Firefighters’ physical work capacity

Ann-Sofie Lindberg
To my wonderful husband Ronnie who supported me throughout the writing of this thesis, patiently assisting with bracing words, and many nice cups of coffee.

To my wonderful children Rasmus, Albin and Saga, whose love is a source of inspiration and encouragement.

Thank you for keeping me in the reality.
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Abstract

Background Physical work capacity is one of several dimensions affecting firefighters’ work performance. Aerobic fitness, anaerobic fitness, muscular strength, and muscular endurance have previously been deemed important for firefighters’ work capacity. Laboratory tests require access to complicated and expensive equipment, and are time-consuming. All fire stations should have equal opportunities of testing firefighters’ physical work capacity, and therefore field tests should be used instead of laboratory tests, if possible. The overall aim of this doctoral thesis was to identify valid, simple, and inexpensive physical tests for evaluation of firefighters’ physical work capacity.

Methods In Study I, firefighters’ (n = 193) perceived physical demands of firefighting work tasks were ranked, and rankings of full-time and part-time firefighters were compared. In Studies II-III, male full-time – and part-time firefighters, civilian men and women (n = 38) performed laboratory and field physical tests, and simulated firefighting work tasks, and correlations were analyzed with Spearman’s rho. In Study IV, a selection of the investigated work tasks were included and physical tests for evaluation of firefighters’ work capacity were identified, using multivariate statistics (n = 38). In addition, an external validation was executed, using a prediction-set including male and female full-time and part-time firefighters, and male and female civilians (n = 90).

Results Carrying a hose or hose baskets up stairs, victim rescue in different ways, carrying a stretcher over terrain and hose pulling were by most firefighters identified as physically demanding, and significant differences in ratings were found between full-time- and part-time firefighters (Study I). Work tasks included in further studies were carrying hose baskets up stairs, demolition at or after a fire, hose pulling, victim rescue, carrying hose baskets over terrain (Studies II-IV), cutting holes in the roof for fire-gas ventilation, and vehicle extrication (Studies II-III). Performance in both laboratory tests and field tests were significantly correlated with simulated firefighting work capacity, using bivariate correlation (Studies II-III). In five out of six investigated work tasks, aerobic capacity (VO\textsubscript{2max} in L·min\textsuperscript{-1}) had higher correlations (r, closer to +1 or −1) with work capacity than aerobic power (VO\textsubscript{2max} in mL·kg\textsuperscript{-1}·min\textsuperscript{-1}) (Study II). The highest correlations between work capacity and muscular performance (r, closest to +1 or −1) was found with upper body muscle strength and endurance and trunk muscle endurance, except for the demolition work task (Study III). Multivariate statistics showed that models for prediction of firefighters’ physical work capacity was equally high with field tests, as with laboratory tests (Study IV). With laboratory tests excluded, the best predictive model of firefighters’ physical work capacity (overall fit, R\textsuperscript{2}: 0.77 to 0.88, predictive power,
Q^2: 0.71 to 0.85, external validation, R^2: 0.44 to 0.80) included rowing 500 m (s),
3000 m track running (s and s·kg\(^{-1}\)), maximal handgrip strength (kg), endurance
bench press (number), standing broad jump (m), upright barbell row (number),
body weight (kg) and height (m). With laboratory tests excluded, the overall fit
and predictive power was slightly lower without anthropometrics in three out of
five studied work tasks (Study IV).

**Conclusion** The perceived physical demands of firefighting work tasks were high,
and part-time firefighters had a lack of experience in several work tasks (Study I).
Consequently, because full-time – and part-time firefighters are aimed to do the
same job, work-related exercises are important in order to maintain good skills
within all groups of firefighters. Aerobic fitness, muscle strength, and muscle en-
durance are of vital importance for firefighters’ work capacity (Studies II-IV), and
with equal results, field tests and laboratory tests can be used to predict firefighters’
physical work capacity (Study IV). Rowing 500 m (s), maximal handgrip strength
(kg), endurance bench press (n), running 3000 m (s and s·kg\(^{-1}\)), upright barbell
row (n) and standing broad jump (m) together provides valid information about
firefighters’ physical work capacity (carrying hose baskets up stairs, hose pulling, victim
rescue, and carrying hose baskets over terrain). Anthropometric (weight and height)
may be omitted in absolute values, and the models for prediction of firefighters’
physical work capacity will remain valid (Study IV).
### Abbreviations

Aerobic capacity | Maximal oxygen uptake measured in L·min⁻¹
--- | ---
Aerobic power | Maximal oxygen uptake measured in mL·kg⁻¹·min⁻¹
ATP | Adenosine triphosphate
BA | Breathing apparatus
CM | Civilian men
CP | Creatine phosphate
Cutting | Cutting holes in the roof for fire-gas ventilation
CV | Coefficient of variation
CW | Civilian women
Demolition | Demolition at or after a fire
FWT | Field Walk Test
FFF | Female full-time firefighters
FPF | Female part-time firefighters
Full-time FF | Full-time firefighters
HR | Heart rate
% HRₘₐₓ | Percentage use of maximal Heart rate
ICC | Intra Class Correlation
LT | Lactate threshold
MFF | Male full-time firefighters
MPF | Male part-time firefighters
OBLA | Onset of Blood Lactate Accumulation
OPLS | Orthogonal Projection to Latent Structure
Part-time FF | Part-time firefighters
PCA | Principal Component Analyze
PHT | Pack Hike Test
Pulling | Hose pulling
RER | Respiratory Exchange Ratio
Rescue | Victim rescue
RM | Repetition Maximum
RPE | Ratings of Perceived Exertion
SEM | Standard Error of Measurement
SI | Stability Index
Stairs | Carrying hose baskets up stairs
Terrain | Carrying hose baskets over terrain
Vehicle | Vehicle extrication
VIP | Variables of Importance for Projection
VO₂ | Oxygen uptake
VO₂peak | Peak oxygen uptake, in a specific exercise
VO₂max | Maximal oxygen uptake
Inledning
I Sverige måste samtliga brandmän genomföra medicinska kontroller samt ett test av fysisk arbetsförmåga för att få utföra rökdykning, detta regleras av Arbetsmiljöverkets författningssamling ”Medicinska kontroller i arbetslivet”. Den medicinska kontrollen inkluderar en medicinsk undersökning samt ett arbetsprov (ramp-test) med samtidig EKG-registrering. Test av fysisk arbetsförmåga inkluderar ett rullbandstest: iförd larmställ (total buren vikt: 24 kg ± 0.5 kg) går brandmannen på ett rullband med lutningen 8° och en hasighet av minst 4.5 km i timmen i 6 minuter, testet bedöms godkänt om brandmannen klarar hela testet. Tidsintervallet för den medicinska kontrollen regleras av brandmannens biologiska ålder, test av fysisk arbetsförmåga utförs varje år.

Fysiska tester inom Sveriges räddningstjänst
Vid nyanställning genomförs vanligtvis ytterligare fysiska tester för att få ett mått på brandmannens fysiska kapacitet, såsom kondition, muskelstyrka och muskulär uthållighet. Dessa fysiska tester finns ej reglerade från Arbetsmiljöverket och har fram till denna avhandlings framläggande ej någon vetenskaplig grund. Varje enskild kommun beslutar själv om ytterligare fysiska tester skall utföras, samt vilka tester som skall utföras. För att minska risken för diskriminering och för att kunna utvärdera fysisk arbetskappacitet är det av yttersta vikt att de fysiska tester som används är relevanta till det arbete som brandmannen skall utföra.

Prestation och kapacitet
Arbetsprestation är ett omfattande begrepp som påverkas av fler individuella kvaliteter och externa faktorer än bara fysisk kapacitet, såsom ergonomiska faktorer, mentala faktorer och miljö. I denna avhandling undersöks den fysiska kapaciteten och huvudsyftet är att identifiera ett batteri av enkla fysiska tester som kan användas för bedömning av brandmannens fysiska arbetskappacitet.

Val av arbetsmoment
I Studie I fann vi att de arbetsmoment som flest brandmän i Sverige subjektivt skattar som fysisk tunga är: bära brandslangar och slangkorgar upp för trappor, olika varianter av livräddning, bära bär i terräng samt att dra en vattenfylld slang. Det fanns skillnader i den subjektiva skattningen mellan de som arbetar som heltidsbrandmän och de som arbetar som deltidsbrandmän. Dessutom hade deltidsbrandmän som grupp, mindre erfarenhet av flera arbetsmoment, t.ex. livräddning, slangdragning i trapphus (4 samt 8 våningar), samt rökdykning med brandsläckning (4 samt 8 våningar).

Alla brandmän i Sverige som med godkänt resultat har genomfört de av Arbetsmiljöverket reglerade testerna förväntas kunna utföra samtliga arbetsuppgifter. Därför är deltidsbrandmännens frånvaro av erfarenhet i vissa arbetsmoment allvarlig och
man bör fråga sig om heltidsbrandmän och deltidsbrandmän skall utföra samma arbetsuppgifter? Om svaret på den frågan är ja, är arbetsrelaterade övningar som inkluderar dessa arbetsmoment av yttersta vikt för att upprätthålla god kvalité i arbetet samt för att skydda för den anställde.

**Fysiologiska mätningar av arbetskapacitet**

Baserat på resultaten i *Studie I*, samt diskussioner med en expertgrupp inom Räddningsverket undersöktes några arbetsmoment ytterligare (*Studie II-IV*). Andra forskare har tidigare konstaterat att kondition, muskelstyrka, muskulär uthållighet och anaerob kapacitet är viktiga fysiska kvalitéer för brandmannens fysiska arbetskapacitet. Taster av fysisk kapacitet kan utföras i laboratorier (t.ex. syreupptagning) eller i fält (t.ex. bänkpress). Taster i laboratorier är tidskrävande och dyra, medan fälttester är relativt enkla att genomföra och billiga. Avancerade laboratorier som utför fysiska tester finns inte tillgängligt i närhet till alla räddningstjänster i Sverige. För att ge alla räddningstjänster samma möjlighet till testning av fysisk kapacitet, bör fälttester användas istället för laboratorietester om tillfredsställande med sådana tester.

I *Studierna II-III* utförde totalt 38 personer (män: heltidsbrandmän, deltidsbrandmän, civila: kvinnor och män) fysiska tester i laboratorier och i fält, samt simulerade arbetsmoment: losstagnning ur bil, slangkorgbärning uppför trappor, rivning av innertak, slangdragning, livräddning, håltagning i yttertak samt slangkorgbärning i terräng. Vi fann att nivån på kondition, muskelstyrka och muskulär uthållighet är viktiga för att uppnå god arbetskapacitet i de undersökta arbetsmomenten.

Ett urval av arbetsmoment undersöktes vidare i *Studie IV*: slangkorgbärning uppför trappor, rivning av innertak, slangdragning, livräddning, samt slangkorgbärning i terräng. Med alla tester inkluderade byggdes statistiska modeller för att kunna påvisa vilka tester som är mest tillförlitliga för att bedöma brandmäns fysiska arbetskapacitet i de undersökta arbetsmomenten. Resultaten varierade mellan olika arbetsmoment och den bästa modellen fann vi för arbetsmomentet *slangkorgbärning i trapphus*, och den svagaste modellen fann vi för arbetsmomentet *rivning av innertak*. Modeller för *slangdragning*, *rivning av innertak*, samt *slangkorgbärning i terräng* var något svagare utan inkludering av kroppslängd och kroppsvikt.

Baserat på alla ingående studier i denna avhandling går det lika bra att använda sig av enkla fälttester som att använda sig av avancerade laboratorietester, för att bedöma brandmäns fysiska arbetskapacitet.

**Rekommendationer**

Tester som rekommenderas för bedömning av brandmäns fysiska arbetskapacitet är rodd 500 m (tid i sekunder), bänkpress med 30 kg (antal), maximal gripstyrka (kg), lyft till hakan med en Z-stång (antal), stående längdhopp (m), löpning 3000 m (tid i sekunder samt tid i sekunder delat på kroppsvikt). Kroppsängd (m) och kroppsvikt (kg) kan exkluderas med bibehållen god bedömning av brandmannens fysiska arbetskapacitet om fler fysiska tester inkluderas.
List of publications

This doctoral thesis is based on the following original articles. They will be referred to by their roman numerals.


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Introduction

In accordance with government regulations [1], both full-time and part-time firefighters in Sweden have to pass medical examinations and a test of physical work capacity for permission to execute smoke diving. The medical examination includes a medical check-up and a ramp test with simultaneous electrocardiograph registration; the time intervals between the tests are regulated by the firefighters’ biological age [1]. The physical work capacity test includes a pass or fail test: each year firefighters perform 6 min walking with the incline 8° and a minimum treadmill speed of 4.5 km·h⁻¹, dressed in firefighting protective clothes and breathing apparatus (total weight: 24 kg ± 0.5 kg) [1].

Additional tests of physical capacity (others than those included in the government regulations) of the aspiring firefighters are one of several skills commonly included in the employment procedure. Testing firefighters’ physical work capacity is important for personal safety and health, coworker safety, and improved operations.

In Sweden, each individual municipality decides if additional tests of physical capacity should be included in the employment procedure, and if so, what kind of tests are to be done. These tests are neither in regulations, nor based on scientific studies. Some municipalities use simulated work tasks, some use isolated field tests, and some uses both for evaluation.

The absence of scientific evidence of physical tests included in the employment procedure has at least two risks; first, the selected physical tests might be irrelevant for evaluating work capacity, and second, the selected physical tests might be discriminative on sex. Firefighters’ work performance constitutes an overall assessment of several abilities, of which the physical capacity is one. This thesis focuses on work capacity, with the overall aim to present physical tests that are valid for evaluation of firefighters’ physical work capacity.
Background

Work performance and work capacity

Work performance is a multi-dimensional and dynamic concept [2], and has previously been defined as “Scalable actions, behavior, and outcomes that employees engage in or bring about that are linked with and contribute to organizational goals” [3]. The definition of an individual’s work performance is complex and has different meanings within different disciplines, with some focusing on work productivity and others on the quantity or quality of work. Thus, work performance includes several dimensions and indicators, and these specific indicators may be possible to measure or evaluate [4]. Firefighters’ work performance can be affected by many dimensions, such as physical work capacity [5], ergonomics and equipment [6,7], the use of protective gear [8-10], heat exposure [11,12], time between turn-outs [13], emotional stress [14], mental skills [15,16] and gender differentiations [17,18]. Also, dimensions can be affected by each other.

Work capacity has previously been defined as “physiological capacities in relation to job requirements” [19]. Within several occupations, such as firefighting [5], military [20,21], police [22–24] and paramedics [25–27], a high physical work capacity has been deemed important for work performance. Based on previous arguments of work performance and work capacity, this thesis focuses on the dimension physical work capacity (Figure 1). Within this dimension, indicators such as aerobic fitness, anaerobic fitness, muscular strength and endurance, and balance are included.

Figure 1. Dimensions of firefighters’ work performance

Illustration of a number of dimensions, affecting firefighters’ work performance, such as environment and physical work capacity, and also maybe not known (?) dimensions. This thesis focuses on the dimension physical work capacity.
Work-related physical testing of firefighters’ have previously been studied, such as the Pack-Hike test (PHT) [28-30], Field Walk Test (FWT) [30], and navy shipboard firefighting [31]. Tests including several work tasks executed in sequence, such as stair climbing, carrying equipment, raising and extending ladders, forcible entry, searching, ceiling breach, hose pulling and victim rescue, are more commonly in use [32-38]. Laboratory and/or field tests can also be used for evaluation of physical work capacity. Laboratory tests require access to advanced equipment, specialized personnel, and such tests are complicated, time-consuming, and expensive. Field tests are less complicated, less time-consuming, and also inexpensive.

**Aerobic fitness**

The aerobic metabolic pathways predominate for exercises that are performed at optimal pace with duration longer than two minutes [39]. Maximal oxygen uptake is a measure of cardiorespiratory fitness and has numerous synonyms: aerobic capacity, functional aerobic capacity, aerobic fitness or VO\(_{2\text{max}}\). Aerobic capacity is measured in liters oxygen consumed per minute (L·min\(^{-1}\)) and aerobic power is the aerobic capacity in relation to body weight (mL·kg\(^{-1}\)·min\(^{-1}\)) [40]. VO\(_{2\text{max}}\) is the highest maximal oxygen consumption achieved from different modes of exercise, and VO\(_{2\text{peak}}\) is the highest oxygen consumption for a specific type of exercise [39]. These concepts are often confused, and tests performed on a cycle ergometer by non-cyclists, are sometimes reported as VO\(_{2\text{max}}\) [11,41-43] although treadmill tests in general provide a 5 % to 10 % higher VO\(_{2\text{peak}}\) compared to tests performed on a cycle ergometer [39].

Laboratory testing of aerobic fitness can either be maximal, such as measurement of VO\(_{2\text{max}}\) (or VO\(_{2\text{peak}}\)) [44], or submaximal, such as determination of Onset of Blood Lactate Accumulation (OBLA) and Lactate Threshold (LT) [45]. The golden standard for laboratory measurements of oxygen uptake is the Douglas bag method, introduced by C. G Douglas in 1911 [46]. This method is complicated and time consuming, and today, computerized metabolic systems are more commonly used [47]. Field tests of aerobic fitness are predictions of VO\(_{2\text{max}}\) or aerobic performance tests, and require a minimum of equipment. Field tests can either be submaximal, such as the Åstrand ergometer cycling test [48], or maximal, such as the Cooper 12 min running test [39].

Measurements or predictions of firefighters’ VO\(_{2\text{max}}\) (VO\(_{2\text{peak}}\)) have previously been studied in several countries, the United Kingdom and USA being in the front line based on the number of published papers (Table 1). In general, firefighters have a higher aerobic power compared to reference groups across all ages (20 to 59 years) [49], but not necessarily compared to other physically demanding occupations [50]. The mean measured or predicted VO\(_{2\text{max}}\) (VO\(_{2\text{peak}}\)) among groups of firefighters range from 34.5 to 61.0 mL·kg\(^{-1}\)·min\(^{-1}\) or from 2.7 to 4.4 L·min\(^{-1}\), respectively (Table 1). Comparing studies are often difficult due to the different methods used, and sometimes the methods are not completely described [51-54]. Measurements of firefighters’ VO\(_{2\text{max}}\) have been executed on treadmills [28,31,34,36,49,50,55-75],
stair mill [76], or cycle ergometers [11,41-43,70,77-79]. Predictions have been executed with submaximal step-tests [10,80-83], tests on a cycle ergometer [84,85], 1 mile run tests [86,87], and treadmill tests [35,74,76,80,88-93]. Firefighters’ aerobic power is more frequently reported than the aerobic capacity (Table 1), which may reflect the common use of VO\(_{2\text{max}}\) predictions, or that VO\(_{2\text{max}}\) in mL·kg\(^{-1}\)·min\(^{-1}\) is assumed to be of higher importance for work capacity compared to VO\(_{2\text{max}}\) in L·min\(^{-1}\), as previously suggested by Sharkey and Davis [40].

### Table 1. Previous studies of firefighters’ VO\(_{2\text{max}}\) (VO\(_{2\text{peak}}\))

<table>
<thead>
<tr>
<th>Author, Year, Country</th>
<th>Subjects (n)</th>
<th>VO(_{2\text{max}}) (L·min(^{-1}))</th>
<th>VO(_{2\text{max}}) (mL·kg(^{-1})·min(^{-1}))</th>
<th>M</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lemon &amp; Hermiston, 1977. Canada [94]</td>
<td>20 m</td>
<td>–</td>
<td>–</td>
<td>M</td>
<td></td>
</tr>
<tr>
<td>Davis et al., 1982. USA [71]</td>
<td>100*</td>
<td>3.28±0.6</td>
<td>39.6±6.42</td>
<td>M</td>
<td></td>
</tr>
<tr>
<td>Louhevaara et al., 1985. Finland [84]</td>
<td>9 m</td>
<td>3.9</td>
<td>–</td>
<td>M</td>
<td></td>
</tr>
<tr>
<td>O’Connell et al., 1986. USA [41]</td>
<td>17’</td>
<td>3.97±0.6</td>
<td>–</td>
<td>M</td>
<td></td>
</tr>
<tr>
<td>Skoldstrom, 1987. Sweden [85]</td>
<td>8 m</td>
<td>3.81±0.4</td>
<td>49.0±3.7</td>
<td>M</td>
<td></td>
</tr>
<tr>
<td>Faff and Tutak, 1989. Poland [95]</td>
<td>18 m</td>
<td>3.22±0.6</td>
<td>41.4±8.8</td>
<td>P</td>
<td></td>
</tr>
<tr>
<td>Gavhed &amp; Holmer, 1989. Sweden [11]</td>
<td>VF: 12 m, PF: 12 m</td>
<td>3.57±0.6, 3.59±0.5</td>
<td>–, –</td>
<td>M</td>
<td></td>
</tr>
<tr>
<td>Sothmann et al., 1990. USA [96]</td>
<td>20 m</td>
<td>3.3±0.4</td>
<td>39.9±5.1</td>
<td>M</td>
<td></td>
</tr>
<tr>
<td>Sothmann et al., 1991. USA [60]</td>
<td>10 m</td>
<td>3.2±0.5</td>
<td>40.6±6.2</td>
<td>M</td>
<td></td>
</tr>
<tr>
<td>Saupe et al., 1991. USA [66]</td>
<td>151’</td>
<td>–</td>
<td>39.0*</td>
<td>M</td>
<td></td>
</tr>
<tr>
<td>Gledhill &amp; Jamnik 1992. Canada [97]</td>
<td>53*</td>
<td>3.97±0.5</td>
<td>48.7±7.0</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>Louhevaara et al., 1994. Finland [42]</td>
<td>59 m</td>
<td>3.82</td>
<td>46.8</td>
<td>M</td>
<td></td>
</tr>
<tr>
<td>Louhevaara et al., 1995 [61] Germany/Finland</td>
<td>12’</td>
<td>4.02</td>
<td>46.9</td>
<td>M</td>
<td></td>
</tr>
<tr>
<td>Weller et al., 1995. Canada [98]</td>
<td>76 m, 78 w</td>
<td>–, –</td>
<td>45.8±14.4, 34.7±10.7</td>
<td>M</td>
<td></td>
</tr>
<tr>
<td>Smith &amp; Petruzzelo, 1998. USA [86]</td>
<td>10 m</td>
<td>–</td>
<td>44.8±4.7</td>
<td>M</td>
<td></td>
</tr>
<tr>
<td>Malley et al., 1999. USA [67]</td>
<td>23 m</td>
<td>3.73±0.7</td>
<td>47±10</td>
<td>M</td>
<td></td>
</tr>
<tr>
<td>Hooper et al., 2001. UK [10]</td>
<td>21 m, 1 w</td>
<td>3.49±0.5*, 43.71±6.3*</td>
<td>–, –</td>
<td>P</td>
<td></td>
</tr>
<tr>
<td>Bilzon et al., 2001. UK [31]</td>
<td>34 m, 15 w</td>
<td>–, –</td>
<td>52.6±5.2, 43.0±8.1</td>
<td>M</td>
<td></td>
</tr>
<tr>
<td>Peate et al., 2002. USA [80]</td>
<td>91 m, 10 w</td>
<td>–, –</td>
<td>41.8±8.8, 42.8±8.0</td>
<td>P</td>
<td></td>
</tr>
<tr>
<td>Davis et al., 2002. USA [49]</td>
<td>71 m</td>
<td>–</td>
<td>48.2*</td>
<td>M</td>
<td></td>
</tr>
<tr>
<td>Clark et al., 2002. USA [93]</td>
<td>168 m</td>
<td>–</td>
<td>44.6±5.0</td>
<td>M</td>
<td></td>
</tr>
<tr>
<td>Punakallio et al., 2003. Finland [77]</td>
<td>29*</td>
<td>3.62*, 43.45*</td>
<td>–, –</td>
<td>M</td>
<td></td>
</tr>
<tr>
<td>Eglin et al., 2004. UK [81]</td>
<td>13 m</td>
<td>–</td>
<td>43.1±7.7</td>
<td>P</td>
<td></td>
</tr>
<tr>
<td>Mier &amp; Gibson, 2004. USA [65]</td>
<td>31 m, 23 w</td>
<td>–, –</td>
<td>49.8±8.3, 41.8±8.3</td>
<td>M</td>
<td></td>
</tr>
<tr>
<td>Selkirk et al., 2004. Canada [59]</td>
<td>15 m</td>
<td>–</td>
<td>45.7±1.4</td>
<td>M</td>
<td></td>
</tr>
<tr>
<td>Illmarinen et al., 2004. Finland [54]</td>
<td>8 m</td>
<td>–</td>
<td>51.6</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>Study</td>
<td>Distance</td>
<td>SET</td>
<td>T</td>
<td>Temperature</td>
<td></td>
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<td>--------------------------------------</td>
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<td>-------------</td>
<td></td>
</tr>
<tr>
<td>Smith et al., 2005. USA [87]</td>
<td>10 m</td>
<td>–</td>
<td></td>
<td>43.4±5.7</td>
<td>P</td>
</tr>
<tr>
<td>Fogleman &amp; Bhojani, 2005. USA [51]</td>
<td>78 m</td>
<td>–</td>
<td></td>
<td>37.9±9.5</td>
<td>*</td>
</tr>
<tr>
<td>Garver et al., 2005. USA [88]</td>
<td>MF: 17 m</td>
<td>–</td>
<td></td>
<td>47.6±9.9</td>
<td>P</td>
</tr>
<tr>
<td></td>
<td>IF: 51 m</td>
<td>–</td>
<td></td>
<td>48.6±3.3</td>
<td></td>
</tr>
<tr>
<td>von Heimburg et al., 2006. Norway [58]</td>
<td>40 m</td>
<td>4.40±0.3</td>
<td></td>
<td>53±5</td>
<td>M</td>
</tr>
<tr>
<td>Carter et al., 2007. UK [57]</td>
<td>10 m</td>
<td>–</td>
<td></td>
<td>50.9±7.0</td>
<td>M</td>
</tr>
<tr>
<td>Dreger &amp; Petersen, 2007. Canada [56]</td>
<td>30 m</td>
<td>–</td>
<td></td>
<td>42.4±4.4</td>
<td>M</td>
</tr>
<tr>
<td></td>
<td>22 w</td>
<td>–</td>
<td></td>
<td>34.8±4.0</td>
<td></td>
</tr>
<tr>
<td>Henderson et al. 2007. USA [83]</td>
<td>287 m</td>
<td>–</td>
<td></td>
<td>47.1 B,C</td>
<td>P</td>
</tr>
<tr>
<td>Harvey et al., 2008. Canada [55]</td>
<td>12 m</td>
<td>–</td>
<td></td>
<td>48.0±4.1</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>8 w</td>
<td>3.29</td>
<td></td>
<td>51.0</td>
<td>M</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>45.1</td>
<td></td>
</tr>
<tr>
<td>Richmond et al., 2008. UK [53]</td>
<td>15 m</td>
<td>–</td>
<td></td>
<td>48.0±4.1</td>
<td>*</td>
</tr>
<tr>
<td>Barr et al., 2009. UK [63]</td>
<td>9 m</td>
<td>–</td>
<td></td>
<td>45±5</td>
<td>M</td>
</tr>
<tr>
<td>Williams-Bell et al., 2009. Canada [34]</td>
<td>34 m</td>
<td>3.63 A</td>
<td></td>
<td>46.2 A</td>
<td>M</td>
</tr>
<tr>
<td></td>
<td>23 w</td>
<td>3.07 A</td>
<td></td>
<td>48.9 A</td>
<td></td>
</tr>
<tr>
<td>Sheaff et al., 2010. USA [36]</td>
<td>26 m</td>
<td>–</td>
<td></td>
<td>40.9±1.7</td>
<td>M</td>
</tr>
<tr>
<td></td>
<td>7 w</td>
<td>–</td>
<td></td>
<td>43.6±3.0</td>
<td></td>
</tr>
<tr>
<td>Perroni et al., 2010. Italy [68]</td>
<td>20 m</td>
<td>–</td>
<td></td>
<td>43.1 ± 4.9</td>
<td>M</td>
</tr>
<tr>
<td>El-Kader, 2010. Egypt [73]</td>
<td>40°</td>
<td>BT: 3.06 A</td>
<td>AT: 3.44 A</td>
<td>–</td>
<td>M</td>
</tr>
<tr>
<td>Williams-Bell et al., 2010. Canada [35]</td>
<td>33 m</td>
<td>–</td>
<td></td>
<td>51.6±5.8</td>
<td>P</td>
</tr>
<tr>
<td></td>
<td>3 w</td>
<td>–</td>
<td></td>
<td>46.6±3.5</td>
<td></td>
</tr>
<tr>
<td>Williams-Bell et al. 2010. Canada [69]</td>
<td>33 m</td>
<td>4.47±0.7 A</td>
<td></td>
<td>51.4±6.5 A</td>
<td>M</td>
</tr>
<tr>
<td></td>
<td>3 w</td>
<td>–</td>
<td></td>
<td>46.1±6.3 A</td>
<td></td>
</tr>
<tr>
<td>Tierney et al., 2010. USA [76]</td>
<td>40 m</td>
<td>–</td>
<td></td>
<td>45.3±6.7 A</td>
<td>M</td>
</tr>
<tr>
<td></td>
<td>14 w</td>
<td>–</td>
<td></td>
<td>46.1±6.3 A</td>
<td></td>
</tr>
<tr>
<td>Phillips et al., 2011. Australia [28]</td>
<td>LMFF: 20 m</td>
<td>3.74±0.6</td>
<td>3.47±0.7</td>
<td>43.4±7.1</td>
<td>40.5±6.3</td>
</tr>
<tr>
<td></td>
<td>VFF: 18 m</td>
<td>–</td>
<td></td>
<td>–</td>
<td>P</td>
</tr>
<tr>
<td>Marroyo et al., 2011. Spain [62]</td>
<td>60 m</td>
<td>–</td>
<td></td>
<td>54.2±1.1 A</td>
<td>M</td>
</tr>
<tr>
<td>Dennison et al., 2012. UK [89]</td>
<td>T: 12 m</td>
<td>–</td>
<td></td>
<td>45.6±3.3</td>
<td>P</td>
</tr>
<tr>
<td></td>
<td>UT: 37 m</td>
<td>–</td>
<td></td>
<td>40.2±5.2</td>
<td></td>
</tr>
<tr>
<td>Wynn &amp; Hawdon, 2012. UK [52]</td>
<td>FF: 411°</td>
<td>–</td>
<td></td>
<td>50.1±7.05</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>PF: 95°</td>
<td>–</td>
<td></td>
<td>47.7±7.64</td>
<td></td>
</tr>
<tr>
<td>Herrera et al. 2012. Chile [79]</td>
<td>39°</td>
<td>2.7±0.7</td>
<td></td>
<td>34.5±9.1</td>
<td>M</td>
</tr>
<tr>
<td>von Heimburg &amp; Medbo, 2013 [72]</td>
<td>22 m</td>
<td>–</td>
<td></td>
<td>52±10</td>
<td>M</td>
</tr>
<tr>
<td>Norway</td>
<td>1 w</td>
<td>–</td>
<td></td>
<td>56</td>
<td></td>
</tr>
<tr>
<td>Calavalle et al., 2013. Italy [92]</td>
<td>35 m</td>
<td>–</td>
<td></td>
<td>39.6±6.1</td>
<td>P</td>
</tr>
<tr>
<td>Heath &amp; Hammer, 2013. USA [91]</td>
<td>CVF: 38 m</td>
<td>–</td>
<td></td>
<td>39.9±8.4</td>
<td>P</td>
</tr>
<tr>
<td></td>
<td>UVF: 41 m</td>
<td>–</td>
<td></td>
<td>37.8±8.5</td>
<td></td>
</tr>
<tr>
<td>Prieto et al., 2013. Spain [50]</td>
<td>39 m</td>
<td>–</td>
<td></td>
<td>43.8±9.4</td>
<td>M</td>
</tr>
<tr>
<td>Delisle et al., 2014. USA [74]</td>
<td>25 m</td>
<td>–</td>
<td></td>
<td>45.7±7.2 A</td>
<td>M</td>
</tr>
<tr>
<td></td>
<td>5 w</td>
<td>–</td>
<td></td>
<td>44.6±3.9 A</td>
<td></td>
</tr>
<tr>
<td>Moore et al., 2014. USA [64]</td>
<td>38 m</td>
<td>–</td>
<td></td>
<td>48.4±6.5</td>
<td>M</td>
</tr>
<tr>
<td>Poplin et al., 2014. USA [90]</td>
<td>743 m</td>
<td>–</td>
<td></td>
<td>49.6 A</td>
<td>P</td>
</tr>
<tr>
<td></td>
<td>39 w</td>
<td>–</td>
<td></td>
<td>–</td>
<td></td>
</tr>
</tbody>
</table>
Firefighters’ aerobic capacity [28,34,36,41,58] and aerobic power [28,31,34,38,41,56,67,72,83,92,96,97] has previously been deemed important for work capacity, and 27% to 86% of the total energy expenditure during work is estimated to be delivered by aerobic pathways [31,68,94]. The metabolic demands of firefighting work range from 17 to 55 mL·kg\(^{-1}\)·min\(^{-1}\) [31,68,69,72,94,96,99] or 2.3 to 3.4 L·min\(^{-1}\) [69,96,99] depending on the work task investigated, and the pace of the work performed. The use of self-contained breathing apparatus (BA), aimed for protection, increases the physiological strain [9,61,85,100]. Protective clothing shields the firefighter from extreme environments, but increases core and skin temperature, and cardiorespiratory strain [5]. Furthermore, VO\(_{2\text{max}}\) decreases with increased age [50,78], and Punakallio et al. [78] found an 1.1% and 1.3% decrease in firefighters’ aerobic capacity and aerobic power, respectively, during a 13 year follow up study. Suggestions of minimal VO\(_{2\text{max}}\) levels for firefighters are 39 to 45 mL·kg\(^{-1}\)·min\(^{-1}\) [31,38,41,56,96], or 2.7 to 4.0 L·min\(^{-1}\) [41,58].

Although women have been included in firefighting studies since year 1995, only a few studies report results for both men and women in firefighting studies [31,34-36,55,56,65,72,76,80,98] (Table 1). In 2010, the proportion of female firefighters was 3.2% in the Swedish fire and rescue services [101]. Assuming that this skewed distribution is universal, it explains the low inclusion numbers of female firefighters in previous studies.

### Anaerobic fitness

The anaerobic capacity is the total amount of energy produced from the anaerobic energy systems (Joule) and anaerobic power the amount of energy produced per second (Watt). In general, the anaerobic energy output predominates the aerobic during maximal exercise lasting 0-2 minutes when large muscle groups are used [46].

Laboratory anaerobic tests are measurements of anaerobic power or capacity, such as the Wingate test [39]. Field anaerobic tests requires a minimum of equipment, such as the 40 yard sprint [102], vertical jump [102,103], anaerobic step test [39], 400 m running [104], or standing broad jump tests [28,71], and anaerobic power can be predicted. Anaerobic tests can be divided in to power fitness, power
endurance, and mixed endurance fitness tests [39]. Anaerobic power fitness tests [39] are performed at maximal pace for shorter than 15 s such as the 40 yd sprint running test [102], 20 m sprint running test [82] vertical jumping [82,102,103] and standing broad jump [28,102], and is primarily dependent of the muscles stored ATP and CP. In addition, vertical jumping and standing broad jump capacity is dependent of both dynamic strength and speed. Anaerobic power-endurance tests [39], such as the 30 s Wingate test [36,103,105] or the 60 s step-test [33] are performed at maximum pace for 15 to 60 s and are primarily dependent on the anaerobic glycolytic system [39,106]. Anaerobic mixed endurance-fitness tests [39], such as the 400 m running test [104] is performed at maximal effort for a minimum of 60 s to a maximum of 120 s and is dependent of both the anaerobic glycolytic system and the aerobic system for ATP production [39].

Studies have found anaerobic fitness both to be [28,33,36,71,103,104], and not to be [28,34] important for firefighters’ work capacity (Table 2), and the total energy contribution from the anaerobic system during firefighting work range between 14-73 % [31,68,94].

In contrast to aerobic fitness (Table 1) there is a lack of studies investigating firefighters’ anaerobic fitness (Table 2).

**Table 2. Previous anaerobic tests of firefighters**

<table>
<thead>
<tr>
<th>Author (Year)</th>
<th>Country</th>
<th>Subjects (n)</th>
<th>Test</th>
<th>Imp (Yes/No)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Davis et al., 1982 [71]</td>
<td>USA</td>
<td>100*</td>
<td>Broad jump</td>
<td>Yes</td>
</tr>
<tr>
<td>Misner et al., 1988 [103]</td>
<td>USA</td>
<td>150 w</td>
<td>Wingate 30 s</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Vertical jump</td>
<td>Yes</td>
</tr>
<tr>
<td>Saupe et al., 1991 [66]</td>
<td>USA</td>
<td>150*</td>
<td>Broad jump</td>
<td>*</td>
</tr>
<tr>
<td>Findley et al., 2002 [105]</td>
<td>USA</td>
<td>17 m 3w</td>
<td>400 m sprint</td>
<td>Yes</td>
</tr>
<tr>
<td>Rhea et al., 2004 [104]</td>
<td>USA</td>
<td>14*</td>
<td>40 yard sprint</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Broad jump</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Vertical jump</td>
<td>*</td>
</tr>
<tr>
<td>Peterson et al., 2008 [102]</td>
<td>USA</td>
<td>34 m 23 w</td>
<td>Wingate Time*</td>
<td>No</td>
</tr>
<tr>
<td>Sheaff et al., 2010 [36]</td>
<td>USA</td>
<td>26 m 7 w</td>
<td>Wingate 30 s</td>
<td>Yes</td>
</tr>
<tr>
<td>Michaelides et al., 2011 [33]</td>
<td>USA</td>
<td>67 m</td>
<td>Step-test 60 s</td>
<td>Yes</td>
</tr>
<tr>
<td>Phillips et al., 2011 [28]</td>
<td>Australia</td>
<td>LMFF: 20 m VFF: 18 m</td>
<td>Broad jump Ball toss</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>No</td>
</tr>
<tr>
<td>Perroni et al., 2014 [82]</td>
<td>Italy</td>
<td>161 m</td>
<td>20 m sprint CMJ</td>
<td>*</td>
</tr>
<tr>
<td>Son et al., 2014 [107]</td>
<td>Japan</td>
<td>18 m</td>
<td>Side jump 20 s</td>
<td>*</td>
</tr>
</tbody>
</table>

Different physical tests (Test) are used for evaluation of firefighters’ anaerobic capacity/power, and for statement of the tests importance (Imp) for work capacity. Subjects included men (m), women (W) LMFF: Land management firefighters, VFF: Volunteer firefighters. CMJ: Counter movement jump * Not stated.
Muscle strength and endurance
Maximal muscle strength (1RM) is the maximal weight a person can lift only one time. Muscle endurance is the ability to repeatedly perform series of muscle contractions and includes both aerobic and anaerobic metabolic pathways [39]. Laboratory tests of muscle strength and endurance, such as isokinetic, isotonic and isometric tests need advanced laboratory equipment [39]. With field tests, 1RM can be determined by direct measurements, or indirect predictions by performing maximal number of repetitions at intensities corresponding to 80 to 100 % of 1 RM [39,108,109].

Firefighters’ muscular strength [28,32-34,36,71,83,104,110,111] and muscular endurance [28,32-34,83,104,111] have previously been deemed important for work capacity, with maximal handgrip strength being most frequently studied (Table 3). Boyce et al. [112] found that in North Carolina, USA, male firefighters had lower 1RM bench press results compared to their male police officer counterparts, and that female firefighters had higher 1RM bench press results compared to their female police officer counterparts. Since performance in 1RM bench press and endurance bench press is correlated, Naclerio et al. [113] argued that physical training should primarily focus on increasing maximal muscle strength.

Table 3. Previous studies of firefighters’ muscle strength and power

<table>
<thead>
<tr>
<th>Test</th>
<th>Author/Year/Country</th>
<th>Method</th>
<th>Imp (Yes/No)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper body strength</td>
<td>Harvey et al., 2008. Canada [55]</td>
<td>*</td>
<td>No</td>
</tr>
<tr>
<td>Maximal handgrip strength (kg)</td>
<td>Lemon &amp; Hermiston, 1977. Canada [94]</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>Davis et al., 1982. USA [71]</td>
<td>FM</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Saupe et al., 1991. USA [66]</td>
<td>FM</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>Williford et al., 1999. USA [110]</td>
<td>FM</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Bilzon et al., 2001. UK [31]</td>
<td>FM</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>Davis et al., 2002. USA [49]</td>
<td>FM</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>Rhea et al., 2004. USA [104]</td>
<td>FM</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Garver et al., 2005. USA [88]</td>
<td>FM</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>Williams-Bell et al., 2009. Canada [34]</td>
<td>FM</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Henderson et al., 2007. USA [83]</td>
<td>FM</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Sheaff et al., 2010. USA [36]</td>
<td>FM</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Williams-Bell et al., 2010. Canada [69]</td>
<td>FM</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>Michaelides et al., 2011. USA [33]</td>
<td>FM</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Phillips et al., 2011. Australia [28]</td>
<td>FM</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Son et al., 2014. Japan [107]</td>
<td>FM</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>Storer et al., 2014. USA [75]</td>
<td>FM</td>
<td>*</td>
</tr>
</tbody>
</table>
Different physical tests (Test) are used for evaluation of firefighters’ muscle strength, and the tests importance (Imp) for work capacity. Also, different methods are used: Laboratory measurements (LM), Field Measurement of 1RM (FM) or Field prediction of 1RM (FP). a Sum of 1RM bench press, latissimus dorsi pull down, and bicep curl (kg). b Sum of 1RM leg extension and leg curl (kg).

| Test                  | Authors and Year; Country [Reference] | Method | Imp
|-----------------------|---------------------------------------|--------|-----
| Bench press (1RM)     | von Heimburg et al., 2006. Norway [58] | FP     | No  
|                       | Henderson et al., 2007. USA [83]      | FP     | Yes 
|                       | Michaelides et al., 2008. USA [32]    | FM     | Yes 
|                       | Petersen et al., 2008. USA [102]      | FM     | *   
|                       | Williams-Bell et al., 2009. Canada [34]| FP     | Yes 
|                       | Williams-Bell et al., 2010. Canada [69]| FP     | *   
|                       | Sheaff et al., 2010. USA [36]         | FM     | Yes 
|                       | Michaelides et al., 2011. USA [33]    | FM     | Yes 
|                       | Boyce et al., 2013. USA [112]         | FM     | *   
|                       | Perroni et al., 2014. Italy [82]      | FP     | *   
| Bench press (5RM)     | Rhea et al., 2004. USA [104]           | FM     | Yes 
| Shoulder press (1RM)  | von Heimburg et al., 2006. Norway [58]| FP     | No  
|                       | Williams-Bell et al., 2009. Canada [34]| FP     | No  
|                       | Williams-Bell et al., 2010. Canada [69]| FP     | *   
| Isometric arm lift (N)| Sothmann et al., 2004 USA [111]       | LM     | Yes 
| Isometric chin up (kg)| Lemon and Hermiston, 1977. USA [114]  | LM     | *   
| Bicep curl (1RM)      | Williams-Bell et al., 2009. Canada [34]| FP     | No  
|                       | Williams-Bell et al., 2010. Canada [69]| FP     | *   
| Lat pull down (1RM)   | Henderson et al., 2008. USA [83]      | FP     | Yes 
| Abdominal strength (1RM)| Michaelides et al., 2011. USA [33]     | LM     | Yes 
| Isometric trunk extension (N)| Punakallio et al., 2005. Finland [115] | LM     | *   
| Lower body strength a | Harvey et al., 2008. Canada [55]      | *      | No  
| Leg press (1RM)       | Lemon and Hermiston, 1977. USA [114]  | LM     | *   
|                       | Misner et al., 1988. USA [103]        | FM     | No  
|                       | Von Heimburg et al., 2006. Norway [58]| FP     | No  
|                       | Williams-Bell et al., 2009. Canada [34]| FP     | Yes 
|                       | Williams-Bell et al., 2010. Canada [69]| FP     | *   
|                       | Sheaff et al., 2010. USA [36]         | FM     | No  
| Knee extension (1RM)  | Sheaff et al., 2010. USA [36]         | FM     | No  
| Knee extension (W)    | Sheaff et al., 2010. USA [36]         | LM     | No  
| Isometric knee extension (N)| Punakallio et al., 2005. Finland [115] | LM     | *   
| Squat (1RM)           | Michaelides et al., 2008. USA [32]    | FM     | Yes 
|                       | Petersen et al., 2008. USA [102]      | FM     | *   
|                       | Michaelides et al., 2011. USA [33]    | FM     | Yes 
| Squat (5RM)           | Rhea et al., 2004. USA [104]           | FM     | Yes
Table 4. Previous studies of firefighters’ muscle endurance

<table>
<thead>
<tr>
<th>Test</th>
<th>Author/Year/ Country</th>
<th>Imp (Yes/No)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grip endurance (s)</td>
<td>Smolander et al., 1984. Finland [116]*</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>Rhea et al., 2004. USA [104]</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>Phillips et al., 2011. Australia [28]</td>
<td>Yes</td>
</tr>
<tr>
<td>Weight hold (s)</td>
<td>Phillips et al., 2011. Australia [28]</td>
<td>Yes</td>
</tr>
<tr>
<td>Bicep curl (n)</td>
<td>Rhea et al., 2004. USA [104]</td>
<td>Yes</td>
</tr>
<tr>
<td>Push up (n)</td>
<td>Davis et al., 1982. USA [71]</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Williford et al., 1999. USA [110]</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Davis et al., 2002. USA [49]</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>Garver et al., 2005. USA [88]</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>Fogleman &amp; Bhajani, 2005. USA [51]</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>Michaelides et al., 2008. USA [32]</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>Michaelides et al., 2011. USA [33]</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Phillips et al., 2011. Australia [28]*</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Storer et al., 2014 [75]</td>
<td>*</td>
</tr>
<tr>
<td>Pull-ups (n)</td>
<td>Williford et al., 2009. USA [110]</td>
<td>Yes</td>
</tr>
<tr>
<td>Chin-ups (n)</td>
<td>Davis et al., 1982. USA [71]</td>
<td>Yes</td>
</tr>
<tr>
<td>Bench press (n)</td>
<td>Rhea et al., 2004. USA [104]</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Harvey et al., 2008. Canada [55]*</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>Williams-Bell et al., 2009. Canada [34]*</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Sheaff et al., 2010. USA [36]</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>Williams-Bell et al., 2010. Canada [69]*</td>
<td>*</td>
</tr>
<tr>
<td>Bench press (10RM)</td>
<td>Dennison et al., 2012. UK [89]</td>
<td>*</td>
</tr>
<tr>
<td>Sit-up (n)</td>
<td>Davis et al., 1982. USA [71]</td>
<td>Yes</td>
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<tr>
<td></td>
<td>Saupe et al., 1991. USA [66]</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>Davis et al., 2002. USA [49]</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>Rhea et al., 2004. USA [104]*</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>Garver et al., 2005. USA [88]*</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>Fogleman &amp; Bhajani, 2005. USA [51]</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>Punakallio et al., 2005. Finland [115]*</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>Henderson et al., 2007. USA [83]*</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Michaelides et al., 2008. USA [32]*</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Williford et al., 2009, USA [110]*</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Michaelides et al., 2011. USA [33]*</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Storer et al., 2014. USA [75]</td>
<td>*</td>
</tr>
<tr>
<td>Arm endurance*</td>
<td>Sothmann et al., 2004. USA [111]</td>
<td>Yes</td>
</tr>
<tr>
<td>Prone bridge (s)</td>
<td>Phillips et al., 2011. Australia [28]</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Mayer et al., 2012 [117]</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>Nuzzo &amp; Mayer, 2013. USA [118]</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>Storer et al., 2014 [75]</td>
<td>*</td>
</tr>
<tr>
<td>Isometric back endurance (s)</td>
<td>Mayer et al., 2012 [117]</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>Nuzzo &amp; Mayer, 2013. USA [118]</td>
<td>*</td>
</tr>
<tr>
<td>Shoulder press (n)</td>
<td>Rhea et al., 2004. USA [104]</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Phillips et al., 2011. Australia [28]*</td>
<td>No</td>
</tr>
<tr>
<td>Bent row (n)</td>
<td>Rhea et al., 2004. USA [104]</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Phillips et al., 2011. Australia [28]*</td>
<td>No</td>
</tr>
<tr>
<td>Seated row (10 RM)</td>
<td>Dennison et al., 2012. UK [89]</td>
<td>*</td>
</tr>
<tr>
<td>Test</td>
<td>Study Details</td>
<td>Yes/No/Not Stated</td>
</tr>
<tr>
<td>---------------------</td>
<td>---------------------------------------------------</td>
<td>-------------------</td>
</tr>
<tr>
<td>Leg press (n)</td>
<td>Williams-Bell et al., 2009. Canada [34]</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Sheaff et al., 2010. USA [36]</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>Williams-Bell et al., 2010. Canada [69]</td>
<td></td>
</tr>
<tr>
<td>Wall sit (s)</td>
<td>Phillips et al., 2011. Australia [80]</td>
<td>Yes</td>
</tr>
<tr>
<td>Squat (W)</td>
<td>Petersen et al., 2008 [102]</td>
<td></td>
</tr>
<tr>
<td>Squat (n)</td>
<td>Punakallio et al., 2003. Finland [77]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rhea et al., 2004. USA [104]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Punakallio et al., 2005 Finland [115]</td>
<td></td>
</tr>
</tbody>
</table>

Different physical tests are used for evaluation of firefighters’ muscular endurance or for statement of the tests importance (Imp) for work capacity. s: seconds, * pre-defined testing speed was used, a Number of repetitions in 60 s. c Arm revolutions in 2 min, with an arm ergometer set at 50 W. d Laboratory measurement, all the other physical tests are field tests. * Not stated.

Although some authors report results both for male and female firefighters [31,34,55,111], most studies include men only [28,32,33,58,88,89,104], and one study included only females [103] when muscle strength, endurance, and power were investigated. As for tests of aerobic fitness, different methods are used and comparing results are difficult.

Firefighters’ muscular strength and endurance has previously been rigorously studied. To my knowledge, few studies [33,36,102,111,115,116] have previously investigated firefighters’ muscle strength and endurance in a laboratory setting, as previously requested by Barr et al [5] (Table 3 and 4). In addition, to my knowledge no one has ever executed a large battery of both laboratory tests and field tests of muscle strength and endurance, and simulated firefighting work tasks on the same subject group of firefighters.

**Balance**

Balance is one of the least studied indicators for firefighters’ work capacity. Laboratory tests of balance require advanced equipment, such as a force-plate [77,107,119], or an unstable moving platform [120], or similar equipment. Field tests of balance requires a minimum of equipment, such as the one leg stance test [121] walking on a wooden plank [77,122], or timed up and go test [107]. Others have found that different protecting clothing and BA affects both firefighters’ laboratory [77,107,119] and field [107,122] balance, as well as work capacity [107].

Firefighters aged 43 to 56 years are more affected by the BA compared to younger groups, although the balance decreases during use of BA for all groups [77]. Punakallio et al. [123] found that firefighters having a low to moderate perceived balance also had a lower perceived work ability, and that a low dynamic stability increase the risk to slip and fall [115]. In addition, postural sway increases with time on duty [119].

**In summary**

Based on previous studies, firefighters’ physical capacity is important for work capacity, and previously studied with different laboratory and field measurements. Also, different work tasks are used for evaluation of firefighters’ physical work capacity.
No one has ever developed a scientifically based battery of physical tests, valid for evaluation of physical work capacity among firefighters’ within the Swedish Fire and Rescue services. All fire stations in Sweden do not have access to advanced laboratories for evaluation of physical capacity. In order to promote equal physical testing among groups of firefighters, field tests should be used instead of laboratory tests, if possible. Consequently, laboratory tests, field tests and simulated work tasks must all, and simultaneously, be included in research studies.
Aims

The overall aim of this doctoral thesis was to identify valid, simple, and inexpensive physical tests for evaluation of firefighters’ physical work capacity, in Sweden.

The specific aims were:

**Study I** To rank perceived physical demands of firefighting work tasks and compare rankings of full-time and part-time firefighters.

**Study II** To study correlations between laboratory tests of aerobic capacity and power and field test performance, and their correlations with simulated firefighting work tasks.

**Study III** To study correlations between simulated firefighting work tasks and muscle power, strength and endurance, and dynamic balance.

**Study IV** a) To study if field tests can predict firefighters’ physical work capacity equally well as laboratory tests.  
b) To study if models excluding anthropometric data are valid for prediction of firefighters’ physical work capacity.  
c) To make an external validation of selected field tests.
Subjects and methods

Overall design
When an accident occurs, the SOS (emergency service) operators receive an alarm and communicate the alarm with the emergency services: a rescue operation (such as fire within a building) is identified, and a rescue action (such as firefighting) is initiated. The rescue action most often includes several different work tasks, such as **victim rescue and carrying hose baskets**, all together aimed to complete a successful rescue operation (Figure 2).

A battery of tests, validated to predict firefighters’ physical work capacity was created after stepwise elimination:
1. Identification of physically demanding firefighting work tasks (*Study I*).
2. Rank of correlations between work capacity and test results (*Studies II-III*).
3. External validation and recommendations of test battery (*Study IV*).

Subjects
In total, 193 subjects volunteered to participate in *Study I* (Figure 3, Table 5 and 6) and represented municipalities with varying size and geographical distribution (number of inhabitants within each municipality ranged between < 5000 and > 100 000).
SUBJECTS AND METHODS

Figure 3. Flowchart of subjects included in the questionnaire (Study I) and in the physiological measurements (Study II-IV).

Table 5. Overview of subjects included in Studies I-IV

<table>
<thead>
<tr>
<th>Group</th>
<th>Study I n</th>
<th>Age mean±SD</th>
<th>Study II-III n</th>
<th>Age mean±SD</th>
<th>Study IV n</th>
<th>Age mean±SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Male Full-time FF</td>
<td>99</td>
<td>40.0±9.7</td>
<td>10</td>
<td>38.7±9.1</td>
<td>21</td>
<td>37.0±11.3</td>
</tr>
<tr>
<td>Male Part-time FF</td>
<td>80</td>
<td>40.1±8.9</td>
<td>8</td>
<td>28.4±4.7</td>
<td>21</td>
<td>33.6±9.3</td>
</tr>
<tr>
<td>Female Full-time FF</td>
<td>4</td>
<td>32.3±7.3</td>
<td>0</td>
<td>-</td>
<td>17</td>
<td>29.4±5.6</td>
</tr>
<tr>
<td>Female Part-time FF</td>
<td>10</td>
<td>36.9±7.7</td>
<td>0</td>
<td>-</td>
<td>23</td>
<td>35.0±9.7</td>
</tr>
<tr>
<td>Civilian women</td>
<td>0</td>
<td>-</td>
<td>12</td>
<td>34.0±10.7</td>
<td>24</td>
<td>33.0±9.8</td>
</tr>
<tr>
<td>Civilian men</td>
<td>0</td>
<td>-</td>
<td>8</td>
<td>32.0±11.4</td>
<td>22</td>
<td>36.0±10.6</td>
</tr>
<tr>
<td>Summary</td>
<td>193</td>
<td>39.7±9.2</td>
<td>38</td>
<td>33.6±9.8</td>
<td>128</td>
<td>34.2±9.8</td>
</tr>
</tbody>
</table>

The mean ± standard deviation for age of subjects (n) included in Studies I-IV. Subjects included in Studies II-III were also included in Study IV. FF = Firefighters. Groups marked with different symbols in rows are significant different (p < 0.05) (A different from B).

Significant differences (p < 0.05) in the distribution of full- and part-time firefighters within different municipality sizes were found (Table 6).

Table 6. Distribution of respondents in relation to municipality size, Study I

<table>
<thead>
<tr>
<th>Municipality size (n inhabitants)</th>
<th>Full-time FF (n)</th>
<th>Part-time FF (n)</th>
<th>Total (n)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 5000</td>
<td>0</td>
<td>20*</td>
<td>20</td>
</tr>
<tr>
<td>5000 – 9999</td>
<td>6</td>
<td>17*</td>
<td>23</td>
</tr>
<tr>
<td>10 000 – 14 999</td>
<td>3</td>
<td>23*</td>
<td>26</td>
</tr>
<tr>
<td>15 000 – 19 999</td>
<td>13</td>
<td>3*</td>
<td>16</td>
</tr>
<tr>
<td>20 000 – 29 999</td>
<td>19</td>
<td>5*</td>
<td>24</td>
</tr>
<tr>
<td>30 000 – 49 999</td>
<td>15</td>
<td>12</td>
<td>27</td>
</tr>
<tr>
<td>50 000 – 99 999</td>
<td>23</td>
<td>6*</td>
<td>29</td>
</tr>
<tr>
<td>&gt; 100 000</td>
<td>24</td>
<td>4*</td>
<td>28</td>
</tr>
<tr>
<td>Total</td>
<td>103</td>
<td>90</td>
<td>193</td>
</tr>
</tbody>
</table>

Respondents from different sized municipalities (n of inhabitants) were included in Study I. Significant differences in the distribution of full-time firefighters (Full-time FF) and part-time firefighters (Part-time FF) were found with Binomial test * p < 0.05.
In total, 128 subjects volunteered to participate in the physiological measurements (Figure 3, Table 5 and 7), and 38 are referred to as the training-set (Studies II-IV) and 90 are referred to as the prediction-set (Study IV). It is unknown if subjects included in Study I also were included in Studies II-IV.

Table 7. Descriptive data of subjects included in Studies II-IV

<table>
<thead>
<tr>
<th>Group</th>
<th>Studies II-III</th>
<th>Study IV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n</td>
<td>Height (m)</td>
</tr>
<tr>
<td>Male Full-time FF</td>
<td>10</td>
<td>1.78±0.04</td>
</tr>
<tr>
<td>Male Part-time FF</td>
<td>8</td>
<td>1.82±0.07</td>
</tr>
<tr>
<td>Female Full-time FF</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>Female Part-time FF</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>Civilian women</td>
<td>12</td>
<td>1.70±0.07</td>
</tr>
<tr>
<td>Civilian men</td>
<td>8</td>
<td>1.82±0.05</td>
</tr>
<tr>
<td><strong>Summary</strong></td>
<td><strong>38</strong></td>
<td><strong>1.77±0.08^a</strong></td>
</tr>
</tbody>
</table>

The mean ± standard deviation for body height and weight of subjects (n) included in Studies II-IV. Groups marked with different symbol in rows are significant different (p < 0.05) (A different from B).

All subjects (Studies II-IV) were free from any known disease that affects physical capacity. Subjects included in Studies II-III were represented only from the county of Norrbotten in Sweden, and subjects included in Study IV were represented also from other Swedish counties (Figure 4).
SUBJECTS AND METHODS

Questionnaire
The questionnaire (Study I) was constructed in 2000 and based on Swedish and international reports on work tasks and physical requirements [38,124-126]. The questionnaire was administered twice: once in 2000 and once in 2010. Out of the 32 emergency services included in 2000, 28 accepted to participate in 2010 and four declined due to lack of time. A group of respondents were obtained from the fire-chief within each emergency service.

The questionnaire was sent to a total of 160 and 84 firefighters in 2000 and 2010, respectively. A written introduction was given to the respondents and answers sent to the first author by electronic or surface mail. Subjects were anonymous, and coded for municipality size.

Physiological measurements
Design
Physiological measurements for the training-set included laboratory tests, field tests, and simulated work tasks. (Studies II-IV) (Figure 5). All tests were executed over ten non-consecutive days, with at least one day of rest between each test day. Physiological measurements of the prediction-set included a selection of these field tests and simulated work task tests (Study IV) (Figure 5). These tests were performed over three consecutive days.

Figure 5. Physiological measurements
The training-set (Studies II-IV) performed all laboratory tests, field tests, and simulated work task tests; Vehicle extrication and Cutting were not included in Study IV. The prediction-set (Study IV) performed a selection of these tests (bold styles in the squares).
SUBJECTS AND METHODS

Body weight and height (SECA GmbH & Co. KG, Hamburg, Germany) were measured without subjects wearing shoes (Studies II-IV), and the scale (SECA 770) was calibrated according to the embedded spirit level prior each test. All laboratory and field tests were separated by at least 5 min of rest and were preceded by five to 15 min warm up; simulated work tasks were performed without any warm up (Studies II-IV).

Laboratory tests

Submaximal and maximal treadmill running

Treadmill tests were performed on the treadmill RL 1700 (Rodby Innovation AB, Södertälje, Sweden) that is regularly calibrated for speed and inclination.

Fingertip blood lactate was analyzed with Biosen lactate analyzer (Biosen 5130; EKF-diagnostic, GmbH, Barleben, Germany). Biosen is a valid ($r^2 = 0.97, p < 0.05$ compared to YSI 2300) and reliable ($r^2 = 1.00, p < 0.05$) instrument that was each day calibrated against a 12 mM·L$^{-1}$ lactate standard and checked with a linearity test kit having known lactate concentrations (2, 7, and 18 mM·L$^{-1}$).

Continuous measurement of VO$_2$ and RER were made during the tests, using the valid instrument Jaeger Oxycon Pro (Erich Jaeger GmbH, Hoechberg) (mean CV: 1.2 %, $p < 0.05$ at ventilations 15 to 210 L·min$^{-1}$) and ancillary Hans Rudolph accessories (Hans Rudolph Inc., Kansas City, USA) (Studies II and IV) (Figure 6). A two point calibration using 15.25% O$_2$ and 5.95% CO$_2$ (Air Liquide Gas AB, Kungsängen, Sweden) and room air (approximately 20.93% O$_2$ and 0.04% CO$_2$) was executed twice a day, the flow-meter was automatically calibrated at 0-2 L/s. Prior the calibration procedure the temperature (GMH 330), humidity and pressure (GMH 3160-12) (Svenska termoinstrument AB, Täby, Sweden) was registered. Jaeger Oxycon Pro is regularly validated against the Douglas bag technique.

HR was registered with Polar heart rate monitor S810 (Polar Electro Oy, Kempele, Finland).

Onset of blood lactate accumulation is set to a fixed blood lactate level of 4 mM·L$^{-1}$ [129,130] and LT is the treadmill speed or % VO$_{2\text{max}}$ a person can achieve with less than a 1.0 mM·L$^{-1}$ increase in blood lactate [45,130]. In order to establish treadmill speed and VO$_2$ at OBLA and LT subjects performed at least three submaximal intervals (four min each) at a 0° treadmill incline and an individually set treadmill speed, the first speed started 2 km·h$^{-1}$ below the self-rated race pace for 10 km running. Fingertip blood was sampled at each one-minute stop between the intervals and analyzed for lactate. Because OBLA is suggested to
occur around the Borg’s Ratings of Perceived Exertion [131] of approximately 16 [132,133], the test stopped at the RPE ratings of 16-17. Both LT and OBLA were registered and are measures of increased lactate accumulation and/or decreased lactate clearance (Studies II and IV).

A test of maximal aerobic capacity and aerobic power was executed at a fixed individualized treadmill speed and an each minute increasing treadmill incline (Studies II and IV), the test stopped at voluntary exhaustion. Fingertip blood was sampled at 1 and 3 min after exhaustion for measurement of blood lactate.

Isokinetic tests
Concentric tests of maximal and endurance muscle strength (Studies III-IV) were executed in a BIODEX™ Multi joint system 3 dynamometer (Biodex medical system, New-York, USA) according to the manufacturer’s instructions (Biodex Medical Systems: Operation Manual) and the authors designed test protocol. The Biodex is regularly calibrated by hanging known weights on the leveler arm. The mechanical validity (angular position, isometric torque, and velocity: ICC: 0.99-1.0, SEM: 0.0 to 12.9 %) and reliability (angular position: CV 0 to 3 %, isometric torque: CV 0 to 2 %, and velocity: CV 1 to 4 %) of the Biodex dynamometer has previously been studied [134].

Every isokinetic test was preceded by 3 to 6 submaximal test-specific trial repetitions in the BIODEX. Muscle strength was tested with one set of 5RM and at an angular speed of 60°·s⁻¹, tests included were shoulder flexion and extension, and knee extension and flexion.

Muscle endurance was tested with one set of 15 to 30 RM at an angular speed of 60°·s⁻¹ to 240°·s⁻¹, tests included were shoulder press, deadlift, shoulder flexion and extension (Figure 7A), knee extension and flexion (Figure 7B), and trunk flexion and extension. For bilateral tests, the highest individual performances were presented.

Isokinetic testing of muscular performance offers a wide range of measurements, all giving a measure of strength in different ways. Total work (Joule = J) is the amount of work accomplished for the entire test set, average power (Watt = W) is a measure of an individual’s ability to produce torque or force within the tests range of motion (ROM) divided by time. Peak torque (Newton meter: Nm) and force (Newton: N) is the highest force or torque produced anywhere in the tests ROM [135,136]. In the BIODEX settings, N and Nm are also scaled to bodyweight, and expressed as %. Variables included were W, W·kg⁻¹ (Studies II-IV), Nm, Nm %, N, N %, W, and J (Study IV).
SUBJECTS AND METHODS

**Figure 7 A+B.** Laboratory isokinetic tests in the BIODEX multijoint system
A: Knee extension and flexion, and B: Shoulder flexion and extension, were two out of five laboratory tests of muscle strength and endurance performed by the training-set.

The reliability of knee flexion and extension tests performed at 120°·s⁻¹ test is for flexion ICC: 0.64 to 0.79, p< 0.001 and for extension 0.33 to 0.85, p < 0.01. The fatigue index for knee flexion was not reliable (ICC: -0.003, p = 0.976) [137] and is not included in the thesis. The reliability of the deadlift test is ICC: 0.67 to 0.77, % SEM: 13.2 to 20.1 and previously considered as not reliable [138]. The trunk flexion and extension test reliability is ICC = 0.81-0.89 [139].

**Dynamic balance**
Postural stability (*Studies III-IV*) (Figure 8) was executed on the Biodex Balance System SD (Biodex medical system, New-York, USA) and performed according to previous standards (Biodex Balance system SD: Operation Manual). The test was performed for one minute on Level 4. The Stability Index (SI) represents the degree of variance of the foot platform displacement and a low SI indicates better postural stability compared to a high SI. Performance results included were the overall SI (*Studies III- IV*) and the anterior/posterior SI (*Study IV*). The tilt of the balance platform is always 0° to 20° and eight possible stability levels (based on platform inertia) can be used from the easiest (Level 8) to the most difficult (Level 1).

The reliability during a 20 s test period is r = 0.91 to 0.95, using one leg stand [140].
SUBJECTS AND METHODS

Field tests
Benches, a Smith machine, dips, and chin up equipment (Precor, CL Fitness, Sweden), barbells, dumbbells, and free weights (Casall Sport AB, Sweden) were used. Korg MA-30 metronome (Korg and Moore, Marburg, Germany) was used for pre-defined test speeds (Studies II-IV).

Submaximal cycling
Cycling was executed for six minutes on Ergomedic 839 E (Monark Exercise AB, Vansbro) (Studies II and IV). The pre-defined load and cadency was 200 W, and 60 rpm, respectively; steady-state HR and cycling time was registered, % HR\textsubscript{max} was calculated.

Maximal handgrip strength
The subjects squeezed the hand force dynamometer (Grip-D: Eleiko sport AB, Halmstad) three times on each hand with one minute of rest between trials for the same hand [141] (Studies III-IV). The highest result (kg) on each hand was registered and the highest measurement on any hand used in the analyses.

Endurance handgrip time
A 27.0 kg dumbbell was held in each hand at the same time. Time (s) was measured and stopped when the dumbbell dropped to the floor (Studies III-IV). The highest performance time (s) on any hand was used in the analyses.

Endurance squat
Using a 22.0 kg barbell, 20 squats-min\textsuperscript{-1} was performed in a Smith-machine until voluntary exhaustion: From the position of straight knees, hips and knees were
flexed to a 90 degree knee angle, verified by a goniometer prior the test (*Studies III-IV*). Number of correctly performed squats was registered.

**Sit-ups**
Subjects were lying on their back, the head in contact with the floor, and both lower legs placed on a box (height 0.4 m). In a pre-defined speed of 50 full lifts·min$^{-1}$ subjects lifted their upper body from the starting position (the head and back in contact with the exercise mat) to a pre-defined lifting height depending on the subjects’ body height [142] (Figure 9) (*Studies III-IV*). The test stopped at voluntary exhaustion and number of correctly performed sit-ups was registered.

![Image of a person performing a sit-up](image)

*Figure 9. Field sit-up test*

*The training-set performed the sit-ups test. The taped lines on the exercise mat and angulus inferior scapulae were used to control that the pre-defined lifting height was achieved.*

**Bench press**
With the subjects lying supine on a non-tilted bench, 25 full bench presses·min$^{-1}$ was performed, using a 30 kg barbell (*Studies III-IV*). Number of correctly performed bench presses was registered.

**Chin up and Dips**
These tests were performed with a self-selected speed and the number of correctly performed chins and dips were registered (*Study III-IV*).

**Upright barbell row**
A 7.5 kg barbell was lifted from the position of spina iliaca anterior to chin level, with a speed of 30 full lifts·min$^{-1}$ (*Studies III-IV*). Number of correctly performed rows was registered.

**Crawling 30 m**
With both hands, knees and feet positioned on the floor, subjects crawled 30 m in the four-legged position (*Studies II and IV*). Time (s) was registered.
Standing broad jump
From a standing position, subjects jumped as far as possible, arm swing was allowed (Studies III-IV). The best jump of three performed was registered (m).

Running 3000 m
Track running was executed as fast as possible on a 200 m or 370 m indoor track (Studies II and IV). Time (s) was registered and time scaled to bodyweight (s·kg\(^{-1}\)) calculated.

Step up test
Dressed in fire protective clothing including BA (total weight 24 ± 0.5 kg), subjects executed a six-minute step up test. The height of the box was 0.2 m and the predefined speed was 30 full steps·min\(^{-1}\). Steady state HR was registered and % HR\(_{\text{max}}\) calculated (Studies II and IV) (Figure 10 A).

Treadmill walking
In accordance with government regulations [1], a six-minute treadmill-walking test was executed. Subjects were dressed in fire protective clothing including BA (total weight 24 ± 0.5 kg). After a 2 min warm up at the treadmill speed 4.5 km·h\(^{-1}\) and 0° incline, subjects walked at a fixed treadmill incline (8°) and speed (4.5 km·h\(^{-1}\)) for six minutes. Steady state HR was registered and % HR\(_{\text{max}}\) calculated (Studies II and IV) (Figure 10 B).

Figure 10 A+B. Field step up and treadmill walking tests.
Dressed in fire-protective clothing including BA (total weight 24 ± 0.5 kg), the training-set performed these tests.
SUBJECTS AND METHODS

Rowing 500 m
The test was executed as fast as possible, using the heaviest load (*Study II* and *IV*): time (s) and mean power (W) was registered. The reliability (% SEM) for the mean power output in 500 m rowing with the Concept II rowing machine is 2.8 % [143].

Barbell shoulder press
A 7.5 kg barbell was pressed from the position of the chin to the position of straight arms overhead until voluntary exhaustion (*Studies III-IV*). The pre-defined test speed was 25 full presses·min\(^{-1}\), and number of correctly performed presses was registered.

Maximal heart rate
Was defined as the highest heart rate achieved during any of the laboratory tests, field tests, or simulated work task tests.

Simulated work tasks
The mean, and the highest HR achieved during the work task course and during the *terrain* work task was recorded and the % HR\(_{\text{max}}\) was calculated. Time (s) was registered for each individual work task.

Cutting
A modified concrete saw (Husqvarna 371k, St. Olathe, USA) with a total weight of 16.1 kg was moved backwards along a 2 m by 2 m square drawn on the floor at a rate of 40 moves·min\(^{-1}\). The test was performed until voluntary exhaustion, but with a maximum time of 15 min (not known to the subject prior the test) (*Studies II-III*).

Work task course
The *stairs*, *pulling*, *demolition*, and *rescue* work tasks were performed in sequence with two minutes of active rest between each station; the rest period was aimed to move between the stations. Subjects were dressed in a fire emergency jacket, gloves, and BA (BA, 19.0 kg ± 0.5 kg) (*Studies II-IV*).

*Stairs:* Two hose baskets (each basket aimed for two 25 m long, 42 mm diameter hoses, and adjusted to 16.0 kg) were carried up four floors twice as fast as possible, with a 60 s active rest period while walking down, the total vertical lift was 2*13 m.

*Pulling:* A 25 m long rope or a water-filled hose (diameter 70 mm) was pulled 20 m as fast as possible, without moving the feet. The pull resistance at full length was approximately 220 N, as verified by slowly pulling the rope/hose at a constant speed on a concrete floor, using a hand dynamometer.

*Demolition:* An 8.5 kg EZ bar modified with additional weights was lifted between a 1.40 m and 1.90 m markings above the floor at a frequency 25 lifts·min\(^{-1}\) until voluntary exhaustion.
**Rescue**: A 75 kg dummy was pulled backwards over a concrete floor as fast as possible for 30 m. The dummy wore a chest harness.

**Vehicle extrication**

The front part of an 18.5 kg spreader (Holmatro SP 3240t; Wennergren Maskin AB, Grimslöv, Sweden) was pressed against five wall-marked points at three different heights, using both arms, each point was marked for 15 s. The test was performed to voluntary exhaustion but with a maximum time of 10 min (not known to the subjects prior the test) (*Studies II-III*).

**Terrain**

Two hose baskets (each basket aimed for two 25 m long, 63 mm diameter hoses, and adjusted to 18.7 kg) were carried over a pre-defined course for a total of 600 m, one basket for 300 m, and walked or ran 700 m without hose baskets. The subjects wore gloves and were instructed to complete the work task as fast as possible (*Studies II-IV*).

**Statistics**

Statistical calculations were made in *Study I* by comparing the questionnaire answers in questionnaire part 1 and questionnaire part 2, and also comparing answers between full-time FF and part-time FF, in *Studies II-III* for correlations between physical capacity and work task capacity and for between group differences in physical capacity and work capacity tests, and in *Study IV*, for between group differences, multivariate statistics and external validation of selected physical tests.

Statistical calculations were carried out with the Statistical Package for the Social Sciences (SPSS) version 20.0 (IBM Corporation, USA) (*Studies I-IV*) and with Soft Independent Modeling of Class Analogy (SIMCA) version 13.0 (MKS Umetrics AB, Umeå, Sweden) (*Study IV*).

The questionnaire was analyzed with non-parametric statistics (*Study I*). Data in several of the physical tests (*Studies II-III*) were not normally distributed. This conclusion was made with graphic analyses including the Q-Q plot, and supported by skewness and kurtosis data, and the Shapiro-Wilk’s test [144]. Logarithmic transformation of data did not change all included variables to normal and all data were therefore analyzed without transformation (*Studies II-III*).

**Between group differences**

For parametric data, subject group differences were analyzed with independent sample t-test (*Study I*) or One Way Anova with a post hoc Bonferroni analyze, when appropriate (*Studies II-III*). The unpaired t-test was used to investigate differences in mean between two subject groups, and the One Way Anova compared the means of more than two groups.

For non-parametric data, Kruskal-Wallis and Mann Whitney U-test were used; when significant differences were found with the Kruskal-Wallis test, the Mann
Whitney U-test was carried out if more than two groups were included (Studies I-IV). Bonferroni correction was used to avoid Type 1 error.

When significant differences between subject groups were found in the questionnaire, the Binominal test [145] investigated if the proportion of each response within the specific question was equal for Full-time and Part-time FF (Study I).

**Bivariate correlation analyses**
An overview of the included bivariate correlations is presented in Figure 11 (Studies II-III). Laboratory tests correlation with field tests (Study II), and simulated work tasks correlations with laboratory tests and field tests (Studies II-III) were defined with Spearman’s rho ($r$). Due to the low inclusion of women, data were analyzed as one subject group (Studies II-III).

**Laboratory tests**
- Aerobic fitness
- Muscular fitness, Balance

**Field tests**
- Aerobic fitness
- Muscular fitness

**Simulated firefighting work**

![Figure 11. Overview of correlations in Study II-III](image)

**Multivariate analyses**
Multivariate models were built in Study IV. All data was mean centered and scaled to unit variance (UV) prior to analysis. Variables that were considered as skewed were log$_{10}$ transformed to normality.

First, an unsupervised Principal Component Analysis (PCA) was performed; second an Orthogonal Projection to Latent Structures (OPLS). PCA and OPLS generate one score and one loading plot. The score plot represents the projection subjects (observations) and the loading plot the projection of the variables (loadings). In OPLS, X represents the regressor variables (laboratory and field tests, and anthropometric data) and Y represents the response variables (work tasks). For each work task, an OPLS models and separates the systematic variation in X correlated to Y (predictive variation) and the systematic variation uncorrelated to Y (orthogonal variation). $R^2$ is a measure of the overall fit of the model ($R^2 = 1$, the model explains 100% of the variation in the data) and $Q^2$ is a measure of the ability of the model to predict same variation based on cross-validation (predictive power). Modeling was executed according to Wheelock & Wheelock [146], and included data from the training-set (Studies II-IV) (Figure 3 and 5). External validations of the selected models were executed with the prediction-set (Study IV) (Figure 3 and 5).
Significance level
A p-value < 0.05 (Study I) and p < 0.01 (Studies II-III) were considered statistically significant.

In SIMCA, significance is set to limits based on Q2, cross validation rules for PCA apply, and limit depends on the number of components for PCA. The limit increases with subsequent components to account for the loss in degrees of freedom.

Ethical considerations
All participants included in the training and in the prediction-set signed an informed consent, stating their ability to execute all parts of the study, and absence of any known diseases affecting their physical capacity. The Research Ethics Committee for Northern Sweden at Umeå University approved the studies, and they were conducted in accordance with the WMA Declaration of Helsinki – Ethical Principles for Medical Research Involving Human Subjects 2008.
Results

Self-rated physical loads of work tasks among firefighters

The response rate of the questionnaire in Study I was 78 % in year 2000 and 81 % in year 2010. The overall ratings of perceived physical exertion for the investigated work tasks were the same in year 2000 and 2010 and data was analyzed as one group.

Differences in ratings of physical exertion between Full-time FF and Part-time FF occurred within all categories: aerobic capacity, and hands, arms, legs, and trunk muscle strength. The most common reason for these differences was a higher proportion of Part-time FF rating "I don´t know" and at the same time, a higher proportion of Full-time FF rating a higher perceived physical exertion. These differences were remarkable for the aerobic capacity where 19 out of 31 rated work tasks were rated "I don´t know" by a higher proportion of Part-time FF compared to Full-time FF.

The work tasks making holes in the roof for fire-gas ventilation were rated to require higher hand muscle strength among Full-time FF compared to Part-time FF, without any differences in the "I don´t know" response. Such findings were also observed for external building firefighting (arms, legs, and trunk), and Hose pull (arms). All work tasks were rated as "Very hard" (aerobic capacity) or "Very high" by at least one respondent. Climbing stairs, carrying hose baskets, victim rescue, carrying a stretcher over terrain, vehicle extrication, and hose pull had the highest ratings of physical exertion by most responders. Several of these work tasks includes use of BA.

Field tests for evaluating the aerobic work capacity of firefighters

Between group differences

In Study II we found that the mean \( \text{VO}_2\text{max} \) (L·min\(^{-1}\)) was higher for all groups of men, compared to women. The mean \( \text{VO}_2\text{max} \) (mL·kg\(^{-1}\)·min\(^{-1}\)) was equal for all groups of men, and civilian women had equal \( \text{VO}_2\text{max} \) in mL·kg\(^{-1}\)·min\(^{-1}\) as civilian men and male part-time firefighters. Significant differences between subject groups performances were found in the mean performance time in 30 m crawling, median performance in 3000 m running (s·kg\(^{-1}\)), step test and treadmill walking (mean % HR\(_{\text{max}}\)), 500 m rowing (s and Watt), and the stairs, pulling, demolition, rescue, and terrain work tasks.

All groups of men had equal mean or median performance in all physical tests and simulated work tasks. No significant differences were found between subject groups in median 3000 m running time (s), mean % HR\(_{\text{max}}\) at OBLA and LT, or mean % HR\(_{\text{max}}\) during the work task course or during the terrain work task.

Aerobic work capacity

In Study II we found that in general, work capacity was significantly (p < 0.01) correlated with both laboratory tests and field tests of aerobic fitness. In addition,
submaximal cycling (% HR_{max}), 3000 m running (s·kg\(^{-1}\)) and 500 m rowing (s) were strongly correlated (r\(_s\) > 0.7) both with laboratory VO\(_{2\text{max}}\) (L·min\(^{-1}\)), and with at least one simulated firefighting work task.

The laboratory and field test having the highest correlation (r\(_s\) values closest to +1 or −1) with cutting work capacity was VO\(_{2\text{max}}\) (L·min\(^{-1}\): r\(_s\) = 0.55, p < 0.01) and 500 m rowing (s: r\(_s\) = -0.63, p < 0.01), respectively (Figure 12), no strong correlations were found. The correlation between VO\(_{2\text{max}}\) (L·min\(^{-1}\)) and 500 m rowing (s) was r\(_s\) = -0.84, p < 0.01.

![Figure 12](image)

**Figure 12.** Cutting holes in the roof for fire-gas ventilation
A: laboratory and B: field test with the highest correlation with cutting work capacity time. MFF = Male full-time firefighters, MPF = Male part-time firefighters, CM = Civilian men, CW = Civilian women, n = 37.

The laboratory and field test having the highest correlation with stairs work capacity was VO\(_{2\text{max}}\) (L·min\(^{-1}\): r\(_s\) = -0.75, p < 0.01) and 500 m rowing (W: r\(_s\) = -0.83, p < 0.01), respectively (Figure 13). In addition, 30 m crawling (s) and 500 m rowing (s) were also strongly correlated (r\(_s\) = 0.74 and 0.82, respectively, p < 0.01) with stairs work capacity.

![Figure 13](image)

**Figure 13.** Carrying hose baskets up stairs
A: laboratory and B: field test with the highest correlation with stairs work capacity time. MFF = Male full-time firefighters, MPF = Male part-time firefighters, CM = Civilian men, CW = Civilian women, n = 36.
The laboratory and field test having the highest correlation with *pulling* work capacity was $\text{VO}_{2\text{max}}$ (L·min$^{-1}$; $r_s = -0.74$, $p < 0.01$) and 500 m rowing (s; $r_s = 0.76$, $p < 0.01$), respectively (Figure 14). In addition, 3000 m running (s·kg$^{-1}$) was also strongly correlated ($r_s = 0.72$, $p < 0.01$) with *pulling* work capacity.

![Figure 14. Hose pulling](image)

*Figure 14. Hose pulling*

*A: laboratory and B: field test with the highest correlation with pulling work capacity time. MFF = Male full-time firefighters, MPF = Male part-time firefighters, CM = Civilian men, CW = Civilian women, n = 37.*

The laboratory and field test having the highest correlation with *demolition* work capacity was $\text{VO}_{2\text{max}}$ (L·min$^{-1}$; $r_s = 0.79$, $p < 0.01$) and 3000 m running (s·kg$^{-1}$; $r_s = -0.78$, $p < 0.01$), respectively (Figure 15). In addition, cycling (% HR$_{\text{max}}$) and 500 m rowing (s and W) were also strongly correlated ($r_s = -0.74$ and 0.70, respectively, $p < 0.01$) with *demolition* work capacity.

![Figure 15. Demolition at or after a fire](image)

*Figure 15. Demolition at or after a fire*

*A: laboratory and B: field test with the highest correlation with demolition work capacity time. MFF = Male full-time firefighters, MPF = Male part-time firefighters, CM = Civilian men, CW = Civilian women, n = 37.*

The laboratory and field test having the highest correlation with *rescue* work capacity was $\text{VO}_{2\text{max}}$ (L·min$^{-1}$; $r_s = -0.79$, $p < 0.01$) and 500 m rowing (s; $r_s = 0.79$ and W; $r_s = -0.79$, $p < 0.01$), respectively (Figure 16). In addition, 30 m crawling (s) was also strongly correlated ($r_s = 0.70$, $p < 0.01$) with *rescue* work capacity.

![Figure 16. Rescue work capacity](image)

*Figure 16. Rescue work capacity*

*A: laboratory and B: field test with the highest correlation with rescue work capacity time. MFF = Male full-time firefighters, MPF = Male part-time firefighters, CM = Civilian men, CW = Civilian women, n = 37.*
RESULTS

Figure 16. Victim rescue
A: laboratory and B: field test with the highest correlation with rescue work capacity time. MFF = Male full-time firefighters, MPF = Male part-time firefighters, CM = Civilian men, CW = Civilian women, n = 37.

The laboratory and field test having the strongest correlation with terrain work capacity was VO\(_{2}\max\) (mL·kg\(^{-1}\)·min\(^{-1}\): \(r_s = -0.74, p < 0.01\)) and treadmill walking (% HR\(_{\text{max}}\): \(r_s = 0.71, p < 0.01\)), respectively (Figure 17). In addition, VO\(_{2}\max\) (L·min\(^{-1}\)) was also strongly correlated (\(r_s = -0.70, p < 0.01\)) with terrain work capacity. The correlation between VO\(_{2}\max\) mL·kg\(^{-1}\)·min\(^{-1}\) and treadmill walking (% HR\(_{\text{max}}\)) was -0.74, \(p < 0.01\).

Figure 17. Carrying hose baskets over terrain
A: laboratory and B: field test with the highest correlation with terrain work capacity time. MFF = Male full-time firefighters, MPF = Male part-time firefighters, CM = Civilian men, CW = Civilian women, n = 38.

Laboratory or field tests for evaluating firefighters’ work capacity?

Between group differences
In Study III we found that all groups of men had equal mean or median performance in isokinetic tests of muscle strength and endurance in the upper and the lower body. Significant differences (\(p < 0.01\)) were found between subject groups in all isokinetic tests of muscle strength and endurance, except the maximal and endurance knee flexion (W·kg\(^{-1}\)), endurance deadlift (W·kg\(^{-1}\)), and endurance
trunk extension (W·kg\(^{-1}\)). The dynamic balance was higher for civilian women compared to male full-time firefighters (p < 0.01). Significant differences (p < 0.01) were found between subject groups in all field tests, with all groups of men having higher performance compared to women in six out of 10 performed field tests. A total of 83% and 58% of the included women were unable to do one repetition of chin-up and dips, respectively.

Correlations
In general, work capacity was significantly (p < 0.01) correlated with both laboratory and field tests of muscle strength, muscle endurance, muscle power, and dynamic balance in Study III. All isokinetic tests but three (maximal and endurance knee flexion and endurance deadlift (W·kg\(^{-1}\))) were significantly (p < 0.01) correlated with at least three simulated work tasks. Dynamic balance and all field tests were significantly (p < 0.01) correlated with work capacity in all studied work tasks. In general, the highest correlations (r, closest to +1 or −1) with work capacity were found with upper body muscle strength and endurance.

The laboratory and field test having the highest correlation with cutting work capacity was endurance trunk extension (W: \(r_s = 0.72\), p < 0.01) and maximal handgrip strength (kg: \(r_s = 0.67\), p < 0.01), respectively (Figure 18). In addition, endurance trunk extension (W·kg\(^{-1}\)) was strongly correlated (\(r_s = 0.71\), p < 0.01) with cutting work capacity.

The laboratory and field test having the highest correlation with stairs work capacity was endurance shoulder flexion (W·kg\(^{-1}\): \(r_s = -0.81\), p < 0.01) and barbell shoulder press (n: \(r_s = -0.77\), p < 0.01) (Figure 19). In addition, maximal and endurance knee extension (W: \(r_s = -0.78\) and -0.76, respectively), endurance trunk flexion (W: \(r_s = -0.74\)), the majority (n = 8 out of 10) of isokinetic upper body strength and endurance (W and W·kg\(^{-1}\): \(r_s = -0.70\) to -0.81), bench press (n: \(r_s = -0.73\)), chin ups (n: \(r_s = -0.76\)), dips (n: \(r_s = -0.75\)), and standing broad jump (m: \(r_s = -0.72\)) were also strongly and significantly correlated (p < 0.01) with stairs work capacity.

![Figure 18](image-url)
RESULTS

Figure 19. Carrying hose baskets up stairs
A: laboratory and B: field test with the highest correlation with stairs work capacity time. MFF = Male full-time firefighters, MPF = Male part-time firefighters, CM = Civilian men, CW = Civilian women, n = 36.

The laboratory and field test having the highest correlation with pulling work capacity was endurance shoulder extension (W: $r_s = -0.82$, $p < 0.01$) and bench press (n: $r_s = -0.85$, $p < 0.01$) (Figure 20). In addition, endurance trunk flexion (W: $r_s = -0.77$), all (W) isokinetic tests of upper body strength and endurance ($r_s$ = -0.72 to -0.79), maximal handgrip strength (kg: $r_s = -0.73$), and chin ups (n: $r_s = -0.72$) were also strongly and significantly correlated ($p < 0.01$) with pulling work capacity.

Figure 20. Hose pulling
A: laboratory and B: field test with the highest correlation with pulling work capacity time. MFF = Male full-time firefighters, MPF = Male part-time firefighters, CM = Civilian men, CW = Civilian women n = 37.

The laboratory and field test having the highest correlation with demolition work capacity was endurance knee extension (W: $r_s = 0.75$, $p < 0.01$) and bench press (n: $r_s = 0.83$, $p < 0.01$) (Figure 21). In addition, upright barbell row (n) and barbell shoulder press (n) were also strongly correlated ($r_s = 0.74$ and 0.70, respectively, $p < 0.01$) with demolition work capacity.
RESULTS

Figure 21. Demolition at or after a fire
A: laboratory and B: field test with the highest correlation with demolition work capacity time. MFF = Male full-time firefighters, MPF = Male part-time firefighters, CM = Civilian men, CW = Civilian women, n = 37.

The laboratory and field test having the highest correlation with rescue work capacity was endurance shoulder flexion (W: $r_s = -0.83$, $p < 0.01$) and bench press (n: $r_s = -0.82$, $p < 0.01$) (Figure 22). In addition, maximal and endurance knee extension (W: $r_s = -0.78$ and -0.78, respectively), endurance trunk extension and flexion (W: $r_s = -0.77$ and -0.76, respectively), the majority (6 out of 10) of isokinetic tests of upper body strength and endurance (W and W·kg$^{-1}$: $r_s = -0.74$ to -0.81) were also strongly and significantly correlated ($p < 0.01$) with rescue work capacity.

Figure 22. Victim rescue
A: laboratory and B: field test with the highest correlation with rescue work capacity time. MFF = Male full-time firefighters, MPF = Male part-time firefighters, CM = Civilian men, CW = Civilian women, n = 37.

The laboratory and field test having the highest correlation with terrain work capacity was endurance trunk flexion (W·kg$^{-1}$: $r_s = -0.58$, $p < 0.01$) and upright barbell row (n: $r_s = -0.70$, $p < 0.01$) (Figure 23). No other strong correlations were found with terrain work capacity.
RESULTS

Figure 23. Carrying hose baskets over terrain
A: laboratory and B: field test with the highest correlation with terrain work capacity time. MFF = Male full-time firefighters, MPF = Male part-time firefighters, CM = Civilian men, CW = Civilian women, n= 37.

Multivariate statistical assessment of predictors of firefighters’ muscular and aerobic work capacity

Between group differences

In Study IV we found significant differences (p < 0.01) between the training-set and the prediction-set in maximal handgrip strength, upright barbell row, and standing broad jump tests, and also in stairs, pulling and rescue work capacity. The best performing woman always performed better than the lowest performing man, as exemplified in Figure 24.

Figure 24. Running 3000 m and Maximal handgrip strength
A: Running 3000 m (s): performance time was faster for Male full-time firefighters compared to Female part-time firefighters and Civilian women. B: Maximal handgrip strength: all groups of men were stronger compared to all groups of women. Group 1: Male full-time firefighters, 2: Male part-time firefighters, 3: Female full-time firefighters, 4: Female part-time firefighters, 5: Civilian men, 6: Civilian women. The best performing women always performed better than the lowest performing man. Data not published.

Modeling

The best model (highest Q²) obtained for prediction of stairs (R² = 0.83, Q² = 0.78) (Figure 25 A) and rescue (R² = 0.77, Q² = 0.74) (Figure 25 B) work capacity included field tests only. The predictive power slightly decreased when running
3000 m (s) was replaced by running 3000 m (s·kg\(^{-1}\)) \((R^2 = 0.78, Q^2 = 0.72)\) in the rescue work capacity model.

The best prediction with the highest predictive power of pulling work capacity included both laboratory and field tests \((R^2 = 0.91, Q^2 = 0.83)\). When laboratory tests were excluded \(R^2\) was 0.85 and \(Q^2\) was 0.83, and included both field tests and anthropometrics (Figure 26A). The best model for demolition work capacity included both field tests and anthropometrics \((R^2 = 0.79, Q^2 = 0.71)\) (Figure 26B). Without anthropometric data, and additional field tests included, the models were still satisfying for pulling \((R^2 = 0.80, Q^2 = 0.78)\) and demolition \((R^2 = 0.75, Q^2 = 0.65)\) work capacity.
The best prediction with the highest predictive power of terrain work capacity included field tests and anthropometrics ($R^2 = 0.88$, $Q^2 = 0.85$) (Figure 27). Without anthropometrics, the model was still satisfying for terrain work capacity when other field tests were included, ($R^2 = 0.82$, $Q^2 = 0.76$).

![Figure 27. Variables of importance for projection (VIP) of Carrying hose baskets over terrain work capacity. Grey bars represent variables included in the models; all variables were included in the initial model, $n = 38$.](image)

External validation

The robustness of the models ranged between $R^2 = 0.38$ and 0.80. The highest robustness was found for stairs work capacity ($R^2 = 0.80$), and the lowest robustness was found for demolition work capacity ($R^2 = 0.38$).
Discussion

The overall aim of this thesis was to identify relevant, simple, and inexpensive physical tests that are valid for evaluation of work capacity of Swedish firefighters.

The main results of Study I was that firefighters’ rating of physical demands have not changed over a ten-year period for work tasks included in the questionnaire, giving room for development of tools and equipment. Significant (p < 0.05) rating differences occurred between full-time and part-time firefighters. With both full-time and part-time firefighters included, victim rescue and carrying a stretcher over terrain were ranked as two of the most physically demanding work tasks in terms of aerobic fitness and muscle strength.

The main results of Studies II-IV were that both laboratory and field tests can be used to predict firefighters’ physical work capacity. In line with Sothmann et al. [111] and Henderson et al. [83] I agree that field tests should be used instead of laboratory tests for prediction of firefighters’ physical work capacity since this reduces costs, and increases the possibility of standardized physical testing. Laboratory tests require a higher availability of specialized personnel compared to field tests. Also, it requires access to advanced equipment, and usually only one person can be tested at a time.

Work performance and work capacity

As previously mentioned, work performance is a multi-dimensional and dynamic concept [2], and includes several dimensions and indicators [4]. Consequently, other dimensions than physical capacity affects work capacity as well. When physical demands are rated (Study I), it is impossible to deduce whether the ratings are due to physical work capacity or other important dimensions affecting work capacity, such as ergonomics [6,7] and heat exposure [11,12].

Work tasks included in the thesis

Phillips et al. [29] suggested that work tasks rated as the most physically demanding should first be identified, and secondly what is their prevalence. Others suggest that work capacity readiness should be maintained for commonly occurring work tasks that are at the same time physically demanding [38,147-149]. A combination of these suggestions was used within this thesis, by identifying work tasks that were rated as physically demanding by most responders (Study I). After discussions with an expert group within the Swedish Fire and Rescue Services, the final inclusion of work tasks in Studies II-III was determined. For example, carrying a stretcher over terrain was rated to require very high muscle strength by more than 50% of the responders, but was not included for further investigations both because it can be considered as an unusual work task among firefighters in Sweden, and other included work tasks included carrying moments. Also, in Sweden, transporting patients is the responsibility of the County Council’s (paramedics). This work task...
is physically demanding and the development of fatigue during carrying a loaded stretcher has previously been shown to be significantly correlated with \( \text{VO}_{2\text{max}} \), muscle strength and muscle endurance among paramedics [25]. von Restorff [27] found that the best predictor of performance time of carrying a simulated 90 kg patient on a stretcher was maximal handgrip strength \((r = -0.60, p < 0.01)\).

Content validity [150] is a subjective judgment whether the included measurements represent the content of the work. The results of Study I, and discussions with an expert group from the Swedish Fire and Rescue Services formed the basis for what work tasks to be studied further, consequently increasing content validity. Including the expert group in the set up of work tasks stations also increased the content validity. Some work tasks, such as hose pull upstairs, drag and pull material with a rope, and remove storm-felled trees were not included although they were rated as physically demanding (Study I), consequently decreasing content validity of the firefighters’ overall work.

Firefighting work tasks have previously been studied regarding physical demands and/or work capacity, and the most commonly studied are carrying equipment/hoses [31-34,36,55,56,60,71,72,86,96,99,104], ladder extension [34,36,71], ladder raise [34,36,55,56,94], ladder-climb [55,56,94,97], forcible entry [34,36,55,56,83], hose pull [32-34,36,56,71,72,86,94,97,104], Keiser sled [32,33,110], victim rescue [32-34,36,55,56,58,60,71,83,84,94,96,97,104,110], climbing stairs [32-34,36,42,58,60,83,86,92,97,99,103,104,110], and the PHT [28,30]. Firefighting work tasks that are executed in sequence are often merged to one performance time when relationships between physical work capacity and performance in physical tests are studied [32,34,42,55,60,71,72,83,96]. It is however difficult to determine the importance of one single specific physical capacity when performance is judged by a task-course finishing time. This is due to diversified performances on different work tasks, correlation between tests, and the summation effects of capacities. When each work task is studied alone [33,36,58,97,104] evaluation of both the work task set up and important physical indicators can be evaluated. Thus, in order to analyze correlations (Studies II-III) and predictions (Study IV) of physical work capacities, each work task included in this thesis was analyzed alone. For others [33,36,42,55,58,71,96,104], the mean or median work time on a work task course have ranged from 2 min and 40 s to 14 min and 30 s, active rest periods included, the PHT and FWT have longer performance times [30]. Excluding active rest periods, the median performance time on the work task course was 209 s in Studies II-III and 227 s in Study IV, showing that performance time on the work task course in this thesis is in line with others. To my knowledge, vehicle extrication and cutting have not previously been studied for work capacity. Vehicle extrication was excluded from all analyzes since the performance could not be reliably measured; the cutting work tasks had similar limitations and was excluded from Study IV.

When a battery of physical tests, aimed to predict work capacity is created, it is important to consider what dimensions are under investigation. Timed
DISCUSSION

Ladder-climbing [34,55,56,94] might be affected by acrophobia, solving puzzles [72] might be affected by concentration and deductive reasoning, and connecting hoses [72] might be affected by technique. These dimensions are important for firefighters’ work performance as well, but should not be included if the aim is to investigate physical work capacity. Consequently, it is desirable to exclude or reconfigure work tasks that are affected by other dimensions than physical capacity. Gledhill et al. [97] used a series of work tasks, some of them timed (such as victim drag and hose carry) and some of them untimed (such as ladder climbing). The ladder-climbing test was untimed because the aim was to assess acrophobia and manual dexterity, showing that he studied several dimensions of firefighters’ work performance [97]. This thesis tried to isolate the work task stations in order to measure physical work capacity, and not general work performance (Studies II-IV), which for example can include technique and heat tolerance.

Work capacity among subject groups
It is natural for civilian’s to hold a lower experience of firefighting work compared to firefighters. A group of civilian men and women were included in this thesis (Studies II-IV) because those applying for a rescue service education do not necessarily have experience of firefighting work. Because of the inclusion of civilian’s in the physiological measurements (Studies II-IV) an important question is whether firefighting experience affected the outcomes. Groups of civilians had equal work capacity as part-time firefighters with the same sex (Men: Studies II-IV, Women: Study IV), and on some work tasks also equal performance as full-time firefighters. This demonstrates that work capacity was studied rather than work performance in Studies II-IV.

Physiological measurements and statistical modeling
A large number of physiological measurements were included in Studies II-IV, both laboratory and field tests. Based on Studies II-IV we can conclude that valid physical tests were found with both sexes included in the models. More specific, predictions of work capacity were satisfying for the stairs, pulling, demolition, rescue, and terrain work tasks (Study IV).

In general, validity can be defined as measuring what you intend to measure. Criterion-validity [150] indicates the relationship between performances in the physical tests and simulated work tasks, and was analyzed both with bivariate (Studies II-III) and multivariate (Study IV) analyzes. Previously both bivariate [2 8,30,32,33,36,42,55,58,71,104,110] or/and multivariate linear regressions [32-34,36,55,71,110] have been used in an attempt to evaluate firefighters’ physical work capacity. Strong bivariate correlations (r > 0.7) with work capacity were found (Studies II-III) both with tests of aerobic fitness as well as muscle strength and endurance. With bivariate correlations, such as Spearman r_s, the strength between two variables is indicated, but correlations does not necessarily imply causation and we cannot conclude that one variable causes the other, although it is possible
In modeling (Study IV), the most important variables for prediction of work capacity were not always the ones having the highest bivariate correlation (Studies II-III). Consequently, multivariate statistics should preferably be used in physical test selections, but bivariate correlations are of interest in a first step to receive isolated variables correlations. Valid models were found both with and without anthropometric data included. To avoid discrimination of subjects that are short and have a low body weight, anthropometrics may be excluded from determination of firefighters’ physical work capacity. Theoretically, having a small body size may be advantageous when crawling into tight spaces. Also, it is possible to compensate for low body weight and height with physical capacity qualities. This thesis studied a fraction of all work tasks that may be part of the firefighter’s work, and crawling into tight spaces was not one of them.

The external validation strengthens the findings, by executing modeling on another subject group, giving a measure of the representativeness of selected physical tests among Swedish fire firefighters in general, and not only from the county of Norrbotten. The external validation was satisfying for the stairs, pulling, rescue, and terrain work tasks, but not for the demolition work task, as verified by a subjective assessment: the difference between prediction from the training-set ($R^2 = 0.75$ to $0.79$) and external validation ($R^2 = 0.38$ to $0.44$) with the prediction-set was large.

When multivariate statistics is used, the selection of physical tests depends of what tests are included. Because of that, selections of physical tests may differ between different studies.

**Aerobic and anaerobic fitness**

Laboratory measurements of firefighters’ aerobic fitness is well documented, and the mean measured aerobic capacity and aerobic power from previous studies are $3.6 \text{ L·min}^{-1}$ and $46 \text{ mL·kg}^{-1} \cdot \text{min}^{-1}$, respectively (Table 1). The mean $\text{VO}_{2\text{max}}$ ($4.0 \pm 0.8 \text{ L·min}^{-1}$ and $52.7 \text{ mL·kg}^{-1} \cdot \text{min}^{-1}$) of the training-set (Studies II-IV) ranged within the results from previous studies of firefighters $\text{VO}_{2\text{max}}$ ($\text{VO}_{2\text{peak}}$) (Figure 28).

![Figure 28. Firefighters’ aerobic capacity and aerobic power, previous studies.](image_url)

*Previous studies of firefighters’ A: $\text{VO}_{2\text{max}}$ (L·min$^{-1}$) and B: $\text{VO}_{2\text{max}}$ (mL·kg$^{-1}$·min$^{-1}$). The figure is based on results from Table 1. The dashed line represents the mean from previous studies and the black solid circle is the mean values from the training-set.*
Dreger et al. [56] found significant correlations between work capacity and energy cost, reflecting the linear relationship between work intensity and VO₂. In accordance with others, we found both VO₂ max in L·min⁻¹ [28,34,36,41,58] and mL·min⁻¹·kg⁻¹ [28,31,34,38,41,56,67,72,83,92,96,97] to be significantly (p < 0.01) correlated with work capacity (Study II). Surprisingly, Harvey et al. [55] found neither VO₂ max in L·min⁻¹ (r² = 0.001 to 0.1, p > 0.05) nor VO₂ max in mL·kg⁻¹·min⁻¹ (r² = 0.004 to 0.18, p > 0.05) to be important indicators of firefighters’ work capacity, the reason may be inclusion of another variable having higher importance for prediction of work capacity on the studied work task circuit. They found peak work rate during arm cycling to be an important indicator (r² = 0.46, p < 0.05) [55], and we have not found any other study including peak arm work rate in selections of physical tests for firefighters. In this thesis, work capacity had higher bivariate correlations with VO₂ max in L·min⁻¹ (rₛ = 0.55 to 0.79, p < 0.01 (positive or negative)) than with VO₂ max mL·kg⁻¹·min⁻¹ (rₛ = 0.46 to 0.57, p < 0.01 (positive or negative)) in the cutting, stairs, pulling, demolition, and rescue work tasks, showing that a high VO₂ max increases work capacity. The field test with the highest correlation with VO₂ max in L·min⁻¹ was running 3000 m (s·kg⁻¹) (Figure 29) and these results were R² = 0.81, p < 0.001 (Study II).

In addition, running 3000 m had higher rₛ values (rₛ closer to +1 or -1) with work capacity when reported in s·kg⁻¹ (rₛ = 0.55 to 0.79 (positive or negative), p < 0.01), compared to when reported in seconds only (rₛ = 0.47 to 0.74 (positive or negative), p < 0.01) (Study II). Instead, running 3000 m (s) had higher bivariate correlations (rₛ closer to +1 or -1) with VO₂ max in mL·kg⁻¹·min⁻¹ (rₛ = -0.84, p < 0.01). In a multivariate context, the influence of body weight (3000 m: s or s·kg⁻¹) was less important for prediction of work capacity, with both men and women included in the models (Study IV).
**Carrying hose baskets over terrain** was the only work task significantly correlated with running speed at OBLA and LT ($r_s = -0.65$ and $-0.63$, respectively, $p < 0.01$) (*Study II*). Lactate threshold is suggested to be related to performance in 10 km running [152]. Although the terrain work task not was as long as 10 km, these correlations may show that firefighters need both high aerobic capacity and aerobic endurance.

Submaximal cycling, step-test, and treadmill walking (% HR$_{max}$) were significantly ($p < 0.01$) correlated with work capacity (cycling and treadmill walking: all work tasks, step-test: all work tasks but cutting) using bivariate correlations (*Study II*). Predictions of physical capacity from field tests % HR$_{max}$ is problematic since a subjects’ true maximal HR will be unknown at a pre-employment test. Besides, multivariate statistics only included treadmill walking and step test (% HR$_{max}$) when terrain work capacity was predicted (Model 1: $R^2 = 0.84$, $Q^2 = 0.77$), and the prediction and predictive power was equally high using other tests (Model 2: $R^2 = 0.88$, $Q^2 = 0.85$, and Model 3: $R^2 = 0.82$, $Q^2 = 0.76$) (*Study IV*). In the government regulations [1] pass/fail of treadmill walking is regulated despite unknown HR$_{max}$ and HR at testing.

This thesis (*Studies III-IV*) and others [28,71,103] have found firefighters’ anaerobic power fitness [39] important for work capacity. Using bivariate correlations (*Study III*), jumping length in the standing broad jump test was highly correlated with stairs ($r_s = -0.72$, $p < 0.01$) and rescue ($r_s = -0.74$, $p < 0.01$) work capacity (*Study III*), and in combination with other physical tests an important predictor of rescue work capacity (*Study IV*). No previously used test of anaerobic power endurance [33,36,103] or anaerobic mixed endurance [104] was included in this thesis although such physical qualities have been deemed important for firefighters’ work capacity. In *Study II* we found that rowing 500 m (s and W) was strongly correlated both with VO$_{2max}$ in L·min$^{-1}$ ($r_s = -0.84$, $p < 0.01$) and work capacity in the stairs ($r_s = 0.82$, $p < 0.01$), pulling ($r_s = 0.76$, $p < 0.01$), demolition ($r_s = -0.70$, $p < 0.01$) and rescue ($r_s = 0.79$, $p < 0.01$) work tasks. In addition, rowing 500 m was an important predictor of work capacity within these work tasks in combination with other physical tests (*Study IV*). We have not found any study including the 30 m crawling test when analyzing firefighters’ physical work capacity. Although it was strongly correlated with stairs ($r_s = 0.74$, $p < 0.01$) and rescue ($r_s = 0.70$, $p < 0.01$) work capacity (*Study II*) it was excluded when combined with other physical tests (*Study IV*). Due to the mean exercise time during rowing 500 m (*Study II*: mean 110±10.8 s, *Study IV*: mean 104±11.1 s) and 30 m crawling (*Study II*: mean 15± 8 s) it can be argued that these tests includes a large anaerobic component, and may therefore be considered as an anaerobic mixed endurance fitness test and an anaerobic power endurance test, respectively [39].

**Muscular strength and endurance**

Both maximal and endurance muscle strength has previously been deemed important for firefighters’ work capacity, and there is a plethora of tests included in
studies of firefighters (Table 3 and 4), with maximal handgrip strength as the most frequently included. The mean/median maximal handgrip strength has ranged from 34.5 to 61 kg [28,34,71,83,104], showing that performance of subjects included in this thesis is in line with others (Study III: mean: 54 kg (32 to 79 kg) and Study IV: mean: 48 kg (29 to 79 kg)). Based on this thesis and other studies it is evident that maximal handgrip strength is important for firefighters work capacity [28,33,34,36,83,104,110]. Also, this test has high face validity, because carrying and/or pulling is frequently occurring in a rescue operation. In combination with other tests, maximal handgrip strength was an important predictor of work capacity for all work tasks included in Study IV. No other field test of maximal muscle strength was included in this thesis. Instead, maximal muscle strength in the upper and lower body was tested with laboratory isokinetic concentric tests. However, due to the work performed during the standing broad jump test, it can be assumed that maximal leg strength is important for standing broad jump performance. Laboratory tests of firefighters’ muscle strength and endurance are uncommon and have previously been requested by Barr et al [5]. When included, isometric [111,114,115] measurements or concentric tests [33,36] are used, and performance both found to be [33,111] and not to be [36] important for work capacity. This thesis included a large battery of laboratory tests. Bivariate correlations between work capacity and maximal and endurance muscle strength in the upper and lower body (Study III) was often higher ($r$ values closer to +1 or -1) when expressed in absolute (W) compared to relative (W·kg$^{-1}$) terms, but the differences were small (Study III). These results are expected because the external load of firefighting equipment is equal, irrespectively of body weight. Because of the differences in models, both muscle performances in absolute and relative terms should be included when testing firefighters in a laboratory setting. However, including several of each (absolute/relative) is redundant and unnecessary (Figure 30).

Figure 30. Principal Component Analyze of maximal and endurance knee extension
A: Between and within group differences for men and women B: Isokinetic test of maximal and endurance knee extension. Performance results in absolute (dashed line) terms are correlated, as well as results in relative (bold line) terms.
In combination with other physical tests, maximal shoulder flexion was a good predictor of demolition (maximal shoulder flexion: J, W) and rescue (maximal shoulder flexion: Nm) work capacity, and the best model of pulling work capacity included all physical tests. Using both bivariate (Study III) and multivariate correlations (Study IV), we can conclude that muscle strength and endurance in the upper body is important for firefighters’ work capacity. However, these results can only be used as indicators because isokinetic testing most often implies isolated movements performed over one joint. In a real time situation, such as firefighting work, several joints (and several muscle groups) are included simultaneously, and both concentric and eccentric work is executed. Consequently, the face validity is low. Isokinetic testing is more commonly used within sports [153,154] and rehabilitation [155,156].

In this thesis, all field tests of muscle strength and endurance were significantly correlated with all work tasks, using bivariate correlation ($r = 0.42$ to $0.85$ (positive or negative) $p < 0.01$). Sit-ups, endurance handgrip and endurance squat did not strongly correlate with work capacity (Study III), and were only included in the multivariate models of pulling work capacity. In line with this thesis, muscle endurance in the upper body have previously been found important for firefighters’ work capacity: hand grip endurance [28], bench press [34,104] and shoulder press [104] are some of these tests.

Balance

Fire protective clothing can both impair [77,107] and improve [119] postural stability. This thesis found that victim rescue during smoke diving was ranked to require both high work posture, and high body control (Study I). Bivariate correlations between dynamic balance and work capacity were significant ($r = 0.42$ to $0.53$ (positive or negative), $p < 0.01$) with work capacity in all studied work tasks except the terrain ($r = -0.36$, $p > 0.01$). Interestingly, the directions of the correlations were that subjects with a high dynamic stability index (lower balance) had higher work capacity compared to subjects with a low stability index (better balance), and may reflect the lower balance among males compared to women (Study III).

In the multivariate models, balance was not selected as an important indicator for work capacity (Study IV), although perceived work ability is lowered among firefighters’ with a low dynamic balance [77]. The postural sway increases after work tasks performances [119], and the reason may be muscular fatigue. Based on previous studies [77,107,119] we can argue that balance affects firefighters’ work performance, and probably also work capacity when muscles are exhausted. No balance field test was included in this thesis. The laboratory balance test was executed in training clothes, without fire-protective equipment and breathing apparatus, and without prior exhaustive exercise. Thus, this indicator for work capacity needs to be further studied.
Limitations

The low inclusion of women in Studies I-III was a known limitation. The first time the questionnaire was distributed (year 2000); female firefighters were uncommon (and still is) within the Swedish Fire and Rescue Services. Since comparisons between the questionnaire responses were done, we strived for equal inclusion of men and women the second time of the questionnaire distribution (year 2010). The questionnaire was comprehensive, being both strength, and a limitation. A comprehensive questionnaire increases the risk of fatigued responders. All work tasks were not included for all rating options, and building models of perceived physical demands for a specific work task was not possible. However, a measure of this would have entailed an even more comprehensive questionnaire.

One might argue that the physical test selection would have been different with a higher inclusion of women in Studies II-III, but when the external validation with the prediction-set (including more women than men) was compared with the training-set (including more men than women), the models were still valid for all work tasks but demolition.

The testing method of pulling was slightly different for subjects included in the training-set compared to those included in the prediction-set. These differences may have influenced the results, but the models were still valid.

Including previously used anaerobic tests would have been interesting, but theoretically, anaerobic tests were included and I can argue that anaerobic fitness is important for firefighters’ physical work capacity.

In this thesis, performance was not executed in heat, although an increased core temperature increases the cardiac strain [11,12]. Heat is one of several dimensions affecting firefighters’ work performance; this thesis strived to isolate the studies to work capacity and consequently heat and cold exposure was excluded.

Future direction

Implementation of selected physical tests within the Swedish Fire and Rescue Service is an important mission because the findings of this study may affect the success of firefighting work. In order to maintain a high validity of the selected tests, test-leaders within the Fire and Rescue Services need education and training in the test-procedure.

Uniform physical tests of firefighters’ physical work capacity irrespective of sex, were requested when this thesis work started. We can recommend valid physical tests based on the aggregated physical capacity of men and women. Because the limiting factors for physical work capacity can differ for men and women, different tests may in the future be developed (Figure 31). There are advantages with having uniform physical tests, irrespective of sex: using one test station reduces cost and facilitates the testing procedure. In addition, using different physical tests may be unfavorable for group dynamics between men and women in the same work place.
Conclusion

In conclusion, with equal results, field tests and laboratory tests can be used to predict firefighters’ physical work capacity (carrying hose baskets up stairs, hose pulling, victim rescue, and carrying hose baskets over terrain). Rowing 500 m (s), maximal handgrip strength (kg), endurance bench press (n), running 3000 m (s and s·kg\(^{-1}\)), upright barbell row (n) and standing broad jump (m) together provides valid information about firefighters’ physical work capacity. Anthropometric (weight and height) may be omitted in absolute values. With additional physical tests included instead, the models for prediction of firefighters’ physical work capacity will remain valid.
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