Technische Universität München

Fakultät für Sport- und Gesundheitswissenschaften

Professur für Biomechanik im Sport

Physical job demands and occupational fitness requirements for professional firefighters based on strength and endurance performance tests and a 15-week exercise program

Stephanie Windisch

Vollständiger Abdruck der von der Fakultät für Sport- und Gesundheitswissenschaften der Technischen Universität München zur Erlangung des akademischen Grades eines

Doktors der Naturwissenschaften (Dr. rer. nat)

genehmigten Dissertation.

Vorsitzender:	Prof. Dr. Henning Wackerhage
Prüfer der Dissertation:	1. Prof. Dr. Ansgar Schwirtz
	2. Prof. Dr. Daniel Hahn
	3. Prof. Dr. Martin Klingenspor

Die Dissertation wurde am 23.11.2017 bei der Technischen Universität München eingereicht und durch die Fakultät für Sport- und Gesundheitswissenschaften am 03.05.2018 angenommen.

For those

who are ready on every call

who save victims and lives

who protect homes and property from fire

those who are first in and last out.

Thank you, firefighters!

Table of contents

1 Summary

Background and Aim: Firefighters are a unique occupational group, given that they perform strenuous work in unpredictable emergency situations. Their physically-demanding work requires high levels of fitness. The primary aim of this doctoral thesis is to determine the physical demands of firefighting and establish the relationship with important fitness variables. The secondary aim of the thesis is to find an exercise program that improves important fitness variables within a given exercise time on-duty. The research outcome should be a best practice recommendation for effective exercises to meet the physical job demands required by professional firefighting. In Study I, the aim is to quantify the physical demands of a simulated firefighting exercise and identify the relationship between firefighting performance and important endurance and strength parameters. The aim of Study II is to examine physiological responses to two different simulated firefighting exercises: one in extreme temperatures (300°) in a burning container and a standard firefighting exercise in temperate conditions (20-30°). Moreover, a second aim of Study II is to examine changes in the contribution of strength and endurance capacities to firefighting performance when the demands of the firefighting exercise change. The aim of Study III is to evaluate the effects of a 15-week endurance program for professional firefighters while exercising one hour on-duty by comparing the effects of a high-intensity interval training (HIIT) based on a polarized concept vs. more traditional continuous training.

Participants and methods: In Study I, 41 professional male firefighters performed a maximum treadmill test, a battery of strength and endurance tests and a simulated firefighting exercise twice on four different days. Firefighting performance during the simulated exercise was evaluated by a simple time-strain-air depletion model (TSA) taking the sum of z-transformed parameters of time to finish the exercise, strain in terms of mean heart rate and air depletion from the breathing apparatus. Multiple regression analysis based on the TSA model served to identify the most relevant physiological determinants for professional firefighting. In Study II, sixteen professional male firefighters performed a maximum treadmill test, strength testing, a standard simulated firefighting exercise without heat and flashovers and a firefighting exercise with a simulation of the flashover phenomenon in a burning container on four separate days. Firefighting performance was again evaluated by the TSA model and correlations were subsequently established between TSA-based firefighting performance parameters and fitness variables representing strength and endurance. In Study III, the impact of a high-intensity interval training (HIIT) within a polarized training concept was compared to continuous endurance training (CT) within one hour exercising on-duty. Thirty professional firefighters were randomly assigned to two experimental (HIIT n=10; CT n=10) and one control (CON n=10) group. Key endurance parameters were assessed during a maximum treadmill test before (baseline-test) and after (post-test) a 15-week intervention.

Results: In Study I, three main factors with a strong influence on firefighting performance were identified (70.1% of total explained variance): relative maximum oxygen uptake (VO_{2peak}), the time during which the firefighter exercised below their individual ventilatory threshold 1 (VT1) and mean breathing frequency. In Study II, the physiological responses to firefighting in extreme temperatures were found to be significantly higher compared to the standard simulated firefighting exercise. A high level of relative VO_{2peak} was clearly determined as the most important variable to complete firefighting exercises in both temperate and extreme environments. In Study III, the HIIT training within a polarized training concept improved key endurance parameters such as VO_{2peak}, VT1, respiratory compensation point (RCP) and time to exhaustion during treadmill running (TT) significantly more than continuous training within one hour exercising on-duty.

Conclusion: Endurance in terms of VO_{2peak} was established as an important prerequisite for firefighting in temperate and extreme conditions. However, for standard simulated firefighting exercises it is important to work below VT1. For firefighting exercises in extreme temperatures with smoke, poor visibility and unexpected flashovers, a high fitness level is required to keep the time spent above RCP as short as possible. Based on the results of this thesis, we recommend that professional firefighter incumbents take part in annual fitness screening to monitor important key endurance variables. Furthermore, we highly recommend that firefighters include HIIT and a polarized training concept in their endurance training because significant improvements can be achieved within one hour exercising on-duty.

2 Zusammenfassung

Hintergrund und Ziele: Die Arbeitstätigkeit von Einsatzkräften der Feuerwehr ist durch Aufgaben mit hoher körperlicher Belastung, Schichtarbeit und ständiger Einsatzbereitschaft charakterisiert. Besonders die Brandbekämpfung stellt dabei durch das Tragen von Schutzbekleidung und körperlich anstrengende Aufgaben unter teils extremen Umweltbedingungen hohe Anforderungen an das physische Level der Einsatzkräfte. Einsatzkräfte der Feuerwehr benötigen daher ein Mindestmaß an körperlicher Fitness um ihren Job sicher und effizient ausüben zu können. Primäres Ziel dieser Dissertationsarbeit war es, ein physisches Anforderungsprofil für Berufsfeuerwehrmänner zu erstellen und daraus wichtige Fitnessvariablen abzuleiten. Diese Fitnessvariablen sollen in einer regelmäßigen Leistungsdiagnostik kontrolliert werden. Dazu wurde in Studie I dieser Arbeit das Beanspruchungsprofil während einer simulierten Feuerwehrübung in moderater Umgebungstemperatur (20°-30°) untersucht und wichtige Ausdauer- und Kraftparameter als Voraussetzung für ein effizientes Absolvieren der Übung bestimmt. In Studie II wurden die physiologischen Anforderungen zweier unterschiedlicher simulierter Feuerwehrübungen miteinander verglichen: einer Feuerwehrübung in moderater Umgebungstemperatur (20°-30°) sowie einer Feuerwehrübung in extremer Umgebungstemperatur (bis zu 300°). Des Weiteren wurde untersucht, inwiefern sich wichtige Fitnessvariablen ändern, wenn sich die physiologischen Anforderungen eines simulierten Feuerwehreinsatzes verändern. Die Entwicklung eines Trainingsprogramms zur Verbesserung der zuvor determinierten wichtigsten Fitnessvariablen war sekundäres Ziel dieser Dissertationsarbeit. Dazu wurde in Studie III ein 15-wöchiges Ausdauerprogramm für Einsatzkräfte der Feuerwehr untersucht, die das Programm lediglich während des einstündigen, tariflich festgelegten Dienstsports trainierten. Hier wurden die Effekte eines polarisierten Ausdauertrainings mit einem moderaten Ausdauertraining, das auch Schwellentraining beinhaltete, verglichen.

Methoden: 41 Werkfeuerwehrmänner der Flughafen-Feuerwehr München nahmen an Studie I teil. An vier verschiedenen Testtagen absolvierten sie einen Ausbelastungstest mit Spiroergometrie am Laufband, eine Testbatterie hinsichtlich Kraft, Beweglichkeit und Gleichgewicht und je zweimal eine simulierte Feuerwehrübung. Die Leistung in dieser Feuerwehrübung wurde anhand eines Time-Strain-Air Depletion Models (TSA) beurteilt. Dazu wurden die z-transformierten Parameter Übungszeit, durchschnittliche Herzfrequenz während der Übung sowie der Luftverbrauch aus dem Pressluftatmer nach Aufsummierung der einzelnen Variablen in einen gemeinsamen Score überführt (TSA-Score). In Studie II nahmen 16 Werkfeuerwehrmänner der Flughafen-Feuerwehr München teil. Der Ausbelastungstest mit Spiroergometrie am Laufband, die Kraft- und Beweglichkeitstestbatterie sowie die simulierte Feuerwehrübung wurden an 3 verschiedenen Testtagen analog zu Studie I absolviert. Am 4. Testtag nahm jeder Proband an einer simulierten Feuerwehrübung unter extremen Temperaturen (bis zu 300°) in einem Brandübungscontainer teil. Die Leistung in den absolvierten simulierten Feuerwehrübungen wurde ebenfalls analog zu Studie I mit dem TSA-Model sowie dem TSA-Score bewertet. In weiterer Folge wurde mithilfe von Korrelationen ermittelt, ob sich die Zusammenhänge zwischen den Anforderungen des simulierten Feuerwehreinsatzes und wichtigen Fitnessvariablen hinsichtlich Kraft und Ausdauer verändern, wenn sich die physiologischen Anforderungen der simulierten Feuerwehrübung verändern. In Studie III wurden die Effekte zweier unterschiedlicher Ausdauertrainingsmethoden mit einem 15-Wochen

Ausdauertrainingsprogramm verglichen. In einem randomisierten kontrollierten Testdesign absolvierten insgesamt 30 Werkfeuerwehrmänner der Flughafen-Feuerwehr München entweder ein High-Intensity-Intervalltraining (HIIT) basierend auf einem polarisierten Trainingskonzept (n = 10) oder folgten einem moderaten Ausdauertraining (n=10). 10 weitere dienten als Kontrollgruppe. Jeweils vor (Baseline Test) und nach (Post-Training Test) dem 15-wöchigen Programm wurden folgende vier Ausdauerparameter kontrolliert: maximale Sauerstoffaufnahme (VO_{2peak}), ventilatorische Schwelle 1 (VT1), respiratorischer Kompensationspunkt (RCP) sowie die maximale Laufbandzeit (TT).

Ergebnisse: In Studie I wurden drei Faktoren mit großem Einfluss auf die Leistung während des simulierten Feuerwehreinsatzes festgestellt (70,1% Varianzaufklärung): relative maximale Sauerstoffaufnahme (VO_{2peak}), die Zeit, die unter der 1. ventilatorischen Schwelle gearbeitet werden kann sowie die durchschnittliche Atemfrequenz. In Studie II wurde eine signifikant höhere physiologische Beanspruchung während der simulierten Feuerwehrübung in extremer Umgebungstemperatur im Vergleich zu moderater Umgebungstemperatur festgestellt. Erneut konnte hier ein hohes VO_{2peak}-Level als wichtigste Voraussetzung sowohl für simulierte Feuerwehrübungen in moderaten als auch extremen Temperaturen festgelegt werden. Die Ergebnisse von Studie III zeigten, dass ein High-Intensity-Intervalltraining im Rahmen eines polarisierten Trainingskonzepts wichtige Schlüsselparameter im Ausdauerbereich (VO_{2peak}, VT1, RCP, TT) signifikant mehr verbessert verglichen mit einem moderaten Ausdauertraining, das u.a. auch Schwellentraining beinhaltet.

Schlussfolgerungen: Ein hohes VO_{2peak}-Level ist die wichtigste Voraussetzung für das Absolvieren von Feuerwehrtätigkeiten, sowohl in moderaten als auch in

extremen Umgebungstemperaturen. Für Einsätze in moderaten Umgebungstemperaturen ist es wichtig, mit einer Herzfrequenz unter der 1. ventilatorischen Schwelle arbeiten zu können. Für Einsätze in extremen Umgebungstemperaturen mit Rauch, schlechter Sicht und unerwarteten Flashover-Ereignissen ist ein hohes Level an Fitness erforderlich, um die Zeit, in der mit einer Herzrequenz über dem respiratorischen Kompensationspunkt gearbeitet wird, so gering wie möglich zu halten. Auf Basis der Ergebnisse dieser Dissertationsarbeit wird Berufsfeuerwehrmännern empfohlen, wichtige Ausdauerwerte in einer jährlichen Leistungsdiagnostik zu überprüfen. Hinsichtlich eines effektiven Trainings wird Einsatzkräften der Feuerwehr empfohlen, regelmäßig HIIT-Blöcke im Rahmen eines polarisierten Trainingskonzepts zu absolvieren, da mithilfe dieses Trainingsmodells signifikante Verbesserungen im Ausdauerbereich in nur einer Stunde verpflichtendem Dienstsport erzielt wurden.

3 Publication and submission record

This present work is submitted as a cumulative thesis and is based on three research papers that have been accepted (or submitted) for publication:

Paper I published in *Scientific Reports* (Impact Factor: 4.259)

Windisch S., Seiberl W., Schwirtz A., Hahn D. (2017) Relationships between strength and endurance parameters and air depletion rates in professional firefighters. *Scientific Reports 7:44590. doi: 10.1038/srep44590*

Paper II published in *frontiers in Physiology* (Impact Factor: 4.134)

Windisch S., Seiberl W., Hahn D., Schwirtz A. (2017) Physiological responses to firefighting in extreme temperatures do not compare to firefighting in temperate conditions. *Front. Physiol. 8:619. doi: 10.3389/fphys.2017.00619*

Paper III submitted to *Medicine & Science in Sports & Exercise* (Impact Factor: 3.54)

Windisch S., Hahn D., Schwirtz A., Seiberl W. (2017) Exercising 1h on-duty: Polarized training is most effective for firefighters. *Submitted*

4 Introduction

Firefighting is widely acknowledged as a strenuous and physically very demanding occupation taking place in a hazardous environment (Barnard and Duncan, 1975; Gledhill and Jamnik, 1992b). The safety of possible victims as well as the firefighters themselves hold crucial importance for successful job performance. Due to the unpredictability of situations and time constraints at an emergency scene, firefighters always have to be prepared to perform various physically-demanding tasks quickly, safely and efficiently. Therefore, it is important that the physical capacities of firefighters are commensurate with the demands of their occupation (Beck, Billing and Carr, 2015; Siddall et al., 2016).

Due to the strenuous nature of their occupation, some fire brigades are considering guidelines for physical performance assessment and appropriate training programs (Williford et al., 1999; Siddall et al., 2016). While firefighters have strong physical performance requirements prior to being hired professionals, they often do not undergo a regular fitness check once the job recruitment has been completed. Sothmann and colleagues (2004) reported that 97% of all US fire departments require physical performance standards for hiring, although only 33% require annual fitness measurements for incumbents. Some national fire brigades (e.g. in Germany) use a periodically-simulated work task testing to check whether firefighter incumbents meet occupational performance standards (Committee for Firefighting Issues, Civil Protection and Civil Defense, 2002). The test is categorized as “passed” or “failed” afterwards, whereas no fitness parameters or other physical performance-determining variables are collected and evaluated. Furthermore, periodic medical surveillances – e.g. the G26.3 occupational health check in

Germany – solely provide information about the ability to work from a medical perspective.

Given that most fire brigades currently have no periodic physical examinations after recruitment for firefighting incumbents, this results in little knowledge about the maintenance of physical fitness during the service years. As described by Williford et al. (1999) and Sothmann et al. (2004), successful and effective job performance has been shown to be dependent on a firefighter's ability to perform strenuous work. If a firefighter is physically unable to perform his duty due to a poor fitness level, the risk of injuries, cardiac events and occupational accidents will increase for his fellow workers and himself (Cady et al., 1985; Kales et al., 2007; Siddall et al., 2016). Furthermore, an appropriate fitness level could help to prevent individual health complaints and minimize individual physical overload.

Therefore, the periodic assessment of physical fitness in firefighter incumbents is an important objective to maintain employability as long as possible and incur financial losses due to early retirement or the possible consequences of an accident. Some national fire brigades (Siddall et al., 2016) have given consideration to recommendations concerning minimal levels of physical fitness. However, it is important that these fitness criteria must reflect the job demands. As a result, it is necessary to quantify physical relevant job demands and thoroughly assess the relationship between job performance and physical fitness. Despite numerous individual studies conducted on this field (e.g. Davis, Dotson and Laine, 1982; Williford et al., 1999; Rhea, Alvar and Gray, 2004; Michaelides et al., 2011; Lindberg et al., 2013; Lindberg, Oksa and Malm, 2014), the relationship between common fitness tests and firefighting job performance is not clear and inconsistent. Therefore, the purpose of this doctoral thesis was to examine the physiological responses of firefighting in temperate conditions and under extreme temperatures to better understand the characteristics of firefighting in different environments. Furthermore, another purpose of this thesis was to ascertain whether the contribution of strength and endurance capacities changes when the demands of a firefighting exercise change. This approach results in a firefighting-specific job demands profile. Perhaps one of the most desirable outcomes of this research would be a clear picture of specific variables that can predict firefighting performance allowing a firefighter to complete his job tasks safely and effectively.

Once the most important fitness variables related to firefighting performance in temperate and extreme conditions are identified, these variables could be monitored by conducting fitness tests regularly for firefighter incumbents. Furthermore, training programs can be designed more specifically to improve these identified important capacities and firefighting performance concurrently. Indeed, some national fire brigades require their firefighters to exercise on-duty to maintain an appropriate level of fitness to perform firefighting tasks. For instance, in Germany professional airport firefighters have to exercise for one hour while on-duty as part of the collective wage agreement (Committee for Firefighting Issues, Civil Protection and Civil Defense, 2002). Thus, it is important that firefighters utilize training methods that effectively target the previously-defined specific variables and capacities within this exercise on-duty time. Although many studies recommend that firefighters maintain a high fitness level (Gledhill and Jamnik, 1992b; Siddall et al., 2016), only few studies provide data regarding the effect of appropriate exercise programs for firefighters (Roberts et al., 2002; Dennison et al., 2012).

Based on the physical demands profile and relevant endurance capacities, a specific exercise programs for firefighters will be developed. This program should contain individualized prescriptions to meet the needs of the individual firefighter to improve the capacities required for the job. The special challenge lies in designing an exercise program that effectively targets the defined specific capacities. By conducting this study as a third part of the doctoral research, it is expected to gain more detailed information on the extent of physiological adaptations possible within one hour exercising on-duty time.

In conclusion, three studies will be part of this doctoral thesis to draw a physical job demands profile for professional firefighters, relate it to fitness tests and offer recommendations for best practice exercise programs.

5 Aims of the dissertation

The primary aim of the present dissertation is to quantify the physical demands of firefighting and determine fitness tests accurately related to firefighting performance. The relationship between physical job demands and fitness parameters is ascertained by comparing the physiological responses of two simulated firefighting exercises to variables of strength and endurance by regression models or correlations. These tests could then be implemented as periodic physical fitness examinations for fire brigades. The secondary aim of this dissertation is to determine the effects of two different endurance exercise programs to improve previously established important endurance variables within a given exercise on-duty time.

The specific aims of the studies are as follows:

Study I

(1) Quantifying the physical demands of a simulated firefighting exercise by a simple formula – the TSA score – taking into account completion time of the exercise, heart rate and air depletion rate.

(2) Establishing the relationship between firefighting performance and highly standardized fitness measurements to identify the most relevant physical and physiological attributes to fulfill the job demands of a professional firefighter.

Study II

(1) Examining physiological responses to two different simulated firefighting exercises: a firefighting exercise with flashovers, smoke, poor visibility and extreme temperatures (300°) in a burning container and a standard firefighting exercise in temperate conditions (20-30°).

(2) Examining changes in the contribution of strength and endurance capacities to firefighting performance when the demands of the firefighting exercise change.

Study III

(1) Examining the effects of a 15-week endurance program for professional firefighters while exercising for one hour on-duty: comparing the effects of a high-intensity interval training based on a polarized concept vs. more traditional continuous training.

6 Current state of research

The following chapter provides insights into the physical demands of firefighting and the relationship between firefighting performance and firefighting-specific fitness variables. Some points of this chapter are also overviewed in a review on the physical demands of firefighting and related fitness assessments, which is currently in progress. This review is planned to be submitted to the Journal *Applied Ergonomics.*

6.1 Physical demands of firefighting

Firefighters perform strenuous and physically-demanding work during their daily job routine: they climb stairs and ladders, pull hoses, search and rescue victims and carry heavy equipment in awkward positions (Barnard and Duncan, 1975; Gledhill and Jamnik, 1992a; Bilzon et al., 2001; Elsner and Kolkhorst, 2008; Smith, 2011; Phillips et al., 2012). Furthermore, they often perform these activities in extreme environments due to high ambient temperatures, smoke and poor visibility. During their work, firefighters also face time urgency and unpredictable situations in emergencies. Additionally, they usually wear personal protective gear and a self-containing breathing apparatus to protect them against fire, smoke and high ambient temperatures. Besides the strain induced by the activities that they perform, the protective clothing adds an additional physical burden for the cardiovascular and muscular system (Dreger et al., 2006; Dorman and Havenith, 2009; Taylor et al., 2012; Phillips et al., 2016).

The combination of the aforementioned factors makes firefighting one of the most physically-demanding occupations that humans undertake (Smith, 2011), affecting the cardiovascular, muscular and thermoregulatory system. A huge number of studies have attempted to determine the physical demands of firefighting in recent years (e.g. Barnard and Duncan 1975; Bilzon et al. 2001; Heimburg, Rasmussen and Medbö 2006; Elsner and Kolkhorst 2008, Taylor et al. 2012). Due to the nature of firefighting, measurements of physiologic responses such as oxygen uptake (VO_2) or similar respiratory and cardiovascular parameters to live-fire work are difficult or even impossible. Therefore, experimental settings during real interventions solely provide information on parameters such as heart rate (Sothmann et al., 1992; Smith and Petruzzello, 1998; Bos et al., 2004). Consequently, the majority of scientific studies have used simulated firefighting tasks to quantify the workload of firefighting in terms of aerobic fitness, muscular strength and endurance (e.g. Williford et al. 1999; Bilzon et al., 2001; Rhea, Alvar and Gray et al., 2004; Heimburg, Rasmussen and Medbö, 2006; Elsner and Kolkhorst, 2008; Michaelides et al., 2011).

6.1.1 Physiological Responses to live-fire and 24-hour shift work

A limited number of studies have used experimental settings during real intervention in terms of investigating physical parameters during live-fire work and/or during a 24-hour shift at a fire station. Sothmann et al. (1992) monitored the heart rate (HR) response to actual emergencies among ten firefighters and reported an average HR of 157 ± 8 beats per minute (bpm) over a period of 15 ± 7min, which represented 88 ± 6% of HR_{max}. By comparison, Bos et al. (2004) found that actual firefighting activities during 24-hour shifts were dominated by activities with a low to moderate energetic workload. During this experimental study, heart rate percentage (%HRR) was calculated for activities during the shift. Tasks connected with wearing the self-contained breathing apparatus (SCBA) were found to be the most demanding tasks. Smith and Petruzzello (1998) offered evidence of high physiological strain during live-fire work with stair climbing and victim rescue. Ten firefighters performed three consecutive trials of the same drill, whereby the mean heart rate increased from 164 ± 8 bpm (1st trials) to 179 ± 4 (2nd trials) and 184 ± 3 (3rd trials).

6.1.2 Physical loads of simulated firefighting

The physical loads of simulated firefighting have been determined by either performing a set of consecutive firefighting tasks without interruption (Williford et al., 1999; Elsner and Kolkhorst, 2008; Sheaff et al., 2010; Perroni et al., 2010; Michaelides et al., 2011) or studying the physiological responses to single firefighting tasks (O'Connell et al. 1986; Rhea, Alvar, and Gray, 2004). The most common physical strain during performing simulated firefighting exercises averaged between 80% and 90% of heart rate maximum (Deakin et al., 1996; Del Sal et al., 2009; Williams-Bell et al., 2009; Perroni et al., 2010; Dennison et al., 2012; Lord et al., 2012). Some studies have also offered evidence of average heart rates above 90% of maximum heart rate (Sothmann et al., 1991; Schonfeld, Doerr, and Convertino et al., 1994).

Some researchers have conducted direct measurements of maximum oxygen uptake (VO_2) to characterize the metabolic demands of firefighting. The values reported from task-simulated testing ranged from 23 ml/min/kg for boundary cooling (Bilzon et al., 2001) to 47 ml/min/kg for a hose run (Siddall et al., 2016). Several authors have further offered evidence of a high physical strain above 80% of maximum relative oxygen uptake (VO_2) during the completion of a simulated task circuit (Bilzon et al., 2001; Heimburg, Rasmussen, and Medbö, 2006; Perroni et al., 2010). Others have reported values between 60% and 80% of relative maximal oxygen uptake (Sothmann et al., 1991; Elsner and Kolkhorst, 2008; Harvey et al., 2008). The most arduous tasks were stair climbing and victim rescue. Victim rescue required a VO_2 of 29.3 ml/min/kg (70% of VO_{2max}) in the study of Perroni et al. (2010) and 42.2 ml/min/kg in the study of Lemon and Hermiston (1977b). Holmer and Gavhed (2007) reported a VO_{2peak} of 43.8 ml/min/kg for stair climbing. This value was in close agreement with those reported by Gledhill and Jamnik (1992b) and Siddall et al. (2016).

6.2 Fitness assessments for firefighters

Perhaps one of the most commonly-targeted outcomes of previous firefighter research was to build up a clear profile of specific variables that are closely related to firefighting performance (Davis, Dotson and Laine, 1982; Williford et al., 1999; Rhea, Alvar and Grey, 2004; Henderson, Berry and Matic, 2007; Williams-Bell et al., 2009; Michaelides et al., 2011; Calavalle et al., 2013; Lindberg, Oksa and Malm, 2013; Lindberg et al., 2014). Therefore, the authors of the aforementioned studies conducted a combination of aerobic endurance and strength tests. The resulting fitness variables were subsequently related to firefighting performance variables by either identifying strong correlations or predicting firefighting performance by multiple regression. The identified contribution of important variables to the performance of firefighting tasks would enable firefighter trainers and instructors to concentrate exercise program efforts on those specific variables (Michaelides et al., 2011). If important fitness variables were improved, this would then improve performance on the specific firefighting tasks, provided that they have been correlated accurately.

6.2.1 Relationship between firefighting tasks and fitness parameters

To achieve this outcome, the vast majority of studies have conducted more than seven fitness tests regarding endurance and strength. The most commonly reported aerobic fitness tests were VO_{2max} treadmill tests. The most frequently used tests for upper body limb strength measurements were hand grip strength (11 studies) and bench press (6 studies). Upper body muscular endurance was most commonly evaluated by push-ups (6 studies), bench press endurance (4 studies) as well as chin-ups (4 studies). Lower limb strength was mostly tested by squats (2 studies) or a leg extension test (2 studies). Squats and leg press were also the most frequently used fitness measurements for lower limb strength endurance (2 studies). Core strength endurance was mostly frequently assessed by sit-ups (8 studies). Flexibility testing was also part of many studies and tested by the Sit & Reach Test (5 studies). Four studies assessed anaerobic power. The most frequently used tests were a standing long jump and vertical jump. Tab. 1 provides a detailed overview of the combination of different tests used in all selected studies (see Tab. 1).

Tab. 1. *Combination of fitness tests (aerobic, AE= anaerobic, muscular strength, muscular endurance, anPo = anaerobic power, Flex= flexibility, balance) used in selected studies*

		Calavalle (2013)	Davis (1982)	Deakin (1996)	Gledhill	Harvey (2008)	Henderson (2007)	Lindberg (2013)	Lindberg (2014)	Lindberg (2015)	Michaelides (2011)	Philipps (2011)	Rhea (2004)	Schonfeld (1994)	Sheaff (2010)	Sothmann (2004)	Walker (2014)	Williams-Bell (2009)	Williford (1999)	**TOTAL**
Aerobic	**VO_{2max} Treadmill**	x	x	x		x		x				x		x	x			x	x	**10**
	Step Test = or > 3min		x	x			x	x							x					**5**
	6min Cycling							x												**1**
	Crawl Test							x												**1**
	Cooper Test												x							**1**
	3000m Running Indoor Track							x												**1**
	Rowing Test (Rowing Machine)							x												**1**
	1.5 mile run			x															x	**2**
AE	**Step-Test (60seconds) or Wingate 30s Test**			x							x			x	x					**4**
	400m - Run												x							**1**
Muscular Strength	**Hand Grip Strength**		x	x			x				x	x	x	x	x		x	x	x	**11**
	Bench Press					x	x				x		x		x			x		**6**
	Latissimus Dorsi Pull-Down					x	x													**2**
	Biceps Curl					x												x		**2**
	Shoulder Press																	x		**1**
	Leg Extension					x									x					**2**
	Leg Press														x					**1**
	Leg Curl					x														**1**
	Squat										x		x							**2**
	Isokinetic Knee Flextion													x						**1**
	Isokinetic Knee Extension													x						**1**
	Isometric Abdominal Strength										x									**1**
	Isometric Arm Lift															x				**1**
Muscular Endurance	**Squats**								x				x							**2**
	Wall Sit											x								**1**
	Leg Press														x			x		**2**
	Sit-Ups		x	x			x		x		x		x	x					x	**8**
	Endurance Hand Grip								x			x	x							**3**
	Weight Hold at Hip Height											x								**1**
	Push-Ups		x	x							x	x		x					x	**6**
	Bench Press					x			x				x					x		**4**
	Chest Press														x					**1**
	Chin-Ups		x	x					x										x	**4**
	Shoulder Press								x			x	x							**3**
	Rowing with Barbells								x			x	x							**3**
	Biceps Curl												x							**1**
	Dips								x											**1**
	Prone Bridge											x								**1**
	Arm cranking exercise					x										x				**2**
AnPo /Flex	**Jump**		x						x		x	x								**4**
	Flexibility		x	x							x			x					x	**5**

The most frequently investigated tasks were victim rescue (14 studies), stair/ladder climb (11 studies) and hose carry (11 studies). Tab. 2 provides an overview of the combinations of different firefighting tasks of the selected studies to make it clarify the fitness measurements to which they were related.

Tab. 2. *Combinations of different firefighting tasks and relationship analyses between firefighting tasks and fitness variables in the selected studies (Reg= Multiple Regression, PCA= Principal Component Analyses, SEM= Structural Equation Modeling)*

	Calavalle (2013)	Davis (1982)	Deakin (1996)	Gledhill	Harvey (2008)	Henderson (2007)	Lindberg (2013)	Lindberg (2014)	Lindberg (2015)	Michaelides (2011)	Philipps (2011)	Rhea (2004)	Schonfeld (1994)	Sheaff (2010)	Sothmann (2004)	Walker (2014)	Williams-Bell (2009)	Williford (1999)	**TOTAL**
Stair/Ladder climb	x		x		x		x	x		x		x	x	x			x	x	**11**
Standpipe carry		x																	**1**
Ladder extension		x	x		x	x								x			x		**6**
Ladder lower			x		x	x								x			x		**5**
Hose carry/pull/drag		x	x		x		x	x		x		x		x	x	x	x		**11**
High volume hose pull			x		x					x								x	**4**
Hoist																		x	**1**
Tool carry			x		x	x	x	x				x		x	x		x		**9**
Victim rescue	x	x	x		x		x	x		x		x	x	x	x	x	x	x	**14**
Forcable entry/Demolition		x	x		x		x	x		x			x	x				x	**9**
Cutting holes in a roof/ Ceiling Breach and Pull							x	x						x			x		**4**
Hydrant Hook-Up										x									**1**
Pack Hike Test											x								**1**
CPAT-Test (Candidate Physical Ability Test)														x					**1**
Fire Fit Circuit					x														**1**
Total time	x	x	x	x	x	x	x			x		x	x	x	x	x	x	x	**15**
Physical strain parameters (HR etc.)			x				x												**2**
Correlations			x		x		x							x				x	**5**
Correlations to single tasks			x				x	x		x			x	x				x	**7**
Predictors	PCA	Reg			Re g	Re g/S EM				Reg			Reg	Reg	Reg		Reg	Reg	**10**
Task Circuit	x	x	x		x	x				x			x	x	x	x	x	x	**12**
Single Tasks						x	x				x								**3**

From Tab. 2, it can also be seen that all studies aside from three chose total completion time of the tasks as the performance-determining parameter. Only two studies (Deakin et al., 1996, Lindberg, Oksa and Malm, 2013) reported the physical strain in terms of heart rates (HR) besides completion time as performance parameters. The vast majority of studies (12 studies) used a task circuit with different firefighting tasks completed without interruption. Only three studies investigated single firefighting tasks (see also Tab. 2).

The relationships between firefighting tasks and physical fitness measurements have been represented either in terms of single correlations between a specific fitness test and an operational tasks (e.g. Williford et al., 1999; Rhea, Alvar, and Gray, 2004; Michaelides et al., 2011) or a subset of tests predicting total completion time of a simulated circuit by multivariate regression analysis (Davis, Dotson, and Laine, 1982; Sothmann et al., 2004; Henderson, Berry, and Matic, et al. 2007; Harvey et al., 2008; Williams-Bell et al., 2009). Two studies (Harvey et al., 2014; Walker et al., 2014) reported fitness measurements in combination with simulated operational power testing as an analysis of differences between age groups or different samples (municipal vs. industrial firefighters). However, these studies did not present any correlations to establish the relationship between fitness and simulated work tasks. Calavalle et al. (2013) predicted performance with Principal Component Analyses.

Tab. 3. *Correlations between aerobic, anaerobic fitness and flexibility measurements and performance in simulated firefighting work tasks. *Significant at p ≤ 0.05, **Significant at p ≤ 0.01*

	Overal Fitness	Aerobic Fitness		Anaerobic Endurance	Flexibility	
	Overall Fitness	12min Run	1,5 mile run	400m run	Sit and reach	
Total Performance	-0,62*	n.s.	0,38**	0,79*	n.s.	n.s.
	Rhea	Rhea	Williford	Rhea	Williford	Michaelides
Hose pull	-0,49*	n.s.	n.s.	0,67*	n.s.	
	Rhea	Rhea	Williford	Rhea	Williford	
Victim drag/rescue	-0,62*	n.s.	0,23*	0,81*	n.s.	
	Rhea	Rhea	Williford	Rhea	Williford	
Stair climb	-0,51*	n.s.	0,56**	0,63*	-0,25**	
	Rhea	Rhea	Williford	Rhea	Williford	
Equipment hoist	n.s.	n.s.	0,30**	0,59*	n.s.	
	Rhea	Rhea	Williford	Rhea	Williford	
Forcible Entry			0,25*		n.s.	
			Williford		Williford	

The relationships between aerobic and anaerobic field measurements, anthropometric parameters and simulated work tasks are shown in Tab. 3. Anaerobic endurance in terms of a 400m run showed the strongest relationship to *victim rescue* (r = 0.81) and a moderate relationship to *hose pull* (r = 0.67) and *stair climb* (r = 0.63). Williford et al. (1999) offered evidence of small to moderate correlations of the 1.5 mile run to *hose pull, victim rescue, stair climb, forcible entry* and *equipment hoist* (r = 0.25 to r = 0.56). By contrast, Rhea, Alvar and Gray (2004) could not find any significant correlations between a 12-minute run (Cooper-Test) and various simulated firefighting tasks. Tab. 2 only shows weak relationships between firefighting and anthropometric parameters in terms of the percent of body fat and fat-free weight. In this respect, Williford et al. (1999) and Michaelides et al.

(2011) could establish moderate correlations for *equipment hoist* (r = -0.54) and *stair climb* (r = -0.54). Both research groups could not offer any significant evidence of the relationship between work tasks and flexibility in terms of the sit and reach test.

Lindberg et al. (2013) found stronger Spearman's rank correlations (r_s) between absolute VO_{2max} ($l*min^{-1}$) and firefighting tasks (r_s= -0.70 to -0.79) than for VO_{2max} expressed relative to body weight (r_s= -0.46 to -0.58). An exception to this applies to the relationship between VO_{2max} (ml/min/kg) and carrying equipment over terrain resulting in a strong correlation of r_s= -0.74. By contrast, Harvey et al. (2008) found no significant correlations between absolute VO_{2max} and completion time of a simulated task circuit.

Tab. 4. *Correlations (Spearman's correlation r_s) or structural equation models (SEM) between muscular strength tests and performance in simulated firefighting tasks. Publication year is only mentioned when authors had more than one publication on the same topic. *Significant $p \le 0.05$; **Significant $p \le 0.01$; n.s. non-significant)*

	Musuclar Strength												Explosive Strength	
	Bench press			Squat		Hand grip					Lat pull-down	Abdominal Strength (isometric device)	Vertical Jump (Power)	Standing broad jump
		Michaelides			Michaelides		Michaelides					Michaelides	Michaelides	
Charged Hose advance		-0.36**			n.s.		n.s.					-0.43**	-0.28*	
										Lindberg (2014)				Lindberg (2014)
Cutting holes in a roof for ventilation										0.67**				0.40**
		Michaelides		Michaelides			Michaelides		Williford	Lindberg (2014)		Michaelides	Michaelides	Lindberg (2014)
Forcible entry/ Demolition		-0,41**		-0,33**			-0,30*		-0,53**	0.66**		-0,35**	n.s.	0.53
	Rhea	Michaelides		Rhea	Michaelides	Rhea	Michaelides		Williford			Michaelides	Michaelides	
Equipment hoist	-0,68*	-0,30*		n.s.	n.s.	-0,66*	n.s.		-0,55**			-0,49**	n.s.	
	Rhea	Michaelides		Rhea	Michaelides	Rhea	Michaelides		Williford	Lindberg (2014)		Michaelides	Michaelides	Lindberg (2014)
Stair climb	-0,39*	n.s.		n.s.	n.s.	-0,46*	n.s.		-0,39**	-0.69**		-0,38**	n.s.	-0.72**
	Rhea	Michaelides		Rhea	Michaelides	Rhea	Michaelides		Williford	Lindberg (2014)		Michaelides	Michaelides	Lindberg (2014)
Victim drag/ rescue	-0,65*	-0,31*		n.s.	n.s.	-0,68*	-0.41**		-0,59**	-0.79**		-0,29*	-0.31*	-0.74**
	Rhea	Michaelides		Rhea	Michaelides	Rhea	Michaelides		Williford	Lindberg (2014)		Michaelides	Michaelides	Lindberg (2014)
Hose pull	-0,8*	n.s.		-0,48*	n.s.	-0,85*	-0.36**		-0,41**	-0.73**		-0.41**	n.s.	-0.67**
	Rhea	Michaelides	Henderson	Rhea	Michaelides	Rhea	Michaelides	Henderson	Williford		Henderson	Michaelides	Michaelides	
Total Performance	-0,66*	-0,31**	SEM	n.s.	n.s.	0,71*	n.s.	SEM	-0,54**		SEM	-0,53**	-0,41	

Correlations between muscular strength (Tab. 4) as well as muscular endurance (Tab. 5) and simulated job tasks show how predictive and related to job performance the different tests are. Muscular strength and endurance were divided into upper and lower limb strength and endurance measurements as well as explosive strength.

Tab. 5. *Correlations (Spearman's correlation r_s) between muscular endurance tests and performance in simulated firefighting tasks. Publication year is only mentioned when authors had more than one publication on the same topic. *Significant $p \le 0.05$; **Significant $p \le 0.01$; n.s. non-significant)*

	Muscular Endurance																						
	Row	Time to row 500m	Bench press		Shoulder press		Bicep curl	Squat		Ab curl	Hand grip		Push-Ups		Sit-Ups (1-minute)			Pull-Ups	Chin-Ups	Dips	Step-Test (Anaerobic Power)		30m crawling
Stair climb with equipment		Lindberg (2013)																				Lindberg (2013)	Lindberg (2013)
		0.82																				0.58	0.74
Cutting holes in a roof for ventilation		Lindberg (2013)		Lindberg (2014)		Lindberg (2014)			Lindberg (2014)			Lindberg (2014)					Lindberg (2014)		Lindberg (2014)	Lindberg (2014)		Lindberg (2013)	Lindberg (2013)
		-0.63		0.47**		0.55**			0.42**			0.59**					0.50**		0.54**	0.50**			0.49
Forcible entry/ Demolition				Lindberg (2014)		Lindberg (2014)			Lindberg (2014)			Lindberg (2014)	Michaelides	Williford	Michaelides	Williford	Lindberg (2014)	Williford	Lindberg (2014)	Lindberg (2014)	Michaelides	Lindberg (2013)	
				0.47**		0.53**			0.56**			0.62**	n.s.	-0.36**	n.s.	-0.22*	0.51**	-0.30**	0.69**	0.69**	n.s.	-0.69	
Equipment hoist	Rhea	Lindberg (2013)	Rhea		Rhea		Rhea	Rhea		Rhea	Rhea		Michaelides	Williford	Michaelides	Williford		Williford			Michaelides	Lindberg (2013)	Lindberg (2013)
	-0.52*	0.65	-0.71*		-0.55*		-0.52*	n.s.		n.s.	n.s.		-0.30*	-0.35**	-0.52**	-0.22*		-0.30**			-0.34**	0.69	n.s.
Stair climb	Rhea		Rhea	Lindberg (2014)	Rhea	Lindberg (2014)	Rhea	Rhea	Lindberg (2014)	Rhea	Rhea	Lindberg (2014)	Michaelides	Williford	Michaelides	Williford	Lindberg (2014)	Williford	Lindberg (2014)	Lindberg (2014)	Michaelides		
	-0.45*		-0.52*	-0.73**	-0.54*	-0.72**	-0.55*	n.s.	-0.63**	n.s.	n.s.	-0.59**	-0.39**	-0.47**	-0.5**	-0.41**	-0.56**	-0.47**	-0.76**	-0.75**	-0.39**		
Victim drag/rescue	Rhea	Lindberg (2013)	Rhea	Lindberg (2014)	Rhea	Lindberg (2014)	Rhea	Rhea	Lindberg (2014)	Rhea	Rhea	Lindberg (2014)	Michaelides	Williford	Michaelides	Williford	Lindberg (2014)	Williford (1999)	Lindberg (2014)	Lindberg (2014)	Michaelides	Lindberg (2013)	Lindberg (2013)
	-0.58*	0.79	-0.67*	-0.82**	-0.68*	-0.74**	-0.66*	n.s.	-0.59**	n.s.	n.s.	-0.68**	n.s.	-0.38**	n.s.	-0.22*	-0.44**	-0.32**	-0.74**	-0.81**	n.s.	-0.54	0.7
Hose pull	Rhea	Lindberg (2013)		Lindberg (2014)	Rhea	Lindberg (2014)	Rhea	Rhea	Lindberg (2014)	Rhea	Rhea	Lindberg (2014)	Michaelides	Williford	Michaelides	Williford	Lindberg (2014)	Williford	Lindberg (2014)	Lindberg (2014)	Michaelides	Lindberg (2013)	Lindberg (2013)
	-0.63*	0.76		-0.85**	-0.75*	-0.67**	-0.67*	-0.56*	0.57**	n.s.	n.s.	-0.67**	n.s.	-0.27**	n.s.	n.s.	-0.51**	-0.30**	-0.72**	-0.61**	n.s.	0.66	0.62
Total Performance	Rhea		Rhea		Rhea		Rhea	Rhea		Rhea	Rhea		Michaelides	Williford	Michaelides	Williford		Williford			Michaelides		
	-0.61		-0.73		-0.71*		-0.69*	-0.47*		n.s.	n.s.		-0.27	-0.38**	-0.41	-0.32**		-0.38**			-0.40		

The strongest correlations between completion time of the firefighting activities and muscular strength and endurance tests were found for *Pulling*, *Rescue* and *Equipment hoist*. *Hose pull* had the strongest correlations with the predicted one-repetition maximum of bench press (r = -0.8; Rhea, Alvar, and Gray, 2004) and maximum hand grip strength (r = -0.85; Rhea, Alvar, and Gray, 2004 and r = -0.73; Lindberg, Oksa, and Malm, 2014). Moderate correlations for *hose pull* and rowing (r = -0.63 to r= 0.76) and *hose pull* and dips (r = -0.61) were also confirmed. As shown in Tab. 4, bench press endurance (r = -0.85), shoulder press (r = -0.75) and chin-ups (r = -0.72) showed a strong relationship with *hose pulling*. Furthermore, the strongest correlations between *stair/ladder climb* and fitness assessments were reported for chin-ups (r = -0.76), dips (r = -0.75), bench press endurance (r = -0.73), shoulder press endurance (r = -0.73) and explosive strength in terms of a standing long jump (r = -0.72). *Victim drag and rescue* as an important firefighting task was strongly related to fitness measurements such as maximum hand grip strength (r = -0.79), the time to row 500 meters (r = -0.79), bench press endurance (r = -0.82) and standing broad jumps (r = -0.74). The strongest correlations of fitness tests corresponding with *equipment hoist* occurred for the predicted one-repetition maximum of bench press (r = -0.68) as well as bench press endurance (r = - 0.71). Pull-ups (r = 0.69), chin-ups (r = 0.69) and hand grip strength (r = -0.53) showed moderate relationships with *demolition* and *forcible entry*.

Most studies have used field tests to establish the relationship between fitness measurements and work capacity (e.g. Williford et al., 1999; Rhea, Alvar, and Gray, 2004; Michaelides et al., 2011). Lindberg, Oksa and Malm (2014) presented results of a study comparing laboratory to field tests when evaluating the work capacity of firefighters. Despite reporting strong correlations (Spearman’s rank correlation coefficient $r_s > 0.7$) for most laboratory tests of muscular strength and endurance, the authors found that isokinetic laboratory testing – as used in their study – was more suitable for sports than for evaluating work capacity. The field tests of their study also resulted in strong correlations and were described as being more adequate for job performance testing as they are simpler and save both time and costs.

6.2.2 Recommended subsets of screening tests

A study conducted by Henderson, Berry and Matic (2007) provided strong evidence of a decrease in firefighting performance for subjects with strength levels below the male 25th percentile of their sample. The authors established muscular strength (bench press, latissimus pull-down and grip strength) as the primary predictor for the effective execution of firefighting activity. Aerobic endurance – in terms of relative VO_{2max} – represented only a subordinate parameter. Williford et al. (1999) investigated the relationship between firefighting tasks and physical fitness, finding a 1.5-mile run, fat-free weight and pull-ups to be the best predictors ($R^2 = 0.73$) for physical performance assessment in terms of stair climb, hoist, forcible entry, hose advance and victim rescue. According to Davis, Dotson and Laine (1982), maximal heart rate, sit-ups, grip strength, age and submaximal oxygen pulse represent a test battery of physical performance variables that best predicts the physical work capacity ($R^2 = 0.63$) of five sequentially-performed firefighting tasks of at least 7 minutes' duration (ladder extension, standpipe carry, hose pull, simulated rescue, simulated forcible entry). Furthermore, the authors defined the maximal aerobic capacity as a second factor accounting for the performance of the five mentioned tasks ($R^2 = 0.39$), especially for the chopping and simulated rescue tasks. Lean body weight, maximal heart rate, final treadmill grade, age and percent body fat best predicted maximal aerobic capacity. Calavalle et al. (2013) conducted a Principal Component Analyses and found four main factors that influence firefighting performance: the capacity to carry extra load, body fat, age and fitness level. Investigating a battery of field tests to evaluate the aerobic capacity of firefighters, Lindberg et al. (2013) established the time to row 500 meters, the time to run 3000m relative to bodyweight ($s*kg^{-1}$) and the percentage of maximal heart rate during treadmill walking as the most important tests. Furthermore, the same research group recommended maximal hand grip strength, bench press, chin-ups, dips, upright barbell row, standing broad jump and barbell shoulder press for evaluating firefighters' work capacity in terms of muscular strength (Lindberg, Oksa, and Malm, 2014). Harvey et al. (2008) reported peak work rate during an arm cycling exercise test as being the most relevant for the completion time of a modified Fire Fit Test (Deakin et al., 1996), but found only poor correlations for completion time and absolute as well as relative VO_{2max} values. Williams-Bell et al. (2009) offered evidence of the relative maximum of oxygen uptake, body mass and hand grip strength being the most important factors for successful firefighting performance, accounting for more than 67% of variance in multiple regression analyses. The percentage of body fat was also demonstrated as a contributing factor to work capacity by Michaelides et al. (2011), in addition to abdominal isometric strength, push-ups and a step test (accounting for more than 60% of variance in the regression model). Sothmann et al. (2004) were the only research group to recommend a subset of screening tests for firefighters existing of both simulated work tasks and fitness measurements. The combination of test items such as a hose drag, high-rise pack, arm cranking and lifting accounted for 50% of the variance associated with the completion of a work task circuit.

6.3 Exercise programs for firefighters

Several studies have shown that less fit firefighters perform firefighting tasks significantly slower than their physically fit counterparts (Sothmann et al., 2004; Dennison et al., 2012). As also stated by Storer (2014), suboptimal fitness might result in a mismatch with the high physical demands determined for firefighting job performance. One possibility to improve and maintain one's fitness level is through participation in regular exercise, as proposed by several national fire associations (e.g. Committee for Firefighting Issues, Civil Protection and Civil Defense, 2002; Dennison et al., 2012). These national fire associations suggest that firefighters should participate in regular exercise programs while on-duty. As postulated by many researchers, endurance and strength training should be an integral part of firefighter training programs (e.g. Durand et al., 2011; Michaelides et al., 2011).

When designing exercise programs for firefighters, exercise prescriptions need to address the unique and specific physiological demands of firefighting (Smith, 2011). These prescriptions should also include individual and progressive programs to meet the individual needs of low-fit to highly-trained firefighters (Smith, 2011).

However, only a small number of studies have evaluated exercise training for firefighters (Brown et al., 1982; Roberts et al., 2002; Peterson et al., 2008; Dennison et al., 2012; Jahnke et al., 2014). While Dennison et al. (2012) and Peterson et al. (2008) investigated the effects of a strength exercise program, Brown et al. (1982), Roberts et al. (2002) and Jahnke et al. (2014) researched the impact of endurance training programs on selected endurance variables. A high level of endurance is deemed most important for firefighters' work performance (Windisch et al., 2017a; Windisch et al., 2017b). Out of all endurance parameters, the relative VO_{2peak} holds fundamental importance for firefighting performance. One possible approach to promote endurance and especially VO_{2peak} is high-intensity interval training (HIIT). Another exercise prescription for improving VO_{2peak} would be continuous training (CT), which includes prolonged sessions of moderate-intensity exercise (e.g. ≥ 1 h at ~65-75% of VO_{2peak}) performed repeatedly for at least several weeks. This training improves VO_{2peak} and alters substrate utilization during exercise, resulting in improved endurance capacity (Midgley, McNaughton and Wilkinson, 2006).

Both CT and HIIT can increase endurance, although they considerably differ in the time needed for effective exercises with significant improvements in selected variables. HIIT has proven a time-efficient exercise paradigm that improves exercise performance to the same extent as CT (e.g. Burgomaster et al., 2005; Gibala et al., 2006). This could be an important argument for including it in firefighters' training. There is limited evidence of HIIT concepts in which firefighters are engaged (Brown et al., 1982; Roberts et al. 2002). Brown et al. (1982) found that an exercise program comprising 15-minute shuttle running on four days for 8 or 11 weeks improved VO_{2peak} by around 16%. Roberts et al. (2002) reported even greater improvements (~28%) in VO_{2peak} after a 16-week HIIT program. However, HIIT sessions were performed continuously for the 11 or 16 weeks in the mentioned studies. To date, there is no scientific evidence concerning how firefighters trained before or after these HIIT blocks. A periodization concept with varying low- and high- intensity as well as low- and high-volume periods is currently missing.

7 Study design

Study	Design	Participants	Outcome measures	Data analysis
I	Experimental study design	n = 41 Professional male firefighters	Physiological responses to a simulated firefighting exercise (heart rate, oxygen uptake, carbon dioxide output) Performance evaluation by the Time-Strain-Air Depletion Model (TSA score) Relationship to strength and endurance measurements	Descriptive Statistics; Pearson Correlations; Multiple Regression
II	Experimental study design	n = 16 Professional male firefighters	Comparison between physiological responses to two different firefighting exercises in a) temperate conditions and b) extreme conditions Performance evaluation by the Time-Strain-Air Depletion Model (TSA Score) Changes in important relationships to strength and endurance measurements due to firefighting in different environments	Descriptive Statistics; Pearson Correlations; SPM 1D-statistics
III	Randomized-controlled pre-post design study	n = 30 Professional male firefighters	Impact of a polarized training concept compared to a continuous training concept on key endurance parameters in professional firefighters while exercising one hour on-duty Changes in maximum oxygen uptake, ventilatory threshold 1, respiratory compensation point and time to exhaustion during treadmill running	Descriptive Statistics; One-way ANOVA; ANCOVA

8 Results

8.1 Relationships between strength and endurance parameters and air depletion rates in professional firefighters (Study I)

Authors: Stephanie Windisch, Wolfgang Seiberl, Ansgar Schwirtz and Daniel Hahn

First Author: Stephanie Windisch

Current Status: Published in *Scientific Reports*

Individual contribution:

The author of this dissertation is the main author of this paper. The PhD candidate was mainly responsible for developing the research idea, the theoretical framework and the design of the study in agreement with Prof. Dr. Ansgar Schwirtz and Prof. Dr. Daniel Hahn. The author of this dissertation collected the data at Munich Airport, Germany. The author carried out the analysis of the data and wrote the manuscript, always in agreement with Prof. Dr. Ansgar Schwirtz, Prof. Dr. Daniel Hahn und Dr. Wolfgang Seiberl. The manuscript was revised by Prof. Dr. Daniel Hahn und Dr. Wolfgang Seiberl. The final approval of the manuscript was provided by the author of this dissertation in agreement with Prof. Dr. Ansgar Schwirtz, Prof. Dr. Daniel Hahn and Dr. Wolfgang Seiberl. The PhD candidate was mainly responsible for the whole submission process and the integration of the reviewer’s feedback into the paper, in agreement with Prof. Dr. Ansgar Schwirtz, Prof. Dr. Daniel Hahn and Dr. Wolfgang Seiberl.

Summary and main results:

This section provides a summary of the main results of Study I. For details regarding the methods, results, discussion and conclusions, please see the original manuscript in Appendix A. The primary aim of this study was to quantify the physical demands of a simulated firefighting circuit by a simple formula, the Time-Strain-Air Depletion Score (TSA score), taking into account the completion time of the exercise, heart rate and air depletion rate. Furthermore, a second aim of the study was to establish the relationship between job performance and endurance and strength fitness measurements to identify the most relevant physical attributes to fulfill the job demands of a professional firefighter.

Forty-one professional firefighters (39 ± 9 yr, 179.6 ± 2.3 cm, 84.4 ± 9.2 kg, BMI 26.1 ± 2.8 kg/m^2) from Munich Airport participated in the test procedure. The subjects had a mean relative oxygen uptake of 45.0 ± 6.0 ml/min/kg. The total treadmill time to exhaustion averaged 10.5 ± 1.2 min with mean maximum heart rates of 181 ± 11 bpm. The total exercise time of the Respiratory Protection Exercise Standard ($REPE_{standard}$) averaged 801 ± 129 s (13.4 ± 2.2 min). The mean heart rate of the $REPE_{standard}$ was 143.2 ± 12.1 beats per minute (bpm), which corresponded to 79.2 ± 6.6 % of maximum heart rate (HR_{max}) determined on the treadmill. The subjects spent 21.3 ± 24.3 % of total exercise time in Zone 1, 69.9 ± 25.1 % of time in Zone 2 and 8.8 ± 17.3 % in Zone 3. The mean air depletion from the air cylinder averaged 161.7 ± 28.7 bar. Overall, subjects consumed 54.1 ± 9.9% of the capacity of a nominal 30min cylinder.

The exercise total time of the Respiratory Protection Exercise with Spirometry ($REPE_{spirometry}$) averaged 797 ± 122 s (13.3 ± 2.0 min). The mean heart rate during the $REPE_{spirometry}$ was 144.3 ± 12.7 bpm, corresponding to 79.8 ± 7.3 % of HR_{max}.

Mean heart rates (*p* = .433) and exercise total time (*p* = .858) showed no significant differences between $REPE_{standard}$ and $REPE_{spirometry}$. The mean oxygen consumption for the whole $REPE_{spirometry}$ exercise was 2.13 ± 0.32 l/min. The two most demanding tasks required 38 ± 6 ml/min/kg over 20 seconds *during orientation section crawling* and 38 ± 5 ml/min/kg for the *ladder climb*. The mean minute ventilation during the whole exercise was 67.5 ± 13.1 l/min. *Hoist* showed the highest mean minute ventilation rate (74.5 ± 17.4 l/min). Furthermore, mean breathing volume values during the exercise were 2.08 ± 0.33 l and the mean breathing frequency was registered with 34.1 ± 4.8 breaths per minute. The respiratory exchange ratio (RER) averaged 1.08 ± 0.08 across the total exercise. 36.0 ± 21.7 % of total exercise time subjects had a RER < 1.0 and 64.0 ± 21.7 % of time a RER ≥ 1.0.

Thirteen firefighters obtained a TSA score of -0.99 to +0.99 *(average)*, nine firefighters a TSA score between -1 and -2 *(above average)* and six firefighters a score smaller than -2 *(outstanding)*. Furthermore, six firefighters obtained a score between 1 and 2 *(below average)* and seven subjects a TSA score of more than 2 *(poor)*. It was assumed that the strain and duration of both exercises were comparable, as there was no significant difference between mean HR and the mean completion time of $REPE_{standard}$ and $REPE_{spirometry}$. Therefore, all $REPE_{standard}$ and $REPE_{spirometry}$ variables were used in addition to variables from treadmill and muscular strength, flexibility and balance testing to find the most predictive parameters for firefighting by multiple regression. Based on the performance model, three main factors with a strong influence on firefighting performance were identified (70.1% of total explained variance): VO_{2peak}, the time during which the firefighter exercised below their individual ventilatory threshold and the mean breathing frequency.

The results showed that outstanding performers had significantly higher VO_{2peak} (*p* = *.001*) and significantly lower mean heart rates during REPE (*p* = .001) while completing the exercise faster (p = .001) compared to *average*, *below average* and *poor* performers. The *outstanding* performers were the only subjects performing the REPE parcours without spending any time in Zone 3 and showing the highest fraction of time spent in Zone 1.

www.nature.com/scientificreports

SCIENTIFIC REPORTS

OPEN

Received: 11 October 2016
Accepted: 10 February 2017
Published: 17 March 2017

Relationships between strength and endurance parameters and air depletion rates in professional firefighters

Stephanie Windisch[1], Wolfgang Seiberl[1], Ansgar Schwirtz[1] & Daniel Hahn[2,3]

The aim of this study was to quantify the physical demands of a simulated firefighting circuit and to establish the relationship between job performance and endurance and strength fitness measurements. On four separate days 41 professional firefighters (39 ± 9 yr, 179.6 ± 2.3 cm, 84.4 ± 9.2 kg, BMI 26.1 ± 2.8 kg/m^2) performed treadmill testing, fitness testing (strength, balance and flexibility) and a simulated firefighting exercise. The firefighting exercise included ladder climbing (20 m), treadmill walking (200 m), pulling a wire rope hoist (15 times) and crawling an orientation section (50 m). Firefighting performance during the simulated exercise was evaluated by a simple time-strain-air depletion model (TSA) taking the sum of z-transformed parameters of time to finish the exercise, strain in terms of mean heart rate, and air depletion from the breathing apparatus. Multiple regression analysis based on the TSA-model served for the identification of the physiological determinants most relevant for professional firefighting. Three main factors with great influence on firefighting performance were identified (70.1% of total explained variance): VO_{2peak}, the time firefighter exercised below their individual ventilatory threshold and mean breathing frequency. Based on the identified main factors influencing firefighting performance we recommend a periodic preventive health screening for incumbents to monitor peak VO_2 and individual ventilatory threshold.

Many studies proved evidence for the high physical strain induced by firefighting activity[1–8]. The studies revealed that firefighters showed physiological responses of 80% of heart rate maximum (HR_{max}) on average with a range from 60–90% HR_{max} (e.g. refs 3, 5, 7 and 9). These previous studies used physically demanding simulated firefighting tasks to characterize the physiological responses during such activities. Research focused on oxygen uptake (VO_2) or heart rates (HR), and quantified push- and pull forces in order to relate the outcome to aerobic fitness and muscular strength with the main goal to establish the relationship between job demands and fitness parameters[10–13]. VO_{2peak}, hand grip strength, number of push-ups and pull-ups completed were some of the most common found fitness variables to be important for firefighters[9,13,14]. However, the physical strain induced by firefighting can be a limiting factor for firefighting performance. High strain, e.g. working with anaerobic metabolism over a long period of time, requires a high fitness level to maintain operating speed.

The primary focus when assessing firefighting performance in previous research lay on completion time of the simulated firefighting exercises as the performance determining parameter[11,15,16]. Therefore, previous studies showed positive correlations between completion time and fitness variables[11,16,17]. Other researchers predicted performance time by multiple regression[2,9,12,14,15]. Doubtless, time is a critical parameter for firefighters. When they arrive at an emergency scene, they have to work as fast as possible in order to prevent the spread of burning fires, destruction of property as well as to save lives of victims. However, apart from time there can be other limiting factors such as compressed air depletion from the self-containing breathing apparatus (SCBA). This air cylinder has a nominal capacity of recirculating compressed air for approximately 30 minutes, however, previous observations showed that the capacity of the SCBA was exceeded before the end of the exercise[18]. The lower air depletion, the longer a firefighter can work at an emergency scene and prolong interventions requiring air cylinder use. Aside from two studies that showed high rates of air consumption during simulated firefighting, air

[1]Department of Biomechanics in Sports, Technical University of Munich, Germany. [2]Human Movement Science, Ruhr-University Bochum, Germany. [3]School of Human Movement and Nutrition Sciences, University of Queensland, Australia. Correspondence and requests for materials should be addressed to S.W. (email: stephanie.windisch@tum.de)

depletion from the SCBA has hardly been researched yet[19,20]. Moreover, the relationship between fitness variables and air depletion has not been established yet.

Together with well-researched parameters of completion time and physical strain, we propose that air depletion from the SCBA can provide additional, extremely valuable information. To our knowledge, there is no study researching firefighting performance as a combination of these three parameters. For this study, we therefore defined a simple formula to quantify the demands of the simulated firefighting exercise adding time needed for the exercise, heart rate and air depletion from SCBA. The aim of our study was 2-fold: (1) Quantification of the physical demands of a simulated firefighting exercise by the simple formula taking into account completion time of the exercise, heart rate and air depletion rate. (2) Establishment of the relationship between firefighting performance and highly standardized fitness measurements in order to identify the most relevant physical and physiological attributes to fulfill the job demands of a professional firefighter. From this approach we expected to characterize firefighting more in detail. We hypothesized that firefighters with lower air depletion from the SCBA, fast completion time and lower physical strain during the simulated firefighting exercise possess a higher fitness level.

Materials and Methods

Subjects. Forty-one male career firefighters (39 ± 9 yr, 179.6 ± 2.3 cm, 84.4 ± 9.2 kg, BMI 26.1 ± 2.8 kg/m^2) of the Munich Airport volunteered to participate in the research. Full written and verbal details about the study were provided. Informed written consent was obtained from all participants prior to testing. The ethic statement for this study was approved by the Dean of the Faculty of Sports and Health Sciences of the Technical University of Munich. All tests were conducted according to the Declaration of Helsinki. All participants were in possess of a valid G26.3 medical examination for operational fitness, a mandatory periodically medical health check for firefighters in Germany.

Material and methods. The tests were conducted on four days each separated by at least 4 days in the following order: *Day 1* - Test of VO_{2peak} during maximal treadmill running and anthropometric evaluation. *Day 2* - Flexibility, balance, muscular strength and muscular endurance testing. *Day 3* - Respiratory protection exercise ($REPE_{standard}$) with SCBA. *Day 4*: Respiratory protection exercise ($REPE_{spirometry}$) with a spirometry mask.

All subjects wore functional sportswear and -shoes during the VO_2 peak testing, muscular strength and endurance testing.

Anthropometric evaluation. Body mass (kg) was recorded with the nearest 0.1 kg on a scale with shoes removed. Body height was measured by a tapeline with the nearest 0.1 cm of the maximum distance from the floor to the vertex of the head with shoes removed. Body Mass Index (BMI) was calculated by the following formula: Bodyweight in kilograms divided by height in meters squared (kg/m^2).

VO_2 peak testing. Minute ventilation (V_E) and gas exchange (oxygen consumption - VO_2, carbon dioxide output - VCO_2, respiratory exchange ratio - RER) were measured breath-by-breath with the Cortex Metamax 3B (Cortex Biophysics GmbH, Germany). An incremental exercise test based on the Ellestad Protocol[21] was conducted on a motorized treadmill (Life Fitness, Integrity Series, Germany) to determine peak oxygen uptake (VO_{2peak}), minute ventilation (V_E) and heart rate maximum (HR_{max}). The test was terminated when subjects reached volitional fatigue and were not able to continue running. VO_{2peak} and HR_{max} were taken as the highest 30s-average during the final minute of the test. In addition, two thresholds were determined based on the test: ventilatory threshold 1 (VT1) and respiratory compensation point (RCP). The VT1 was determined from the V-slope method[22] in combination with the break point of the ventilatory equivalent for O_2 against VO_2[23]. The RCP was identified by the break points of the ventilatory equivalent for CO_2 and the end tidal CO_2 concentration against VO_2[23]. These two thresholds were then used to establish three physiological intensity zones that correspond to the heart rates at the following exercise intensities: Zone 1, 2 and 3 were represented by the percentage of time subjects experienced HR below VT1 (Zone 1), HR between VT1 and RCP (Zone 2) and HR above RCP (Zone 3), respectively.

Flexibility, balance, muscular strength and endurance testing. A description of standardized fitness tests can be found in Table 1. All tests were completed sequentially with a break of at least 4 minutes between each test. A standardized warm up of 20 minutes on a cross-trainer (Life Fitness, Integrity Series, Germany) preceded the tests.

Simulated firefighting exercise test protocol. The simulated firefighting exercise was completed twice by each subject. One trial was with wearing full gear and the second trial was with full gear, but without the facemask, and wearing a portable metabolic measurement system.

Respiratory Protection Exercise Standard ($REPE_{standard}$): This exercise is a standardized, mandatory and periodically performed ability test for professional German firefighters. The test was conducted as prescribed by German firefighting test regulations[24]. Subjects were tested in a purpose-built practice area, wearing full personal protection gear (clothing, helmet, gloves, belt, facial mask, boots) and SCBA. The SCBA cylinders were filled with 300 bar according to the standard protocol for the fire services. The weight of the protection gear and SCBA was approximately 22 kg. The tasks included *ladder climb* (20 m), a 200 m *treadmill walk*, pulling a wire rope *hoist* (15 times) and *crawling* a 50 m *orientation section* in the dark with bottlenecks and a narrow tunnel. Subjects were instructed to perform the REPE safely and as fast as possible but in a pace similar to the work at a real fire emergency scene. The tasks were performed in succession without interruption but with individually chosen pace and possible breaks in case of exhaustion. During the $REPE_{standard}$, heart rate was measured continuously (Polar,

Test	Description
One-leg standing with eyes closed	Subjects had to show their one-leg standing balance with eyes closed for 15 seconds. Subjects stand on the supporting leg with the free leg raised and bent 90°. Assessment scheme: 2 points – Subject remained unmoving for 15 s. 1 point – Subject performed the exercise with compensation movements. 0 points – The supporting leg leaves its position (jumping as compensation movement) or the free leg was moved back to the ground or eyes were opened.
Sit and Reach Testing	This test, performed on a traditional 32.4-cm-high and 53.3-cm-long box, was used to obtain flexibility assessments for lower back and hamstring muscles. The subject sat on the floor with its legs fully extended with the bottom of the bare feet against the box. The subject placed one hand on top of the other, slowly bended forward and reached along the top of the ruler as far as possible holding the stretch for two seconds. The distance reached by the subject's finger tips (cm) was recorded. The test was performed three times. The average of the three distances were calculated
Standing Long Jump	Subjects placed their toes behind the takeoff line and were instructed to jump as far as possible forward with arm swing being allowed. The best jumping distance (cm) out of three trials was registered
1-RM testing legpress (one-legged)	Maximum strength was obtained using a predictive one-repetition (1-RM) formula as described by Brzycki[42]. Values (in kg) were taken from the left and the right leg and the maximum values of both legs averaged
Hand grip strength	The grip size of the force dynamometer (Jamar: Lafayette Instrument, Lafayette USA) was individually adjusted to fit the proximal interphalangeal joint of the third finger. In a standing position, with the elbow bent 90 degrees alongside the body, the subjects squeezed the dynamometer as hard as they could. The best of three trials on each hand was registered for the maximum (in kg) and the maximum values of both sides averaged
Push-ups (reps to fatigue)	The test was taken as the number of times the firefighter could perform push-ups with shoulder-width space between his hands at a rate of 30 lifts per minute
Partial Curl-Ups	The partial curl-ups test was used to measure muscular endurance of the abdominal muscle[43]. The total number of properly performed curl-ups (reps to fatigue) was recorded.
Shoulder Press (20 kg)	In a sitting upright position, subjects grasped two 10 kg dumbbells with a pronated grip, vertically pushed the attachment from chin level up to straight arms overhead, and then pulled back to the starting position. The test was taken as the number of times the firefighter could raise and lower the dumbbells in a seating position at a rate of 25 lifts per minute (metronome set at 50)
Rowing	In a seating position, the subjects grasped two 7.5 kg dumbbells with a pronated grip. The test was taken as the number of times the firefighter could row in a seating position by abducting arms (90°) in sagittal plane with two 10 kg dumbbells. The weight was lifted between the spina iliaca anterior superior and the chin at a rate of 30 full lifts per minute (metronome set at 60). The number of completed lifts was registered

Table 1. Description of balance, flexibility, strength and muscular endurance testing.

Finland) and ratings of perceived exertion[25] as well as air depletion from the SCBA were taken at the end of the exercise. Individual task time and total performance time were recorded.

Respiratory Protection Exercise with Spirometry ($REPE_{spirometry}$): The exercise protocol for the $REPE_{spirometry}$ was identical with the testing of the $REPE_{standard}$ but included spirometric measurements. This measurement provided additional information in terms of respiratory variables during firefighting. The standard facial mask of the SCBA was replaced by the mobile spirometry mask of the Cortex Metamax device to measure VO_2, VCO_2, VE, RER and ventilatory equivalents (VE/VO_2; VE/VCO_2). These variables were measured breath-by-breath and were then used to define the metabolic demands of the REPE. Subjects still wore the SCBA (without facial mask) to simulate the weight of their equipment.

Firefighting performance formula. We defined a simple formula to quantify the demands of the simulated firefighting exercise adding time needed for the exercise, mean heart rate during exercise expressed as percentage of the treadmill determined HR_{max} and air depletion from SCBA. We included the three variables in our formula because we defined optimal firefighting performance due to three important key aspects: (1) How much time do firefighters need to complete a given simulated firefighting exercise? (2) What are their physiological responses to the chosen operation speed? (3) How much air do they consume from their SCBA due to operation speed and work intensity? We defined this as the time-strain-air depletion (TSA) formula resulting in a TSA score:

$$TSA = Time + HR + Air\ Depletion(AD)$$

As the impact of every single factor on overall TSA-score is not clear at the moment, we used z-transformations to prevent different weighting of the parameters due to their different absolute values and normal distributions. The resulting z-scores allow us to compare and sum up the three parameters resulting in the TSA-score. As this score is based on the function of a z-score, the TSA-score indicates the resultant firefighting performance in relation to the sample mean, with the distance measured in standard deviations. A TSA-score of 0 represents the average. We ranked performers according to their TSA-scores into 5 categories based on standard deviations: "*Outstanding*" ($TSA < -2$), "*Above Average*" (TSA -1 to -2), "*Average*" (TSA -0.99 to $+0.99$), "*Below Average*" (TSA 1 to 2), and "*Poor*" ($TSA > 2$). Individual performance scores for the TSA should be kept at a minimum achieved through fast completion time, low heart rate as well as low air depletion during the exercise.

Data analyses. Statistical calculations were carried out with SPSS version 23.0 (IBM Corporation, USA). Descriptive statistics (means, standard deviations (SD)) were calculated to define subjects with respect to physical characteristics and performance in the tests. For legpress, handgrip and one-leg standing, data were taken as the average of left and right. Data were assumed to be normally distributed if the Shapiro-Wilk's test was >0.05.

Variable	Mean	±SD
Treadmill total time to exhaustion (min)	10.5	1.2
VO_{2peak} relative (ml/min/kg)	45.0	6.0
VO_{2peak} absolute (l/min)	3.75	0.43
HF_{max} (bpm)	181.2	11.1
V_E at VO_{2peak}(l/min)	126.5	29.4
Leg press (one leg) kg	125.5	31.6
Hand grip (kg)	58.7	7.1
Partial-Curl Ups (reps to fatigue)	82	34
Push-Ups (reps to fatigue)	29	16
Shoulderpress (reps to fatigue)	23	6
Rowing (reps to fatigue)	10.1	3.0
Standing Long Jump (cm)	219	22
One-Leg Standing Score (eyes closed)	1.1	0.5
Sit and Reach (cm)	9.3	3.3

Table 2. Aerobic fitness, muscular strength, flexibility and balance testing. Data are means ± SD. BMI: Body Mass Index, VO_{2peak}: peak oxygen uptake during maximal treadmill running, HF_{max}: peak heart rate during maximal treadmill running, V_E: Ventilation.

As all data was normally distributed, parametric tests were consequently carried out. The alpha level was set to 0.05. A paired t-test was calculated to show up differences between the two firefighting exercises $REPE_{standard}$ and $REPE_{spirometry}$. Reference values according to Cohen[26] were used to interpret the correlations. Values from 0.10–0.29 were considered 'small', 0.30–0.49 'moderate' and ≥0.50 'strong'. The combination of physical characteristics that best predict TSA was determined by multiple regression (Enter Method). The combination of variables that resulted in the highest explained variance that predicted the largest portion of the variance was then selected.

Results

Aerobic fitness, muscular strength, flexibility and balance testing. Table 2 provides an overview over the results of treadmill, muscular strength, flexibility and balance testing.

Physiological demands of the $REPE_{standard}$. Total exercise time averaged 801 ± 129 s (13.4 ± 2.2 min). The time required for completion of each of the four tasks during the $REPE_{standard}$ was 85 ± 15 s (1.4 ± 0.2 min) for *ladder climb*, 141 ± 13 s (2.3 ± 0.2 min) for *treadmill walking*, 35 ± 8 s (0.6 ± 0.1 min) for *hoist* and 412 ± 96 s (6.9 ± 1.6 min) for *orientation section crawling*. Mean heart rate of the $REPE_{standard}$ was 143.2 ± 12.1 beats per minute (bpm), which corresponded to 79.2 ± 6.6% of maximum heart rate (HR_{max}) determined on the treadmill. Mean HR values for *ladder climb* were 81 ± 7.4% of HR_{max} and for *orientation section crawling* 81 ± 6.7% of HR_{max}. *Hoist* averaged 78.8 ± 5.1% of HR_{max} and *treadmill walking* 75.4 ± 7.8% of HR_{max}.

Subjects spent 21.3 ± 24.3% of total exercise time in Zone 1, 69.9 ± 25.1% of time in Zone 2 and 8.8 ± 17.3% in Zone 3. Mean air depletion from the air cylinder averaged 161.7 ± 28.7 bar. In the first part of the $REPE_{standard}$ (*ladder climb*, *treadmill walk* and *hoist*), mean air depletion was 85.6 ± 16.8 bar which corresponded to 28.6 ± 5.6% of the capacity of a nominal 30 min-cylinder. In the second part, the *orientation section crawling*, air depletion ended up in 76.3 ± 19.1 bar (25.5 ± 6.3%). In total subjects consumed 54.1 ± 9.9% of the capacity of a nominal 30 min-cylinder.

Respiratory demands of the $REPE_{spirometry}$. Mean heart rate during the $REPE_{spirometry}$ was 144.3 ± 12.7 bpm corresponding to 79.8 ± 7.3% of HR_{max}. Exercise total time of the $REPE_{spirometry}$ averaged 797 ± 122 s (13.3 ± 2.0 min). Mean heart rates ($p = 0.433$) and exercise total time ($p = 0.858$) showed no significant differences between $REPE_{standard}$ and $REPE_{spirometry}$. The mean oxygen consumption for the whole $REPE_{spirometry}$ exercise was 2.13 ± 0.32 l/min. Among the different exercise elements, *ladder climb* required the highest absolute oxygen uptake (2.51 ± 0.39 l/min). Corrected for body mass, mean VO_2 was 25 ± 3 ml/min/kg across the whole exercise, 30 ± 4 ml/min/kg during *ladder climb*, 27 ± 6 ml/min/kg during *hoist* and 26 ± 6 ml/min/kg both during *treadmill walk* and the *orientation section crawling*. The two most demanding tasks required 38 ± 6 ml/min/kg over 20 seconds *during orientation section crawling* and 38 ± 5 ml/min/kg at the *ladder climb* (Fig. 1).

Mean minute ventilation during the whole exercise was 67.5 ± 13.1 l/min. *Hoist* showed the highest mean minute ventilation rate (74.5 ± 17.4 l/min), followed by the *orientation section* (70.9 ± 14.5 l/min) and the *ladder climb* (60.9 ± 16.7 l/min). Mean breathing volume values during the exercise were 2.08 ± 0.33 l. *Ladder climb* and *hoist* required breathing volumes of 2.4 l, the *treadmill walk* 2.28 ± 0.45 and the *orientation section* 1.9 ± 0.33 l. The mean breathing frequency was registered with 34.1 ± 4.8 breaths per minute. The *orientation section* required the highest number of breaths per minute (38.9 ± 5.8), followed by *hoist* (32.0 ± 5.5), *ladder climb* 29.1 ± 4.9) and *treadmill walk* (27.4 ± 5.1) (see Fig. 1). Furthermore, respiratory exchange ratio (RER) averaged 1.08 ± 0.08 across the total exercise. 36.0 ± 21.7% of total exercise time subjects had a RER <1.0 and 64.0 ± 21.7% of time a RER ≥1.0.

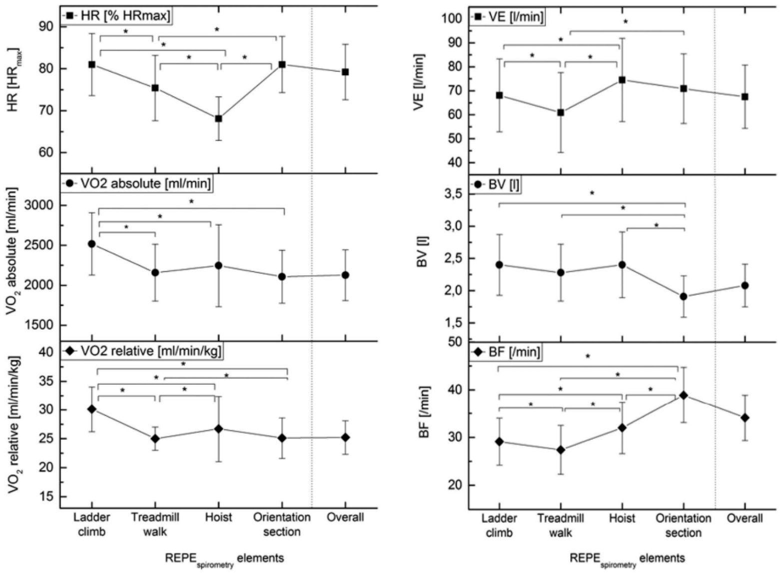

Figure 1. Physiological responses during the REPE: Heart rate (HR), peak oxygen uptake absolute (VO_{2peak} absolute) and relative (VO_{2peak} relative), minute ventilation (VE), breathing volume (BV) and breathing frequency (BF) during ladder climb, treadmill walk, hoist, orientation section and the overall exercise. Data are shown as means ± standard deviations (SD). *Significant difference between tasks ($P < 0.05$).

Relationship between TSA-score and fitness characteristics. Thirteen firefighters obtained a TSA-score of −0.99 to +0.99 (average), 9 firefighters a TSA-score between −1 and −2 (above average) and 6 firefighters a score smaller than −2 (outstanding). Furthermore, 6 firefighters obtained a score between 1 and 2 (below average) and 7 subjects a TSA-score of more than 2 (poor) (Fig. 2). As there was no significant difference between mean HR and mean completion time of $REPE_{standard}$ and $REPE_{spirometry}$, we assumed that strain and duration of both exercises were comparable. Therefore, we used all $REPE_{standard}$ and $REPE_{spirometry}$ variables in addition to variables from treadmill and muscular strength, flexibility and balance testing to find the most predictive parameters for firefighting by multiple regression. Based on our performance model (Table 3), multiple regression identified three main factors that show a great influence on optimal firefighting performance in terms of the TSA-score (70.1% of total explained variance): relative VO_{2peak} from maximum treadmill testing, mean breathing frequency and the percentage of time spent in Zone 1 during $REPE_{standard}$. Figure 3 shows the relationship of all three parameters to TSA-score. To better understand the characteristics of firefighters with respect to different TSA-scores, Table 4 shows TSA-parameters, the main identified variables by regression and additional variables for all categories of performers. It can be noted that outstanding performers had significantly higher VO_{2peak} (*p* = *0.001*) and significantly lower mean heart rates during REPE (*p* = 0.001) while completing the exercise faster (p = 0.001) compared to *average*, *below average* and *poor* performers. The differences of VO_{2peak}-levels and time spent in zone 1 of different TSA-performers are highlighted in Table 4. The poorest performers also showed an increased perceived exertion when rating the BORG scale after the exercise. Furthermore, the outstanding performers were the only subjects performing the REPE parcours without spending any time in Zone 3 and showing the highest fraction of time spent in Zone 1.

Discussion

The results of this research describe, for the first time, firefighting performance as a combination of operating speed (time to complete the circuit), physical strain and air depletion during a simulated firefighting exercise.

Firefighting is a physically demanding occupation. Several authors offered evidence for high physiological responses above 80% of peak relative oxygen uptake (VO_2) during the completion of simulated task circuits[1,5,7]. Others reported values between 47% and 80% of relative peak oxygen uptake[4,8,15,20]. In our study, relative VO_2 averaged at 56% of VO_{2peak} across the exercise, which was towards the lower end of the range of average values reported from other studies. The values reported for single firefighting tasks within circuits varied from 23 ml/min/kg for boundary cooling[1] to 44 ml/min/kg for tower stair climbing[27]. Literature indicates stair climbing[6,27] and victim rescue[28] to be the most arduous tasks, requiring a VO_2 of 38–43 ml/min/kg over 20 seconds. These findings are comparable to our values determined for *ladder climb* and *orientation section crawling*, although

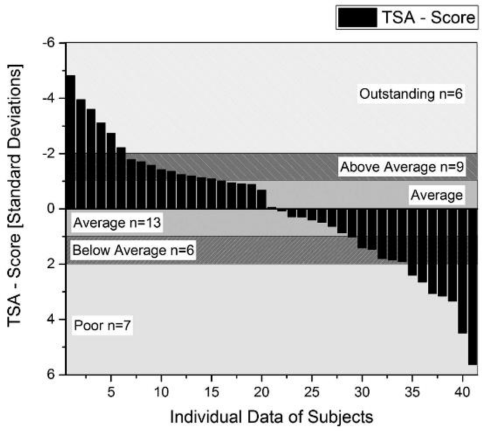

Figure 2. Individual TSA-Scores of all 41 subjects classified into *Outstanding, Above Average, Average, Below Average* and *Poor*.

Variable			
Model	β	**Standard error** β	β **- weight**
Relative VO_{2max}	−0.193	0.038	−0.508
Time spent in Zone 1	−0.037	0.010	−0.389
Mean breathing frequency (BF) during $REPE_{spirometry}$	0.122	0.043	0.256

Table 3. Multiple regression model (using Enter-Method) to predict optimal firefighting performance (TSA-score). Multiple r = 0.850, r^2 = 0.723, corrected r^2 = 0.701, standard error = 1.250.

measured VO_2 rather represent the lower end of the reported ranges. During the REPE circuit, HR averaged at 79.2 ± 6.6% of HR_{max} determined on the treadmill. These findings were consistent with values reported from other studies ranging from 61%[29] to 95%[4] of HR_{max}. The most common physiological responses in terms of mean HR during the firefighting exercises averaged between 80% and 90% of HR_{max}[3,7,9]. However, in our study, we analyzed not only mean heart rate but also the time spent in the three defined physiological intensity zones. These zones indicate the contribution of different energy sources to total exercise performance and provide more detailed information on cardiovascular load during firefighting. Subjects spent most time of their exercise time in Zone 2, the aerobic-anaerobic metabolic transition zone (69% of time), whereas the aerobic fraction (Zone 1) represented approximately 22% of exercise time. The smallest fraction (9% of time) was Zone 3 representing an anaerobic metabolism and indicating the onset of hyperventilation. A high fraction of time in Zone 3 will lead to subject's rapid fatigue, whereas a high fraction of time in Zone 1 confirms a subject's good aerobic metabolism[30]. To our knowledge, only one other study analyzed the three physiological intensity zones in the same way and found a distribution of energy metabolism of approximately 84% Z1, 12% Z2 and 2% Z3[31]. These results show important differences to our findings, however, it should be noted that the mentioned study investigated prolonged (>120 min) wildland firefighting and exercise time was almost 10 times longer than the simulated firefighting tests we investigated.

Subjects showed a RER ≥ 1.0 during 64% of total exercise time indicating a major contribution of anaerobic energy due to more CO_2 being produced than O_2 consumed. An increase of RER above 1.0 would only be expected, if VO_2 exceeded 89% VO_{2peak}[32]. During the maximum treadmill testing in our study, we established an average RER of 1.08 not before subjects ran at an intensity of 90% to 97% of VO_{2peak}. However, during the firefighting exercise, subjects reached an average RER 1.08 already at an intensity of 56% of VO_{2peak}. These observed RERs were out of line with RERs found during other moderate activities between 50 and 60% VO_{2peak}. For example, Davis *et al.*[33] reported average RER values of 0.85 during treadmill running at exercise intensities of 58% VO_{2peak}. Although the mean values for VO_2 were relatively low in our study, RER averaged 1.08 across the total exercise, representing an unexpected high level close to maximal exertion of subjects which would correspond to a RER of 1.15. One primary reason for the differences in RER in relation to VO_2 can be the different muscular strain that occurs during a running treadmill test compared to a simulated firefighting test. Firefighting includes many start-and-stop motions similar to game sports. Previous studies showed that the muscular strain during game sports affected metabolic parameters such as RER differently compared to respiratory parameters like VO_2[34,35]. This unusual VO_2/RER relationship has also been found by Harvey *et al.*[15] and Williams-Bell *et al.*[18]

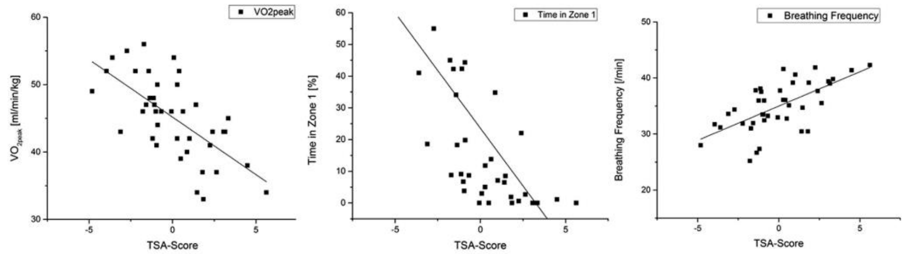

Figure 3. Relationship between the three main performance predictors and TSA-scores identified by multiple regression: relative VO_{2peak} (*left*), time in Zone 1 (*middle*) and breathing frequency (*right*).

		$REPE_{standard}$ Time (seconds)	$REPE_{standard}$ HR (%HRmax)	$REPE_{standard}$ AD (bar)	VO_{2peak} (ml/min/kg)	Zone 1 (% time)	BF (reps/min)	Zone 2 (% time)	Zone 3 (% time)	BORG
Outstanding	n=6	664 ± 51	71.7 ± 0.04	126.7 ± 19.7	50.8 ± 4.4	55.8 ± 23.1	32.2 ± 7.5	44.2 ± 25	0.0 ± 0	12.0 ± 3
Above Average	n=9	757 ± 96	75.8 ± 0.05	147.2 ± 16.2	48.2 ± 3.9	37.0 ± 22.7	32.7 ± 5.2	62.4 ± 27	0.6 ± 2	12.0 ± 3
Average	n=13	799 ± 127	79.7 ± 0.06	157.3 ± 13.6	45.9 ± 4.7	19.0 ± 14.2	34.3 ± 3.5	68.9 ± 28	12.1 ± 21	12.0 ± 2
Below Average	n=6	830 ± 34	84.5 ± 0.04	178.3 ± 4.1	39.0 ± 5.3	4.1 ± 4.3	34.4 ± 5.5	87.4 ± 7	8.5 ± 7	14.1 ± 1
Poor	n=7	955 ± 117	84.7 ± 0.04	204.3 ± 21.5	40.4 ± 4.1	3.6 ± 8.8	36.8 ± 2.5	75.6 ± 22	20.8 ± 27	14.3 ± 2

Table 4. Characteristics of the firefighters with TSA-scores ranked into 5 categories: *"Outstanding"* (TSA < −2), *"Above Average"* (TSA −1 to −2), *"Average"* (TSA −0.99 to +0.99), *"Below Average"* (TSA 1 to 2), *"Poor"* (TSA > 2). Means ± SD are presented for REPE (Respiratory Protection Exercise) in terms of exercise completion time, heart rate (HR) and air depletion (AD), the three main performance predictors identified by regression - peak oxygen uptake (VO_{2peak}), physiological intensity zone 1 (Zone 1) and breathing frequency (BF) as well as additional parameters: physiological intensity zones (Zone 2, Zone 3), ratings of perceived exertion (BORG-scale).

during firefighting exercises. Another possible explanation for that can be the influence of a firefighter's turn-out gear and equipment (e.g. SCBA) on different physiological variables. According to Perroni *et al.*[36], wearing additional weight in terms of full protective clothing and the SCBA reduces a subject's VO_{2peak} by ~27% from 55 to 43 ml/min/kg. Therefore, and based on our findings, we suggest that assessing only mean VO_2 values from a simulated firefighting test will fail to represent the demands of firefighting. The pattern of RER provides considerable inside into the true metabolic demands which we found were hidden when assessing only mean VO_2-values.

Mean minute ventilation (67.5 ± 13.2 l/min) across the whole $REPE_{spirometry}$ exercise was lower compared to the values reported from Holmer and Gavhed[27]. Mean breathing frequency was highest averaging 38.9 ± 5.8 breaths per minute during the last task, the *orientation section crawling*. In contrast, subjects mean breathing frequency in the final minute of maximum treadmill testing averaged at 41 ± 5 breaths per minute. Accordingly, subjects were close to their maximum breathing frequency during the *orientation section crawling*, which indicates the strenuous nature of the exercise. These findings are underlined by McArdle, Katch, & Katch[37] showing that breathing frequency increased to 35 to 45 breaths per minute during strenuous exercise. Subjects consumed 54% of the capacity of a nominal 30 min-cylinder during the $REPE_{standard}$ circuit which lasted 801 s (13.2 minutes). However, these rates of compressed air consumption from the SCBA would have depleted the air supply after 1464 s (24.4 min) and that is before the nominal time of 30 min described for the cylinders. These findings are in line with the data reported from Williams-Bell *et al.*[20] who determined similar air consumption rates (~51%) and mean VO_2 values (24 ml/min/kg) for a firefighting exercise of 12.1 minutes duration. For example, the best firefighter regarding his TSA-Score (−4.81) completed the exercise in 10 minutes, consumed 90 bar of compressed air while showing a mean heart rate of 74.2% HR_{max}. He had a VO_{2peak} -level of 49 ml/min/kg, spent 72% of time in zone 1 and breathing frequency averaged at 19 breaths per minute. With the shown values he would not have depleted the air supply before the nominal time.

The reasons for the selection of time for completion, heart rate and air depletion rates for our firefighting performance formula were primarily based on the rationale nature of firefighting. When arriving at an emergency scene, firefighters have to work as fast as possible in order to e.g. save lives or prevent the spread of fires. Furthermore, previous data showed that less fit firefighters experienced higher physiological strain near HR maximum not being able to sustain operating speed and therefore not being able to complete firefighting tasks successfully[12]. Finally, firefighters can run out of air supply due to the limited amount of air compressed in the SCBA. Based on these considerations each of the three factors is thought to be important so that all three parameters were included into our TSA firefighting performance formula. Since at present we do not know which factor is most important or whether one factor is more important than another, we used z-transformations in order to avoid unintended weighting of one of the three parameters.

The results demonstrate that performers of different TSA-levels showed significant differences in maximal endurance parameters, the capacity to work below their ventilatory threshold 1 and breathing variables. This is a strong argument that a high firefighting performance comes along with a good aerobic metabolism and confirms our initial hypothesis: firefighters with lower air depletion from the self-containing breathing apparatus, faster completion time and lower physical strain during the simulated firefighting exercise possess a higher aerobic fitness level in terms of VO_{2peak}. Indeed, this can clearly be proven by a low TSA-score which can be seen as evidence for the usefulness of the new developed firefighting performance formula. For practical application, the TSA-formula also can be used without z-transforming all three parameters. The product of time for exercise completion, mean heart rate and air depletion from the SCBA (Time*Strain*Air Depletion) is highly related to our z-transformed TSA-formula (Time + Strain + Air Depletion) ($r_s = 0.974$, $p = 0.000$). However, further research is needed to validate the model, as a variety of weighting options may even improve predictability of firefighting performance.

Out of all parameters we measured we identified the most important firefighting determinants by means of multiple regression. We found a combination of laboratory (VO_{2peak}) and occupation-specific parameters (breathing frequency and time spent in intensity zone 1 during the simulated firefighting exercise) that predicted TSA-score best, accounting for 70% of the observed variance. These results are in line with the results of Sothmann *et al.*[12], who were one of few research groups recommending a subset of screening tests for firefighters incorporating simulated work tasks as well as fitness measurements. In their study the combination of test items such as hose drag, high rise pack, arm cranking and lifting accounted for 50% of the variance associated with the completion of a work task circuit. However, like other previous studies, Sothmann *et al.*[12] only focused on the completion time of the simulated firefighting tasks for the classification of performance. Other authors found combinations of aerobic fitness and strength parameters accounting for variances around 60%[2,9,14] and 70%[13]. As one of the main differences between our study and previous research, we could not identify any strength parameters as important performance predictors in the regression model. This is surprising given that the characteristics of typical firefighting tasks such as chopping, carrying heavy equipment require the intense use of upper body muscular strength. Except push-ups ($p = 0.039$, $r_s = -0.40$), we found no significant correlations between TSA-score and muscular strength, flexibility and balance variables. Moreover, integrating push-ups into the regression model could not increase the predictive power of 70% of explained total variance. However, with regard to the strength fitness profile our subjects showed a comparable strength level to other studies[11,14,16,38].

Although muscular strength and flexibility in this study did not show significant relevance for the predictive power of job demands, both should be essential components of firefighting training in order to decrease the risk of job injuries.

The results of multiple regression support the idea that aerobic fitness, in terms of VO_{2peak} and the time spent in zone 1, considerably contributes to how fast (time) and effective (low air depletion from SCBA and minimal physical strain) a firefighter can perform his tasks. Treadmill determined VO_{2peak} has been established previously to be important for firefighters[1,5,9,10,28] and thus a high level of VO_{2peak} is postulated. Recommendations for a minimum relative VO_{2peak} - threshold varied between the suggestions of O' Connell[6] with 39 ml*kg^{-1}*min^{-1} and the recommended values by Gledhill and Jamnik[10] with 45 ml*kg^{-1}*min^{-1}. Our results also emphasized the importance of VO_{2peak}, as a high VO_{2peak} is related to a faster operating speed, lower strain and lower air depletion from SCBA. Based on our results, we now recommend a slightly higher minimum VO_{2peak} of 46 ml*kg^{-1}*min^{-1} as this value was identified for subjects showing at least average performance in terms of TSA-scores.

In addition to VO_{2peak} as one of the primary determinants of aerobic endurance performance[30], the time spent in zone 1 was identified to be the second most important fitness factor. Therefore, heart rate kinetics and the contribution of aerobic energy sources need to be considered to play a major role in preparation and shaping of fit and healthy firemen. Furthermore, we found a strong correlation ($r = 0.69$, $p = 0.001$) between VO_2 at VT1 on the treadmill and the time spent in Zone 1 across the REPE exercise. This means that subjects with a high percentage of time spent in zone 1 possessed a high VO_2 at VT1. Those subjects can work at a higher exercise intensity while still covering the energy demand aerobically. Lemon and Hermiston[28] pointed out that firefighters with a higher VO_{2peak} and a high VT1 (as $\%VO_{2peak}$) are able to supply a greater percentage of the total energy demand aerobically which results in more work efficiency in terms of total physiological demands on the organism. These findings can help to design endurance exercise programs for firefighters more detailed by focusing not only on VO_{2peak}-training but also improving VT1. According to Jones and Carter[30], an improvement in VT1 with training is a clear marker of an enhanced endurance capacity.

In our study, VT1 averaged at 49% of VO_{2peak} across all subjects. This is a strong indication to extend basic aerobic endurance training, as values between 50 to $60\%VO_{2peak}$ are related to a low basic endurance level[39]. As suggested by Farrell *et al.*[40], aerobically better trained subjects can exercise at 75–85% of VO_{2peak} while still covering their energy demands aerobically. We therefore recommend a VT1 at 60–80% VO_{2peak} for professional firefighters as it would allow better metabolic adaptation to physical work at this level[41]. It would also enable to increase Zone 1-fraction and reduce the physical strain during firefighting, respectively. Furthermore, breathing rate can be sustained at lower intensity levels and the blow off of the extra CO_2 produced by the buffering of lactic acid metabolites is reduced. Oxygen needs can then be primarily met by an increase in tidal volume instead of increased breathing frequency. Moreover, increased breathing frequency was identified to have a negative effect on TSA-score based on the results of multiple regression.

Conclusions

Firefighting is a physically demanding activity challenging both the aerobic and anaerobic system. While other studies researching firefighting activity focused on VO_2 and HR, we strongly emphasize to also take RER values and VT1 into account when assessing the fitness level of firemen. Based on the results of our study, we recommend a 3-fold fitness analyses for firefighters that allows for designing optimized, detailed and individualized exercise programs for firefighters:

1. Conducting a maximum treadmill test to determine VO_{2peak}, VT1 and RCP
2. Conducting a simulated firefighting exercise to determine physical strain with the help of three physiological intensity zones
3. Using our new developed model TSA: $HR+time + AD$ to characterize performance during specific firefighting simulation.

This approach will help to improve firefighters' physical fitness in order to work healthy, safe and effective. For practical application, the TSA-formula also works without z-transformations and can therefore serve as a simple model for daily use in fire brigades.

References

1. Bilzon, J., Scarpello, E. G., Smith, C. V., Ravenhill, N. A. & Rayson, M. P. Characterization of the metabolic demands of simulated shipboard Royal Navy fire-fighting tasks. *Ergonomics.* **44,** 766–780 (2001).
2. Davis, P. O., Dotson C. O. & Laine D. Relationship between simulated fire fighting tasks and physical performance measures. *Medicine & Science in Sports & Exercise* **14,** 65–71 (1982).
3. Del Sal, M. *et al.* Physiologic Responses Of Firefighter Recruits During A Supervised Live-Fire Work Performance Test. *Journal of Strength and Conditioning Research* **23,** 2396–2404 (2009).
4. Elsner, K. & Kolkhorst, F. W. Metabolic demands of simulated firefighting tasks. *Ergonomics* **51,** 1418–1425 (2008).
5. Heimburg, E., Rasmussen, A. & Medbö, J. Physiological responses of firefighters and performance predictors during a simulated rescue of hospital patients. *Ergonomics* **49,** 111–126 (2006).
6. O'Connell, E., Thomas, P. C., Cady, L. D. & Karawasky, R. J. Energy Cost of Simulated Stair Climbing as a Job-Related Task in Fire Fighting. *J Occup Med.* **28,** 282–284 (1986).
7. Perroni, F. *et al.* Energy Cost And Energy Sources During A Simulated Firefighting Acitivity. *Journal of Strength and Conditioning Research* **24,** 3457–3463 (2010).
8. Sothmann, M. S. *et al.* Oxygen consumption during fire suppression: error of heart rate estimation. *Ergonomics* **34,** 1469–1474 (1991).
9. Williams-Bell, F. M., Villar, R., Sharrat, M. T. & Hughson, R. L. Physiological Demands of the Firefighter Candidate Physical Ability Test. *Medicine & Science in Sports & Exercise* **41,** 653–662 (2009).
10. Gledhill, N. & Jamnik, V. K. Development and validation of a fitness screening protocol for firefighter applicants. *Can J Sport Sci.* **17,** 199–206 (1992).
11. Rhea, M. & Alvar, B. & Gray, R. Physical Fitness and Job Performance of Firefighters. *Journal of Sport and Health Science* **18,** 348–352 (2004).
12. Sothmann, M. S., Gebhardt, D. L., Baker, T. A., Kastello, G. M. & Sheppard, V. A. Performance requirements of physically strenuous occupations: validating minimum standards for muscular strength and endurance. *Ergonomics* **47,** 864–875 (2004).
13. Williford, H. N., Duey, W. J., Olson, M. S., Howard, R. & Wang, N. Relationship between fire fighting suppression tasks and physical fitness. *Ergonomics* **42,** 1179–1186 (1999).
14. Michaelides, M., Koulla, M. P., Leah, J. H., Gerald, B. T. & Brown, B. Assessment Of Physical Fitness Aspects And Their Relationship To Firefighters' Job Abilities. *Journal of Strength and Conditioning Research* **24,** 956–965 (2011).
15. Harvey, D. G., Kraemer, J. L., Sharatt, M. T. & Hughson, R. L. Respiratory gas exchange and physiological demands during a fire fighter evaluation circuit in men and women. *Eur J Appl Physiol.* **103,** 89–98 (2008).
16. Lindberg, A. S., Oksa, J. & Malm, C. Laboratory or Field Tests for Evaluating Firefighters' Work Capacity? *PloS One* **9,** 1–13 (2014).
17. Lindberg, A. S., Oksa, J., Gavhed, G. & Malm, C. Field Tests for Evaluating the Aerobic Work Capacity of Firefighters. *PloS One* **8,** 1–8 (2013).
18. Williams-Bell, F. M., Boisseau, G., McGill, J., Kostiuk, A. & Hughson, R. L. Air management and physiological responses during simulated firefighting tasks in a high-rise structure. *Applied Ergonomics* **41,** 251–259 (2010).
19. Gendron, P., Freiberger, E., Laurencelle, L., Trudeau, F. & Lajoie, C. Greater physical fitness is associated with better air ventilation efficiency in firefighters. *Applied Ergonomics* **47,** 229–235 (2015).
20. Williams-Bell, F. M., Boisseau, G., McGill, J., Kostiuk, A. & Hughson, R. L. Physiological responses and air consumption during simulated firefighting tasks in a subway system. *Applied physiology, nutrition, and metabolism = Physiologie appliquée, nutrition et métabolisme* **35,** 671–678 (2010).
21. Ellestad, M., Allen, W., Wan, M. & Kemp, G. Maximal Treadmill Stress Testing for Cardiovascular Evaluation. *Circulation* **39,** 517–522 (1969).
22. Beaver, W. L., Wassermann, K. & Whipp, B. J. A new method for detecting anaerobic threshold by gas exchange. *J. Appl. Physiol.* **60,** 2020–2027 (1986).
23. Oshima, Y. *et al.* Relationship between isocapnic buffering and maximal aerobic capacity in athletes. *European Journal of Applied Physiology and Occupational Physiology* **76,** 409–414 (1997).
24. Committee for Firefighting Issues, Civil Protection and Civil Defense. *Firefighting Service Regulations 7*. 1–25 (Bodenheim, Germany, 2002).
25. Borg, G. Psychophysical bases of perceived exertion. *Med Sci Sports Exerc.* **14,** 377–381 (1982).
26. Cohen J. *Statistical Power Analysis for the Behavioral Sciences. 91* (Hillsdale, NJ: Erlbaum, 1988).
27. Holmer, I. & Gavhed, D. Classification of metabolic and respiratory demands in fire fighting activity with extreme workloads. *Applied Ergonomics* **38,** 45–52 (2007).
28. Lemon, P. W. R. & Hermiston, P. H. D. The Human Energy Cost of Fire Fighting. *J Occup Med.* **19,** 558–562 (1977).
29. Ljubicic, A., Varnai, V. M., Petrinec, B. & Macan, J. Response to thermal and physical strain during flashover training in Croatian firefighters. *Applied Ergonomics* **45,** 544–549 (2014).
30. Jones, A. M. & Carter, H. The Effect of Endurance Training on Parameters of Aerobic Fitness. *Sports Medicine* **29,** 373–386 (2000).
31. Rodríguez-Marroyo, J. A. *et al.* Physical and thermal strain of firefighters according to the firefighting tactics used to suppress wildfires. *Ergonomics* **54,** 1101–1108 (2011).
32. Tordi, N., Perrey, S., Harvey, A. & Hughson, R. L. Oxygen uptake kinetics during two bouts of heavy cycling separated by fatiguing sprint exercise. *J Appl Physiol.* **94,** 533–541 (2003).
33. Davis, J. A., Vodak, P., Wilmore, J. H., Vodak, J. & Kurtz, P. Anaerobic threshold and maximal aerobic power for three modes of exercise. *Journal of Applied Physiology* **4,** 544–550 (1976).
34. Ferrauti, A., Bergeron, M. F., Pluim, B. M. & Weber, C. Physiological responses in tennis and running with similar oxygen uptake. *Eur J Appl Physiol.* **85,** 27–33 (2001).

35. Smekal, G. *et al.* Changes in blood lactate and respiratory gas exchange measures in sports with discontinuous load profiles. *Eur J Appl Physiol.* **89,** 489–495 (2003).
36. Perroni, F. *et al.* Do Italian fire fighting recruits have an adequate physical fitness profile for fire fighting? *Sport Sci Health.* **4,** 27–32 (2008).
37. McArdle, W. D., Katch, F. I. & Pechar, G. Reliability and interrelationships between maximal oxygen intake, physical work capacity, and step-test scores in college women. *Med Sci Sports.* **4,** 182–186 (1972).
38. Perroni, F. *et al.* Physical Fitness Profile of Professional Italian Firefighters: Differences between age-groups. *Applied Ergonomics* **45,** 456–461 (2014).
39. Wassermann, K. & Whipp, B. J. Exercise Physiology in Health and Disease. *American Review of Respiratory Disease* **112,** 219–249 (1975).
40. Farrell, P., Wilmore, J. H., Coyle, E. F., Billing, J. E. & Costill, D. L. Plasma lactate accumulation and distance running performance. *Med Sci Sports Exerc.* **11,** 338–334 (1979).
41. Bunc, V., Heller, J., Leso, J., Sprynarova, S. & Zdanowicz, R. Ventilatory Threshold in Various Groups of Highly Trained Athletes. *Int J Sports Med.* **8,** 275–280 (1987).
42. Brzycki, M. Strength Testing - Predicting a One-Rep Max from Reps-to-Fatigue. *Journal of Physical Education, Recreation & Dance* **64,** 88–90 (1993).
43. American College of Sports Medicine. *ACSM's Guidelines for Exercise Testing and Prescription. 325,* (MD: Lippincott Williams & Wiki, 2010).

Acknowledgements

The authors thank AOK Bayern – Die Gesundheitskasse (German health insurance) and Flughafen München GmbH (Munich airport) for the financial support. Finally, the authors especially thank Munich Airport firefighters for volunteering for this research. This work was also supported by the German Research Foundation (DFG) and the Technische Universität München within the funding programme Open Access Publishing.

Author Contributions

St.W., A.S. and D.H. conceived and designed the experiments. St.W. performed the experiments. St.W., W.S. and D.H. analyzed the data. All authors discussed the results and contributed equally to the elaboration of the manuscript.

Additional Information

Competing Interests: The authors declare no competing financial interests.

How to cite this article: Windisch, S. *et al.* Relationships between strength and endurance parameters and air depletion rates in professional firefighters. *Sci. Rep.* **7**, 44590; doi: 10.1038/srep44590 (2017).

Publisher's note: Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

This work is licensed under a Creative Commons Attribution 4.0 International License. The images or other third party material in this article are included in the article's Creative Commons license, unless indicated otherwise in the credit line; if the material is not included under the Creative Commons license, users will need to obtain permission from the license holder to reproduce the material. To view a copy of this license, visit http://creativecommons.org/licenses/by/4.0/

© The Author(s) 2017

8.2 Physiological responses to firefighting in extreme temperatures do not compare to firefighting in temperate conditions (Study II)

Authors: Stephanie Windisch, Wolfgang Seiberl, Daniel Hahn and Ansgar Schwirtz

First Author: Stephanie Windisch

Current Status: Published in *Scientific Reports*

Individual contribution:

The author of this dissertation is the main author of this paper. The PhD candidate was mainly responsible for the development of the research idea, the theoretical framework and the design of the study in agreement with Prof. Dr. Ansgar Schwirtz and Prof. Dr. Daniel Hahn. The author of this dissertation collected the data at Munich Airport, Germany. The author carried out the analysis of the data and wrote the manuscript, always in agreement with Prof. Dr. Ansgar Schwirtz, Prof. Dr. Daniel Hahn und Dr. Wolfgang Seiberl. The manuscript was revised by Prof. Dr. Daniel Hahn und Dr. Wolfgang Seiberl. The final approval of the manuscript was provided by the author of this dissertation in agreement with Prof. Dr. Ansgar Schwirtz, Prof. Dr. Daniel Hahn and Dr. Wolfgang Seiberl. The PhD candidate was mainly responsible for the whole submission process and the integration of the reviewer's feedback into the paper, in agreement with Prof. Dr. Ansgar Schwirtz, Prof. Dr. Daniel Hahn and Dr. Wolfgang Seiberl.

Summary and main results:

This section provides a summary of the main results of Study II. For details regarding the methods, results, discussion and conclusions, please see the original manuscript in Appendix B. The primary aim of this study was to examine physiological responses to two different simulated firefighting exercises: a firefighting exercise with flashovers, smoke, poor visibility and extreme temperatures (300°) in a burning container and a standard firefighting exercise in temperate conditions (20° - 30°). Furthermore, a second aim of the study was to ascertain whether the contribution of strength and endurance capacities to firefighting performance changes when the demands of the firefighting exercise change.

Sixteen professional firefighters from Munich Airport took part in the study (39 ± 9 yr, 176.9 ± 0.1 cm, 82.1 ± 7.6 kg, BMI 26.3 ± 2.4 kg/m^2). Relative VO_{2peak} averaged 44.1 ± 5.8 ml/min/kg in the treadmill testing, with a mean HR_{max} of 182.4 ± 11.9 bpm. VT1 averaged at 2.12 ± 0.27 l/min (59.4 % VO_{2peak}), and RCP averaged at 3.27 ± 0.40 l/min (87.9 % VO_{2peak}). Expressed as a percentage of HR_{max}, VT1 showed up at 70.3 ± 7.7 % HR_{max} and RCP at 91.1 ± 6.0 % HR_{max}. No significant difference (p = .899) could be found between the TSA scores of the SFE (0.07 ± 2.01) and FOT (0.00 ± 2.12). Mean HR was lower (p = .005) during SFE (145 ± 12 bpm) than during the FOT (155 ± 11 bpm). When the mean HR was given as a percentage of maximal HR, SFE averaged at 79.9 ± 6.9 % HR_{max} and FOT at 85.4 ± 5.2 % HR_{max}. 1D-SPM analyses showed that the HR trajectories of SFE and FOT were significantly different over long periods of time. The critical threshold of 3.656 was first exceeded within the first 10% of completion time, albeit only for 25 seconds. However, the second time the threshold was exceeded after 43% of the mean completion time.

From this point, the significant difference showed up until the end of the exercise. During SFE, subjects spent 24.6 ± 30.2 % of the time in Zone 1, 65.8 ± 28.1 % in Zone 2 and 9.7 ± 16.6 % in Zone 3. During FOT, subjects spent 16.3±12.8 % in Zone 1, 50.4 ± 13.2 % in Zone 2 and 33.3 ± 16.6 % in Zone 3.

Out of all correlations, relative VO_{2peak} showed the highest relation to mean HR during SFE (r = -.593) as well as FOT (r = -.693). Furthermore, firefighting performance in terms of TSA scores during the SFE was strongly correlated to the time that subjects spent in Zone 1 during this exercise (r = - .547). TSA scores of the FOT were strongly correlated to the time that subjects spent in Zone 3 during FOT (r = .587).

frontiers in Physiology

ORIGINAL RESEARCH
published: 23 August 2017
doi: 10.3389/fphys.2017.00619

Physiological Responses to Firefighting in Extreme Temperatures Do Not Compare to Firefighting in Temperate Conditions

Stephanie Windisch[1], Wolfgang Seiberl[1], Daniel Hahn[2,3] and Ansgar Schwirtz[1]*

[1] Department of Biomechanics in Sports, Technical University of Munich, Munich, Germany, [2] Human Movement Science, Ruhr-University Bochum, Bochum, Germany, [3] School of Human Movement and Nutrition Sciences, University of Queensland, Brisbane, QLD, Australia

Purpose: The aim of this study was to examine physiological responses to two different simulated firefighting exercises: a firefighting exercise with flashovers, smoke, poor visibility and extreme temperatures (300°) in a burning container and a standard firefighting exercise in temperate conditions. Furthermore, a second purpose of the study was to find out if the contribution of strength and endurance capacities to firefighting performance changes when the demands of the firefighting exercise change.

Methods: Sixteen professional firefighters performed a maximum treadmill test, strength testing, a standard simulated firefighting exercise (SFE) without heat and flashovers and a firefighting exercise with a simulation of the flashover phenomenon in a burning container (FOT). The treadmill testing was used to determine peak oxygen uptake (VO_{2peak}), ventilatory threshold (VT1) and respiratory compensation point (RCP). Three intensity zones were identified according to heart rate (HR) values corresponding to VT1 and RCP: zone 1–HR below VT1, zone 2-HR between VT1 and RCP, zone 3–HR above RCP. Firefighting performance was determined by a simple time-strain-air depletion model (TSA) taking the sum of z-transformed parameters of time to finish the exercise, strain in terms of mean heart rate, and air depletion from the breathing apparatus. Correlations were then established between TSA based firefighting performance parameters and fitness variables representing strength and endurance.

Results: HR was significantly lower during SFE ($79.9 \pm 6.9\%HR_{max}$) compared to FOT ($85.4 \pm 5.2\%HR_{max}$). During SFE subjects spent 24.6 ± 30.2% of time in zone 1, 65.8 ± 28.1% in zone 2 and 9.7 ± 16.6% in zone 3. During FOT subjects spent 16.3 ± 12.8% in zone 1, 50.4 ± 13.2% in zone 2 and 33.3 ± 16.6% in zone 3. Out of all correlations, relative VO_{2peak} showed the highest relation to mean HR during SFE (−0.593) as well as FOT (−0.693).

Conclusions: Endurance in terms of VO_{2peak} is an important prerequisite for both firefighting exercises. However, for standard simulated firefighting exercises it is important to work below VT1. For firefighting exercises in extreme temperatures with smoke, poor visibility and unexpected flashovers a high fitness level is required in order to keep the time spent above RCP as short as possible.

Keywords: simulated firefighting in extreme temperatures, firefighting performance model, strength and endurance tests, firefighter fitness, aerobic anaerobic metabolism during firefighting

OPEN ACCESS

Edited by:
Igor B. Mekjavic,
Jožef Stefan Institute, Slovenia

Reviewed by:
Ben Rattray,
University of Canberra, Australia
Naoto Fujii,
University of Tsukuba, Japan

****Correspondence:***
Stephanie Windisch
stephanie.windisch@tum.de

Specialty section:
This article was submitted to Exercise Physiology, a section of the journal Frontiers in Physiology

Received: *05 May 2017*
Accepted: *09 August 2017*
Published: *23 August 2017*

Citation:
Windisch S, Seiberl W, Hahn D and Schwirtz A (2017) Physiological Responses to Firefighting in Extreme Temperatures Do Not Compare to Firefighting in Temperate Conditions. Front. Physiol. 8:619. doi: 10.3389/fphys.2017.00619

INTRODUCTION

Firefighting is an occupation characterized by sudden bouts of high-intensity workloads when firefighters respond to an emergency. Previous studies revealed that firefighters showed physiological responses of 80% heart rate maximum (HR_{max}) on average with a range from 60 to 90% HR_{max} (e.g., von Heimburg et al., 2006; Del Sal et al., 2009; Williams-Bell et al., 2009; Perroni et al., 2010). Researchers found these values while conducting simulated firefighting tasks carried out at a safe and efficient pace. Furthermore, the majority of the reported data were collected without environmental stressors such as extreme temperatures caused by fire. Firefighters are also required to perform sudden exercises in hot and extreme environments accompanied by smoke and poor visibility. Therefore, it is important to know which job-related physiological fitness requirements they need for carrying out firefighting tasks in a safe, healthy and efficient manner. Based on the established job demands for standard workload bouts for the routine job, researchers varied in their recommendations for fitness levels such as a minimum of peak oxygen uptake (VO_{2peak}) between 39 and 45 ml/min/kg (O'Connell et al., 1986; Gledhill and Jamnik, 1992; Siddall et al., 2016).

Maintaining the proposed fitness levels means that standard workload bouts can be completed safely. However, as stated by Astrand et al. (2012), the level of fitness should be well above the one required for completing the job routine as researched in simulated firefighting exercises. This extra level of fitness can be required when the exposure to heat represents an additional burden for the cardiovascular system leading to reduced productivity and increased exertion (Larsen et al., 2015). This was observed in some studies reporting more than 88% HR_{max} during simulated firefighting with thermal stress or actual emergencies (Barnard and Duncan, 1975; Sothmann et al., 1992; Smith et al., 1997) while simulated firefighting without heat averaged at 80% HR_{max} (von Heimburg et al., 2006; Del Sal et al., 2009; Perroni et al., 2010). Furthermore, the unpredictability of changing situations in real fire emergency scenes can be an additional stressor. Feared hazards are, for example, suddenly occurring flashovers. This happens when a fire reaches its ignition temperature and spreads rapid unexpectedly.

Firefighters' responses to heat in combination with suddenly occurring dangerous situations such as a flashover have hardly been established yet. A few studies documented significantly higher physiological strain of firefighting exercises in hot environments (up to 100°) compared to those without heat in temperate conditions (<40°) (Smith et al., 1996, 1997; Larsen et al., 2015) but flashover training was not part of these studies. Additionally, they did not provide any information on how endurance and strength variables were related to firefighting in distinct thermal environments.

Abbreviations: BMI, Body-Mass-Index; FOT, Flashover training; HR, Heart rate; HR_{max}, Maximum heart rate; RCP, Respiratory compensation point; RER, Respiratory exchange ratio; SCBA, Self-containing breathing apparatus; SD, Standard deviation; SFE, Standard simulated firefighting exercise; TSA, Time-strain-air depletion; VCO_2, Carbon dioxide output; V_E, Ventilation; VO_2, Oxygen consumption; VO_{2peak}, Peak oxygen uptake; VT1, Ventilatory threshold 1.

In a previously published study (Windisch et al., 2017), we investigated a simulated standard firefighting exercise (SFE) without heat, smoke, poor visibility and unpredictable situations such as flashovers and determined firefighting performance by a time-strain-air depletion model (TSA-model). By conducting the present study, we now seek to understand whether and how physiological strain changes when performing a flashover training (FOT) in a burning container including smoke, poor visibility, extreme temperatures and unpredictable situations like flashovers. Both exercises, the SFE and the FOT, are mandatory standard exercises for professional firefighters in Germany and claim to represent firefighting job demands, albeit they are quite different. Therefore, we defined two main objectives for this research: (1) To examine the extent to which the two different simulated firefighting exercises impact on physiological responses of firefighters. (2) To show whether and to what extent the importance of strength and endurance capacities change when the demands of the firefighting exercise change. To define firefighting performance, we used our previously established model, the TSA score (Windisch et al., 2017). Understanding the fitness contribution with respect to the different characteristics of various firefighting exercises enables firefighters to properly prepare for the job requirements.

MATERIALS AND METHODS

Study Subjects

Sixteen professional firefighters from Munich Airport volunteered for this research (39 ± 9 yr, 176.9 ± 0.1 cm, 82.1 ± 7.6 kg, BMI 26.3 ± 2.4 kg/m^2). Mean service time of participants was 17 ± 8 years. All participants were in possession of a valid G26.3 medical examination for operational fitness, a mandatory periodically medical health check for professional firefighters in Germany. The G26.3 medical examination includes an eye test, a hearing test, an exercise electrocardiogram, a blood test and a pulmonary function test.

Experimental Design

All participants completed four tests on four different days to investigate differences in physiological responses to firefighting with and without the presence of extreme heat and which fitness parameters were sensitive for both exercises.

Treadmill Testing

Subjects were dressed in T-shirts, shorts and training shoes. Minute ventilation (V_E) and gas exchange (oxygen consumption—VO_2, carbon dioxide output—VCO_2, respiratory exchange ratio - RER) were measured breath-by-breath with the Cortex Metamax 3B (Cortex Biophysics GmbH, Germany). The incremental exercise test based on the Ellestad Protocol (Ellestad et al., 1969) was conducted on a motorized treadmill (Life Fitness, Integrity Series, Germany) to determine peak oxygen uptake (VO_{2peak}), total time to exhaustion and heart rate maximum (HR_{max}). The test was terminated when subjects reached volitional fatigue and were not able to continue running. VO_{2peak} and HR_{max} were taken as the highest 30 s-average during the final minute of the test. In addition, based on the test, two thresholds were determined: ventilatory threshold 1 (VT1) and respiratory compensation point (RCP). The VT1 was determined from the V-slope method (Beaver et al., 1986) in combination with the break point of the ventilatory equivalent for O_2 against VO_2 (Oshima et al., 1997). The RCP was identified by the break points of the ventilatory equivalent for CO_2 and the end tidal CO_2 concentration against VO_2 (Oshima et al., 1997). VT1 indicates the first turnpoint of ventilation (V_E) and ventilatory equivalent ratio for oxygen (V_E/VO_2) (Wassermann and McIlroy, 1964). In contrast, RCP indicates the maximal lactate steady state, equivalent to the second turn point for V_E and V_E/VO_2. These two thresholds were then used to establish three physiological intensity zones that correspond to the heart rates at the following exercise intensities: HR below VT1 (Zone 1), HR between VT1 and RCP (Zone 2) and HR above RCP (Zone 3) (Windisch et al., 2017).

Standard Simulated Firefighting Exercise (SFE)

This exercise is a standardized, mandatory and periodically performed ability test for professional German firefighters. The test was conducted as prescribed by German firefighting test regulations (Committee for Firefighting Issues Civil Protection and Civil Defense, 2002). Subjects were tested in a purpose-built practice area, wearing full personal protection gear and a self-containing breathing apparatus (SCBA). The SCBA cylinders were filled with 300 bar (metric unit of the pressure in the SCBA; 1 bar = 100 kPa). The tasks included *ladder climb* (20 m), a 200 m *treadmill walk*, pulling a wire rope *hoist* (15 times) and *crawling* a 50 m *orientation section* in the dark with bottlenecks and a narrow tunnel. Subjects were instructed to perform the SFE safely and as fast as possible but in a pace similar to the work at a real fire emergency scene. The environmental conditions were temperate (20°–30°). HR was measured continuously (Polar, Finland) and ratings of perceived exertion (Borg, 1982) as well as air depletion from the SCBA were taken at the end of the exercise. Total performance time was recorded.

Flashover-Training (FOT)

The FOT was performed in a special container with a computer-controlled and gas-fired mobile fire simulation training system (Model Firetrainer112, Blaul und Seifert GmbH, Germany). This exercise is also part of periodically performed simulated firefighting exercises in Germany. The training closely simulated the variety and intensity of tasks during a real fire suppression while subjects were exposed to extreme heat (300°) and smoke. Participants were dressed with their personal protective gear (clothing, helmet, gloves, belt, facial mask, boots) and the SCBA for air supply (24.5 kg). Air cylinders were filled with 300 bar. The pressure gauge on the display of the SCBA measured depletion in steps of 10 bar. At the end of the FOT the remaining pressure in the cylinder was read from the SCBA display to determine depletion. The amount of changes in pressure was defined as air depletion. Similar to a real emergency case, each firefighter carried various hand tools (e.g., a hose for fire suppression, a thermal imaging camera). An expert specialized on carrying out flashover trainings supervised the training drill.

Firefighters had to complete the following tasks without interruption:

1. Participants first climbed a 4-m ladder up to the top of the container for access through a door on the top.
2. After opening the door, they had to extinguish the first staircase fire on the stairs that would allow them to enter the container.
3. After successfully extinguishing the staircase fire, firefighters entered the container checking further fire (5 different kinds of fires across the enclosed area (20 m^2) of the training container: stair case fire again, gas cylinder fire, armchair fire, simulation of an oil fire). Furthermore, every firefighter experienced two unexpected flashovers.
4. The sequence of fires was generated randomly for each subject in order to perpetuate the realistic character of a real fire scene in terms of the unpredictability of a situation at an emergency scene.

Heart rate was measured during the drill, and recovery of HR was measured 1, 3, 5, and 30 min after terminating the drill. Ratings of perceived exertion (Borg, 1982) were recorded after the end of the FOT.

For both, the SFE and FOT, firefighting performance was defined by the TSA-model resulting in a TSA-score as shown in a previous study (Windisch et al., 2017). The TSA-model is a simple formula to quantify the demands of the exercises adding time needed for the exercise, mean heart rate during exercise expressed as percentage of the treadmill determined HR_{max} and air depletion from the SCBA. As the score is based on the function of a z-score, the TSA-score indicates the resultant firefighting performance in relation to the sample mean, with the units measured in standard deviations. A TSA-score of 0 represents the average. We ranked performers according to their TSA-scores into 5 categories based on standard deviations: "Outstanding" (TSA < -2), "Above Average" (TSA -1 to -2), "Average" (TSA -0.99 to $+0.99$), "Below Average" (TSA 1–2), and "Poor" (TSA > 2). Individual performance scores for the TSA should be kept at a minimum achieved through fast completion time, low heart rate as well as low air depletion during the exercise.

Strength Testing

Strength testing included a standing long jump, legpress 1-RM testing, and maximum handgrip strength. Furthermore, subjects performed maximal possible repetitions of push-ups, partial curl-ups, shoulder press and rowing. The tests were conducted as described in our previously published study (Windisch et al., 2017).

Data Analyses

All data are presented as means ± standard deviation (SD). Data were analyzed using SPSS (Version 23.0, SPSS Inc. Chicago, IL, USA). Data were assumed to be normally distributed if the Shapiro-Wilk's test revealed $p > 0.05$. As all data was normally distributed, parametric tests were carried out. The alpha level was set to 0.05. Paired t-tests were calculated to show up differences between different variables of the two firefighting exercises SFE and FOT. Pearson correlations were computed for specific physiological parameters. Statistical significance was set at $p < 0.05$ and correlations were interpreted according to Cohen (1988). Values from 0.10 to 0.29 were considered "small," 0.30–0.49 "moderate" and ≥0.50 "strong." In order to identify significant differences in heart rate trajectories of the SFE vs. the FOT, methods of one-dimensional (1D) statistical parametric mapping (SPM) were used (Friston et al., 1995). SPM 1D-analyses were processed as described in Pataky (2010). All data were implemented in Matlab R2016a (8.3.0.532) and normalized to the participants' individual completion time using matlab "interpft" function. Basically, a FFT method was used, where the original vector was transformed to the Fourier domain and then transformed back with desired data points (here 100, representing 100% of completion time). In addition, data was processed with the open source SPM code by Pataky (2016) for two-tailed paired t-tests. The critical test statistic threshold that retained a family-wise error rate of $\alpha = 0.05$ was calculated as described by Pataky et al. (2015). If the SPM{t} trajectory crossed the critical threshold at any time node, the null hypothesis was rejected meaning that the HR trajectories of SFE and FOT are significantly different.

RESULTS

Treadmill and Strength Testing

Total time to exhaustion during treadmill testing averaged 10.3 ± 0.9 min and subjects reached a mean HR_{max} of 182.4 ± 11.9 bpm on the treadmill and a mean absolute VO_{2peak} of 3.59 ± 0.43 l O_2/min. Corrected for body mass, relative VO_{2peak} averaged 44.1 ± 5.8 ml/min/kg. V_E at VO_{2peak} was 124.7 ± 23.3 l/min. VT1 averaged at 2.12 ± 0.27 l/min (59.4% VO_{2peak}), RCP averaged at 3.27 ± 0.40 l/min (87.9% VO_{2peak}). Expressed as a percentage of HR_{max}, VT1 showed up at 70.3 ± 7.7% HR_{max} and RCP at 91.1 ± 6.0% HR_{max}.

Subjects performed 115.1 ± 22.6 kg at the legpress, 81 ± 36 partial-curl ups and 25 ± 12 push-ups. Hand grip strength averaged 56.5 ± 8.6 kg and standing long jump 211 ± 22 cm. Mean repetitions to fatigue of shoulderpress and rowing were 22 ± 6 and 10 ± 4, respectively.

Physiological Responses to SFE and FOT

No significant difference ($p = 0.899$) could be found between TSA-scores of the SFE (0.07 ± 2.01) and FOT (0.00 ± 2.12). We could not identify a significant correlation between the two TSA-scores of both exercises ($r = 0.495$, $p = 0.051$). We also analyzed every single component of the TSA-model (completion time, strain in terms of heart rates and air depletion from SCBA). There was a significant difference in completion time between both exercises ($p = 0.003$). Mean completion time of the SFE was 13.2 ± 1.8 min, for the FOT completion time averaged at 15.5 ± 1.2 min. Air depletion from the SCBA were significantly higher ($p = 0.001$) during the SFE with 162 ± 24 bar (54.0 ± 0.08% of full SCBA) compared to the FOT 140 ± 24 bar (46.7 ± 0.08%). Mean HR was lower ($p = 0.005$) during SFE (145 ± 12 bpm) than during the FOT (155 ± 11 bpm). When mean HR was given as a percentage of maximal HR, SFE averaged at 79.9 ± 6.9% HR_{max} and FOT at 85.4 ± 5.2% HR_{max}. **Figure 1** displays mean HR-kinetics of all subjects across both exercises and the time they spent in the three defined physiological intensity zones (zone 1, zone 2, zone 3).

1D-SPM analyses showed that HR trajectories of SFE and FOT were significantly different over long periods of time (see **Figure 2**). The critical threshold of 3.656 was first exceeded within the first 10% of completion time but only for 25 s. However, the second time the threshold was exceeded after 43% of mean completion time. From this point the significant difference showed up until the end of the exercise. The precise probability that a supra-threshold cluster of this size – as described by Pataky et al. (2015)—would be observed in repeated random samplings was $p = 0.008$ for the first and $p < 0.001$ for the second cluster.

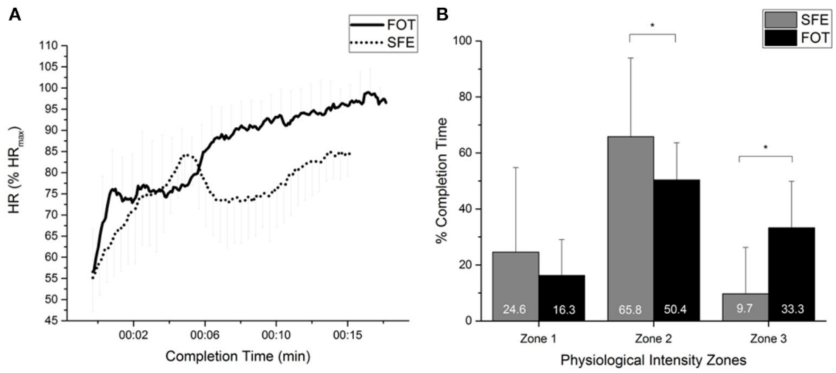

FIGURE 1 | Physiological responses and energy contributions of both exercises **(A)** Kinetics of HR during SFE and FOT, taken as the average value of % of HR_{max} (± SD) of all 16 subjects **(B)** Percentage of time spent in three physiological intensity zones (zone 1 – Z1: below treadmill-determined ventilatory threshold 1 (VT1); zone 2 – Z2: between VT1 and RCP; zone 3- Z3: above treadmill-determined respiratory compensation point (RCP). *Significant difference between physiological intensity zones ($P < 0.05$).

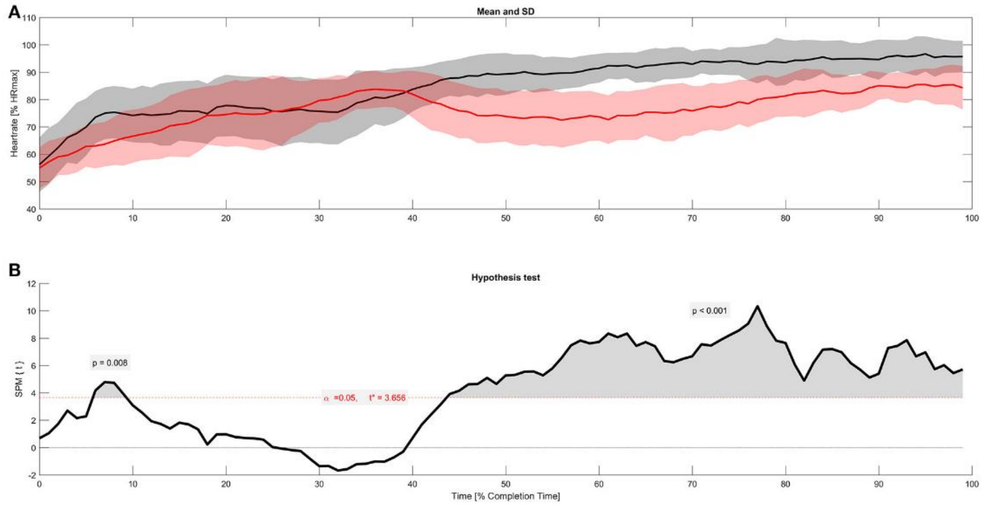

FIGURE 2 | 1D-SPM analyses **(A)** Kinetics of HR of all 16 subjects during SFE and FOT, taken as the average value of % of HR_{max} (± SD) and normalized on subject's individual completion time **(B)** 1D-SPM trajectory resulting from 1D-SPM statistics retaining a family-wise error rate of $\alpha = 0.05$. The critical threshold was at $t = 3.656$.

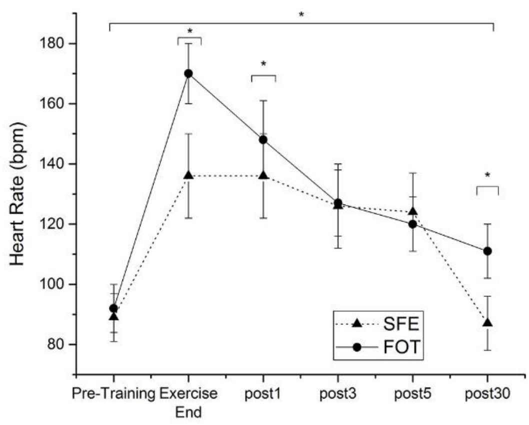

FIGURE 3 | Heart rate (HR) at the end of the exercise and HR recovery 1, 3, 5, and 30 min after SFE and FOT. *Significant difference between heart rate recovery of SFE and FOT ($P < 0.05$).

Heart rates decreased to baseline values after the SFE whereas HR remained elevated compared to pre-training values 30 min after FOT (plus 20 ± 10 bpm). BORG ratings of perceived exertion showed significant differences ($p = 0.000$) between SFE (12 ± 2) and FOT (15 ± 1). **Figure 3** gives an overview of HR recovery 1, 3, 5, and 30 min after SFE and FOT.

Firefighting Performance Related to Fitness Measurements

Firefighting performance in terms of TSA-scores during the SFE was strongly correlated to the time subjects spent in zone 1 during this exercise ($r = -0.547$). TSA-scores of the FOT were strongly correlated to the time subjects spent in zone 3 during FOT ($r = 0.587$). Correlations between TSA-scores and its single components completion time, heart rates and air depletion during both exercises are shown in **Table 1**.

No significant correlations between recovery heart rates of SFE and TSA-Score could be found. For FOT, TSA-score ($r = -0.760$) and air depletion ($r = -0.904$) were highly related to recovery heart rate after 1 min.

TSA-scores were strongly correlated to relative VO_{2peak} during both SFE ($r = -0.505$) and FOT ($r = -0.621$). Significant correlations between TSA-scores of the SFE and strength are shown in **Table 2**. No significant correlations could be found between TSA-scores of the FOT and strength parameters.

Two physiological intensity zones (zone 1, zone 2) were strongly related ($r > 0.50$) to different physiological and strength variables for the SFE, but we found no significant correlation between fitness variables and zone 3 (see **Table 3**). Only one significant relationship (curl-ups, $r = 0.720$) could be found between the time spent in zone 1 during FOT and strength. Time spent in zones 2 and 3 were strongly ($r > 0.50$) related to many of the physiological and strength variables (see **Table 3**).

DISCUSSION

Physiological Responses to SFE and FOT

Based on a previous study we considered three parameters important for firefighting performance: time to exercise completion, heart rate during the exercise and air depletion, which we combined in the TSA-model (Windisch et al., 2017). According to this model, the performance of firefighters during the two firefighting exercises in this present study were classified as average. We also investigated the relationship between TSA-scores of both exercises but they were not significantly related to each other. We determined a p-value of $p = 0.051$ meaning that significance was narrowly missed. On closer inspection, we found one outlier indicating above average performance (TSA-score: −1.58) in the firefighting exercise without heat compared to below average performance (TSA-score: 2.85) during the firefighting exercise in extreme temperatures. This firefighter showed the largest change of performance as measured by the TSA-score between both exercises. When excluding this outlier from our data, we found a strong and significant relationship between the two TSA-scores of both exercises ($r = 0.629$, $p = 0.012$) (**Figure 4**). This means that firefighters with a good TSA-score in the standard firefighting exercise showed also a good score in the flashover training. Basically, this strong relationship proves that determining firefighting performance with the TSA-score works and that the TSA-score can be applied to different firefighting exercises.

Regarding the single components of the TSA-model, we found completion time to be shorter during the standard firefighting exercise while participants depleted more air compared to the firefighting exercise in extreme temperatures. One possible reason for these different breathing responses could be hyperthermia-induced hyperventilation meaning that hyperventilation patterns during exercise are changed due to hyperthermia. As shown by Fujii et al. (2008), ventilatory sensitivity to increasing core temperature above the threshold for hyperventilation was lower during moderate exercise in the heat than at rest. This means that ventilation can be attenuated at certain submaximal exercise levels due to hyperthermic conditions in the body (Beaudin et al., 2009; Tsuji et al., 2012).

The physical demands of the standard firefighting exercise in terms of heart rates were considerably less compared to the training in extreme temperatures with smoke and unexpected flashovers. Here our results were in line with the findings of Larsen et al. (2015) comparing also simulated firefighting in very hot and temperate conditions. Mean heart rate as the most commonly reported physiological response to exercises similar to the SFE averaged at 80% HR_{max} with a range from 60 to 90% HR_{max} (e.g., Romet and Frim, 1987; von Heimburg et al., 2006; Del Sal et al., 2009; Williams-Bell et al., 2009; Perroni et al., 2010). The mean HR in our study was in good accordance with the reported values (SFE: 79.0% HR_{max}; FOT: 85.4% HR_{max}). According to these previous studies, the level of physiological strain during firefighting varies depending on the intensity, duration of the physical tasks and environmental stressors. The environmental conditions (high ambient temperature and radiant heat) during the flashover training may have an impact on the physiological strain during the flashover training. It is difficult to establish whether the physiological strain was the result of the physical demands of the activities or the heat stress imposed by the environment, or a combination of both. In this regard, future measurements of core temperature would provide more insights what type of stress impacts heart rate responses. Barr et al. (2010) reported that firefighters were under greater physiological strain in terms of higher heart rates during hot conditions (>40°) compared to temperate conditions (15°–40°) like during the standard simulated firefighting exercise. Similarly, Walker et al. (2015) showed that the completion of a standard work protocol in very hot conditions (up to 100°) resulted in increased core

TABLE 1 | Correlation matrix between TSA scores, completion time, heart rates and air depletion rates of the standard simulated firefighting exercise (SFE) and the flashover training (FOT) and the time spent in the three defined physiological intensity zones (Zone 1, Zone 2, Zone 3).

Respective SFE and FOT parameter	Respective TSA Score	
	SFE	FOT
Completion time	0.611*	0.510**
HR (% HR_{max})	0.663**	0.810**
Air Depletion	0.937**	0.801**
SFE Zone 1	−0.547*	−0.344
SFE Zone 2	0.477	−0.403
SFE Zone3	0.184	0.587*

*Significant at $p \le 0.05$; **Significant at $p \le 0.01$.

TABLE 2 | Correlation matrix between TSA scores, completion time, heart rates and air depletion rates of SFE and FOT and endurance (treadmill testing) and strength (strength testing) characteristics.

	TSA-score SFE	TSA-score FOT	SFE completion time	FOT completion time	SFE HR (%HR_{max})	FOT HR (%HR_{max})	SFE air depletion	FOT air depletion
VO_{2peak} relative	−0.505*	−0.621*	−0.074	−0.065	−0.593*	−0.693**	−0.391	−0.560*
VO_{2peak} absolute	−0.144	−0.400	−0.029	−0.140	−0.178	−0.515*	−0.091	−0.195
Treadmill time to exhaustion	−0.409	−0.503*	−0.094	−0.150	−0.481	−0.482	−0.286	−0.434
Legpress	−0.449	−0.450	−0.259	−0.329	−0.271	−0.314	−0.464	−0.312
Handgrip	−0.188	−0.134	0.133	0.016	−0.380	−0.234	−0.106	−0.060
Curl-ups	−0.085	−0.201	0.007	0.153	−0.144	−0.240	−0.040	−0.338
Push-ups	−0.491*	−0.444	−0.211	−0.267	−0.394	−0.293	−0.469	−0.380
Shoulder press	−0.490	−0.198	−0.520*	0.008	−0.128	−0.223	−0.479	−0.190
Rowing	−0.343	−0.358	−0.124	−0.213	−0.285	−0.241	−0.343	−0.306
Standing longjump	−0.261	−0.444	0.237	−0.024	−0.542*	−0.491	−0.186	−0.424

*Significant at $p \le 0.05$; **Significant at $p \le 0.01$.

TABLE 3 | Correlation matrix between time spent in the three defined physiological intensity zones (Z1, Z2, Z3) for SFE and FOT and aerobic (treadmill testing) and strength variables.

	SFE Z1	SFE Z2	SFE Z3	FOT Z1	FOT Z2	FOT Z3
VO_{2peak} relative	0.603*	−0.554	−0.155	0.451	0.556*	−0.792**
VO_{2peak} absolute	0.181	−0.85	−0.184	0.119	0.672**	−0.628**
Time to exhaustion during TT	0.566*	0.627**	−0.033	0.427	0.174	−0.469
VE	0.144	−0.122	−0.054	0.070	0.503*	−0.455
VT1	0.351	−0.286	−0.152	0.453	0.143	−0.464
% VO_{2peak} at VT1	0.208	−0.264	0.070	0.409	−0.482	0.067
RCP	0.095	0.017	−0.202	0.062	0.688**	−0.596*
% VO_{2peak} at RCP	−0.032	−0.040	0.126	−0.038	0.080	−0.034
Legpress	0.210	−0.180	−0.075	−0.325	0.573*	−0.205
Hand grip	0.059	0.216	−0.468	−0.394	0.585*	−0.161
Curl-ups	0.375	−0.452	0.088	0.720**	−0.228	−0.375
Push-ups	0.547*	−0.613*	0.045	0.210	0.111	−0.252
Shoulder press	0.224	−0.269	−0.051	−0.179	0.403	−0.183
Rowing	0.545*	−0.375	−0.352	0.443	−0.019	−0.328
Standing longjump	0.441	−0.382	−0.151	0.409	0.400	−0.634**

*Significant at $p \leq 0.05$; **Significant at $p \leq 0.01$.

temperature and heart rates (from 74 to 90% HR_{max}). Extreme conditions (up to 300°) refer to those encountered during a flashover (Barr et al., 2010). Within this context, it might be that heavier firefighters have more heat capacity and therefore lower core temperature, which can result in lower heart rates. We calculated the relationships between body mass and heart rate but we did not find statistical evidence for a correlation of heat capacity and body weight of subjects in our study (% HR_{max} FOT vs. body mass $r = 0.485$ with $p = 0.057$). However, as statistical significance was just narrowly missed, we think that there can be effects of body mass on the heat capacity of subjects and this aspect should be considered in future studies in combination with core temperature.

The time spent in the three physiological time zones differed significantly between both exercises. During SFE subjects worked for longer time in zone 1 compared to FOT (24.6 and 16.3% of completion time for SFE and FOT, respectively). Zone 1 represents the time subjects worked below ventilatory threshold 1 indicating a high percentage of aerobic metabolism. The SFE revealed significantly lower mean HR with punctual highs and lows, however, never exceeding 86.0% HR_{max}. In contrast, the demands of the FOT in extreme temperatures involved continuously increasing heart rates which rarely stayed below VT1. Firefighters spent most of the time in zone 2 (SFE: 65.8%; FOT: 50.4%). Zone 2 represents the time between VT1 and RCP indicating mostly aerobic-anaerobic metabolism. In contrast to SFE (9.7%), during FOT subjects spent one third (33.3%) of the completion time in zone 3 indicating HR above 90% HR_{max}. Further, after crossing the threshold to zone 3, heart rate was continuously increasing until to the end of the exercise. Accordingly, heart rate was above firefighter's RCPs indicating that energy production could be heavily supported by anaerobic processes from the middle of the 8th minute until the end of the FOT. During the final 4 min of the FOT firefighters worked on average above 95% of HR_{max}, which is considered as very hard physical activity by the American College of Sports Medicine (2013).

The FOT highly challenged subjects, even 30 min post-FOT HR-levels remained elevated compared to pre-exercise. Here, our results go in line with the findings of Smith et al. (1997) and Perroni et al. (2010) who found elevated recovery HR 10 and 30 min post-exercise compared to baseline values. Physiological measures indicated that firefighters experienced symptoms and changes to their health consistent with an overtraining type condition the longer they were exposed to heat (Watt et al., 2016). These changes to health can be enhanced the higher the physiological strain and the longer the subsequent period needed for recovery was (Watt et al., 2016). The increasing core temperature might then also limit firefighting performance. This underlines the need for a high fitness level in order to reduce this strain.

Firefighting Performance Related to Fitness Measurements

Both simulated firefighting exercises of the present study are state of the art exercises to simulate firefighting. Accordingly, both trainings claim to represents job requirements of firefighters. We were interested in how the relationship between firefighting performance in terms of the TSA-score and various fitness parameters changes when the demands of the exercise change from a standard simulated exercise to a simulated exercise that is much closer to a real live scenario in an emergency. The exploration of important relationships was similar to previous work on the topic (e.g., Williford et al., 1999; Rhea et al., 2004; Michaelides et al., 2011). A changing sensitivity of performed tests to assess fitness variables for both exercises would then mean that firefighters need different fitness prerequisites to perform the different exercises successfully. As a result, these changing

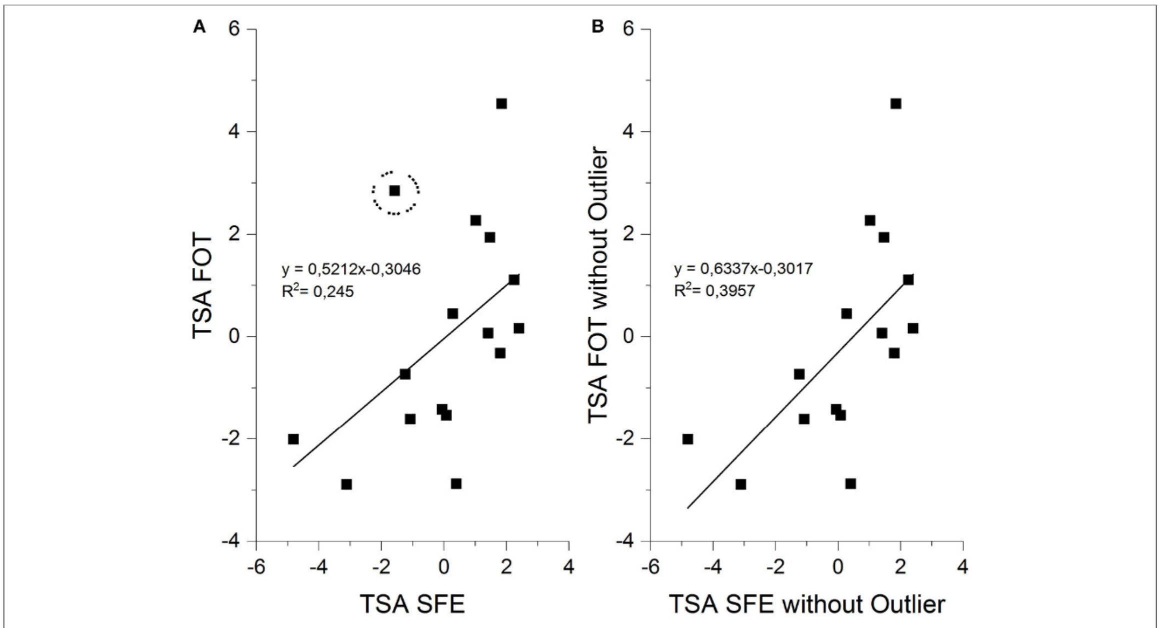

FIGURE 4 | (A) Correlation between TSA-scores of both firefighting exercises including all 16 subjects. The outlier was marked by the dotted circle **(B)** Correlation between TSA-scores of both firefighting exercises excluding the outlier that influenced the correlation significantly.

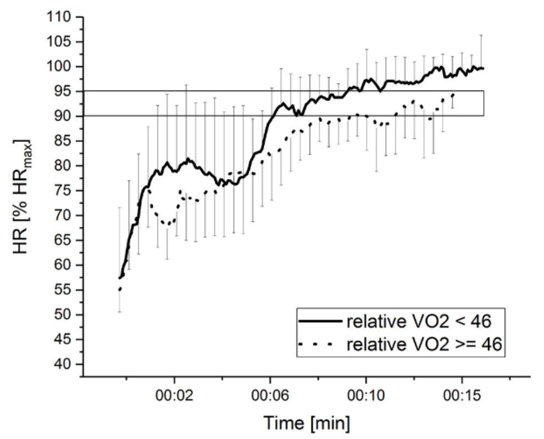

FIGURE 5 | Kinetics of HR during FOT, taken as the average value of % of HR_{max} (± SD) of subjects with a relative VO2peak of ≥ than 46 and < than 46.

variables should be considered when conducting fitness tests for endurance and strength to focus on relevant parameters.

Concerning the comparability of the two firefighting exercises, we found a substantial similarity between both exercises although they were different in their demands: a high relative VO_{2peak} can be assumed to be the most important fitness prerequisite for good firefighting performance in both scenarios. Furthermore, the ability to work in specific physiological intensity zones were the second most important aspect of firefighting performance. However, here we found notable differences between the demands of the exercises as zone 1 was highly related to SFE and zone 3 to FOT. To find the most important (VO_{2peak}) as well as the changing fitness variables due to the demands of the exercise was the second aim of our study. To know these variables is important to design appropriate exercise programs for firefighters. The present results show that the TSA-model can be applied for firefighting in extreme conditions (heat, smoke, poor visibility, flashovers) as the same kind of fitness parameters (i.e., endurance) were sensitive to predict performance.

These results are in line with our previous research (Windisch et al., 2017), where we found three variables highly related to the TSA-score: VO_{2peak}, the time spent in zone 1 during a simulated standard firefighting exercise and breathing frequency. Firefighters with a higher relative VO_{2peak}—level and a greater fraction of time spent in physiological intensity zone 1 showed a lower, i.e., better TSA-score. Accordingly, lower TSA-score means that a firefighter is able to operate faster, with less air depletion from the SCBA and lower physical strain indicated by heart rate during the exercise. Unfortunately, due to radiant heat and extreme temperatures, we were not able to collect any data for breathing frequency—the third performance predicting parameter of the TSA-model (Windisch et al., 2017)—during the flashover training.

Firefighters with a higher relative VO_{2peak} showed a better TSA-score during the flashover training in this study ($r = -0.621$). As relative VO_{2peak} is associated with overall endurance (Jones and Carter, 2000), a high endurance level can be associated to good TSA scores during firefighting in extreme temperatures. The present findings have particular relevance for the published relative VO_{2peak} recommendations for firefighters that vary between 39 and 45 ml/min/kg (O'Connell et al., 1986; Gledhill and Jamnik, 1992; Siddall et al., 2016). These studies recommended minimum values based on firefighting exercises without heat and additional stressors such as flashovers. In general, subjects with a $VO_{2peak} < 45$ ml/min/kg are classified as "healthy, but sedentary and not so active individuals" while subjects with a $VO_{2peak} > 45$ ml/min/kg are seen as "recreationally actives" (Laursen and Jenkins, 2002). In our previous study (Windisch et al., 2017), we suggested a minimum VO_{2peak} of 46 ml/min/kg as this was the mean VO_2-level of the average performers. Dividing now our sample of the present study into two groups (VO_{2peak} < and ≥ 46 ml/min/kg), significantly less physical strain ($p = 0.002$) was found in firefighters with a $VO_{2peak} > 46$ ml/min/kg. They worked with an average of 91.5% HR_{max} from the 8th minute until the end of FOT compared to subjects with a VO_{2peak} of less than 46 ml/min/kg who worked with an average of 97.5% HR_{max} (see **Figure 5**). Arguments for this minimum VO_{2peak} were also underlined by Périard et al. (2011) who found that in environments with high temperatures, exhaustion occurred after crossing 96% of HR_{max} and was accompanied by significant declines in stroke volume (15–26%), cardiac output (5–10%), and an increase in mean arterial pressure (9–13%). A minimum VO_{2peak} of 46 ml/min/kg in combination with good anaerobic metabolism therefore could help to reduce possible negative health consequences for firefighters as it would allow them to keep strain below 96% HR_{max}. However, this recommended minimum value needs to be investigated in future studies to prove that it is a justified threshold.

Endurance training cannot only help to increase VO_{2peak} but also to accelerate HR recovery, which was strongly related to VO_{2peak} in our study ($r > 0.613$). This goes in line with other studies observing faster HR recovery in subjects with higher VO_{2peak} (Darr et al., 1988; Du et al., 2005). Faster HR recovery will then also have an indirect effect on a better TSA-score because we found that air depletion rates from the SCBA were strongly related to HR recovery 1, 3, and 5 min post-FOT. However, it should also be considered that endurance training can improve the sweating response, which accelerates dehydration. Given the fact that sweat can hardly evaporate inside the protective clothing, the increased sweat accumulation could add some discomfort for the firefighter (Aoyagi et al., 1998). Greater sweating makes it difficult to maintain body core temperature at lower level. However, this does not mean that firefighters should not keep a high endurance level. Cross-sectional comparisons between groups of high and low aerobic fitness have revealed that a high aerobic fitness is associated with extended tolerance time when protective clothing is worn (McLellan, 2001). According to McLellan (2001), elevations in core temperature that occur with long-term training in normal training sessions may familiarize the more fit subjects to the discomforts of exercise in the heat.

Study limitations

Measuring core temperature would provide more insights into what type of stress—physical demand or heat stress—impacted more on heart rate responses. Together with the measurement of dehydration this would be an important aspect to be considered in future studies because there was no data available from the present study (e.g., measurements of mass prior to and following the exercises). Furthermore, the mental stress-induced tachycardia due to flashovers could also influence heart rate responses. Unfortunately, we were not able to separate HR responses exactly between the different fires as the sequence of fires was generated randomly for each subject in order to perpetuate the realistic character of a real fire scene in terms of the unpredictability of a situation at an emergency scene. The fires were overlapping during the exercises which made it impossible to attribute mental stress-induced heart rate responses to flashovers. Finally, our subjects were instructed to complete the different exercises as fast as possible but in a pace similar to the work at a real fire emergency scene. Mean firefighting service time of our subjects was 17 years, so we expected them to make an appropriate assessment about the pace they worked with our instruction to complete the exercises as fast as possible. However, a real emergency (in terms of putting out a real fire) might change the judgment about the pace a firefighter can fight the fire.

CONCLUSIONS

Firefighting performance can be determined by the TSA-model adding time for exercise completion, physical strain indicated by mean heart rate and air depletion from the SCBA. The comparison of the two investigated firefighting exercises showed that the fitness contribution differs with respect to the different demands of the exercise. For standard firefighting exercises like the exercise under temperate conditions in our study, it is important that firefighters are able to spend a great portion of time below VT1. For simulated firefighting in extreme temperatures with smoke, poor visibility and unexpected flashovers, firefighters need a good fitness level in order to spend as little time as possible in zone 3. From all variables researched in our study, we found relative VO_{2peak} to be the primary physiological variable related to the different aspects of firefighting, strengthening our plea to consider endurance as the most important prerequisite for firefighting. For practical application, we strongly recommend firefighters to sustain a high level of relative VO_{2peak}, VT1 and RCP. We measured energy contributions during simulated firefighting very indirectly in this study by relating HR during the firefighting exercises to the established HR-levels at VT1 and RCP during the maximum treadmill test, this is also an indirect indicator for the different metabolisms that are important for successful firefighting. Here the data can help to design appropriate exercise programs for firefighters. Furthermore, we recommend to work on recovery heart rates with endurance training. These parameters can easily be tested in the laboratory, which allows for valid standardization and requires fewer resources compared to simulated firefighting exercises. We recommend a minimum VO_{2peak} of 46 ml/min/kg and regular standardized endurance tests, to allow firefighters to perform their jobs healthy and safely.

ETHIC STATEMENTS

Full written and verbal details about the study were provided and all subjects gave written informed consent before participating in the study. The ethic statement for this study was approved by the Dean of the Faculty of Sports and Health Sciences of the Technical University of Munich. All procedures performed in this study involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

AUTHOR CONTRIBUTIONS

Study conception and design by SW, AS, DH; Data acquisition by SW. Data analysis and/or interpretation by SW, WS, DH; Drafting of the manuscript by SW; Revising by WS, DH; Final approval of manuscript provided by SW, WS, DH, AS.

FUNDING

This study was funded by AOK Bayern—Die Gesundheitskasse (German health insurance) and Flughafen München GmbH (Munich airport). This work was also supported by the German Research Foundation (DFG) and the Technische Universität München within the funding programme Open Access Publishing.

ACKNOWLEDGMENTS

The authors thank AOK Bayern—Die Gesundheitskasse (German health insurance) and Flughafen München GmbH (Munich airport) for the financial study support. The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript. Finally, the authors especially thank Munich Airport firefighters for volunteering for this research.

REFERENCES

American College of Sports Medicine (2013). *ACSM's Guidelines for Exercise Testing and Prescription, 9th Edn*. Philadelphia, PA: Lippincott Williams&Wilki.

Aoyagi, Y., McLellan, T. M., and Shepard, R. J. (1998). Effects of endurance training and heat acclimation on psychological strain in exercising men wearing protective clothing. *Ergonomics* 41, 328–357. doi: 10.1080/001401398187071

Astrand, P. O., Rodahl, K., Dahl, H. A., and Strömme, S. B. (2012). *Textbook of Work Physiology. Physiologial Bases of Exercise*. Champaign, IL: Human Kinetics.

Barnard, R. J., and Duncan, H. W. (1975). Heart rate and ECG responses of fire fighters. *J. Occup. Med.* 17, 247–250.

Barr, D. W., Gregson, W., and Reilly, T. (2010). The thermal ergonomics of firefighting reviewed. *Appl. Ergon.* 41, 161–172. doi: 10.1016/j.apergo.2009.07.001

Beaudin, A. E., Clegg, M. E., Walsh, M. L., and White, M. D. (2009). Adaptation of exercise ventilation during an actively-induced hyperthermia following passive heat acclimation. *Am. J. Physiol. Regul. Integr. Comp. Physiol.* 297, R605–R614. doi: 10.1152/ajpregu.90672.2008

Beaver, W. L., Wassermann, K., and Whipp, B. J. (1986). A new method for detecting anaerobic threshold by gas exchange. *J. Appl. Physiol.* 60, 2020–2027.

Borg, G. (1982). Psychophysical bases of perceived exertion. *Med. Sci. Sports Exerc.* 14, 377–381. doi: 10.1249/00005768-198205000-00012

Cohen, J. (1988). *Statistical Power Analysis for the Behavioral Sciences, 2nd Edn.* Hillsdale, MI: Lawrence Erlbaum Associates.

Committee for Firefighting Issues, Civil Protection and Civil Defense (2002). *Firefighting Service Regulations* 7. Bodenheim: German Federal Agency for Civil Protection and Disaster Assistance, 1–25.

Darr, K. C., Bassett, D. R., Morgan, B. J., and Thomas, D. P. (1988). Effects of age and training status on heart rate recovery after peak exercise. *Am. J. Physiol.* 254, 340–343.

Del Sal, M., Barbieri, E., Gabbati, P., Sisti, D., Rocchi, M., and Stocchi, V. (2009). Physiologic responses of firefighter recruits during a supervised live-fire work performance test. *J. Strength Cond. Res.* 23, 2396–2404. doi: 10.1519/JSC.0b013e3181bb72c0

Du, N., Bai, S., Oguri, K., Kato, Y., Matsumoto, I., Kawase, H., et al. (2005). Heart rate recovery after exercise and neural regulation of heart rate variability in 30-40 year old female marathon runners. *J. Sports Sci. Med.* 4, 9–17.

Ellestad, M. H., Allen, W., Wan, M. C., and Kemp, G. L. (1969). Maximal treadmill stress testing for cardiovascular evaluation. *Circulation* 39, 517–522. doi: 10.1161/01.CIR.39.4.517

Friston, K. J., Holmes, A. P., Worsley, K. J., Poline, J. P., Frith, C. D., and Frackowiak, R. S. J. (1995). Statistical parametric maps in functional imaging: a general linear approach. *Hum. Brain Mapp.* 2, 189–210. doi: 10.1002/hbm.460020402

Fujii, N., Honda, Y., Hayashi, K., Soya, H., Kondo, N., and Nishiyasu, T. (2008). Comparison of hyperthermic hyperpnea elicited during rest and submaximal, moderate-intensity exercise. *J. Appl. Physiol.* 104, 998–1005. doi: 10.1152/japplphysiol.00146.2007

Gledhill, N., and Jamnik, V. K. (1992). Characterization of the physical demands of firefighting. *Can. J. Sport Sci.* 17, 207–213.

Jones, A. M., and Carter, H. (2000). The effect of endurance training on parameters of aerobic fitness. *Sports Med.* 29, 373–386. doi: 10.2165/00007256-200029060-00001

Larsen, B., Snow, R., Williams-Bell, M., and Aisbett, B. (2015). Simulated firefighting task performance and physiology under very hot conditions. *Front. Physiol.* 6:322. doi: 10.3389/fphys.2015.00322

Laursen, P. B., and Jenkins, D. G. (2002). The scientific basis for high-intensity interval training. *Sports Med.* 32, 53–73. doi: 10.2165/00007256-200232010-00003

McLellan, T. M. (2001). The importance of aerobic fitness in determining tolerance to uncompensable heat stress. *Comp. Biochem. Physiol. A.* 128, 691–700. doi: 10.1016/S1095-6433(01)00275-6

Michaelides, M., Koulla, M. P., Leah, J. H., Gerald, B. T., and Brown, B. (2011). Assessment of physical fitness aspects and their relationship to firefighters' job abilities. *J. Strength Cond. Res.* 24, 956–965. doi: 10.1519/JSC.0b013e3181cc23ea

O'Connell, E., Thomas, P. C., Cady, L. D., and Karawasky, R. J. (1986). Energy cost of simulated stair clibming as a job-related task in fire fighting. *J. Occup. Med.* 28, 282–284.

Oshima, Y., Miyamoto, T., Tanaka, S., Wadazumi, T., Kurihara, N., and Fujimoto, S. (1997). Relationship between isocapnic buffering and maximal aerobic capacity in athletes. *Eur. J. Appl. Physiol. Occup. Physiol.* 76, 409–414. doi: 10.1007/s004210050269

Pataky, T. C. (2010). Generalized n-dimensional biomechanical field analysis using statistical parametric mapping. *J. Biomech.* 43, 1976–1982. doi: 10.1016/j.jbiomech.2010.03.008

Pataky, T. C. (2016). *SPM 1d*. Available online at: http://www.spm1d.org/index.html#. (Assessed February19, 2017).
Pataky, T. C., Vanrenterghem, J., and Robinson, M. A. (2015). Zero- vs. one-dimensional, parametric vs. non-parametric, and confidence interval vs. hypothesis testing procedures in one-dimensional biomechanical trajectory analysis. *J. Biomech.* 48, 1277–1285. doi: 10.1016/j.jbiomech.2015.02.051
Périard, J. D., Caillaud, C., and Thompson, M. W. (2011). The role of aerobic fitness and exercise intensity on endurance performance in uncompensable heat stress conditions. *Eur. J. Appl. Physiol.* 112, 1989–1999. doi: 10.1007/s00421-011-2165-z
Perroni, F., Tessitore, A., Cortis, C., Corrado, L., D'Artibale, E., Cignetti, L., et al. (2010). Energy cost and energy sources during a simulated firefighting acitivity. *J. Strength Cond. Res.* 24, 3457–3463. doi: 10.1519/JSC.0b013e3181b2c7ff
Rhea, M. R., Alvar, B. A., and Gray, R. (2004). Physical fitness and job performance of firefighters. *J. Sport Health Sci.* 18, 348–352. doi: 10.1519/00124278-200405000-00026
Romet, T. T., and Frim, J. (1987). Physiological responses to fire fighting activities. *Eur. J. Appl. Physiol.* 56, 633–638. doi: 10.1007/BF00424802
Siddall, A. G., Stevenson, R. D. M., Turner, P. F. J., Stokes, K. A., and Bilzon, J. L. J. (2016). Development of role-related minimum cardiorespiratory fitness standards for firefighters and commanders. *Ergonomics* 59, 1335–1343. doi: 10.1080/00140139.2015.1135997
Smith, D. L., Petruzello, S. J., and Kramer, J. M. (1996). Physiological, psychophysical, and psychological responses of firefighters to firefighting training. *Aviat. Space Environ. Med.* 67, 1063–1068.
Smith, D. L., Petruzzello, S. J., Kramer, J. M., and Misner, J. E. (1997). The effects of different thermal environments on the physiological and psychological responses of firefighters to a training drill. *Ergonomics* 40, 500–510. doi: 10.1080/001401397188125
Sothmann, M. S., Saupe, K., Jasenof, D., and Blaney, J. (1992). Heart rate response of firefighters to actual emergencies. *J. Occup. Med.* 34, 797–800. doi: 10.1097/00043764-199208000-00014
Tsuji, B. T., Honda, Y., Fujii, N., Kondo, N., and Nishiyasu, T. (2012). Comparison of hyperthermic hyperventilation during passive heating and prolonged light and moderate exercise in the heat. *J. Appl. Physiol.* 113, 1388–1397. doi: 10.1152/japplphysiol.00335.2012
von Heimburg, E. D., Rasmussen, A. K., and Medbö, J. I. (2006). Physiological responses of firefighters and performance predictors during a simulated rescue of hospital patients. *Ergonomics* 49, 111–126. doi: 10.1080/00140130500435793
Walker, A., Keene, T., Argus, C., Driller, M., Guy, J. H., and Rattray, B. (2015). Immune and inflammatory responses of Australian firefighters after repeated exposures to the heat. *Ergonomics* 58, 2032–2039. doi: 10.1080/00140139.2015.1051596
Wassermann, K., and McIlroy, M. B. (1964). Detecting the threshold of anaerobic metabolism in cardiac patients during exercise. *Am. J. Cardiol.* 14, 844–852. doi: 10.1016/0002-9149(64)90012-8
Watt, P. W., Wilmott, A. G., Maxwell, N. S., Smeeton, N. J., Watt, E., and Richardson, A. J. (2016). Physiological and psychological responses in fire instructors to heat exposures. *J. Therm. Biol.* 58, 106–114. doi: 10.1016/j.jtherbio.2016.04.008
Williams-Bell, F. M., Villar, R., Sharrat, M. T., and Hughson, R. L. (2009). Physiological demands of the firefighter candidate physical ability test. *Med. Sci. Sports Exerc.* 41, 653–662. doi: 10.1249/MSS.0b013e31818ad117
Williford, H. N., Duey, W. J., Olson, M. S., Howard, R., and Wang, N. (1999). Relationship between fire fighting suppression tasks and physical fitness. *Ergonomics* 42, 1179–1186. doi: 10.1080/001401399185063
Windisch, S., Seiberl, W., Schwirtz, A., and Hahn, D. (2017). Relationships between strength and endurance parameters and air depletion rates in professional firefighters. *Sci. Rep.* 7, 1–10. doi: 10.1038/srep44590

Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Copyright © 2017 Windisch, Seiberl, Hahn and Schwirtz. This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY). The use, distribution or reproduction in other forums is permitted, provided the original author(s) or licensor are credited and that the original publication in this journal is cited, in accordance with accepted academic practice. No use, distribution or reproduction is permitted which does not comply with these terms.

8.3 Exercising 1h on-duty: Polarized training is most effective for firefighters (Study III)

Authors: Stephanie Windisch, Daniel Hahn, Ansgar Schwirtz, Wolfgang Seiberl

First Author: Stephanie Windisch

Current Status: Published in *Scientific Reports*

Individual contribution:

The author of this dissertation is the main author of this paper. The PhD candidate was mainly responsible for the development of the research idea, the theoretical framework and the design of the study in agreement with Prof. Dr. Ansgar Schwirtz and Prof. Dr. Daniel Hahn. The author of this dissertation collected the data at Munich Airport, Germany. The author carried out the analysis of the data and wrote the manuscript, always in agreement with Prof. Dr. Ansgar Schwirtz, Prof. Dr. Daniel Hahn und Dr. Wolfgang Seiberl. The manuscript was revised by Prof. Dr. Daniel Hahn und Dr. Wolfgang Seiberl. The final approval of the manuscript was provided by the author of this dissertation in agreement with Prof. Dr. Ansgar Schwirtz, Prof. Dr. Daniel Hahn and Dr. Wolfgang Seiberl. The PhD candidate was mainly responsible for the whole submission process and the integration of the reviewer’s feedback into the paper, in agreement with Prof. Dr. Ansgar Schwirtz, Prof. Dr. Daniel Hahn and Dr. Wolfgang Seiberl.

Summary and main results:

This section provides a summary of the main results of Study III. For details regarding the methods, results, discussion and conclusions, please see the original manuscript in Appendix C. This study aimed to analyse the effects of a 15-week low-volume (1h/day sport on-duty) high-intensity interval-based (HIIT) exercise program as part of a polarized training concept (POL) on relative maximum oxygen uptake (VO_{2peak}), ventilatory threshold 1 (VT1), respiratory compensation point (RCP) and time to exhaustion during treadmill running (TT) among professional firefighters, as well as comparing it with a continuous training (CT).

The comparison of the four tested parameters revealed no significant between-group differences at baseline ($p > 0.05$). After the post-test, POL differed significantly from CT and CON in all variables ($p < 0.05$). We found significant improvements ($p < 0.001$) for the POL-group in relative VO_{2peak} (+5.4 ± 1.2 ml/min/kg), VT1 (+5.0 ± 0.8 ml/min/kg), RCP (+6.2 ± 2.2ml/min/kg) and TT (+76 ± 19s). The CT group improved only in two parameters significantly: VT1 (+1.2 ± 0.3 ml/min/kg, $p = 0.003$) and TT (+21 ± 9s, $p = 0.029$), while the CON group remained unchanged in all variables ($p \geq 0.05$).

Medicine & Science in Sports & Exercise

Exercising 1h on-duty: Polarized training is most effective for firefighters

--Manuscript Draft--

Manuscript Number:	
Full Title:	Exercising 1h on-duty: Polarized training is most effective for firefighters
Short Title:	Exercise Programs for Firefighters
Article Type:	Original Investigation
Keywords:	firefighter exercise program, peak oxygen uptake, ventilatory threshold, interval training
Corresponding Author:	Stephanie Windisch, M.Sc. Technical University of Munich Munich, GERMANY
Corresponding Author Secondary Information:	
Corresponding Author's Institution:	Technical University of Munich
Corresponding Author's Secondary Institution:	
First Author:	Stephanie Windisch, M.Sc.
First Author Secondary Information:	
Order of Authors:	Stephanie Windisch, M.Sc.
	Daniel Hahn, Prof. Dr.
	Ansgar Schwirtz, Prof. Dr.
	Wolfgang Seiberl, Dr.
Order of Authors Secondary Information:	
Abstract:	Purpose This study aimed to analyse the effects of a 15-week exercise program for professional firefighters exercising on duty. A high intensity interval-based (HIIT) exercise program as part of a polarized training concept (POL) was compared to a continuous training (CT). The key outcome variables in terms of training effects were relative maximum oxygen uptake (VO2peak), ventilatory threshold 1 (VT1), respiratory compensation point (RCP) and time to exhaustion during treadmill running (TT). Methods Thirty professional firefighters were randomly assigned to two experimental (POL n=10; CT n=10) and one control (CON n=10) group. VO2peak, VT1, RCP and TT were assessed during a maximum treadmill test before (baseline-test) and after (post-test) a 15-week intervention (1h/day; 3 days/week). An ANCOVA was conducted to compare the effectiveness of the two exercise modes versus controls regarding VO2peak, VT1, RCP and TT. Results The comparison of the four tested parameters revealed no significant between-group differences at baseline (p>0.05). After the post-test, POL differed significantly from CT and CON in all variables (p<0.05). We found significant improvements (p<0.001) for the POL-group in relative VO2peak (+5.4 ±1.2 ml/min/kg), VT1 (+5.0 ±0.8 ml/min/kg), RCP (+6.2 ± 2.2ml/min/kg) and TT (+76 ±19s). The CT group improved only in two parameters significantly: VT1 (+1.2 ±0.3 ml/min/kg, p=0.003) and TT (+21 ±9s, p=0.029), while the CON group remained unchanged in all variables (p≥0.05). Conclusion The POL-exercise program led to greater improvements in all variables in professional firefighters, despite the reduction in overall training volume. We highly recommend firefighters to include HIIT and a polarized training concept into their endurance training

Powered by Editorial Manager® and ProduXion Manager® from Aries Systems Corporation

	as it turned out that important improvements can already be achieved within just one hour exercising on-duty.
Funding Information:	

Powered by Editorial Manager® and ProduXion Manager® from Aries Systems Corporation

Exercising 1h on-duty: Polarized training is most effective for firefighters

Windisch, Stephanie[1*], Daniel Hahn[2,3], Ansgar Schwirtz[1], Wolfgang Seiberl[1]

1 Department of Biomechanics in Sports, Technical University of Munich

2 Human Movement Science, Ruhr-University Bochum

3 School of Human Movement and Nutrition Sciences, University of Queensland

Corresponding Author:

Stephanie Windisch (M.Sc.)

Department of Biomechanics in Sports
Faculty of Sport and Health Sciences
Technical University of Munich
Georg-Brauchle-Ring 62
80992 Munich
phone: +49.89.289.24587
fax: +49.89.289.24582
email: stephanie.windisch@tum.de

Keywords

firefighter exercise program, peak oxygen uptake, ventilatory threshold, interval training

Abstract

Purpose

This study aimed to analyse the effects of a 15-week exercise program for professional firefighters exercising on-duty. A high intensity interval-based (HIIT) exercise program as part of a polarized training concept (POL) was compared to a continuous training (CT). The key outcome variables in terms of training effects were relative maximum oxygen uptake (VO_{2peak}), ventilatory threshold 1 (VT1), respiratory compensation point (RCP) and time to exhaustion during treadmill running (TT).

Methods

Thirty professional firefighters were randomly assigned to two experimental (POL n=10; CT n=10) and one control (CON n=10) group. VO_{2peak}, VT1, RCP and TT were assessed during a maximum treadmill test before (baseline-test) and after (post-test) a 15-week intervention (1h/day; 3 days/week). An ANCOVA was conducted to compare the effectiveness of the two exercise modes versus controls regarding VO_{2peak}, VT1, RCP and TT.

Results

The comparison of the four tested parameters revealed no significant between-group differences at baseline ($p>0.05$). After the post-test, POL differed significantly from CT and CON in all variables ($p<0.05$). We found significant improvements ($p<0.001$) for the POL-group in relative VO_{2peak} (+5.4 ±1.2 ml/min/kg), VT1 (+5.0 ±0.8 ml/min/kg), RCP (+6.2 ± 2.2ml/min/kg) and TT (+76 ±19s). The CT group improved only in two parameters significantly: VT1 (+1.2 ±0.3 ml/min/kg, $p=0.003$) and TT (+21 ±9s, $p=0.029$), while the CON group remained unchanged in all variables ($p\geq0.05$).

Conclusion

The POL-exercise program led to greater improvements in all variables in professional firefighters, despite the reduction in overall training volume. We highly recommend firefighters to include HIIT and a polarized training concept into their endurance training as it turned out that important improvements can already be achieved within just one hour exercising on-duty.

Introduction

Firefighting is a physically very demanding occupation challenging the cardiovascular capabilities of firemen (9, 23, 37). Many studies on the physical demands of firefighting pointed out that it is important to possess a high level of peak oxygen uptake (VO_{2peak}) for firefighting performance (e.g. 17, 20, 33). Recent studies also showed VO_{2peak} to be a primarily variable associated with the physiological demands of firefighting (38, 39). Furthermore, we found that substrate utilization during a simulated firefighting exercise and the level of ventilatory thresholds was performance determining for firefighting (39). Although many studies recommend firefighters to maintain a high level of relative VO_{2peak} (17, 33) only few studies provide data regarding the effect of appropriate endurance exercise programs that can serve as recommendations on how to improve or maintain VO_{2peak} (7, 29).

In general, prolonged sessions of moderate-intensity exercise (e.g. ≥ 1 h at ~65-75% of VO_{2peak}) performed repeatedly for at least several weeks, improve VO_{2peak} and alter substrate utilization during exercise, resulting in improved endurance capacity (25). Besides this traditional approach, also known as “continuous training” (CT), literature emphasizes high-intensity interval training (HIIT) as another possibility to improve VO_{2peak} and further endurance parameters (16, 21, 26, 32, 36). In contrast to continuous training, which is characterized by prolonged, continuous activity, HIIT is characterized by repeated bouts of short to moderate duration exercises (i.e. 15 seconds to 5 minutes) completed at an intensity that is greater than the individual lactate threshold (22). HIIT can be used in combination with low intensity high volume exercise in the concept of the so-called “Polarized training” (POL). The 80% (low intensity training) to 20% (HIIT) intensity distribution of POL was originally derived from retro-perspective analysis of the intensity, duration and frequency distribution of the training load of well-trained athletes (e.g. 2, 11, 31, 34).

Both CT and HIIT within the POL concept can increase endurance, however, they differ considerably in the time needed for physiological adaptations. HIIT has been shown to be a time-efficient exercise paradigm that improves exercise performance to the same extent as CT (e.g. 4, 15). This could be an important aspect in choosing an appropriate training method for professional firefighters on-duty. The general importance of exercising regularly has been recognized by several national fire brigades suggesting that firefighters participate in exercise training while on-duty. For instance, in Germany professional airport firefighters have to exercise one hour while on-duty as part of the collective wage agreement (6). In our previous studies (38, 39) we found that endurance parameters were stronger related to good firefighting performance than strength parameters. Thus, it is important that firefighters utilize training methods that effectively target the aerobic capacity in order to enhance endurance outcomes within this exercise on-duty time.

To date, there have been no known attempts to compare the effects of different methods of endurance training (CT, POL) within a given mandatory exercise on-duty time on adaptations in relative VO_{2peak}, ventilatory threshold 1 (VT1), respiratory compensation point (RCP) and total time to exhaustion on the treadmill (TT) of professional firefighters. We selected these four variables as key endurance parameters based on our previous firefighting research (38, 39). Improvements for CT methods are expectable, as continuous training including threshold training has been shown to be an effective exercise method to improve endurance parameters like VO_{2peak} (32). However, polarized training reduced to one hour exercising on-duty has not been researched before in a group of sedentary or recreationally active subjects similar to firefighters. In order to improve training concepts for professional firefighters exercising 1h on-duty time, our research aims to gain more detailed information which of the two exercise modes (CT vs. POL) has a greater impact on specific endurance parameters. We hypothesized that the POL training would lead to superior improvements compared with CT, as this has been shown in a previous study with professional athletes (34).

Methods

a. Study subjects

Thirty healthy professional firefighters from Munich Airport volunteered for this research (38.4 ± 9.1 yr, 177.1 ± 0.1 cm, 84.1 ± 7.6 kg, BMI 26.6 ± 2.4 kg/m2). Mean service time of participants was 14 ± 5 years. Full written and verbal details about the study were provided. Informed written consent was obtained from all participants prior to testing. The ethic statement for this study was approved by the Dean of the Faculty of Sports and Health Sciences of the Technical University of Munich. All tests were conducted according to the Declaration of Helsinki. All participants were in possess of a valid G26.3 medical examination for operational fitness, a mandatory periodically medical health check for professional firefighters in Germany.

b. Experimental program

The experimental program consisted of 1) the baseline-test, 2) the 15-week exercise program, and 3) the post-training test.

<u>Treadmill test:</u>

Endurance variables were evaluated before the 15-week exercise programs (baseline-test) and again upon completion of training (post-test). Gas exchange (oxygen consumption - VO_2, carbon dioxide output - VCO_2) was measured breath-by-breath with the Cortex Metamax 3B (Cortex Biophysics GmbH, Germany). The incremental exercise test based on the Ellestad Protocol (8) was conducted on a motorized treadmill (Life Fitness, Integrity Series, Germany) to determine peak oxygen uptake (VO_{2peak}), total time to exhaustion and heart rate maximum (HR_{max}). The test was terminated when subjects reached volitional fatigue and were not able to continue running. VO_{2peak} and HR_{max} were taken as the highest 30s-average during the final minute of the test. In addition, based on the test, two thresholds were determined: ventilatory threshold 1 (VT1) and respiratory compensation point (RCP). The VT1 was determined from the V-slope method (1) in combination with the break point of the ventilatory equivalent for O_2 against VO_2 (27). The RCP was identified by the break points of the ventilatory equivalent for CO_2 and the end tidal CO_2 concentration against VO_2 (27). VT1 indicates the first turnpoint of ventilation (V_E) and ventilatory equivalent ratio for oxygen (V_E/VO_2) (35). On contrary, RCP indicates the maximal lactate steady state, equivalent to the second turn point for V_E and V_E/VO_2. These two thresholds were then used to establish three physiological intensity zones that correspond to the heart rates at the following exercise intensities: HR below VT1 (zone 1), HR between VT1 and RCP (zone 2) and HR above RCP (zone 3).

Exercise programs:

Subjects were randomly assigned to two experimental groups each including ten participants (CT, POL). Ten additional subjects served as a control group. Each subject exercised one hour on-duty. Subjects worked 24h-shifts meaning they spent one day on-duty followed by one day off. Therefore, we determined three exercise days per week for every exercise group, including CON. The program for the CT group followed closely the ACSM exercise guidelines recommending an intensity distribution of 46, 35, and 19% for zones 1, 2, and 3 (32). The POL group performed a relatively higher percentage of their total training volume in zone 1, below their individual VT1. They followed the so-called “polarized” training intensity distribution of 80-20% of exercise time for zones 1 and 3 (32). Training intensity was heart rate controlled. Subjects documented the number of training sessions and the reached training intensity goals in terms of heart rate and time in a diary.

Continuous training (CT):

The CT included three blocks, each lasting five weeks: Three weeks each including one low-intensity training (Low, HR < individual VT1), one training with HR between VT1 and RCP per week (fartlek training) and one training at the lactate threshold (LT), in total three sessions per week. Every training session was separated by one recovery day. After these three weeks, subjects performed two of the mentioned LT-trainings and a fartlek training per week for additional two weeks (Figure 1). Each fartlek-session included varying changes in intensity between VT1 and RCP, and above RCP (1min with 5-10 HR beats/minute above RCP in the first block, 1.30min with 5-10 HR beats/minute above RCP in the second block and 2min with 5-10 HR beats/minute above RCP in the third block). The intervals exercised above RCP during the fartlek-session were separated by 4 minutes exercising between VT1 and RCP.

High-intensity interval training as part of a polarized training concept (POL):

Like the CT the POL included three blocks, each lasting five weeks: Three weeks of low intensity training in zone 1 followed by 2 weeks HIIT in zone 3. A low intensity week included three 45 to 60 min sessions, with the duration depending on the exercise: cycling for 60min or running for 45min. Two of the sessions in the low intensity week included four to six maximal sprints of 8s separated by at least 5min. A HIIT week included three 30-40min HIIT-sessions each separated by at least 1 day of recovery (Figure 1). All HIIT sessions included a 10min warm-up with HR below individual VT1, 3-5 HIIT intervals (cycling or running) with individual recovery and a 10min cool-down with HR below individual VT1. Each HIIT-week started by a session of short HIIT-intervals for adaptation purposes to the load of a HIIT-training. Each short HIIT lasted 45s with a work-rest ratio of 0.5 (90 s rest) and was repeated six times in the first micro cycle, seven times in the second micro cycle and eight times in the third micro cycle. After the short HIIT two long individualized HIITs at 90-95% HR_{max} were conducted. The individual HIIT interval-length was determined according to the individual duration of time from VO_2 crossing RCP until reaching VO_{2peak} during treadmill testing. For example, if a subject ran 1:45min after crossing RCP until to total exhaustion, this time was taken to determine the individualized long-HIIT. The work-rest-ratio for all subjects was 0.66 (e.g. 1:49 min interval = 2:45min active resting), resulting in individual resting times for each subject between the individualized intervals. The interval exercise volume in terms of interval repetitions became progressively more challenging starting with four interval repetitions in the first micro cycle, followed by five repetitions in the second micro cycle and six repetitions in the third micro cycle.

Controls (CON):

The control group was asked to maintain their normal unsupervised training without any specific or planned intervention. This means subjects participated regularly in their mandatory 1h exercise on-duty (3 times/week) where they used the cardio machines (cycle ergometer, treadmill, step machine) in the gym at the fire station for the one hour of exercising. Their endurance training was of no certain heart rate intensity and participants in CON groups were not engaged in any sort of structured endurance exercise program.

For comparison of the training load of POL and CT, we compared the total loads (intensity and volume) with Foster's approach to the TRIMP concept as used in many studies to estimate the total exercise load (e.g. 13, 24, 11, 12). TRIMP stands for training impulse and offers a strategy for integrating the intensity of a training into a single term (the TRIMP score) that allows a systematic analysis approach to training (13). This method uses HR data during exercise to integrate both total volume and total intensity relative to the 3 intensity zones (zone 1, zone 2, zone 3). An exercise score in terms of TRIMP for each zone was then computed by multiplying the accumulated time spent in this zone by an intensity-weighted multiplier for the respective zone. 1 minute in zone 1 was given a score of 1 TRIMP, 1 minute in zone 2 was given 2 TRIMPs and 1 minute in zone 3 was given a score of 3 TRIMPs. The total TRIMP score was then calculated by summing the results of the 3 zones.

c. Statistical analyses:

Statistical analyses were performed using the software program SPSS, version 23.0 (Statistical Package for Social Science, Chicago, IL). All data exhibited a Gaussian distribution verified by the Shapiro - Wilk's test and, accordingly, the values are presented as means ± SD. In all cases, $p < 0.05$ was taken as the level of significance. A one-way ANOVA model was used to test differences in baseline levels between the different exercise groups regarding VO_{2peak}, VT1, RCP und TT. A one-way ANCOVA was conducted to compare the effectiveness of the three exercise modes regarding VO_{2peak}, VT1, RCP and TT whilst controlling for the baseline level of each of the parameters. Estimated marginal means were calculated within the ANCOVA to show the adjusted means (controlling for the covariate "baseline of each variable") for each training group. To observe significant effects over time, paired *t*-tests within each group were carried out. A Bonferroni correction was used for multiple comparisons. Pearson product-moment correlations were used to determine if significant relationships existed between variables of interest. For all correlation analyses, the *p*-value was set at 0.05.

Results

Three subjects withdrew from the study (2 in CT, 1 in POL) due to loss of interest or an unrelated injury. Accordingly, results are based on nine participants in CT and eight participants in POL. All subjects of CON completed the baseline-test as well as the post-training test.

We found no significant differences between the baseline levels of the three groups POL, CT and CON regarding relative VO_{2peak} ($p = 0.514$), VT1 ($p = 0.340$), RCP ($p = 0.563$) and TT ($p = 0.877$). After the 15 weeks exercise program, there was a significant difference between the three groups POL, CT and CON in VO_{2peak} ($p < 0.001$), VT1 ($p < 0.001$), RCP ($p < 0.001$), and TT ($p < 0.001$).

Relative VO_{2peak} values averaged 48.8 ± 3.6 ml/min/kg (POL), 44.2 ± 3.5 ml/min/kg (CT) and 43.4 ± 3.5 ml/min/kg) in the post-test. Post hoc tests proved significant differences in VO_{2peak} between POL and CT ($p = 0.004$) and POL and CON ($p < 0.001$). Comparing the estimated marginal means after the 15 weeks-program the POL-group had the highest VO_{2peak} (+6.1 ml/min/kg compared to CON), followed by the CTs (+ 2.2 ml/min/kg compared to CON). In relation to the baseline level, the POL-group was the only group improving VO_{2peak} significantly from pre- to post-test ($p < 0.001$).

VT1 averaged at 31.0 ± 1.9 ml/min/kg (POL), 26.6 ± 1.4 ml/min/kg (CT) and 26.0 ± 2.0 ml/min/kg (CON) after the 15 weeks-program. There was a significant difference in VT1 between POL and CT ($p < 0.001$) and POL and CON ($p < 0.001$), but no significant difference between CT and CON ($p = 0.239$). The estimated marginal means showed the highest VT1 for POL (+5.1 compared to CON), followed by CT (+1.3 ml/min/kg compared to CON). The POL ($p < 0.001$) and the CT ($p = 0.003$) group both improved VT1 significantly compared to the baseline level. No significant improvements were found for the controls between pre- and post-test ($p = 0.560$). Figure 2 displays relative VO_{2peak} and VT1 data collected upon study entry and again following the 15-week exercise program.

After the 15 weeks exercise program, RCP averaged at 45.8 ± 3.7 ml/min/kg (POL), 40.0 ± 3.1 ml/min/kg (CT) and 39.9 ± 3.4 ml/min/kg (CON). There was a significant difference in RCP between POL and CT ($p < 0.001$) and POL and CON ($p < 0.001$), but none between CT and CON ($p = 0.474$). Estimated marginal means showed the highest RCP for POL (+6.9 ml/min/kg compared to CON, followed by CT (+5.3 ml/min/kg compared to CON). In relation to the baseline level determined in the pre-test, the POL-group was the only group improving RCP significantly from pre- to post-test ($p < 0.001$).

TT averaged 691 ± 30s in the POL-group, 635 ± 43s in the CT-group and 616 ± 46s for CON. A significant difference in TT showed up between POL and CT ($p = 0.004$) and POL and CON ($p < 0.001$). Again there was no significant difference between CT and CON ($p = 0.139$). Estimated marginal means showed the highest TT for POL (+ 48s) followed by CT (+ 27s) compared to CON, respectively. The POL ($p < 0.001$) and the CT ($p = 0.029$) group both improved TT significantly compared to the baseline level. No significant improvements were found for the controls between pre- and post-test (p = 0.508). Changes in RCP and TT between pre- and post-test are presented in Figure 3.

The comparison of TRIMP scores of the POL- and the CT-group in this study showed that the total training load of the CT-group resulted in a higher TRIMP score (4213 ± 421 vs. 3111 ± 398 in the POL-group, $p < 0.002$). TRIMP scores of the two controlled exercise programs are shown in Figure 4. To get an overview over the intended TRIMP scores and the actually done exercises expressed in TRIMP scores, the executed exercise loads are shown in Figure 5.

Discussion

Previous studies emphasized periodic assessments of endurance parameters e.g. relative VO_{2peak} in professional firefighters (17, 20, 33). It has also been shown that VO_{2peak} and other key endurance parameters can be improved by either high-intensity interval training as well as continuous training in elite and recreational athletes (e.g. 15, 26, 32). However, the main two questions prior to this study were: (1) is it possible for professional firefighters to improve selected endurance variables when performing a structured exercise program within 1h on-duty? (2) To what extent can the selected endurance variables be improved with the different exercise modes POL and CT?

The most salient result of the present study is that POL improved relative VO_{2peak}, VT1, RCP and TT significantly more than CT. Additionally, the major novel finding here is that these results were observed in a group of professional firefighters exercising on-duty for only one hour, three times per week.

The polarized training had a positive effect on various aspects of endurance. Most importantly, relative VO_{2peak} experienced large increases of 12.7 ± 4.2 %, thereby exceeding the level of 46 ml/min/kg relative VO_{2peak}, a minimum level we previously deemed appropriate for the performance of firefighting duties (38, 39). All subjects had an initial VO_{2peak} lower than 45 ml/min/kg (POL: 43.3 ± 3.4; CT: 42.5 ± 3.6; CON: 44.6 ± 4.9) and were classified as “healthy, but sedentary and not so active individuals” (22). After the intervention, the POL-group (48.8 ± 3.6 ml/min/kg) was the only group exceeding VO_{2peak} of 46 ml/min/kg and therefore, they can be seen as “recreationally actives” (22). Only few studies reported effects of endurance exercise programs for firefighters exercising one hour on-duty. Roberts et al. (2002) induced an increase of 28% in relative VO_{2peak} in a 16-week-exercise program for firefighter recruits. The intensity distribution was similar to the CT-group in our study. At first glance, the 28% increase in relative VO_{2peak} may appear high. However, subjects in the study of Roberts et al. (2002) had a lower relative VO_{2peak} (35 ± 7 ml/min/kg) compared to the subjects in our study (43.5 ± 4.0 ml/min/kg) in the baseline test. The initial low VO_{2peak} level may have affected the strong increase in VO_{2peak} by their exercise program.

Although there is less data on endurance training studies with firefighters, the literature contains a legion of HIIT studies on sedentary or recreationally active subjects, comparable to the subjects in the present study. Not surprisingly, similar increases in relative VO_{2peak} and further endurance parameters have been noted in comparable studies (10, 14, 18, 21). In contrast to the present study, most of these studies observed these improvements within an intervention duration of 6-8 weeks of HIIT (14, 18, 21). Noteworthy, Esfandiari et al. (2014) found increases of relative VO_{2peak} of +11% and therefore comparable to results of our study, but with only 6 HIIT-sessions within 2 weeks. The difference to the present study is that our subjects followed a periodization of low- and high intensity training and the HIIT-blocks were part of the polarized exercise concept for this group. The increases in different parameters have been observed within 15 weeks of training. In total, participants performed 3 x 2 weeks of HIIT-training interspersed by 3 weeks of low intensity training. The improvements may have been already observable after the first HIIT-block within this periodization. However, as we conducted no interim tests within the 15 weeks, no information is available from what point in time significant improvements get obvious.

Our study demonstrated that training above lactate threshold in combination with training below VT1, as done in POL, is more effective in enhancing endurance than training below or at the lactate threshold, if time for exercise is limited (3 x 1h per week). Applying the POL concept, the majority of training time (~80%) is below VT1, usually ending up in a high-volume low intensity training > 1h. Professional firefighters often have a mandatory hour to exercise while on-duty (e.g. 6). Here we altered the concept in our study as we restricted every training session, including the high-volume low-intensity part of the POL, to a maximum of 1h while maintaining the 80-20% distribution. The HIIT was the second part of the POL-training (~20%). HIIT is often conducted as a block of 5-15 sessions within a short period of time e.g. 5-15 days (3, 5, 10). Many studies practice HIIT-training every day of the session block (e.g. 3, 28). However, Parra et al. (2000) showed that this method increased citrate synthase (CS) maximal activity but did not change anaerobic work capacity, possibly because of chronic fatigue induced by daily training. We also performed the sessions in blocks in the current study (6 sessions within 12-14 days), but with one rest day between every session to promote recovery and to avoid fatigue. In the context of on-duty training of professional firefighters sufficient recovery is of great importance since firefighters must maintain their ability to adequately respond to emergencies. In contrast to previous studies (e.g. 3), we did not use fixed but individualized interval lengths for every subject for the long-HIIT sessions, based on a subject's exercise time after crossing RCP in the preceding treadmill test. The main idea behind this individualized concept was to reduce the risk of overstraining individual participants on-duty. To our knowledge, no other study investigated individualized long-HIIT interval training, practiced in several microcycles within a polarized training concept and further research is needed to evaluate our concept.

CT was also shown to improve relative VO_{2peak}, lactate or ventilatory thresholds in moderately trained subjects (14). However, these findings can only partly be supported by our work, as improvements were only observed for VT1 and TT. It might be speculated that the training stimulus in our CT-concept was not high enough and greater volume of training (~4-5 sessions/week) is needed to improve relative VO_{2peak} or RCP (19, 22). This indicates that a CT-model might not be able to provide an adequate stimulus for further adaptations within just one hour exercising on-duty. To achieve similar improvements comparable to the POL-group, it might be necessary to increase the frequency and to prolong duration of the CT sessions, however, this would outreach the time firefighters get to exercise on-duty.

As the POL-group improved all selected key endurance variables (relative VO_{2peak}, VT1, RCP and TT) significantly more than the CT-group, the questions arose whether this could be due to a higher total training load in the POL-group. However, the calculation of the TRIMP score showed that the total training load was higher in the CT-group. Therefore, a salient result of the present study was that, despite a higher total training load of the CT-group, the POL-group improved all selected endurance variables with significantly less exercise time and training load. The great majority of previous studies reported exercise effects based on the polarized concept or similar concepts with a change of high- and low-intensity exercises for the very specific group of elite endurance athletes (e.g. 3, 30). To our best knowledge, we are the first study investigating whether the polarized training concept works for the occupation-specific group of moderately trained professional firefighters within an exercise time of 1h on-duty. Based on the findings of the current study, this modified polarized training concept as used in the current study could serve for structured long-term exercise planning in firefighters. Finally, the results of this study showed that systematic and individualized training periodization on a scientific basis and the selection of appropriate exercise modes goes beyond ensuring the sole opportunity of training on-duty. This is proven by the results of the CON-group which maintained their normal unsupervised endurance training without any specific or planned intervention. This means subjects participated regularly in their mandatory 1h exercise on-duty (3 days/week), but none was engaged in any sort of structured exercise program. For practical implications, the results of this study can be highly relevant for other occupational groups that have only a limited amount of time available but have to improve fitness through participation in a regular exercise program.

Conclusions

Our results suggest a particular advantage of the individualized polarized training concept. The polarized distribution of low-intensity and individualized high-intensity interval training can be considered superior to a continuous training with higher total training load mainly below or at lactate threshold. Given the difference in training volume, high-intensity interval training, as part of a polarized training concept, is a time-efficient strategy to induce great improvements in key endurance variables such as relative VO_{2peak}, VT1, RCP and TT. Importantly, the results of this study showed that endurance exercises without structured guidance showed no positive effects. This leads to the conclusion that a polarized training concept is the method of choice when there is a limited amount of time such as for firefighters or comparable jobs having the possibility to exercise one hour on-duty.

Conflicts of interest

All authors declare that they have no conflicts of interest.

Acknowledgments

The authors thank AOK Bayern – Die Gesundheitskasse (German health insurance) and Flughafen München GmbH (Munich airport) for the financial study support. The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript. The results of the present study do not constitute endorsement by ACSM and are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation. Finally, the authors especially thank Munich Airport firefighters for volunteering for this research.

References

1. Beaver WL, Wassermann K, Whipp BJ. A new method for detecting anaerobic threshold by gas exchange. *J. Appl. Physiol.* 1986;60(6):2020–7.

2. Billat VL, Demarle A, Slawinski J, Paiva M, Koralszstein J-P. Physical and training characteristics of top-class marathon runners. *Medicine & Science in Sports & Exercise*. 2001;33(12):2089–97.

3. Breil FA, Weber SN, Koller S, Hoppeler H, Vogt M. Block training periodization in alpine skiing: effects of 11-day HIT on VO2max and performance. *European Journal of Applied Physiology*. 2010;109(6):1077–86.

4. Burgomaster KA, Howarth KR, Phillips SM, et al. Similar metabolic adaptations during exercise after low volume sprint interval and traditional endurance training in humans. *The Journal of physiology*. 2008;586(1):151–60.

5. Burgomaster KA, Hughes SC, Heigenhauser GJ, Bradwell SN, Gibala MJ. Six sessions of sprint interval training increases muscle oxidative potential and cycle endurance capacity in humans. *J Appl Physiol.* 2005;98:1985–90.

6. Committee for Firefighting Issues, Civil Protection and Civil Defense (2002). Firefighting Service Regulations 7. Edition 2002 with adjustments 2005: FwDV 7. Committee for Firefighting Issues, Civil Protection and Civil Defense (2002); 2002, with adjustments 2005.

7. Dennison K, Mullineaux DR, Yates JW, Abel MG. The Effect Of Fatigue And Training Status On Firefighter Performance. *Journal of Strength and Conditioning Research.* 2012;26(4):1101–9.

8. Ellestad M, Allen W, Wan M, Kemp G. Maximal Treadmill Stress Testing for Cardiovascular Evaluation. *Circulation.* 1969;39:517–22.

9. Elsner K, Kolkhorst FW. Metabolic demands of simulated firefighting tasks. *Ergonomics.* 2008;51(9):1418–25.

10. Esfandiari S, Sasson Z, Goodman JM. Short-term high-intensity interval and continuous moderate-intensity training improve maximal aerobic power and diastolic filling during exercise. *European Journal of Applied Physiology*. 2014;114(2):331–43.

11. Esteve-Lanao J, Foster C, Seiler S, Lucia A. Impact of training intensity distribution on performance in endurance athletes. *Journal of Strength and Conditioning Research*. 2007;21(3):943–9.

12. Esteve-Lanao J, Juan AFS, Eearnest CP, Foster C, Lucia A. How Do Endurance Runners Actually Train?: Relationship with Competition Performance. *Medicine & Science in Sports & Exercise*. 2005;37(3):496–504.

13. Foster C, Florhaug JA, Franklin J, et al. A New Approach to Monitoring Exercise Training. *Journal of Strength and Conditioning Research.* 2001;15(1):109–15.

14. Franch J, Madsen, K., Djurhuus, M., Pedersen, P.K. Improved running economy following intensified training correlates with reduced ventilatory demands. *Med Sci Sports Exerc.* 1998;30(8):1250–6.

15. Gibala MJ, Little JP, van Essen M, et al. Short-term sprint interval versus traditional endurance training: similar initial adaptations in human skeletal

muscle and exercise performance. *The Journal of Physiology.* 2006;575(Pt 3):901–11.

16. Gibala MJ, McGee SL. Metabolic adaptations to short-term high-intensity interval training: a little pain for a lot of gain? *Exercise and sport sciences reviews*. 2008;36(2):58–63.

17. Gledhill N, Jamnik VK. Characterization of the physical demands of firefighting. *Can J Sport Sci.* 1992b;17(3):207–13.

18. Gorostiaga EM, Walter CB, Foster C, Hickson RC. Uniqueness of interval and continuous training at the same maintained exercise intensity. *Eur J Appl Physiol*. 1991;63(2):101–7.

19. Green HJ, Jones LL, Painter DC. Effects of short-term training on cardiac function during prolonged exercise. *Med Sci Sports Exerc.* 1990;22(4):488–93.

20. Heimburg E, Rasmussen A, Medbö J. Physiological responses of firefighters and performance predictors during a simulated rescue of hospital patients. *Ergonomics*. 2006;49(2):111–26.

21. Helgerud J, Høydal K, Wang E, et al. Aerobic high-intensity intervals improve VO2max more than moderate training. *Medicine and Science in Sports and Exercise.* 2007;39(4):665–71.

22. Laursen PB, Jenkins DG. The Scientific Basis for High-Intensity Interval Training. *Sports Medicine.* 2002;32(1):53–73.

23. Lemon PWR, Hermiston P. The Human Energy Cost of Fire Fighting. *J Occup Med.* 1977;19(8):558–62.

24. Lucia A, Hoyos J, Santalla A, Earnest C, Chicharro JL. Tour de France versus Vuelta a Espana: which is harder? *Medicine and Science in Sports and Exercise*. 2003;35(5):872–8.

25. Midgley AW, McNaughton LR, Wilkinson M. Is there an Optimal Training Intensity for Enhancing the Maximal Oxygen Uptake of Distance Runners? *Sports Medicine*. 2006;36(2):117–32.

26. Milanovic Z, Sporis G WM. Effectiveness of High-Intensity Intervall Training (HIT) and Continuous Endurance Training for VO2max Improvments: A Systematic Review and Meta-Analysis of Controlled Trials. *Sports Medicine.* 2015;45:1469–81.

27. Oshima Y, Miyamoto T, Tanaka S, Wadazumi T, Kurihara N, Fujimoto S. Relationship between isocapnic buffering and maximal aerobic capacity in athletes. *European Journal of Applied Physiology and Occupational Physiology*. 1997;76(5):409–14.

28. Parra J, Cadefau JA, Rodas G, Amigó N, Cussó R. The distribution of rest periods affects performance and adaptations of energy metabolism induced by high-intensity training in human muscle. *Acta physiologica Scandinavica.* 2000;169(2):157–65.

29. Roberts MA, O'Dea J, Boyce A, Mannix ET. Fitness Levels of Firefighter Recruits Before and After a Supervised Exercise Training Program. *J Strength Cond Res.* 2002;16(2):271–7.

30. Rønnestad BR, Hansen J, Thyli V, Bakken T, Sandbakk Ø. 5-week block periodization increases aerobic power in elite cross-country skiers. *Scand J Med Sci Sport.* 2016:26(2):140-146.

31. Seiler KS, Kjerland GØ. Quantifying training intensity distribution in elite endurance athletes: is there evidence for an "optimal" distribution? *Scandinavian journal of medicine & science in sports.* 2006;16(1):49–56.

32. Seiler S, Tönnesen E. Intervals, Thresholds, and Long Slow Distance: the Role of Intensity and Duration in Endurance Training. *Sportscience.* 2009;13:32–53.

33. Siddall AG, Stevenson RDM, Turner PFJ, Stokes KA, Bilzon JLJ. Development of role-related minimum cardiorespiratory fitness standards for firefighters and commanders. *Ergonomics.* 2016;59(10):1335–43.

34. Stöggl T, Sperlich B. Polarized training has greater impact on key endurance variables than threshold, high intensity, or high volume training. *Frontiers in Physiology.* 2014;5:33.

35. Wassermann K, McIlroy MB. Detecting the threshold of anaerobic metabolism in cardiac patients during exercise. *The American Journal of Cardiology.* 1964;14(6):844–52.

36. Weston M, Taylor KL, Batterham AM, Hopkins WG. Effects of Low-Volume High Intensity Interval Training (HIT) on Fitness in Adults: A Meta-Analysis of Controlled and Non-Controlled Trials. *Sports Med.* 2014;44:1005–17.

37. Williams-Bell FM, Boisseau G, McGill J, Kostiuk A, Hughson RL. Air management and physiological responses during simulated firefighting tasks in a high-rise structure. *Applied Ergonomics.* 2010;41(2):251–9.

38. Windisch S, Seiberl W, Hahn D, Schwirtz A. Physiological Responses to Firefighting in Extreme Temperatures Do Not Compare to Firefighting in Temperate Conditions. *Front. Physiol.* 2017b;8:1–11.

39. Windisch S, Seiberl W, Schwirtz A, Hahn D. Relationships between strength and endurance parameters and air depletion rates in professional firefighters. *Scientific Reports*. 2017a;7:1–10.

Figures

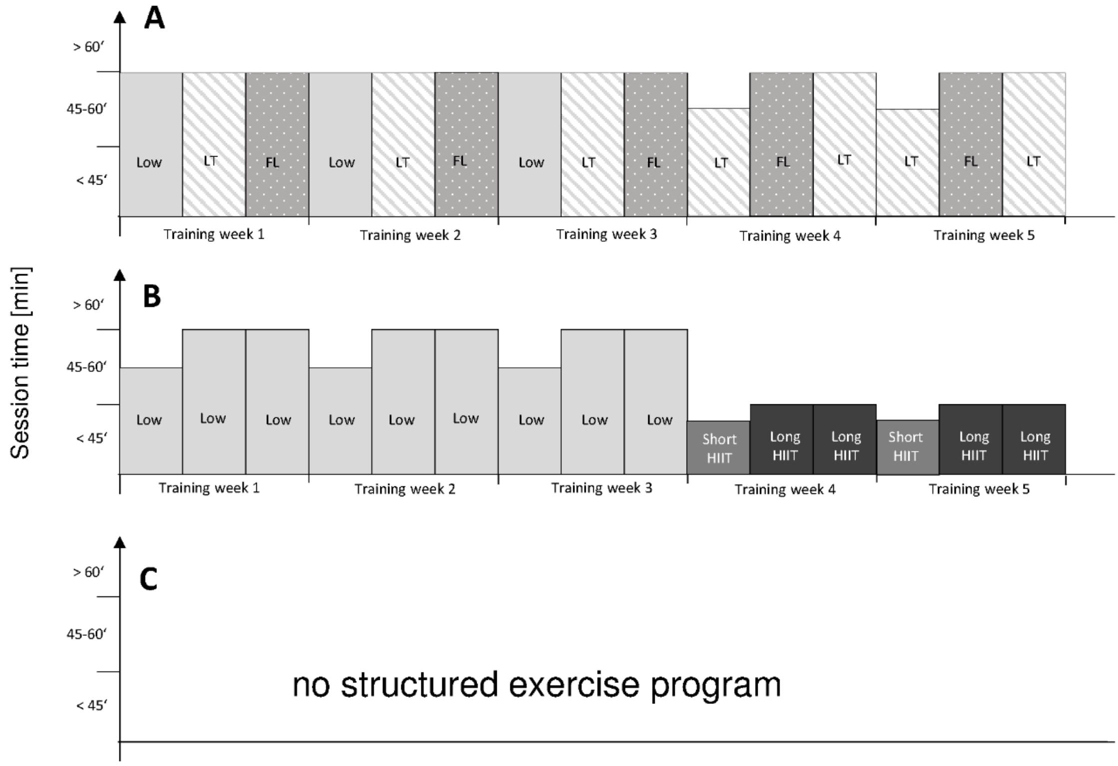

Figure 1 – **Micro-cycle (5 weeks) in an exercise program of 15 weeks** (Repetition of every micro-cycle: 3x) of **(A) continuous training** (CT), **(B) polarized high-intensity interval training (HIIT)** and **(C) unstructured training of the control group** (CT). (Abbreviations: Low, low intensity training (HR < VT1); LT, training intensity around the lactate threshold/respiratory compensation point (RCP); FL, fartlek)

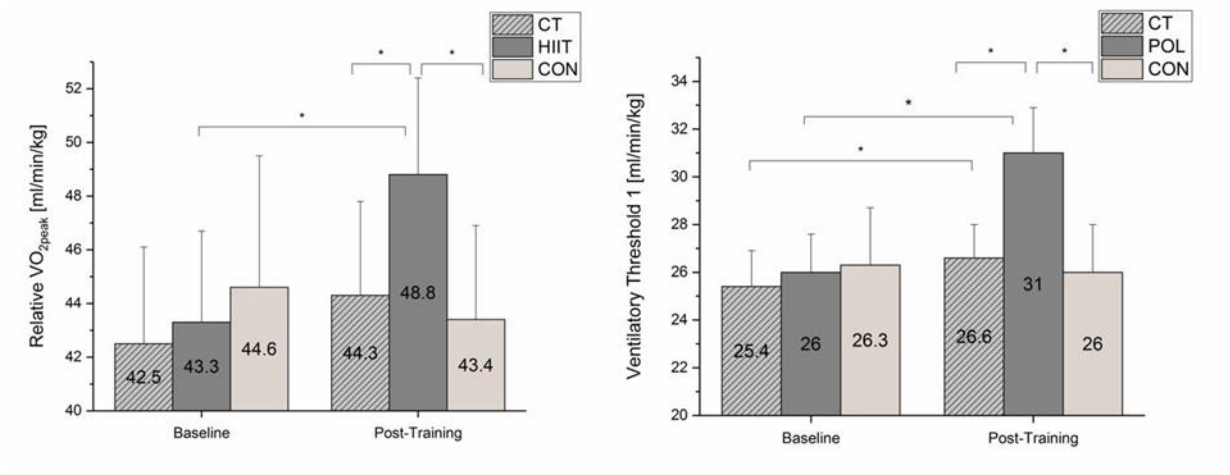

Figure 2 – Changes in relative VO_{2peak} (left) and VT1 (right) prior (Baseline) and following (post-Training) a 15-week exercise program. Values are means ± SD. *Significant differences between baseline and post-training test (p < 0.05)

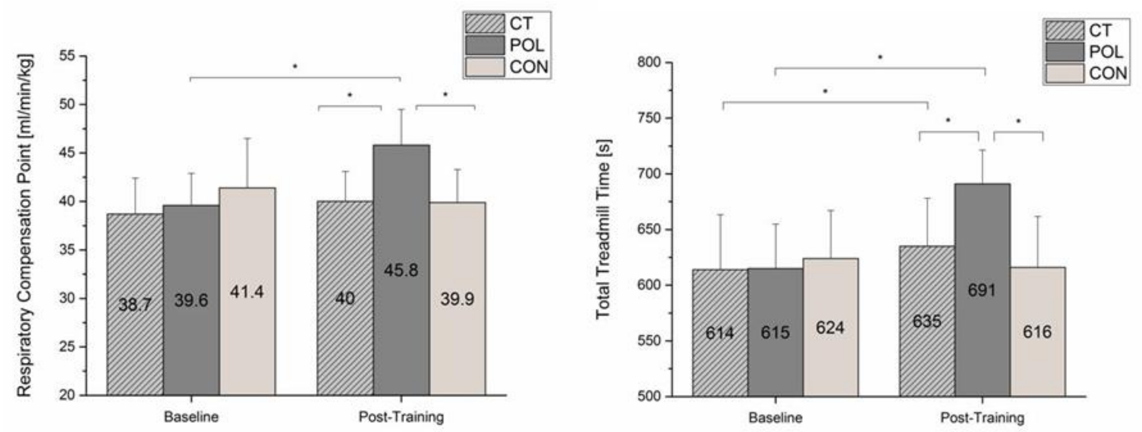

Figure 3 - Changes in VT1 (left) and anaerobic capacity (right) prior (Baseline) and following (post-training) a 15-week exercise program. Values are means ± SD. *Significant differences between baseline and post-training test (p < 0.05)

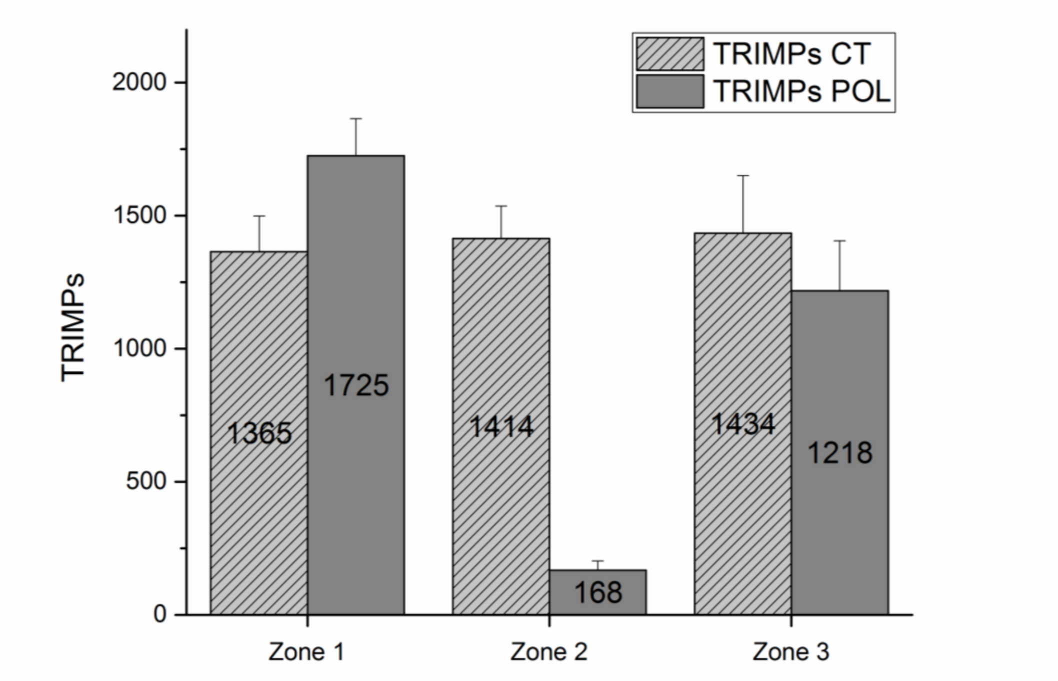

Figure 4 – Calculated TRIMP scores for CT and POL exercise programs. The TRIMP score is calculated based on the TRIMP concept, integrating exercise volume and intensity (see: Lucia et al., 2003)

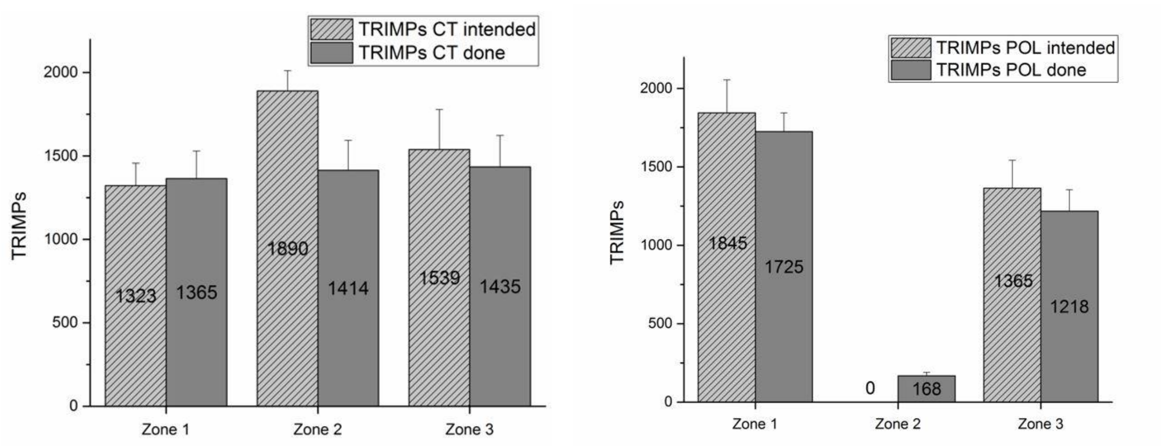

Figure 5 – Intended TRIMP scores for zone 1, zone 2 and zone 3 based on the exercise program plan and actually done TRIMP scores. Left: TRIMP scores intended and done for the continuous training. Right: TRIMP scores intended and done for the polarized training.

9 Discussion and research perspectives

In the first part, this chapter provides a summary of the discussion of the key findings of the three conducted studies. Details can be found in the discussion parts of every paper in Appendix A, B and C. Furthermore, the limitations of the current research are discussed later in this chapter. Finally, this chapter provides an overview of future research perspectives based on the key findings of this dissertation.

9.1 Discussion and summary of the main findings

One of the main aims of this research was to quantify firefighting job demands in their various aspects. There is no doubt that firefighting is a very physically-demanding occupation, as proven by previous studies in this field (Davis, Dotson and Laine, 1982; Bilzon et al., 2001; Heimburg, Rasmussen and Medbö, 2006; Elsner and Kolkhorst, 2008). In parts, the results of the current research have confirmed these earlier findings. Due to new comparisons made in the conducted studies (respiratory protection exercise with standard facial mask and SCBA vs. spirometry mask), it is possible to describe the physiological strain occurring during firefighting in further detail. Furthermore, the results of the dissertation describe – for the first time – firefighting performance as a combination of operating speed (time to complete a pre-defined circuit), physical strain and air depletion during simulated firefighting.

The results of Study I demonstrate that performers of different TSA levels show significant differences in maximal endurance parameters, the capacity to work below their ventilatory threshold 1 and breathing variables. This is a strong argument that strong firefighting performance is associated with a good aerobic metabolism and thus confirms our initial hypothesis in this first study, namely that firefighters with lower air depletion from the self-containing breathing apparatus, faster completion time and lower physical strain during the simulated firefighting exercise possess a higher aerobic fitness level in terms of VO_{2peak}. Indeed, this can clearly be proven by a low TSA score, which can be seen as evidence of the usefulness of the newly-developed firefighting performance formula.

Out of all parameters that we measured, we identified the most important firefighting determinants for a simulated standard firefighting exercise in temperate conditions by means of multiple regression. We found a combination of laboratory (VO_{2peak}) and occupation-specific parameters (breathing frequency and time spent in intensity Zone 1 during the simulated firefighting exercise) that beat predicted TSA score, accounting for 70% of the observed variance. 70% can be seen as a very good value for the observed variance, as it is one of the highest values observed for explaining firefighting performance by a combination of fitness variables. Other authors have found combinations of aerobic fitness and strength parameters accounting for variances between 40% and 70% (Davis, Dotson and Laine, 1982; Williford et al., 1999; Sothmann et al., 2004; Williams-Bell et al., 2009). The results of the multiple regression support the idea that aerobic fitness – in terms of VO_{2peak} and the time spent in Zone 1 – considerably contributes to how fast (time) and effectively (low air depletion from SCBA and minimal physical strain) a firefighter can perform his tasks.

One of the main aims of this dissertation was not only to determine the physical strain induced by simulated firefighting in temperate conditions (20° - 30°), but also to draw up a physical demands profile of a firefighting exercise when performing it in extreme conditions (up to 300°). The reason for this was that this firefighting exercise was much closer to a real live-fire scenario. In fact, most previous studies have investigated firefighting in temperate conditions (e.g. Davis, Dotson and Laine, 1982; Williford et al., 1999; Rhea, Alvar and Gray, 2004; Sothmann et al., 2004; Williams-Bell et al., 2009; Perroni et al., 2010). Both the simulated firefighting exercises conducted in Study I and Study II are state-of-the-art exercises for German firefighters (standard simulated firefighting exercise SFE vs. flashover training FOT). Thus, both trainings claim to represent firefighting job demands, which was the reason for choosing both exercises to draw up a detailed firefighting job demands profile. The physical demands of the standard firefighting exercise in terms of heart rates were considerably less compared to the training in extreme temperatures with smoke and unexpected flashovers. The mean HR in our studies (SFE: 79.0% HR_{max}; FOT: 85.4% HR_{max}) was in good accordance with the reported values from previous studies, ranging from 60% to 90% HR_{max} (Romet and Frim, 1987; von Heimburg et al., 2006; Del Sal et al., 2009; Perroni et al., 2010). Furthermore, the time spent in the three physiological time zones significantly differed between the two exercises. During SFE, subjects worked for a longer time in Zone 1 compared to FOT (24.6 and 16.3% of completion time for SFE and FOT, respectively). Zone 1 represents the time during which subjects worked below ventilatory threshold 1, indicating a high percentage of aerobic metabolism. Firefighters spent most of the time in Zone 2 (SFE: 65.8%; FOT: 50.4%), which represents the time between VT1 and RCP, indicating mostly aerobic-anaerobic metabolism. In contrast to SFE (9.7%), during FOT subjects spent one-third (33.3%) of the completion time in Zone 3, indicating a HR above 90% HR_{max}. Heart rates above the individual RCP indicate that energy production could be strongly supported by anaerobic processes.

Based on this knowledge, the question emerges concerning how the relationship between firefighting performance in terms of the TSA score and various fitness parameters changes when the demands of the exercise change from a standard simulated exercise to a simulated exercise that is much closer to a real live scenario in an emergency. This research question has not previously been investigated and thus the investigation of this specific point was another main aim of the current research.

The exploration of important relationships in this dissertation was similar to previous work on the topic (e.g., Williford et al., 1999; Rhea, Alvar and Gray, 2004; Michaelides et al., 2011). A changing sensitivity of performed tests to assess fitness variables for both exercises would subsequently mean that firefighters need different fitness prerequisites to perform the different exercises successfully. Although the two firefighting exercises in temperate and extreme conditions differed in their demands, substantial similarity between them was found, namely that a high relative VO_{2peak} can be assumed to be the most important fitness prerequisite for good firefighting performance in both scenarios. Furthermore, the ability to work in specific physiological intensity zones was the second most important aspect of firefighting performance. However, notable differences were found between the demands of the exercises, as Zone 1 was strongly related to SFE and Zone 3 to FOT.

The present findings hold particular relevance for the published relative VO_{2peak} recommendations for firefighters, which vary between 39 and 45 ml/min/kg (O'Connell et al., 1986; Gledhill and Jamnik, 1992; Siddall et al., 2016). These studies recommended minimum values based on firefighting exercises without heat and additional stressors such as flashovers. Based on the results of the conducted studies (Study I and II), a slightly higher minimum VO_{2peak} of 46 ml/min/kg is now recommended as this value was identified for subjects showing at least average performance in terms of TSA scores in both studies. However, this recommended minimum value needs to be investigated in future studies to prove that it is a justified threshold.

As the most important physical parameters for firefighting are now identified, it is highly recommended to conduct regular and standardized tests to monitor them. The identified variables can easily be tested in the laboratory, which allows for valid standardization and requires fewer resources compared to simulated firefighting exercises. Although many studies recommend firefighters to maintain e.g. a high level of relative VO_{2peak} (Gledhill and Jamnik, 1992; Siddall et al. 2016), only few studies provide data regarding the effect of appropriate endurance exercise programs that can serve as recommendations concerning how to improve or maintain VO_{2peak} (Roberts et al., 2002; Dennison et al., 2012).

Therefore, in Study III we compared the effects of a 15-week endurance exercise program of polarized training to continuous training and the non-structured endurance training of a control group. The particular feature of this study was that firefighters exercised for only 1 hour while on-duty (3 times/week). The results suggest a particular advantage for high-intensity training within a polarized training concept. This exercise mode improved all investigated parameters (VO_{2peak}, VT1, RCP and maximum treadmill time until exhaustion) significantly more than continuous training with a lot of training around the lactate threshold. These results show that systematic and individualized training periodization on a scientific basis and the selection of appropriate exercise modes goes beyond ensuring the sole opportunity of training on-duty.

9.2 Limitations of the current research

This section will outline some methodological limitations of the current research that were partly considered in the conducted three studies.

All simulated firefighting exercises carried out in this work were state-of-the-art exercises of German professional firefighters. Therefore, they were conducted in a standardized manner in accordance with the regulations (Committee for Firefighting Issues, Civil Protection and Civil Defense, 2002). The regulations also prescribed which tasks should be part of the exercise. It should be mentioned that victim search and victim rescue – which were part of a vast number of other simulated firefighting exercises (e.g. Lemon and Hermiston, 1977b; Davis, Dotson and Lane, 1982; Rhea, Alvar and Gray, 2004; Sothmann et al., 2004; Harvey, 2008; Perroni et al., 2010; Sheaff et al., 2010; Calavalle et al., 2013; Lindberg et al., 2013; Lindberg, Oksa and Malm, 2014) – were not part of the exercises conducted in the current work. With a relative VO_2 of 42 ml/min/kg (e.g. Lemon and Hermiston, 1977b), victim search and rescue are some of the most demanding and commonly-occurring job tasks for firefighters. These tasks might significantly increase the physical strain induced by a firefighting exercise. This could have also happened in the current work if it had been part of the firefighting exercises.

Measuring core temperature would provide more insights into what type of stress – physical demand or heat stress – had a stronger influence on heart rate responses. Together with the measurement of dehydration, this would be an important aspect when assessing thermophysiological responses of a flashover training similar to that conducted in this work (Study II). Unfortunately, there was no data available from the present study. Measurements of core temperature were not accepted as a study method by Munich Airport, where all of the measurements were conducted.

Finally, the subjects in this study were professional airport firefighters, whereby airport firefighting also involves very specific tasks such as aircraft fire protection. When determining the job demands of airport firefighters, it would be important to know what specific physical demands firefighters face at an airport. However, less is known about the physical work demands when firefighting an aircraft fire or responding to an emergency in relation with an aircraft. In order to quantify the physical demands of these specific tasks, they should be simulated in a specific exercise. For instance, some airports have a mock-up aircraft to provide adequate possibilities for firefighters to train different emergency scenarios in relation with aircrafts. This could also be used in future studies to determine the physical job demands of firefighting an aircraft fire. Here, the limitations of the present work move on to the next item, namely future research perspectives.

9.3 Research perspectives

Based on the results of this thesis, several important research perspectives opened up for future studies (Fig. 1):

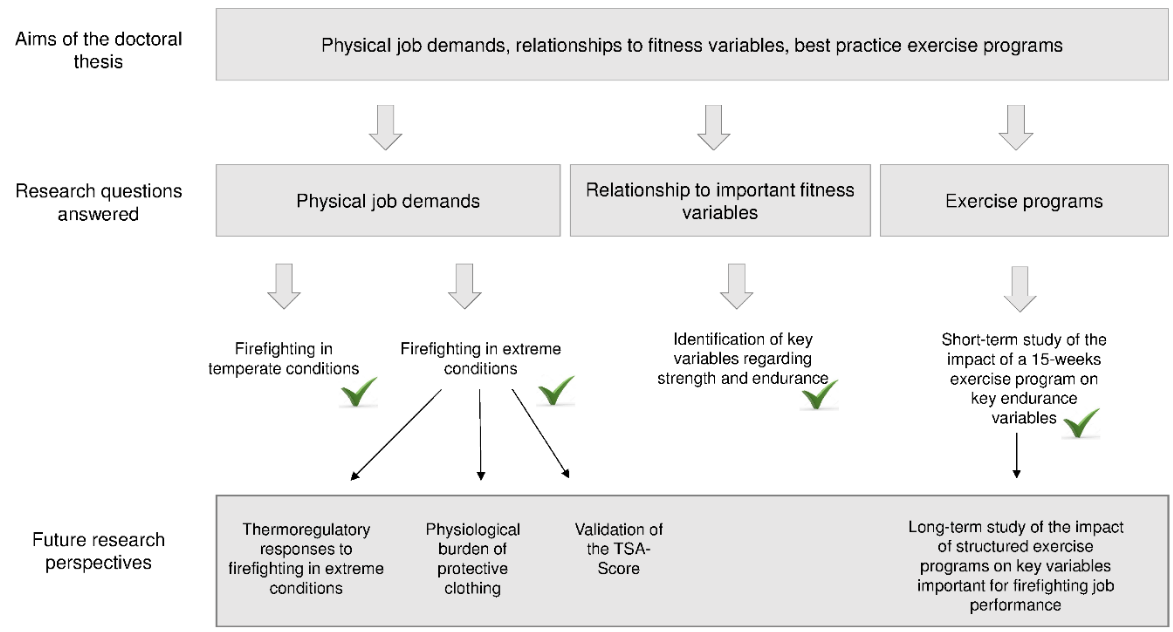

Fig. 1. *Flowchart of the aims of this doctoral thesis, investigated research questions and future research perspectives based on the results of the conducted studies*

9.3.1 Thermoregulatory responses to firefighting in extreme temperatures

The results of this thesis highlight that the physiological responses to firefighting in temperate conditions significantly differ from firefighting in extreme conditions. As a result, we can conclude that the environmental conditions (high ambient temperature and radiant heat) during the flashover training might have had an impact on the physiological strain during the flashover training. It is difficult to establish whether the physiological strain was the result of the physical demands of the activities during the simulated firefighting exercise or the heat stress imposed by the environment, or a combination of both. Here, it is apparent that the high physical strain imposed on firefighters during their job is multifactorial. Heavy personal protective clothing, physically-demanding work tasks, increasing body temperature, time pressure and emotional stress all combine to make many responses to emergencies physically very demanding. During the flashover training, heart rate was the only variable that we measured. When investigating firefighting in extreme temperatures, measuring core temperature and dehydration would provide further insights into the physiological responses to exercises in the heat. This will be an important point for future studies. Therefore, it is strongly recommended to conduct a flashover training – similar to the one in the current thesis – while measuring core temperature, sweat evaporation and dehydration. As already mentioned in the *Study limitations* section, this firefighting exercise could be conducted in an aircraft mock-up to characterize the thermoregulatory responses specific to aircraft firefighting, which have not been investigated thus far.

9.3.2 Physiological consequences of wearing protective clothing

Wearing protective clothing is essential for firefighters as it affords protection from harmful exposures such as chemical hazards, fires, smoke, etc. (Barr, Gregson and Reilly, 2010). A typical firefighting ensemble (including SCBA) weighs ~25 kg. The total ensemble comprises boots, gloves, bunker pants, a coat and flash hood, while self-containing breathing apparatus is also worn during firefighting (SCBA) (Dorman and Havenith, 2009). The personal protective gear comprises an outer shell, moisture barrier and a thermal liner, with each layer having a specific purpose (Barr, Gregson and Reilly, 2010). Increases in perceived exertion and metabolic rate (2.4–20.9%) when wearing personal protective garments compared to a control condition without personal protective clothing have been seen in previous studies, with increases above 10% being significant (Dorman and Havenith, 2009). Other researchers have demonstrated that personal protective clothing and wearing a SCBA have a negative impact on the available individual VO_{2peak}, reducing it by 17% (Dreger, Jones and Petersen, 2006) or even 27% (Perroni et al., 2008).

Building on the previous recommendation to measure core temperature during simulated firefighting exercises in extreme environments, these measurements could also be used for testing different personal protective garments. Different garments might have different effects on thermoregulatory responses of firefighters to a flashover training. Accordingly, the physical strain induced by firefighting could change due to differences in protective garments. Very few studies have investigated the effects of the clothing on the physiological demands of firefighting in terms of heart rates and core temperature (e.g. Dorman and Havenith, 2009; Ljubicic et al., 2014). Among those studies to do so, limited garments have been tested and generally while either walking or stepping only or conducting some job relevant movements (lifting, pushing, pulling, etc.). Therefore, future studies should aim to quantify the effects of different personal protective garments on physiological responses to firefighting in extreme temperatures with a test setup close to a real live-fire scenario.

9.3.3 Validation of the TSA score

The results of this thesis describe – for the first time – firefighting performance as a combination of operating speed (time to complete the circuit), physical strain and air depletion during a simulated firefighting exercise (Windisch et al., 2017a; Windisch et al., 2017b). The reasons for selecting time for completion, heart rate and air depletion rates for the new firefighting performance formula – the TSA model resulting in a TSA score – were primarily based on the rational nature of firefighting.

When arriving at an emergency scene, firefighters have to work as quickly as possible to save lives or prevent the spread of fires. Furthermore, previous data has shown that less fit firefighters experience higher physiological strain near HR maximum, not being able to sustain operating speed and thus not being able to complete firefighting tasks successfully (Sothmann et al., 2014). Finally, firefighters can run out of air supply due to the limited amount of air compressed in the SCBA.

Based on these considerations, each of the three factors is thought to be important, whereby all three parameters were included in the TSA firefighting performance formula. Since at present it is unknown which factor is the most important or whether one factor is more important than another, z-transformations were used to avoid an unintended weighting of one of the three parameters. In previous studies (Windisch et al., 2017a; Windisch et al., 2017b) fitness variables have been related accurately to firefighting performance. Thus, improving the variables should also improve a firefighter's potential to perform firefighting tasks more efficiently. This could be re-examined in a future study to validate the developed TSA score. Increased performance in identified important fitness variables should subsequently improve the TSA score determined from a simulated firefighting exercise. However, as previously stated (Windisch et al., 2017a), further research is needed to validate the model, as a variety of weighting options may even improve the predictability of firefighting performance.

9.3.4 Long-term study on the impact of structured exercise programs on key fitness variables

By investigating the effect of two different endurance training concepts, it has been shown that polarized training could be an effective endurance training concept for firefighters. Within the 15-week program, it was possible to reach significant improvements in all selected key endurance parameters (VO_{2peak}, VT1, RCP and time to exhaustion during treadmill running). In future studies, it would be interesting to explore how the polarized training concept changes the selected parameters when used over extended periods of time (e.g. several years). The changes could be documented by conducting periodically-performed treadmill testing, as recommended in the publications of this thesis (Windisch et al., 2017a; Windisch et al., 2017b).

10 Conclusions and implications for firefighters

Based on the findings of this dissertation, it can be concluded that the most important (VO_{2peak}) as well as changing fitness variables (exercising below individual VT 1 or above individual RCP) due to the demands of a firefighting scenario could be determined within this research. The results of this work also show that the TSA performance model can be applied for firefighting in temperate and extreme conditions (heat, smoke, poor visibility, flashovers) as the same kind of fitness parameters (i.e. endurance) were sensitive to predicting performance. From all variables researched in the current studies, relative VO_{2peak} was found to be the primary physiological variable related to the different aspects of firefighting, strengthening the plea to consider endurance as the most important prerequisite for firefighting. For practical application, it is strongly recommended that firefighters sustain a high level of relative VO_{2peak}, VT1 and RCP. A polarized distribution of low-intensity and individualized high-intensity interval training can be considered superior to a higher total training load mainly below or at the lactate threshold. Given the difference in training volume, high-intensity interval training as part of a polarized training concept is a time-efficient strategy to induce strong improvements in important key endurance variables such as relative VO_{2peak}, VT1, RCP, etc. Particularly, it should be considered that this training concept is more effective than traditional continuous training when there is a limited amount of time, such as for firefighters or comparable jobs with the possibility to exercise for one hour on-duty. Finally, the effects of the exercise program conducted in Study III clearly show that a structured exercise program on a scientific basis offers the almost unique possibility to significantly improve endurance when exercising for only one hour on-duty.

10.1 Implications for firefighters

One of the aims of this doctoral research was to offer recommendations concerning which combination of fitness tests would be useful to evaluate a firefighter's job performance. It is apparent that high endurance capacities are deemed important for firefighters' work performance, as highlighted in previous work (e.g. Lemon and Hermiston, 1977; Gledhill and Jamnik, 1992b; Bilzon et al., 2001; Heimburg, Rasmussen and Medbö, 2006; Siddall et al., 2016). It has now been confirmed by the studies conducted in the current thesis (Windisch et al., 2017a; Windisch et al, 2017b). In contrast to previously-conducted research, the two published studies of this thesis (Windisch et al., 2017a; Windisch et al., 2017b) have compared the changing contribution of endurance and strength capacities to different firefighting environments for the first time. These studies emphasize the importance of a high endurance level. The higher the demands of firefighting, the higher the endurance level required to complete firefighting tasks safely and without physical overload. Endurance capacities can easily be tested by laboratory tests such a maximum treadmill test, etc. In turn, as we correlated them accurately with firefighting performance, job performance could be predicted by the means of these laboratory tests.

In Germany, an applied firefighting field test – the standard simulated firefighting exercise as conducted in this doctoral research – has been used for more than a decade to check whether firefighter incumbents meet occupational performance standards (Committee for Firefighting Issues, Civil Protection and Civil Defense, 2002). The categorization into “passed” and “failed” only refers to the amount of air depletion and does not include any proposed time limits or maximum heart rates. If the firefighter passes the exercise without running out of air supply from the SCBA, his categorization is “passed”. We found that a mean relative VO_2 of 25 ± 3 ml/min/kg is also sufficient to pass this exercise successfully. This is considerably less than our proposed minimum VO_2 threshold of 46 ml/min/kg to complete firefighting exercises in extreme temperatures safely. The physical demands of the standard simulated firefighting exercise have never previously been related to various fitness measurements. The current research has shown that the demands of this firefighting exercise were only moderately related to the demands of more realistic scenarios such as a flashover training. Moreover, this exercise is not suitable for checking a firefighter’s fitness level, neither for endurance nor strength issues. Therefore, a re-examination of the mandatory use of the standard simulated firefighting exercise in terms of possibilities and limitations is recommended. The medical examination in terms of the G26.3 health check should be maintained, serving mainly as a physical check from a medical perspective to fulfill the job as a firefighter (e.g. lung function test, eye test, hearing test, exercise electrocardiogram).

However, based on the new considerations resulting from this doctoral thesis, a periodically-performed fitness screening for firefighter incumbents should also be established. We strongly recommend the implementation of an annually-conducted treadmill test to determine important endurance parameters such as VO_{2peak}, VT1, RCP, etc. Maintaining the recommended minimum levels could help firefighters to avoid physical overload. Neither medical health checks (e.g. the G26.3 health check) nor the standard firefighting exercise can provide information on these specific and important variables for firefighters.

As one of the main differences between our study and previous research (Henderson, Berry and Matic, 2007; Rhea, Alvar and Gray, 2004; Michaelides et al., 2011; Lindberg, Oksa and Malm, 2014), we could not identify any strength parameters as performance-determining prerequisites for firefighting performance. This is surprising given that the characteristics of typical firefighting tasks such as carrying heavy equipment or rescue victims or chopping or running hoses require the intense use of upper body muscular strength. Furthermore, firefighters frequently perform tasks in awkward and injury-prone positions that exacerbate their chance of incurring a musculoskeletal injury (Michaelides et al., 2011). Although muscular strength and flexibility in this study did not show significant relevance for the predictive power of job demands, both should be essential components of firefighting training to reduce the risk of job injuries.

References

1. American College of Sports Medicine. (2013). *ACSM's Guidelines for Exercise Testing and Prescription* (9th revised edition): Lippincott Williams&Wilki.
2. Aoyagi, Y., McLellan, T. M. & Shephard, R. J. (1998). Effects of endurance training and heat acclimation on psychological strain in exercising men wearing protective clothing. *Ergonomics, 41* (3), 328–357.
3. Astrand, P.-O., Rodahl, K., Dahl, H. A. & Strömme, S. B. (2012). *Textbook of Work Physiology. Physiologial Bases of Exercise*: Human Kinetics.
4. Barnard, R. J. & H. W. Duncan. (1975). Heart Rate and ECG Responses of Fire Fighters. *J Occup Med, 17* (4), 247–250.
5. Barr, D., Gregson, W. & Reilly, T. (2010). The thermal ergonomics of firefighting reviewed. *Applied Ergonomics, 41* (1), 161–172.
6. Beaudin, A. E., Clegg, M. E., Walsh, M. L. & White, M. D. (2009). Adaptation of exercise ventilation during an actively-induced hyperthermia following passive heat acclimation. *American journal of physiology. Regulatory, integrative and comparative physiology, 297* (3), R605-14.
7. Beaver, W. L., Wassermann, K. & Whipp, B. J. (1986). A new method for detecting anaerobic threshold by gas exchange. *J. Appl. Physiol., 60* (6), 2020–2027.
8. Beck, B., Billing, D.C. & Carr, A.J. (2016). Developing physical and physiological employment standards. Translation of job analysis findings to assessments and performance standards – A systematic review. *International Journal of Industrial Ergonomics, 56*, 9–16.

9. Billat, V. L., Demarle, A., Slawinski, J., Paiva, M. & Koralsztein, J.-P. (2001). Physical and training characteristics of top-class marathon runners. *Medicine & Science in Sports & Exercise, 33* (12), 2089–2097.

10. Bilzon, J., Scarpello, E. G., Smith, C. V., Ravenhill, N. A., Rayson, M. P. (2001). Characterization of the metabolic demands of simulated shipboard Royal Navy fire-fighting tasks. *Ergonomics, 44* (8), 766–780.

11. Borg, G. (1982). Psychophysical bases of perceived exertion. *Med Sci Sports Exerc, 14* (5), 377–381.

12. Bos, J., Mol, E., Visser, B. & Frings-Dresen, M. (2004). The physical demands upon (Dutch) fire-fighters in relation to the maximum acceptable energetic workload. *Ergonomics, 47* (4), 446–460.

13. Breil, F. A., Weber, S. N., Koller, S., Hoppeler, H. & Vogt, M. (2010). Block training periodization in alpine skiing: effects of 11-day HIT on VO2max and performance. *European Journal of Applied Physiology, 109* (6), 1077–1086.

14. Brown, B., Cotes, J. E., Mortemore, I. L. & Reed, J. W. (1982). An exercise training programme for firemen. *Ergonomics, 25* (9), 793–800.

15. Brzycki, M. (1993). Strength Testing - Predicting a One-Rep Max from Reps-to-Fatigue. *Journal of Physical Education, Recreation & Dance, 64* (1), 88–90.

16. Bunc, V., Heller, J., Leso, J., Sprynarova, S. & Zdanowicz, R. (1987). Ventilatory Threshold in Various Groups of Highly Trained Athletes. *Int J Sports Med, 8*, 275–280.

17. Burgomaster, K. A., Howarth, K. R., Phillips, S. M., Rakobowchuk, M., Macdonald, M. J., McGee, S. L. & Gibala, M. J. (2008). Similar metabolic adaptations during exercise after low volume sprint interval and traditional endurance training in humans. *The Journal of physiology, 586* (1), 151–160.

18. Burgomaster, K. A., Hughes, S. C., Heigenhauser, G. J., Bradwell, S. N. & Gibala, M. J. (2005). Six sessions of sprint interval training increases muscle oxidative potential and cycle endurance capacity in humans. *J Appl Physiol, 98*, 1985–1990.
19. Cady, L. D., Thomas, P. C. & Karwasky, R. J.. (1985). Program for Increasing Health and Physical Fitness of Fire Fighters. *J Occup Med, 27* (2), 110–114.
20. Calavalle, A., Sisti, D., Mennelli, G., Andolina, G., Del Sal, M., Rocchi, M., Benelli, P. & Stocchi., V. (2013). A simple method to analyze overall individual physical fitness in firefighters. *Journal of Strength and Conditioning Research, 7* (3), 769–775.
21. Cohen, J. (1988). *Statistical Power Analysis for the Behavioral Sciences* (2nd ed.). Hillsdale (NJ): Lawrence Erlbaum Associates.
22. Committee for Firefighting Issues, Civil Protection and Civil Defense (2002). (2002, with adjustments 2005). *Firefighting Service Regulations 7. Edition 2002 with adjustments 2005. FwDV 7*.
23. Cornell, D. J., Gnacinski, S. L., Meyer, B. B. & Ebersole, K. T. (2017). Changes in Health and Fitness in Firefighter Recruits: An Observational Cohort Study. *Medicine and Science in Sports and Exercise*.
24. Darr, K. C., Bassett, D. R., Morgan, B. J. & Thomas, D. P. (1988). Effects of age and training status on heart rate recovery after peak exercise. *Am J Physiol, 254*, 340–343.
25. Davis, J. A., Vodak, P., Wilmore, J. H., Vodak, J. & Kurtz, P. (1976). Anaerobic threshold and maximal aerobic power for three modes of exercise. *Journal of Applied Physiology, 41* (4), 544–550.

26. Davis, P., Dotson, C. & Laine D. (1982). Relationship between simulated fire fighting tasks and physical performance measures. *Medicine & Science in Sports & Exercise, 14* (1), 65–71.

27. Deakin, J. M., Pelo, R., Smith, J. T., Stevenson, J. M., Wolfe, L. A. & Lee, S. W. (1996). *Development of a Bona Fide Physical Maintenance Standard for CF and DND Fire Fighters*. Ottawa/Kingston.

28. Del Sal, M., Barbieri, E., Gabbati, P., Sisti, D., Rocchi, M. & Stocchi, V. (2009). Physiologic Responses Of Firefighter Recruits During A Supervised Live-Fire Work Performance Test. *Journal of Strength and Conditioning Research, 23* (8), 2396–2404.

29. Dennison, K., Mullineaux, D. R., Yates J. M. & Abel, M. G.. (2012). The Effect Of Fatigue And Training Status On Firefighter Performance. *Journal of Strength and Conditioning Research, 26* (4), 1101–1109.

30. Dorman, L.E. & Havenith, G. (2009). The effects of protective clothing on energy consumption during different activities. *European Journal of Applied Physiology, 105* (3), 463–470.

31. Dreger, R. W., Jones, R. L. & Petersen, S. R.. (2006). Effects of the self-contained breathing apparatus and fire protective clothing on maximal oxygen uptake. *Ergonomics, 49* (10), 911–920.

32. Du, N., Siquin, B., Oguri, K., Kato, Y., Matsumoto, I., Harumi, K. & Matsuoka, T. (2005). Heart rate recovery after exercise and neural regulation of heart rate variability in 30-40 year old female marathon runners. *Journal of Sports Science and Medicine, 4*, 9–17.

33. Durand, G., Tsismenakis, A. J., Jahnke, S. A., Baur, D. M., Christophi, C. A. & Kales, S. N. (2011). Firefighters' physical activity: relation to fitness and

cardiovascular disease risk. *Medicine and science in sports and exercise, 43* (9), 1752–1759.

34. Ellestad, M., Allen, W., Wan, M. & Kemp, G. (1969). Maximal Treadmill Stress Testing for Cardiovascular Evaluation. *Circulation, 39*, 517–522.
35. Elsner, K. & Kolkhorst, F.W. (2008). Metabolic demands of simulated firefighting tasks. *Ergonomics, 51* (9), 1418–1425.
36. Esfandiari, S., Sasson, Z. & Goodman, J. M. (2014). Short-term high-intensity interval and continuous moderate-intensity training improve maximal aerobic power and diastolic filling during exercise. *European Journal of Applied Physiology, 114* (2), 331–343.
37. Esteve-Lanao, J., Foster, C., Seiler, S. & Lucia, A. (2007). Impact of training intensity distribution on performance in endurance athletes. *Journal of Strength and Conditioning Research, 21* (3), 943–949.
38. Esteve-Lanao, J., Juan, A. F. S., Earnest, C. P., Foster, C. & Lucia, A. (2005). How Do Endurance Runners Actually Train? Relationship with Competition Performance. *Medicine & Science in Sports & Exercise, 37* (3), 496–504.
39. Farrell, P., Wilmore, J. H., Coyle, E. F., Billing, J. E. & Costill, D. L. (1979). Plasma lactate accumulation and distance running performance. *Med Sci Sports Exerc, 11* (4), 338-334.
40. Ferrauti, A., Bergeron, M. F., Pluim, B. M. & Weber, K. (2001). Physiological responses in tennis and running with similar oxygen uptake. *European Journal of Applied Physiology, 85* (1-2), 27–33.
41. Foster, C., Florhaug, J. A., Franklin, J., Gottschall, L., Hrovatin, L. A., Parker, S., Doleshal, P. & Dodge, C. (2001). A New Approach to Monitoring Exercise Training. *Journal of Strength and Conditioning Research, 15* (1), 109–115.

42. Franch, J. & Madsen, K., Djurhuus, M., Pedersen, P. K. (1998). Improved running economy following intensified training correlates with reduced ventilatory demands. *Med Sci Sports Exerc, 30* (8), 1250–1256.

43. Friston, K. J., Holmes, A. P., Worsley, K. J., Poline, J. P., Frith, C. D. & Frackowiak, R. S. J. (1995). Statistical parametric maps in functional imaging: A general linear approach, *2*, 189–210.

44. Fujii, N., Honda, Y., Hayashi, K., Soya, H., Kondo, N. & Nishiyasu, T. (2008). Comparison of hyperthermic hyperpnea elicited during rest and submaximal, moderate-intensity exercise. *Journal of applied physiology (Bethesda, Md.: 1985), 104* (4), 998–1005.

45. Gendron, P., Freiberger, E., Laurencelle, L., Trudeau, F. & Lajoie, C. (2015). Greater physical fitness is associated with better air ventilation efficiency in firefighters. *Applied Ergonomics, 47*, 229–235.

46. Gibala, M. J., Little, J. P., van Essen, M., Wilkin, G. P., Burgomaster, K. A., Safdar, A., Raha, S. & Tarnopolsky, M.A. (2006). Short-term sprint interval versus traditional endurance training: similar initial adaptations in human skeletal muscle and exercise performance. *The Journal of physiology, 575* (Pt 3), 901–911.

47. Gibala, M. J. & McGee, S. L. (2008). Metabolic adaptations to short-term high-intensity interval training: a little pain for a lot of gain? *Exercise and sport sciences reviews, 36* (2), 58–63.

48. Gledhill, N. & Jamnik, V. K. (1992a). Development and validation of a fitness screening protocol for firefighter applicants. *Can J Sport Sci, 17* (3), 199–206.

49. Gledhill, N. & Jamnik, V. K.. (1992b). Characterization of the physical demands of firefighting. *Can J Sport Sci, 17* (3), 207–213.

50. Gorostiaga, E. M., Walter, C. B., Foster, C. & Hickson, R. C. (1991). Uniqueness of interval and continuous training at the same maintained exercise intensity. *European Journal of Applied Physiology and Occupational Physiology, 63* (2), 101–107.
51. Green, H. J., Jones, L. L. & Painter, D. C. (1990). Effects of short-term training on cardiac function during prolonged exercise. *Med Sci Sports Exerc, 22* (4), 488–493.
52. Harvey, D. G., Kraemer, J. I., Sharatt, M. T. & Hughson, R. L. (2008). Respiratory gas exchange and physiological demands during a fire fighter evaluation circuit in men and women. *Eur J Appl Physiol, 103*, 89–98.
53. Heimburg, E., Rasmussen, A. & Medbö, J. (2006). Physiological responses of firefighters and performance predictors during a simulated rescue of hospital patients. *Ergonomics, 49* (2), 111–126.
54. Helgerud, J., Høydal, K., Wang, E., Karlsen, T., Berg, P., Bjerkaas, M., Simonsen, T., Helgesen, C., Hjorth, N., Bach, R. & Hoff, J. (2007). Aerobic high-intensity intervals improve VO2max more than moderate training. *Medicine and Science in Sports and Exercise, 39* (4), 665–671.
55. Henderson, N. D., Berry, M. W. & Matic, T.. (2007). Field measures of strength and fitness predict firefighter performance on physically demanding tasks. *Personnel Psychology, 60*, 431–473.
56. Holmer, I. & Gavhed, D. (2007). Classification of metabolic and respiratory demands in fire fighting activity with extreme workloads. *Applied Ergonomics, 38* (1), 45–52.
57. Jahnke, S. A., Hyder, M. L., Haddock, C. K., Jitnarin, N., Day, R. S. & Poston, W. S. C. (2015). High-intensity Fitness Training Among a National Sample of Male Career Firefighters. *Safety and health at work, 6* (1), 71–74.

58. Jones, A. M. & Carter, H. (2000). The Effect of Endurance Training on Parameters of Aerobic Fitness. *Sports Medicine, 29* (6), 373–386.

59. Kales, S., Soteriades, E. S., Christophi, C. A. & Christiani, D. C. (2007). Emergency Duties and Deaths from Heart Disease among Firefighters in the United States. *N Engl J Med, 356* (12), 1207–1215.

60. Larsen, B., Snow, R., Williams-Bell, M. & Aisbett, B. (2015). Simulated Firefighting Task Performance and Physiology Under Very Hot Conditions. *Front. Physiol., 6* (322).

61. Laursen, P. B. & Jenkins, D.G. (2002). The Scientific Basis for High-Intensity Interval Training. *Sports Medicine, 32* (1), 53–73.

62. Lemon, P. W. R. & Hermiston, P. (1977). The Human Energy Cost of Fire Fighting. *J Occup Med, 19* (8), 558–562.

63. Lindberg, A. S., Oksa, J., Gavhed, G. & Malm C. (2013). Field Tests for Evaluating the Aerobic Work Capacity of Firefighters. *PloS One, 8* (7), 1–8.

64. Lindberg, A. S., Oksa, J. & Malm, C. (2014). Laboratory or Field Tests for Evaluating Firefighters' Work Capacity? *PloS One, 9* (3), 1–13.

65. Ljubicic, A., Varnai, V. M., Petrinec, B. & Macan, J. (2014). Response to thermal and physical strain during flashover training in Croatian firefighters. *Applied Ergonomics, 45* (3), 544–549.

66. Lord, C., Netto, K., Peterson, A., Nichols, D., Drain, J., Phillips, M. & Aisbett, B. (2012). Validating ‘fit for duty’ tests for Australian volunteer fire fighters suppressing bushfires. *Applied Ergonomics, 43* (1), 191–197.

67. Lucia, A., Hoyos, J., Santalla, A., Earnest, C. & Chicharro, J. L. (2003). Tour de France versus Vuelta a Espana: which is harder? *Medicine and Science in Sports and Exercise, 35* (5), 872–878.

68. McArdle, W. D., Katch, F. I. & Pechar, G. (1972). Reliability and interrelationships between maximal oxygen intake, physical work capacity, and step-test scores in college women. *Med Sci Sports, 4* (4), 182–186.

69. McLellan, T.M. (2001). The importance of aerobic fitness in determining tolerance to uncompensable heat stress. *Comparative Biochemistry and Physiology Part A: Molecular & Integrative Physiology, 128* (4), 691–700.

70. Michaelides, M., Koulla, M. P., Leah, J. H., Gerald, B. T. & Brown, B. (2011). Assessment Of Physical Fitness Aspects And Their Relationship To Firefighters' Job Abilities. *Journal of Strength and Conditioning Research, 24* (4), 956–965.

71. Midgley, A. W., McNaughton, L .R. & Wilkinson, M. (2006). Is there an Optimal Training Intensity for Enhancing the Maximal Oxygen Uptake of Distance Runners? *Sports Medicine, 36* (2), 117–132.

72. Milanovic, Z.,Sporis, G. & Weston, M. (2015). Effectiveness of High-Intensity Intervall Training (HIT) and Continuous Endurance Training for VO2max Improvments: A Systematic Review and Meta-Analysis of Controlled Trials. *Sports Medicine, 45*, 1469–1481.

73. O'Connell, E., Thomas, P. C., Cady, L. D. & Karawasky, R. J. (1986). Energy Cost of Simulated Stair Clibming as a Job-Related Task in Fire Fighting. *J Occup Med, 28* (2), 282–284.

74. Oshima, Y., Miyamoto, T., Tanaka, S., Wadazumi, T., Kurihara, N. & Fujimoto, S. (1997). Relationship between isocapnic buffering and maximal aerobic capacity in athletes. *European Journal of Applied Physiology and Occupational Physiology, 76* (5), 409–414.

75. Parra, J., Cadefau, J. A., Rodas, G., Amigó, N. & Cussó, R. (2009). The distribution of rest periods affects performance and adaptations of energy

metabolism induced by high-intensity training in human muscle. *Acta Physiol Scand*, 169 (2), 157-165.

76. Pataky, T.C. (2010). Generalized n-dimensional biomechanical field analysis using statistical parametric mapping. *Journal of biomechanics, 43* (10), 1976–1982.

77. Pataky, T.C., Vanrenterghem, J. & Robinson, M. A. (2015). Zero- vs. one-dimensional, parametric vs. non-parametric, and confidence interval vs. hypothesis testing procedures in one-dimensional biomechanical trajectory analysis. *Journal of biomechanics, 48* (7), 1277–1285.

78. Pataky, T. C. (2016). *SPM 1d*. unter http://www.spm1d.org/index.html#.

79. Périard, J. D., Caillaud, C. & Thompson, M. W. (2012). The role of aerobic fitness and exercise intensity on endurance performance in uncompensable heat stress conditions. *Eur J Appl Physiol, 112* (6), 1989–1999.

80. Perroni, F., Tessitore, A., Cortis, C., Corrado, L., D'Artibale, E., Cignetti, L. & Capranica, L. (2010). Energy Cost And Energy Sources During A Simulated Firefighting Acitivity. *Journal of Strength and Conditioning Research, 24* (12), 3457–3463.

81. Perroni, F., Tessitore, A., Lupo, C., Cortis, C., Cignitti, L. & Capranica, L. (2008). Do Italian fire fighting recruits have an adequate physical fitness profile for fire fighting. *Sport Sci Health, 4* (1-2), 27–32.

82. Perroni, F., Cignitti, L., Cortis, C. & Capranica, L. (2014). Physical fitness profile of professional Italian firefighters: Differences among age groups. *Applied Ergonomics, 45* (3), 456–461.

83. Peterson, M., Dodd, D., Alvar, B., Rhea, M. & Favre, M. (2008). Undulation Training For Development Of Hierarchical Fitness And Improved Firefighter

Job Performance. *Journal of Strength and Conditioning Research, 22* (5), 1683–1695.

84. Phillips, D. B., Stickland, M. K. & Petersen, S. R. (2016). Ventilatory responses to prolonged exercise with heavy load carriage. *European Journal of Applied Physiology, 116* (1), 19–27.

85. Phillips, M., Payne, W., Lord, C., Netto, K., Nichols, D. & Aisbett, B. (2012). Identification of physically demanding tasks performed during bushfire suppression by Australian rural firefighters. *Applied Ergonomics, 43* (2), 435–441.

86. Rhea, M., Alvar, B. & Gray, R. (2004). Physical Fitness and Job Performance of Firefighters. *Journal of Sport and Health Science, 18* (2), 348–352.

87. Roberts, M. A., O'Dea, J., Boyce, A., Mannix, E. T. (2002). Fitness Levels of Firefighter Recruits Before and After a Supervised Exercise Training Program. *J Strength Cond Res, 16* (2), 271–277.

88. Rodríguez-Marroyo, J. A., Villa, J. G., López-Satue, J., Pernía, R., Carballo, B., García-López, J. & Foster, C. (2011). Physical and thermal strain of firefighters according to the firefighting tactics used to suppress wildfires. *Ergonomics, 54* (11), 1101–1108.

89. Romet, T.T. & Frim, J. (1987). Physiological responses to fire fighting activities. *Eur J Appl Physiol, 56*, 633–638.

90. Rønnestad, B.R., Hansen, J., Thyli, V., Bakken, T. & Sandbakk, Ø. (2016). 5-week block periodization increases aerobic power in elite cross-country skiers. *Scand J Med Sci Sport*, 26 (2), 140-146.

91. Schonfeld, B., Doerr, D. & Convertino, V. (1994). An Occupational Performance Test Validation Program for Fire Fighters at the Kennedy Space Center. *Journal of Occupational Medicine, 32* (7), 638–643.

92. Seiler, K. S. & Kjerland, G. Ø. (2006). Quantifying training intensity distribution in elite endurance athletes: is there evidence for an "optimal" distribution? *Scandinavian journal of medicine & science in sports*, 16 (1), 49-56.

93. Seiler, K. S. & Tönnessen, E. (2009). Intervals, Thresholds, and Long Slow Distance: the Role of Intensity and Duration in Endurance Training. *Sportscience, 13*, 32–53.

94. Sheaff, A., Bennett. A., Hanson, E. D., Kim, Y. S., Hsu, J., Shim, J. K., Edwards, S. T. & Hurley, B. F. (2010). Physiological Determinants Of The Candidate Physical Ability Test In Firefighters. *Journal of Sport and Health Science, 24* (11), 3112–3122.

95. Siddall, A. G., Stevenson, R. D. M., Turner, P. F. J., Stokes, K. A. & Bilzon, J. L. J. (2016). Development of role-related minimum cardiorespiratory fitness standards for firefighters and commanders. *Ergonomics, 59* (10), 1335–1343.

96. Smekal, G., Duvillard, S. P. von, Pokan, R., Tschan, H., Baron, R., Hofmann, P., Wonisch, M. & Bachl, N. (2003). Changes in blood lactate and respiratory gas exchange measures in sports with discontinious load profiles. *European Journal of Applied Physiology, 89* (5), 489–495.

97. Smith, D. L., Petruzzello, S. J., Kramer, J. M. & Misner, J. E. (1997). The effects of different thermal environments on the physiological and psychological responses of firefighters to a training drill. *Ergonomics, 40* (4), 500–510.

98. Smith, D. L. (2011). Firefighter fitness: improving performance and preventing injuries and fatalities. *Current sports medicine reports, 10* (3), 167–172.

99. Smith, D. L. & Petruzzello, S. J. (1998). Selected physiological and psychological responses to live-fire drills in different configurations of firefighting gear. *Ergonomics, 41* (8), 1141–1154.

100. Smith, D. L., Petruzello, S. J. & Kramer, J. M. (1996). Physiological, psychophysical, and psychological responses of firefighters to firefighting training. *Aviation, space & environmental medicine, 67*, 1063–1068.

101. Sothmann, M. S., Saupe, K., Jasenof, D. & Blaney, J. (1992). Heart Rate Response Of Firefighters To Actual Emergencies. *Journal of Occupational Medicine, 34* (8), 797–800.

102. Sothmann, M. S., Gebhardt, D. L., Baker, T. A., Kastello, G. M. & Sheppard, V. A. (2004). Performance requirements of physically strenuous occupations: validating minimum standards for muscular strength and endurance. *Ergonomics, 47* (8), 864–875.

103. Sothmann, M. S., Saupe, K., Raven, P., Pawelczyk, J., Davis, P., Dotson, C., Landy, F. & Siljunas, M. (1991). Oxygen consumption during fire suppression: error of heart rate estimation. *Ergonomics, 34* (12), 1469–1474.

104. Stöggl, T. & Sperlich, B. (2014). Polarized training has greater impact on key endurance variables than threshold, high intensity, or high volume training. *Frontiers in Physiology,* 5, 1-14.

105. Storer, T. (2014). Firefighter Health and Fitness Assessment: A call to action. *Journal of Strength and Conditioning Research, 28* (3), 661–671.

106. Taylor, N. A. S., Lewis, M. C., Notley, S. R. & Peoples, G. E. (2012). A fractionation of the physiological burden of the personal protective equipment worn by firefighters. *European Journal of Applied Physiology, 112* (8), 2913–2921.

107. Tordi, N., Perrey, S., Harvey, A., Hughson, R. L. (2003). Oxygen uptake kinetics during two bouts of heavy cycling separated by fatiguing sprint exercise. *J Appl Physiol, 94* (2), 533–541.

108. Tsuji, B., Honda, Y., Fujii, N., Kondo, N. & Nishiyasu, T. (2012). Comparison of hyperthermic hyperventilation during passive heating and prolonged light and moderate exercise in the heat. *Journal of applied physiology (Bethesda, Md.: 1985), 113* (9), 1388–1397.

109. Walker, A., Keene, T., Argus, C., Driller, M., Guy, J. H. & Rattray, B. (2015). Immune and inflammatory responses of Australian firefighters after repeated exposures to the heat. *Ergonomics, 58* (12), 2032–2039.

110. Walker, A., Driller, M., Argus, C., Cooke, J. & Rattray, B. (2014). The ageing Australian firefighter: an argument for age-based recruitment and fitness standards for urban fire services. *Ergonomics, 57* (4), 612–621.

111. Wassermann, K. & Whipp, B. J. (1975). Exercise Physiology in Health and Disease. *American Review of Respiratory Disease, 112* (2), 219–249.

112. Wassermann, K. and McIlroy, M. B. (1964). Detecting the threshold of anaerobic metabolism in cardiac patients during exercise. *The American Journal of Cardiology, 14* (6), 844–852.

113. Watt, P. W., Wilmott, A. G., Maxwell, N. S., Smeeton, N. J., Watt, E. & Richardson, A. (2016). Physiological and psychological rensponses in Fire Instructors to heat exposures. *J Therm Biol., 58*, 106–114.

114. Weston, M., Taylor, K. L., Batterham, A. M. & Hopkins, W. G. (2014). Effects of Low-Volume High Intensity Interval Training (HIT) on Fitness in Adults: A Meta-Analysis of Controlled and Non-Controlled Trials. *Sports Med, 44*, 1005–1017.

115. Williams-Bell, F. M., Boisseau, G., McGill, J., Kostiuk, A. & Hughson, R. L. (2010). Air management and physiological responses during simulated firefighting tasks in a high-rise structure. *Applied Ergonomics, 41* (2), 251–259.

116. Williams-Bell, F. M., Boisseau, G., McGill, J., Kostiuk, A. & Hughson, R. L. (2010). Physiological responses and air consumption during simulated firefighting tasks in a subway system. *Applied physiology, nutrition, and metabolism = Physiologie appliquée, nutrition et métabolisme, 35* (5), 671–678.

117. Williams-Bell, F. M., Villar, R., Sharrat, M. T. & Hughson, R. L. (2009). Physiological Demands of the Firefighter Candidate Physical Ability Test. *Medicine & Science in Sports & Exercise, 41* (3), 653–662.

118. Williford, H. N., Duey, W. J., Olson, M. S., Howard, R. & Wang, N. (1999). Relationship between fire fighting suppression tasks and physical fitness. *Ergonomics, 42* (9), 1179–1186.

119. Windisch, S., Seiberl, W., Schwirtz, A. & Hahn, D. (2017a). Relationships between strength and endurance parameters and air depletion rates in professional firefighters. *Scientific Reports, 7*, 1–10.

120. Windisch, S., Seiberl, W., Hahn, D. & Schwirtz, A. (2017b). Physiological Responses to Firefighting in Extreme Temperatures Do Not Compare to Firefighting in Temperate Conditions. *Front. Physiol., 8*, 1–11.

List of abbreviations

1-RM	One-repetition maximum
ANOVA	Analysis of variance
BMI	Body-Mass-Index
BORG	Ratings of perceived exertion
CT	Continuous training
CON	Controls
FOT	Flashover training
HIIT	High intensity interval training
HR	Heart rate
HR_{max}	Maximum heart rate
POL	Polarized training
RCP	Respiratory compensation point
REPE	Respiratory protection exercise
RER	Respiratory exchange ratio
SCBA	Self-containing breathing apparatus
SD	Standard deviation
SFE	Standard simulated firefighting exercise
TSA	Time–strain-air depletion
TT	Total treadmill time to exhaustion

VCO2	Carbon dioxide output
V_E	Ventilation
VO_2	Oxygen consumption
VO_{2peak}	Peak oxygen uptake
VT1	Ventilatory threshold 1

Figures

Figures belonging to the publications are not included here

Fig. 1. Flowchart of the aims of this doctoral thesis, investigated research questions and future research perspectives based on the results of the conducted studies

Tables

Tab. 1. Combination of fitness tests (aerobic, AE= anaerobic, muscular strength, muscular endurance, anPo = anaerobic power, Flex= flexibility, balance) used in selected studies

Tab. 2. Combinations of different firefighting tasks and relationship analyses between firefighting tasks and fitness variables in the selected studies (Reg= Multiple Regression, PCA= Principal Component Analyses, SEM= Structural Equation Modeling)

Tab. 3. Correlations between aerobic, anaerobic fitness and flexibility measurements and performance in simulated firefighting work tasks. *Significant at $p \leq 0.05$, **Significant at $p \leq 0.01$

Tab. 4. Correlations (Spearmans correlation rs) or structural equation models (SEM) between muscular strength tests and performance in simulated firefighting tasks. Publication year is only mentioned when authors had more than one publication on the same topic. *Significant $p \leq 0.05$; **Significant $p \leq 0.01$; n.s. non significant)

Tab. 5. Correlations (Spearmans correlation rs) between muscular endurance tests and performance in simulated firefighting tasks. Publication year is only mentioned when authors had more than one publication on the same topic. *Significant $p \leq 0.05$; **Significant $p \leq 0.01$; n.s. non significant)

Eidesstattliche Erklärung

Anhang I

Eidesstattliche Erklärung

Ich erkläre an Eides statt, dass ich die bei der promotionsführenden Einrichtung
Fakultät für Sport- und Gesundheitswissenschaften

der TUM zur Promotionsprüfung vorgelegte Arbeit mit dem Titel:
Physical job demands and occupational fitness requirements for professional firefighters based on strength and endurance performance tests and a 15-week exercise program

in Professor für Biomechanik im Sport
Fakultät, Institut, Lehrstuhl, Klinik, Krankenhaus, Abteilung

unter der Anleitung und Betreuung durch: Prof. Dr. Ansgar Schwirtz ohne sonstige Hilfe erstellt und bei der Abfassung nur die gemäß § 6 Ab. 6 und 7 Satz 2 angebotenen Hilfsmittel benutzt habe.

☒ Ich habe keine Organisation eingeschaltet, die gegen Entgelt Betreuerinnen und Betreuer für die Anfertigung von Dissertationen sucht, oder die mir obliegenden Pflichten hinsichtlich der Prüfungsleistungen für mich ganz oder teilweise erledigt.

☒ Ich habe die Dissertation in dieser oder ähnlicher Form in keinem anderen Prüfungsverfahren als Prüfungsleistung vorgelegt.

☐ Die vollständige Dissertation wurde in ______________________
veröffentlicht. Die promotionsführende Einrichtung
____
hat der Veröffentlichung zugestimmt.

☒ Ich habe den angestrebten Doktorgrad noch nicht erworben und bin nicht in einem früheren Promotionsverfahren für den angestrebten Doktorgrad endgültig gescheitert.

☐ Ich habe bereits am ____________ bei der Fakultät für ______________________
____
der Hochschule ______________________
unter Vorlage einer Dissertation mit dem Thema ______________________
____
die Zulassung zur Promotion beantragt mit dem Ergebnis: ______________________
____

Die öffentlich zugängliche Promotionsordnung der TUM ist mir bekannt, insbesondere habe ich die Bedeutung von § 28 (Nichtigkeit der Promotion) und § 29 (Entzug des Doktorgrades) zur Kenntnis genommen. Ich bin mir der Konsequenzen einer falschen Eidesstattlichen Erklärung bewusst.

Mit der Aufnahme meiner personenbezogenen Daten in die Alumni-Datei bei der TUM bin ich

☒ einverstanden, ☐ nicht einverstanden.

München, 2.11.2017 Stephanie Windisch
Ort, Datum, Unterschrift

Permissions

Scientific Reports:

nature.com

Licence to publish

Manuscript id:	SREP-16-39845B
Proposed title:	Relationships between strength and endurance parameters and air depletion rates in professional firefighters
The "Author(s)":	Stephanie Windisch, Wolfgang Seiberl, Ansgar Schwirtz, Daniel Hahn
The "Contribution":	All content of the article, with the Proposed title listed above, including but not limited to all text, supplementary information, tables, graphs and images.
The "Journal":	Scientific Reports
"NPG":	Nature Publishing Group, a division of Macmillan Publishers Ltd

Purpose

NPG will consider publishing the Contribution pursuant to the terms set forth herein, including granting readers rights to use the Contribution on an open access basis identified below.

Open access licence

CC BY*: This licence allows readers to copy, distribute and transmit the Contribution as long as it is attributed back to the author. Readers are permitted to alter, transform or build upon the Contribution, and to use the article for commercial purposes. Please read the full licence for further details at - http://creativecommons.org/licenses/by/4.0.

* The Creative Commons Attribution (CC BY) Licence is preferred by many research funding

bodies. We support use of this licence as it is recommended for maximum dissemination and use of open access materials.

Grant of rights

In consideration of NPG evaluating the Contribution for publication (and publishing the Contribution if NPG so decides) the Author(s) grant to NPG for the full term of copyright and any extensions thereto, except as set out in the Author rights below, the right and irrevocable licence:

a. to edit, adapt, publish, reproduce, distribute, display and store the Contribution in all forms, formats and media whether now known or hereafter developed (including without limitation in print, digital and electronic form) throughout the world;
b. to translate the Contribution into other languages, create adaptations, summaries or extracts of the Contribution or other derivative works based on the Contribution and exercise all of the rights set forth (a) above in the translations, adaptations, summaries, extracts and derivative works;
c. to licence others to do any or all of the above, including but not limited to the right to grant readers the right to use the Contribution under the Creative Commons licence listed above; and
d. to re-licence article metadata without restriction (including but not limited to author name, title, abstract, citation, references, keywords and any additional information, as determined by NPG).

Author rights

Ownership of the copyright in the Contribution remains with the Author(s).

However, the Author(s)' re-use rights in the Contribution are subject to the rights and restrictions set forth in this Section, and in the Pre-print services and Warranties a) Section. After the Author(s) have submitted the Contribution to NPG hereunder, the Author(s)' rights to re-use the Contribution shall be the same as those set forth in the Creative Commons licence listed above, with the following additional re-use rights:

a. to reproduce the Contribution in whole or in part in any printed volume (book or thesis) of which they are the Author(s); and
b. to reuse figures or tables created by the Author(s) and contained in the Contribution in oral presentations and other works created by them.

Pre-print services

NPG acknowledges that an earlier version of the Contribution may have been submitted to a pre-print service (in accordance with that service's standard licence terms).

Warranties

The Author(s) warrant and represent that:

a. the Author(s) are the sole Author(s) of and sole owners of the copyright in the Contribution and the Contribution is the original work of the Author(s) and not copied (in whole or part) from another work. If however the

Contribution includes materials from other sources, the Author(s) warrant they have obtained the necessary rights from the owners of the copyright in all such materials and hereby license to NPG the rights to use such materials in accordance with the Grant of rights Section above. Copies of all such grant of rights from third parties have been submitted.

b. all of the facts contained in the Contribution are true and accurate;
c. the signatory (the Author or the employer) who has signed this Agreement below has full right, power and authority to enter into this Agreement and grant the rights herein on behalf of all of the Authors;
d. nothing in the Contribution is obscene, defamatory, libelous, violates any right of privacy or publicity, infringes any intellectual property rights (including without limitation copyright, patent, database or trademark rights) or any other human, personal or other rights of any person or entity or is otherwise unlawful; and
e. nothing in the Contribution infringes any duty of confidentiality which any of the Author(s) may owe to anyone else or violates any contract, express or implied, of any of the Author(s), and all of the institutions in which work recorded in the Contribution was created or carried out, have authorized such publication.

Dispute resolution

The Author(s) authorise NPG to take such steps as it considers necessary at its own expense in the Author(s) name and on their behalf if NPG believes that a third party is infringing or is likely to infringe copyright in the Contribution including but not limited to initiating legal proceedings.

The Author(s) grant NPG the perpetual right to edit, correct, or retract the Contribution if NPG considers (in its reasonable opinion) that such actions are required. The Author(s) hereby agree that they shall not object to NPG carrying out any such actions.

The Author(s) shall cooperate fully with NPG in relation to any legal action that might arise from the publication of the Contribution and the Author(s) shall give NPG access at reasonable times to any relevant accounts, documents and records within the power or control of the Author(s).

Reversion of rights

If the Contribution is rejected by NPG and not published, all rights under this licence shall revert to the Author(s).

Law & jurisdiction

This Agreement shall be governed by and construed in accordance with the laws of England and Wales. The parties irrevocably agree that the courts of England and Wales shall have exclusive jurisdiction to settle any dispute or claim that arises out of or in connection with this Agreement or its subject matter or formation.

Macmillan Publishers Limited (trading as Nature Publishing Group), registered office: Brunel Road, Houndmills, Basingstoke, Hampshire, RG21 6XS, UK. Company number 785998.

Creative Commons License Deed for articles published in *frontiers in Physiology*:

2.11.2017 Creative Commons — Attribution 3.0 Unported — CC BY 3.0

Creative Commons License Deed

Attribution 3.0 Unported (CC BY 3.0)

Free Cultural Works APPROVED FOR

This is a human-readable summary of (and not a substitute for) the license.

You are free to:

Share — copy and redistribute the material in any medium or format

Adapt — remix, transform, and build upon the material

for any purpose, even commercially.

The licensor cannot revoke these freedoms as long as you follow the license terms.

Under the following terms:

Attribution — You must give appropriate credit, provide a link to the license, and indicate if changes were made. You may do so in any reasonable manner, but not in any way that suggests the licensor endorses you or your use.

No additional restrictions — You may not apply legal terms or technological measures that legally restrict others from doing anything the license permits.

Notices:

You do not have to comply with the license for elements of the material in the public domain or where your use is permitted by an applicable exception or limitation.

No warranties are given. The license may not give you all of the permissions necessary for your intended use. For example, other rights such as publicity, privacy, or moral rights may limit how you use the material.

https://creativecommons.org/licenses/by/3.0/ 1/1