing thermal environment. The authors consider this work applicable to the analysis of fatal fire victims due to their incapacitation with cause of death only defined beyond body recovery with autopsy analysis [14,16,71,72]. Furthermore, this data correlates with the percentage of fatal fire victims that are deceased prior to ignition, with fire undertaken to disguise the cause of death of an individual [73,74].

Table 4
Wrist position movement in compartment scenes.

Scene	Burn Time mins	Max Temp °C	Point 4 X Axis cm Movement	Point 4 Y Axis cm movement	Point 7 X Axis cm movement	Point 7 Y Axis cm movement
2017/6	7.5	1091	.307	.268	.074	.236
2017/7	9	1197	.049	.337	.206	.455
2017/8	6.5	1177	.381	.095	.029	.047
2017/9	7	760	.375	.078	.397	.074
2018/3	27.5	875	.041	.024	.01	.199
2018/6	18	1003	1.442	.561	.358	.514
2018/7	23	1122	.009	N/A	N/A	N/A
2018/8	14	1127	.184	.192	.104	.277
2018/9	6.5	914	.18	.606	.479	.376
2019/3	5.5	649	.708	.222	.351	.379
2019/6	6.5	941	.61	.04	.218	.068
2019/7	3.5	1271	.49	.04	.874	.068
2019/8	305	916	.239	.027	.127	.03
2019/9	6	939	.278	.069	.346	.042

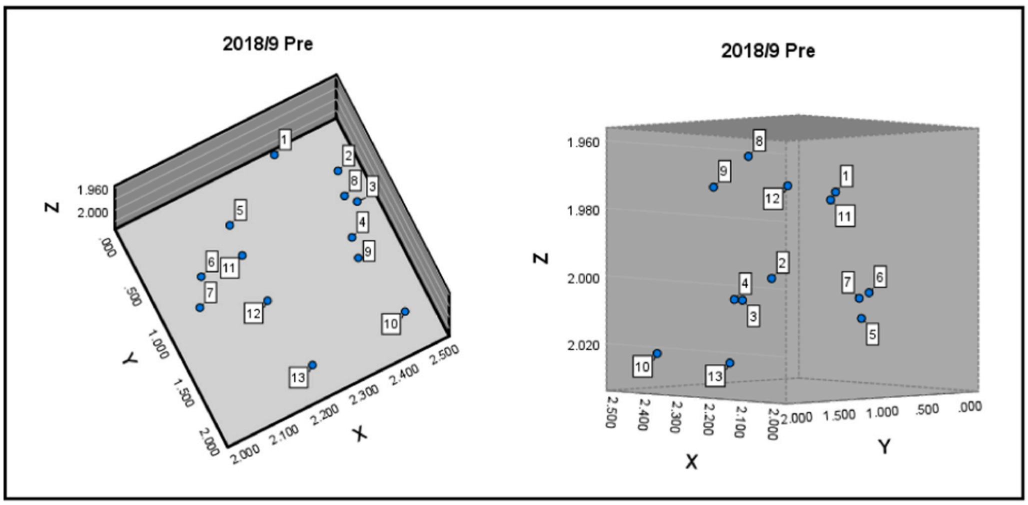


Fig. 6. Pre burn XYZ body points for 2018/9.

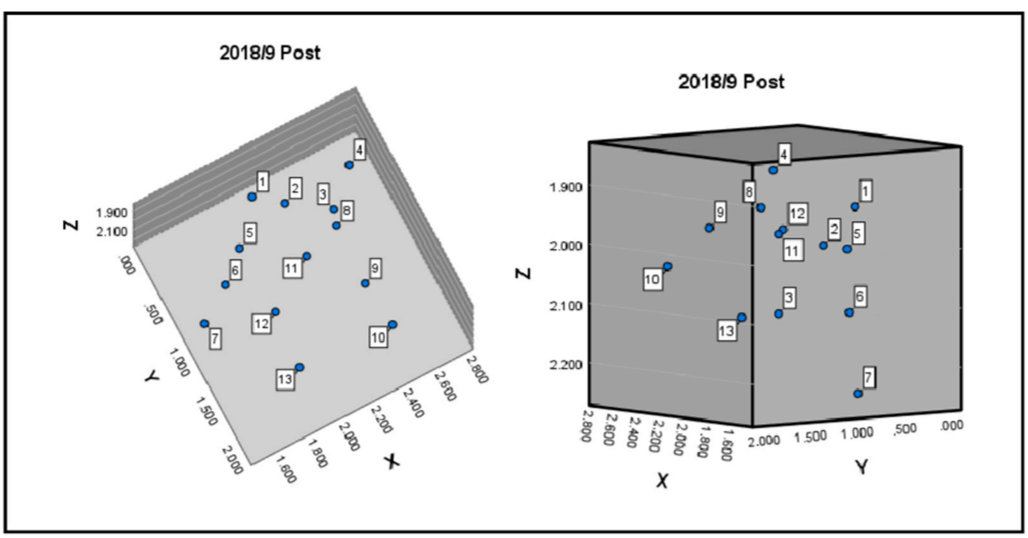


Fig. 7. Post burn XYZ body points for 2018/9.

It is widely accepted that thermal penetration induces the contraction of the limbs with the larger more dominant muscles manoeuvring the limbs into pugilism [2,25,35,36,42,75–77]. Thermal alteration to the human body starts as low as 44 °C with cellular destruction at the trans-epidermal juncture of skin [78–82]. As heat continues to assault the soft tissue of the body it results in the dehydration and denaturation of muscles and tendons [25,35].

Muscles are fibrous, elastic, functional and proteinaceous, constructed from two forms of fibres. Type I fibres (known as slow twitch) are long, strong and resistant to fatigue; type II fibres (fast twitch) are short, easily fatigued and used in anaerobic exercise. It is type II that are found in large quantities within arm muscles and in lower quantities within the leg muscles, with muscle mass affected on an individual basis by nutrition, disease, physical activity, as well as age.

It is reported that sarcopenia (the degenerative loss of skeletal muscle mass and strength) is one the most significant changes in the aging process commencing towards the end of the fifth decade of life [83–85] with reduction in leg muscle mass and muscle quality in older adults [86]. This reduction in mass and functionality is not inevitable and can be minimized or even reversed with training [85]. Age-related pervasion of fat and connective tissue has been identified in both the arm flexors and extensors, and also foot plantar flexors of elderly individuals [87–89], with the volume of fibres not differing significantly between men and women [90].

None of the key texts on burned human remains by Pope (2008), Symes et al. (2012), or DeHaan (2018) discuss the potential degenerative nature of ageing muscular functionality of the human remains used in their studies. The age range of the individuals used in this experimentation was 52 years to 101 years for the entire dataset, with a mean of 67 years, Std $\pm$ 4.03. The smaller subset of individuals in the body point analysis were aged 61 years to 71 years with a mean of 65 years, Std $\pm$ 3.25. Studies have identified that individuals at greatest risk of dying in fires are aged $>$ 60 years [91–93], with the risk doubling over 65 years and quadrupling as age increases over 75 years [94]. These findings reinforce the applicability of this study by enhancing knowledge of thermally induced modification of the body of the fatal fire victim.

Observing thermal alteration to the human body in a real fire setting has enabled conclusions of previous work to be challenged and a new narrative created such as the proposition that hands extend beyond the metacarpals and proximal phalanges are compromised [40].

Results from the qualitative element of this study identified that hands are the most thermally affected area of the body. The dorsal aspect (back) of the hand has less overlying tissue and is naturally thinner, with tendons attached to the phalanges. As heat penetrates through the skin, the tendons dehydrate, shorten and retract creating a splayed appearance to the hand as seen in Fig. 8 below. This is often accompanied by flexion in the wrist but is dependent on body position.

Splaying of fingers in such a manner exposes the palm of the hand to the thermal environment resulting in the dehydration and contraction of the bulkier and stronger flexor muscles, retracting the splayed hand into a fist. This observation challenges Symes and colleagues who proposed that without burning to the forearm there is little hand posturing, and referring to a case study whereby the hyperextended distal phalanges (end of fingers) were indicative of suspected homicide due to the lack of pugilism [40].

Fig. 8. Heat penetrating dorsal side of hand, creating splay of the fingers. (Transition captioned through Adobe photoshop (2019) layering of still photographs).

Following contraction of hands into fists, continued thermal penetration places tension on the thinner soft tissue of the writs . Eventually this tension results in the splitting of the skin, severing of tendons, and as the soft tissue of the forearms and legs are consumed by the fire, dissasociating the hands and exposing the distal ends of long bones.

In the same manner as the hands, heat penetrates into the dorsum aspect (top) of the foot with dehydrated shortened tendons flexing the foot resulting in the toes pointing upwards. This results in exposure of the more robust muscles of the plantar aspect (sole) of the foot resulting in retraction, which in addition to the contraction of the Achilles tendon at the posterior of the lower leg, transitions the foot into a pointed foot appearance [35].

Thermal penetration into the deeper soft tissue and muscles of the body can result in the movement of the body away from its position prior to the fire. Where individuals are bent over at the waist prior to ignition, contraction of muscles in the back can move the torso into an upright sitting position. It was observed that where an individual is positioned at the edge of an element of furniture, or half on/half off at the time of ignition, they may be discovered in a position entirely different post fire (Fig. 9).

Movement of the whole body is predominately a compartment based phenomenon due to the dynamics of the scene, however this experimentation identified that if an individual is lying on the rear seat of a vehicle, it can transition position into the rear footwells. Additionally, bodies located externally to burning vehicles or property have the ability to move position should they be exposed to high enough convection and radiation.

An example is 2017/5 based on a scenario where the individual set fire to a vehicle he had been driving that was involved in a hit and run. Ignition was at the rear of the vehicle, after which the individual sits externally against the front wheel arch committing suicide with a firearm. Following the gunshot, the gun was still positioned in the right hand (Fig. 10).

With the fire ignited at the rear of the vehicle progression of the fire to the front was slow due to the prevailing wind. The internal body temperature rised at 20 mins as the fire developed internally to the front interior of the vehicle. Internal temperature of the body remained significantly lower due to wind exposure, whilst the temperature within the vehicle was maintained at 800–900 °C.

At minute 36 the radiant and convected heat penetrated the body enough to raise the arm and transition the left hand into a fist. Video screen capture at minute intervals commencing at 36 min in orange with the final capture colour coded black at 44 min, enabled observation of the transition from sitting to lying as muscles in the back contracedt, and the left leg moved towards the source of the heat (Fig. 11).

Following suppression of the fire, the position of the individual had altered and the gun was no longer positioned within the hand (Fig. 12). Thermal alteration of the fatal fire victim within the scene also has the potential to displace evidence, and therefore the recording of both the body and its position in relation to evidence is imperative. The complexity of investigating such a case has been published by Simonit et al. (2020) who highlighted the difficulty in assigning death to suicide, ruling out homicide, and the difficulty regarding evidence location within a fatal fire scene [95].

Observing the transition above has demonstrated the gradual movement of the arms into an outstretched position. This series of experiments recorded eleven scenes where arms were outstretched away from the torso following the fire. Two of the scenes were vehicles, with one individual external (2017/5) and the second 2017/4 which was in a large recreational vehicle and therefore the interior dynamics were similar to a compartment. The remaining nine were present within compartments, with a further three observed with flexion at the elbow.

These results challenge the modification pattern of transition into pugilism proposed by Symes et al. (2012) and its use as a standard for assessing the fatal fire victim. Compartment burns evidenced thermally

Fig. 9. Scene 2018/6 Pre and post burn body positions.

Fig. 10. Scene 2017/5 Body sat against wheel arch with gun in right hand indicated by circle.

induced movement from the pre burn position with the transition of hands into fists and outstretching of arms, splaying of the legs and pointing of the feet. This thermally induced movement was observed in bodies lying both in supine and prone positions and it is proposed that the transitioning of the limbs in this manner is the more uniform reaction of the body to the thermal environment.

A single individual evidenced transition into pugilism (Scene 2018/7), which was the only scene left to naturally suppress with temperature recording stopped at 23 min.

Within the vehicle fires, the arms of the individuals did not transition in the same manner but stayed close to their pre fire position. The individuals were primarily seated in the driver and passenger front seats. Fire dynamics within the vehicle alter the balance of energy transfer between convection and radiation, with the interiors enveloping the body in flame more rapidly than compartments where in the early stages heat is transfered through convection, transitioning to radiation as the fire develops. The raised and isolated positioning of the seats allowed for greater circulation of thermal energy transfer and flame; with the seating fabric consumed as a fuel load, the interior is engulfed in flame with the rear of the body exposed to the same non protected environment as the front.

5. Conclusion

Victims of fatal fires are frequently described as being positioned in a pugilistic pose [96] or the pugilistic attitude [43,97]. Pugilism is the effect of heat penetrating into muscle causing contraction with the resultant positioning imitating the stance of a boxer [75].

This work has presented both qualitative and quantitative results from experimentation investigating the effect of real fire environments on the human body. Qualitative observations of 39 compartment and vehicle scenes containing bodies produced results which question the validity of previous work based on observations of cremations. It is proposed here that pugilism is not the universal reaction of the body of the fatal victim to thermal exposure, with the straight extension of the upper limbs away from the torso far more common than has been previously reported.

Quantitative data recording body points in 3D enabled a more robust assessment of movement within the scene. This element of the research underwent dynamic adaptation in its methodology regarding the collection of data. The results offer insight into thermally induced movement in relation to fire venue, body position, body point elements and time.

This study recognises the limitation of the small data set, and presents these results not as definitive conclusion to be utilised in the forensic investigation of fatal fires, but as evidence that robust and quantitative analysis of body movement in fires is achievable and crucial. The authors welcome further experimentation using the techniques discussed above and the opportunity to expand data collection, all of which assists in enhancing understanding of the fatal fire victim.

Research ethics

We further confirm that any aspect of the work covered in this manuscript that has involved human patients has been conducted with the ethical approval of all relevant bodies and that such approvals are

Fig. 11. Scene 2017/5 Video screen capture of movement (Transition captioned through Adobe photoshop (2019) layering of still photographs).

Fig. 12. Scene 2017/5. Post fire body lain on ground, gun no longer in hand indicated by circle.

acknowledged within the manuscript.

Intellectual property

We confirm that we have given due consideration to the protection of intellectual property associated with this work and that there are no impediments to publication, including the timing of publication, with respect to intellectual property. In so doing we confirm that we have followed the regulations of our institutions concerning intellectual property.

Authorship

The International Committee of Medical Journal Editors (ICMJE) recommends that authorship be based on the following four criteria:

1. Substantial contributions to the conception or design of the work; or the acquisition, analysis, or interpretation of data for the work; AND
2. Drafting the work or revising it critically for important intellectual content; AND
3. Final approval of the version to be published; AND
4. Agreement to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

Funding

No funding was received for this work.

CRediT authorship contribution statement

Mary-Jane Harding: Conceptualization, Methodology/Study design, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review and editing, Visualization. **Nicholas Márquez-Grant:** Validation, Writing – review and editing, Visualization, Supervision. **Mike Williams**: Validation, Formal analysis, Writing – review and editing, Visualization, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The primary author wishes express their gratitude to the staff at SLOFIST who encouraged and facilitated the undertaking of this research.

References

[1] C. Garrido-Varras, M. Intiago-Leira, The interpretation and reconstruction of the post-mortem events in a case of scattered remains in Chile, in: T. Thompson (Ed.), The Archaeology of Cremation: Burned Human Remains in Funerary Studies, Oxbow, 2015.

[2] J.D. Dehaan, Post-mortem repositioning of human bodies in fires, Int. J. Crim. Forensic Sci. 2 (2018) 62–78.

[3] S.L. Fairgrieve. Forensic Cremation Recovery and Analysis, CRC Press, Boca Raton, 2007, p. 2007. FL.

[4] D.C. Dirkmaat, G. Olson, A. Klales, S. Getz, The Role of Forensic Anthropology in Recovery and Interpretation of the Fatal Fire Victim, in: D.C. Dirkmaat (Ed.), A Companion to Forensic Anthropology, Blackwell Publishing, 2012.

[5] J. Nichols, R. Irwin, M. Merlin, A fatal fire investigation: the medical, Perspect. Fire Eng. 60 (3) (2007) 123–128.

[6] P. Brahmaji Master, V. Chandra Sekhar, Y.K.C. Rangaiah, D. Perimortem, Differentiating perimortem and postmortem burning, J. Evid. Based Med. Healthc. 2 (3) (2015). Accessed: Mar. 10, 2023. [Online]. Available: www.academia.edu.

[7] J. Giebułtowicz, M. Rużycka, P. Wroczyński, D. Purser, A. Stec, Analysis of fire deaths in Poland and influence of smoke toxicity, Forensic Sci. Int. 277 (2017) 77–87, https://doi.org/10.1016/j.forsciint.2017.05.018.

[8] Gann, Fire conditions for toxic smoke, Fire Mater. 18 (1994) 193–199.

[9] NFPA, 921 Guide for Fire and Explosion Investigation, Fourth Edition. National Fire Protection Association, 2016.

[10] T. Grabowska, R. Skowronek, J. Nowicka, H. Sybirska, Prevalence of hydrogen cyanide and carboxyhaemoglobin in victims of smoke inhalation during enclosed-space fires: a combined toxicological risk, Clin. Toxicol. 50 (8) (2012) 759–763, https://doi.org/10.3109/15563650.2012.714470.

[11] V. Živković, S. Nikolić, Regarding the editorial 'The autopsy evaluation of "straightforward" fire deaths, Forensic Sci. Med. Pathol. 14 (3) (2018) 419–420, https://doi.org/10.1007/s12024-018-9966-x.

[12] A.R. Tümer, et al., Post mortem burning of the corpses following homicide, J. Forensic Leg. Med 19 (2012) 223–228.

[13] S. Tellewar, G. Kumar, A. Yadar, Doctor's perspective in a post-mortem burn: a case report, Indian Acad. Forensic Med. 35 (4) (2013).

[14] B. Knight, P. Saukko. KNIGHT'S Forensic Pathology, Third Edition, CRC Press, Boca Raton, FL,2004, 2004.

[15] H. Bernitz, P.J. Van Staden, C.M. Cronjé, R. Sutherland, Tongue protrusion as an indicator of vital burning, Int. J. Leg. Med. 128 (2) (2014) 309–312, https://doi.org/10.1007/s00414-013-0861-4.

[16] J.L. McAllister, D.J. Carpenter, R.J. Roby, D. Purser, The importance of autopsy and injury data in the investigation of fires, Fire Technol. 50 (6) (2014) 1357–1377, https://doi.org/10.1007/s10694-013-0341-x.

[17] K.N. Olson, M.A. Hillyer, J.S. Kloss, R.J. Geiselhart, F.S. Apple, Accident or arson: Is CO-oximetry reliable for carboxyhemoglobin measurement post mortem? Clin. Chem. 56 (4) (2010) 515–519, https://doi.org/10.1373/clinchem.2009.131334.

[18] K. Stamyr, G. Thelander, L. Ernstgard, J. Ahlner, G. Johanson, Swedish forensic data 1992-2009 suggest hydrogen cyanide as an important cause of death in fire victims, Inhal. Toxicol. 24 (3) (2012) 194–199.

[19] D. Tabian, D. Bulgaru Iliescu, T. Iov, B. Barna, S.I. Toma, G. Drochioiu, Hydrogen cyanide and carboxyhemoglobin assessment in an open space fire-related fatality, J. Forensic Sci. 66 (3) (2021) 1171–1175, https://doi.org/10.1111/1556-4029.14649.

[20] J. Giebułtowicz, M. Rużycka, P. Wroczyński, D.A. Purser, A.A. Stec, Analysis of fire deaths in Poland and influence of smoke toxicity, Forensic Sci. Int 277 (2017) 77–87, https://doi.org/10.1016/j.forsciint.2017.05.018.

[21] J. Nichols, R. Irwin, M. Merlin, A fatal fire investigation: the medical, Perspect. Fire Eng. 160 (3) (2007) 123–134.

[22] D. Tabian, D. Bulgaru Iliescu, T. Iov, B. Barna, S.I. Toma, G. Drochioiu, Hydrogen cyanide and carboxyhemoglobin assessment in an open space fire-related fatality, J. Forensic Sci. 66 (3) (2021) 1171–1175, https://doi.org/10.1111/1556-4029.14649.

[23] D. Drysdale, An Introduction to Fire Dynamics, Second Edition, John Wiley & Sons, Chichester, 2011.

[24] P.S. Veloo, J.G. Quintiere, "Convective Heath Transfer coefficient in compartment fires, J. Fire Sci. 0 (2013) 1–14.

[25] J. DeHaan, Fire and bodies, in: C. Schmidt, S. Symes (Eds.), The Analysis of Burned Human Remains, Elsevier, London, 2008, pp. 1–14.

[26] J. DeHaan, D. Icove, Kirks Fire Investigation, Seventh Edition. Pearson, 2012. Accessed: Jun. 16, 2022. [Online]. Available: ISBN: 0–13-283001–9.

[27] National Institute of Standards and Technology, (2022).

[28] Spearpoint Michael, K. McGrattan, F. Mowrer, Simulation of a Compartment Flashover Fire using Hand Calculations, Zone Models and a Field Model in 3rd International Conference on Fire Research and Engineering, 1999, pp. 3–14.

[29] R.D. Peacock, P.A. Reneke, R.W. Bukowski, V. Babrauskas, Defining flashover for fire hazard calculations, Fire Saf. J. 32 (1999) 331–345.

[30] V. Babrauskas, Estimating room flashover potential, Fire Technol. (1981) 94–112.

[31] S.W. Carman, Improving the understanding of post-flashover fire behaviour CarmenFireInvestigations.com, 2008.

[32] J. Lentini. Scientific Protocols for Fire Investigation, Second Edition, CRC Press, Boca Raton, 2012.

[33] N. Keough, E.N. L'Abbé, M. Steyn, S. Pretorius, Assessment of skeletal changes after post-mortem exposure to fire as an indicator of decomposition stage, For. Sci. Int. 246 (2015) 17–24.

[34] L. Geddes, The body burners, N. Sci. (1956) (2009) 32–35 ([Online]. Available: https://www.bl.uk/help/on-demand-terms-and-conditions).

[35] E. Pope, The Effects of Fire on Human Remains: Characteristics of Taphonomy and Trauma University of Arkansas, 2007.

[36] J.B. Coty, et al., Burned bodies: post-mortem computed tomography, an essential tool for modern forensic medicine, Insights Imaging 9 (5) (2018) 731–743, https://doi.org/10.1007/s13244-018-0633-2.

[37] W. Bass, in: T.A. Rathbun, J.E. Buikstra (Eds.), Is it possible to consume a body completely in a fire? in Human Identification: Case Studies in Forensic Anthropology, Springfield IL: Charles C Thomas, 1984, pp. 159–167.

[38] Stuart James, W. Eckert, S. Katchis, Investigation of cremations and severely burned bodies, Am. J. Forensic Med Pathol. 9 (2008) 188–200.

[39] N. Keough, E.N. L'abbé, M. Steyn, S. Pretorius, Assessment of skeletal changes after post-mortem exposure to fire as an indicator of decomposition stage, Forensic Sci. Int 246 (2015) 17–24.

[40] S. Symes, C. Rainwater, E. Chapman, D. Gipson, A. Piper, Patterned thermal destruction of human remains in a forensic setting, Anal. Burn. Hum. Remains, First (2008).

[41] A.S. Bontranger, The taphanomic analysis if human cremains from the fox hollow fark serial homicide site, in: C. Scmidt, S. Symes (Eds.), The Analysis of Burned Remains, First.London: Elsevier, 2008.
[42] S.A. Symes, D.C. Dirkmaat, S. Ousley, E. Chapman, and L. Cabo, Recovery and Interpretation of Burned Human Remains. Bibliogov.project, 2012.
[43] M. Bohnert, T. Rost, S. Pollak, The degree of destruction of human bodies in relation to the duration of the fire, Forensic Sci. Int 95 (1998) 11–21.
[44] D. Gonçalves, E. Cunha, T. Tju, The estimation of the pre-burning condition of human remains in forensic contexts, International Journal of Legal Medicine 129 (5) 1137–1143.
[45] P. Mayne Correia, O. Beattie, A critical look at methods for recovering, evaluating, and interpreting cremated human remains, in: W.D. Haglund, M.H. Sorg (Eds.), Advances in forensic taphonomy: method, theory, and archaeological perspectives, CRC Press, 2001.
[46] T.J.U. Thompson, Recent advances in the study of burned bone and their implications for forensic anthropology, Forensic Sci. Int 146 (SUPPL.) (2004), https://doi.org/10.1016/j.forsciint.2004.09.063.
[47] C. Fojas, N. Cabo, N. Passalacqua, C. Rainwater, S. Symes, The utility of spatial analysis in the recognition of normal and abnormal patterns in burned human remains, in: N.V. Passalacqua, C.W. Rainwater (Eds.), Skeletal Trauma Analysis. Case Studies in Context, First.Wiley Blackwell, 2015.
[48] E.L. Wilcox, Embalming: Diseases and Conditions. Funeral Service Academy, 2012. [Online]. Available: www.funeralcourse.com.
[49] E. Brenner, Human body preservation - old and new techniques, J. Anat. 224 (3) (2014) 316–344, https://doi.org/10.1111/joa.12160.
[50] V. Alunni, G. Grevin, L. Buchet, G. Quatrehomme, Forensic aspect of cremations on wooden pyre, Forensic Sci. Int 241 (167–162) (2014).
[51] E. Pope, O. Smith, Identification of traumatic injury in burned cranial bone: an experimental approach, J. Forensic Sci. 49 (3) (2004) 1–10, https://doi.org/10.1520/jfs2003286.
[52] J.D. Dehaan, Sustained combustion of bodies: some observations, J. Forensic Sci. 57 (6) (2012) 1578–1584, https://doi.org/10.1111/j.1556-4029.2012.02190.x.
[53] K. Waterhouse The use of archaeological and anthropological methods in fatal fire scene investigation Canadian Police Research Centre Ontario 1 25.
[54] A. Miras, H. Yapo-Ette, C. Vianey-Saban, D. Malicier, L. Fanton, Method for determining if a corpse has been frozen: measuring the activity of short-chain 3-hydroxyacyl-CoA dehydrogenase (SCHAD), Forensic Sci. Int 124 (2001) 22–24.
[55] T. Schafer, J. Kaufmann, What happens in freezing bodies? Experimental study of histological tissue change caused by freezing injuries, Forensic Sci. Int 102 (1999) 149–158.
[56] A. Jones, P.F. Nolan, Discussions on the use of fine water sprays or mists for fire suppression, J. Loss Prev. Process Ind. 8 (1) (1995) 17–22.
[57] J.R. Mawhinney, B.Z. Dlugogorski, A.K. Kim, A closer look at the fire extinguishing properties of water mist, Fire Saf. Sci. - Proc, Fourth Int. Symp. (1994) 47–60.
[58] S. Svensson, M. van de Veire, Experimental study of gas cooling during firefighting operations, Fire Technol. 55 (1) (2019) 285–305, https://doi.org/10.1007/s10694-018-0790-3.
[59] P.T. Chrysostomou, Burned human remains in a double homicide: a forensic case in Cyprus in, in: N.V. Passalacqua, C.W. Rainwater (Eds.), Skeletal Trauma Analysis: Case Studies in Context, Wiley Blackwell, 2015, p. 189.
[60] Morphological findings in burned bodies. *Forensic pathology reviews*, pp. 3–27.
[61] R.H. El-Helbawy, F.M. Ghareed, Inhalation injury as prognastic factor in mortality, Ann. of Burns and Fire Disasters XXIV (2011) 82–88.
[62] D. Tabian, D.B. Iliescu, M.M. Diac, M. Badea, S.I. Toma, G. Drochioiu, Evaluation of hydrogen cyanide in the blood of fire victims based on the kinetics of the reaction with ninhydrin, Appl. Sci. (Switz.) 12 (5) (2022), https://doi.org/10.3390/app12052329.
[63] M. Gorguner, M. Akgun, Acute inhalation injury, Eurasia J. Med 42 (1) (2010) 28–35, https://doi.org/10.5152/eajm.2010.09.
[64] D.J. Icove, G.A. Haynes, Kirks Fire Investigation. Eighth Edition, Pearson, New York, 2017.
[65] D. Icove, J. DeHaan, and G. Haynes, Forensic Fire Scene Reconstruction, Third Edition. NJ: Pearson, 2012. [Online]. Available: ISBN: 0–13-295620–9.
[66] L.A. Ferrari, M.G. Arado, L. Giannuzzi, G. Mastrantonio, M.A. Guatelli, Hydrogen cyanide and carbon monoxide in blood of convicted dead in a polyurethane combustion: a proposition for the data analysis, Forensic Sci. Int. 121 (2001) 140–1453.
[67] A. Jonsson, M. Runefors, J. Gustavsson, F. Nilson, Residential fire fatality typologies in Sweden: Results after 20 years of high-quality data, J. Saf. Res. 82 (2022) 68–84, https://doi.org/10.1016/j.jsr.2022.04.007.
[68] M. Taylor, H. Francis, J. Fielding, An Analysis of Domestic Fire Smoke/Toxic Fumes Inhalation Injuries, Fire Technol 59 (5) (2023) 2662–2681, https://doi.org/10.1007/s10694-023-01446-z.
[69] E.D. Kuligowski, E.D. Kuligowski, The process of human behavior in fires, US Department of Commerce, National Institute of Standards and Technology, Gaithersburg (2009).
[70] D. Tong, D. Canter, The Decision to Evacuate: a Study of the Motivations which Contribute to Evacuation in the Event of Fire*, Fire safety journal 9 (3) (1985) 257–265.
[71] R.W. Byard, The Autopsy Evaluation of 'Straightforward' Fire Deaths. Forensic Science, Medicine, and Pathology, 2018, pp. 273–275, https://doi.org/10.1007/s12024-017-9907-0.
[72] C.J. Sully, G.S. Walker, N.E.I. Langlois, Review of autopsy reports of deaths relating to fire in South Australia 2000–2015, Forensic Sci. Med. Pathol. 14 (2) (2018) 180–187, https://doi.org/10.1007/s12024-018-9981-y.
[73] A. Tomison, C. Ferguson, R. Doley, B. Watt, M. Lyneham, J. Payne, Arson-associated homicide in Australia: a five year follow-up, Trends Issues Crime Crim. Justice 484 (2015) 1–11.
[74] Megan Davies, Jenny Mouzos. Fatal Fires: Fire-associated Homicide in Australia, 1990-2005, Australian Institute of Criminology, 2007, pp. 1–6.
[75] S. Peranantham, G. Manigandan, K. Shanmugam, Forensic approach to a case of death due to burn injury: a case report, Int J. Res. Med. Sci. 2 (3) (2014) 1214, https://doi.org/10.5455/2320-6012.ijrms20140866.
[76] J. Prahlow, Forensic Pathology for Police, Death Investigators, Attorneys, and Forensic Scientists. NEW YORK: Springer, 2010.
[77] C. Schmidt, S. Symes, and (Eds), The Analysis of Burned Human Remains, First Edition. London: Elsevier Ltd, 2008.
[78] G. Ripple, K. Torrington, Y. Phillips, Predictive criteria for burns from brief thermal exposure, J. Occup. Med. 32 (3) (1990) 215–219.
[79] P.K. Raj, A review of the criteria for people exposure to radiant heat flux from fires, J. Hazard Mater. 159 (1) (2008) 61–71, https://doi.org/10.1016/j.jhazmat.2007.09.120.
[80] A. Stoll, L. Green, Relationship between pain and tissue damage due to thermal radiation, J. Appl. Physiol. 14 (3) (1959) 373–382.
[81] S.C. Jiang, N. Ma, H.J. Li, X.X. Zhang, Effects of thermal properties and geometrical dimensions on skin burn injuries, Burns 28 (2002) 713–717.
[82] E. Onofrei, S. Petrusic, G. Bedek, D. Dupont, D. Soulat, T.C. Codau, Study of heat transfer through multilayer protective clothing at low-level thermal radiation, J. Ind. Text. 45 (2) (2015) 222–238, https://doi.org/10.1177/1528083714529805.
[83] M. v Narici, C.N. Maganaris, N.D. Reeves, P. Capodaglio, "Effect of aging on human muscle architecture, J. Appl. Physiol. 95 (2003) 2229–2234, https://doi.org/10.1152/japplphysiol.00433.2003.-The.
[84] L. Larsson, H. Degens, M. Li, L. Salviati, Y.I. Lee, W. Thompson, J.L. Kirkland, M. Sandri, Sarcopenia: aging-related loss of muscle mass and function, Physiological reviews 99 (1) (2019) 427–511, https://doi.org/10.1152/physrev.00061.
[85] D.T. Kirkendall, W.E. Garrett, The effects of aging and training on skeletal muscle, Am. J. Sports Med. 26 (4) (1998) 598–602, https://doi.org/10.1177/03635465980260042401.
[86] Goodpaster, B.H., Park, S.W., Harris, T.B., Kritchevsky, S.B., Nevitt, M., Schwartz, A.V., Simonsick, E.M., Tylavsky, F.A., Visser, M. and Newman, A.B., 2006. The loss of skeletal muscle strength, mass, and quality in older adults: the health, aging and body composition study. *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences*, *61*(10), pp.1059-1064. [Online]. Available: https://academic.oup.com/biomedgerontology/article/61/10/1059/600461.
[87] M.M. Porter, A.A. Vandervoort, J. Lexell, Aging of human muscle: structure, function and adaptability, Scand. J. Med. Sci. Sports 5 (3) (1995) 129–142, https://doi.org/10.1111/j.1600-0838.1995.tb00026.x.
[88] C.L. Rice, D.A. Cunningham, D.H. Patterson, M.S. Lefcoe, Arm and leg composition determined by computed tomography in young and elderly men, Clin. Physiol. Funct. Imaging 9 (3) (1989) 207–220.
[89] B.J. Thompson, E.D. Ryan, T.J. Herda, P.B. Costa, A.A. Herda, J.T. Cramer, Age-related changes in the rate of muscle activation and rapid force characteristics, Age 36 (2) (2014) 839–849, https://doi.org/10.1007/s11357-013-9605-0.
[90] J.S. McPhee, J. Cameron, T. Maden-Wilkinson, M. Piasecki, M.H. Yap, D.A. Jones, H. Degens, The contributions of fiber atrophy, fiber loss, in situ specific force, and voluntary activation to weakness in sarcopenia, The Journals of Gerontology: Series A 73 (10) (2018) 1287–1294, https://doi.org/10.1093/gerona/gly040.
[91] P.G. Holborn, P.F. Nolan, J. Golt, An analysis of fatal unintentional dwelling fires investigated by London Fire Brigade between 1996 and 2000, Fire Saf. J. 38 (2003) 1–42.
[92] I. Miller, P. Beever, Victim behaviours, intentionality, and differential risks in residential fire deaths, Saf. Secur. Eng. 82 (2005) 845–854 ([Online]. Available: www.witpress.com).
[93] L. Xiong, D. Bruck, M. Ball, Comparative investigation of 'survival' and fatality factors in accidental residential fires, Fire Saf. J. 73 (2015) 37–47, https://doi.org/10.1016/j.firesaf.2015.02.003.
[94] A. Hussain, K. Dunn, Burn related mortality in Greater Manchester: 11-year review of regional coronial department data, Burns 41 (2) (2015) 225–234, https://doi.org/10.1016/j.burns.2014.10.008.
[95] F. Simonit, U. da Broi, L. Desinan, The role of self-immolation in complex suicides: a neglected topic in current literature, Forensic Sci. Int. 306 (2020), https://doi.org/10.1016/j.forsciint.2019.110073.
[96] A. Levy, J. Harcke, Death from fire and burns, in: Essentials of Forensic Imaging: A Text Atlas, Taylor & Francis Group LLC, 2011.
[97] T. Murakami, S. Akashi, M. Uetani, T. Murase, T. Yamamoto, and K. Ikematsu, Burned bodies: How do we evaluate the death in a fire on CT? in European Congress of Radiology-ECR, 2015.