Title Page

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Development of muscle mass and body fat reference curves for white male UK firefighters

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Abstract

Objective This study describes the development of the world's first suite of firefighter body composition centile reference curves which can be used as both academic research tools and clinical references, to plot and track individual firefighter skeletal muscle mass (SMM) and fat mass (FM) measurements against the representative reference sample.

Methods The body composition of 497 white male London (England) firefighters was measured by anthropometry and bioelectrical impedance analysis. Smoothed centile curves were then generated for skeletal muscle mass index (SMMI), fat mass index (FMI), body fat percentage (BF%) and waist-to-height ratio (WHtR).

Results Between 48 and 62y, firefighter SMMI is greater than the UK white male age-matched general population by a mean of 0.35 units, although SMMI declines 0.006 units/y faster in firefighters between these ages. This is estimated to translate to a mean decline of approximately 0.6% of absolute SMM per year. Between 40 and 49 y, firefighter FMI is 0.1 units greater than the UK white male age-matched general population, which becomes identical (7 units) between 50 and 54 y. At the 50th centile, WHtR exceeds 0.5 by 39 y reaching 0.55 at 62y. This contrasts with FMI which remains stable from 47y.

Conclusions Firefighters in this study possess greater FM and SMM compared with the UK general population. SMM appears to decline rapidly within older age ranges. These references offer a novel improvement upon the limitations of BMI and BF% for the benefit of an occupational group at elevated risk of cardiovascular disease.

Keywords

- Firefighters
- Skeletal muscle mass
- Adiposity
- Obesity
- Bioelectrical impedance analysis
- Centile curves

Declarations

Author contributions

All authors contributed to the study conception and design. Data collection was performed by Greg Richard Lessons. Data analysis were performed by Greg Richard Lessons and Huw David McCarthy. The first draft of the manuscript was written by Greg Richard Lessons and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Conflicts of interest/competing interests

The authors have no conflicts of interest to declare that are relevant to the content of this article.

Availability of data and material

All relevant data is included within the main body of text and as supplementary tables.

Code availability

Not applicable

Ethics approval

This study was approved by the London Metropolitan University School of Human Sciences Research Ethics Committee and the London Fire Brigade.

Consent to participate

Informed consent was obtained from all individual participants included in the study.

Consent for publication

Not applicable

Acknowledgements

Not applicable

Introduction

Obesity is a rapidly developing workplace epidemic, with obese employees taking an extra four sick days off per year (Harvey *et al.*, 2010), alongside being twice as likely to suffer long-term sickness absence (LSA) (van-Duijvenbode et al., 2009). Prevalence of overweight and obesity in the UK fire service may exceed that of the UK general population (Munir et al., 2012; Lessons and Bhakta, 2018). A complex combination of exposures including the adverse metabolic effects of shift work (Knutsson and Van Cauter, 2008), an obesogenic occupational food environment alongside an increasingly sedentary profession (Dobson et al., 2013) may explain this phenomenon. Overweight and obese firefighters miss 2.7 to 5 times (depending on their level of overweight/obesity) the number of work-days due to injury compared with healthy weight colleagues (Poston et al., 2011). Obese firefighters are three times more likely to make a compensation injury claim compared with healthy weight colleagues (Kuehl et al., 2012). Crucially, in terms of occupational performance, obese firefighters tend to have significantly less physical strength and cardiorespiratory fitness (Clark et al., 2002; Donovan et al., 2009; Tsismenakis et al., 2009; Poston et al., 2011;). To date, BMI has been the system used to categorise firefighter weight status. BMI however is intrinsically unable to differentiate between fat-free mass (FFM) and fat mass (FM). This often results in misclassification of individuals, a problem which is exacerbated in populations possessing above average SMM such as firefighters (Choi et al., 2016), who require relatively high levels of muscular strength and endurance to perform their role safely and effectively (Stevenson et al., 2017).

Whilst BF% provides a body composition measurement of greater validity than BMI (Gallagher et al., 2000), it is still prone to potentially high rates of misclassification due to limitations which are described in detail elsewhere (Bosy-Westphal and Müller, 2015). Briefly, because BF% is a proportional measure as opposed to an absolute measure of adiposity, it is affected by FFM, therefore high/low levels of FFM drive BF% downward/upward respectively.

Waist circumference (WC) and waist-to-height ratio (WHtR), although more valid indicators of cardiometabolic risk than BMI (Ashwell and Gibson, 2016), are limited by their inability to capture whole-body adiposity, which is an important consideration when assessing musculoskeletal injury risk and occupational physical fitness (Poston et al., 2011). A more comprehensive assessment of body composition is therefore necessary for this occupational group, not exclusively focusing on FM, but also paying attention to skeletal muscle mass (SMM) which, to date has not been assessed in the UK fire service even though it is likely to be an important marker of ability to undertake the demands of the job.

SMM is also as an independent marker of metabolic health due to the role of skeletal muscle as a regulator of whole-body glucose homeostasis via insulin-mediated glucose disposal. Low muscle fitness has been associated with increased metabolic risk (Steene-Johannessen et al., 2009) and muscle strength has been positively correlated with insulin sensitivity (Benson et al., 2006). Besides metabolic health, age-related muscle loss (sarcopenia) is an emerging public health and clinical concern (Beaudart et al., 2014). This may be of increasing relevance to the fire service considering the recent change in UK policy which sets the national retirement age of firefighters to a minimum age of 60 y (Williams et al., 2013). Historically, firefighters could retire after 30 y service which resulted in most personnel retiring in their early fifties (Williams et al., 2013). Sarcopenia is the greatest contributor to decreased mobility in older age. It is therefore imperative to monitor firefighter SMM to not only assess occupational fitness and classify risk of metabolic disease, but to also monitor risk of musculoskeletal injury, as a tight relationship exists between sarcopenia and incidence of osteoporotic fractures (Cederholm et al., 2013). Such surveillance could enable appropriate physical activity and nutritional interventions designed to attenuate this decline, as optimal maintenance of SMM throughout adulthood is a key to delaying age-associated muscle loss (Sayer et al., 2008).

Total-body SMM is traditionally measured via Dual-energy X-ray absorptiometry (DXA), magnetic resonance imaging (MRI), 24hr creatinine excretion or whole-body K^+ counting (Shen et al., 2004; Kim et al., 2006; Wang et al., 2007). The limitations of these methods include radiation exposure, invasiveness, procedural duration, financial expense, specialist training requirements and facilities. Bioelectrical impedance analysis (BIA) via segmental whole-body analysis offers a non-invasive, valid and efficient method of assessing both FM and SMM in a field setting. BIA strongly correlates with DXA (Verney et al., 2015), and is a highly viable option due to being relatively inexpensive, rapid, and portable (Pietrobelli et al., 2004). BIA has recently been used to produce reference charts displaying smoothed centile curves for age-related FM and SMM of UK adults over 40 y (Lee et al., 2020). To date there are no equivalent firefighter-specific body composition references available, as UK firefighters have been primarily assessed by BMI. Here we describe the development of a suite of UK firefighter-specific body composition references.

Methods

Participants

The study population comprised 497 full-time white male firefighters from 28 Greater London fire stations who were recruited on their day shifts from June 2019 to March 2020 during scheduled fire station engagements. Stations were chosen for inclusion based upon their geographical location, ensuring an even geographical distribution of urban and suburban stations and a representative sample: BMI was 0.1 kg/m^2 > the average London firefighter, age was 0.2 y < the average English firefighter (Home Office, 2019), age range was 22 – 62 y. Exclusion criteria included: the wearing of pacemakers (applying to no potential participants); amputees (applying to no potential participants); recipients of knee/hip replacements (applying to no potential participants); firefighters on light (administrative) duties (applying to no potential participants); and firefighters who only worked day shifts (applying to 8 potential participants). The firefighters had the study explained to them in full, and those who chose to participate were provided with a participant information sheet and informed signed consent was obtained from each participant. Fig. 1 shows the participant flow through the study.

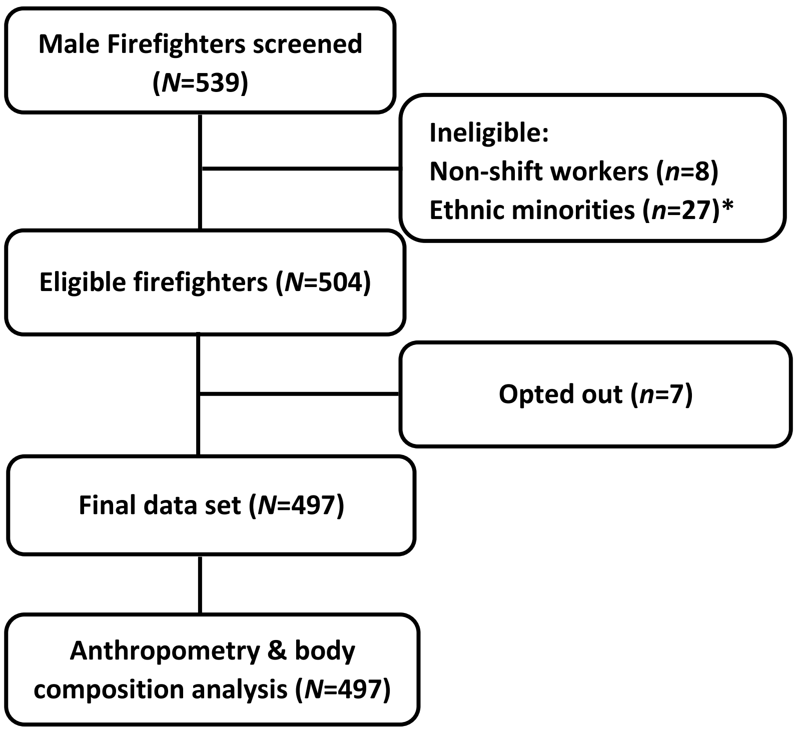

Fig. 1 Participant flow through the study. *All ethnicities were measured but not included due to inherent body composition heterogeneity

Anthropometric and body-composition measurements

Measurements were taken at fire stations, with the majority conducted whilst the firefighters were temporarily made unavailable to attend emergency callouts between 10:00 hrs and 13:00 hrs so to minimise diurnal variation. Height was measured using a calibrated portable stadiometer (Leicester - Marsden HM-250P) to the nearest 0.1 cm with firefighters standing in bare feet, ensuring head alignment to be on the Frankfort horizontal plane. WC was measured using stretch-resistant anthropometric tape (Myotape) to 0.1 cm at the midpoint between the lower margin of the least palpable rib and the top of the iliac crest as recommended by WHO (2008). SMM and FM were measured via BIA utilising the Tanita MC-780MA segmental body composition analyser (Tanita Corporation, Tokyo, Japan) with a 1 kg correction applied for uniform (light clothing). Prior to analysis, participants were also asked to ensure they had empty pockets and an empty bladder, although they were not instructed to refrain from consuming food or liquids. This was deemed acceptable as previous studies have successfully produced national body composition centile reference charts without strict pre-test guidelines for participants (McCarthy et al., 2006; 2014; Franssen et al., 2014; Lee et al., 2020).

FM (kg), BF (%), appendicular skeletal muscle mass (ASMM) (kg) and WHtR were used in the construction of centile references for this study. Segmental BIA enables the calculation of ASMM (kg) by summing the muscle mass of the four limbs for each participant. ASMM acts as a proxy for total SMM (Janssen et al., 2000), accounting for more than 75% of adult total body SMM (Snyder et al., 1975). It is therefore the major fraction of total body SMM, integral for physical activities related to the role of a firefighter such as lifting and carrying. This is also the most modifiable fraction of total body SMM (Gallagher et al., 1997). ASMM and FM were adjusted for participant height by dividing by height $(m)^2$. This converted ASMM to the SMM index (SMMI) and FM to the FM index (FMI). Adjusting measures of ASMM and FM for height overcomes the major limitations of BF% (Bosy-Westphal and Müller, 2015). Calculating the SMMI from ASMM and using it as a valid proxy for total body SMM is an accepted method which has been used in previous studies to produce age related national reference centile values (Lee et al., 2020).

The standard error of the estimate for body-fat and muscle-mass was a ± 2% for both males and females (manufacturer data). The segmental BIA body composition analyser used for this study has been validated against DXA in healthy adults between 19 y and 30 y of age (r = 0.85, p<0.01; r = 0.98, p<0.01 for FM and FFM respectively), and is superior to previous BIA technology (Verney et al., 2015).

Ethical Approval

This study was approved by the London Metropolitan University School of Human Sciences Research Ethics Committee and the London Fire Brigade (LFB).

Statistical analysis

Data was imported to IBM SPSS Statistics for Windows, version 26 (IBM Corp., Armonk, N.Y., USA), and checked for normality. Descriptive statistics were computed for age, anthropometric and body composition measures, and assigned as continuous variables. Normally distributed data were reported as mean ± standard deviation (SD). Non-normally distributed data were reported as median ± interquartile range (IQR). Age categories were assigned as categorical variables and reported as *n* (%). Fire station locations were grouped into urban or suburban categories. Independent samples t-tests were used to test for differences between urban (n = 246) and suburban (n = 251) fire station participants in age and all anthropometric and body composition measures. Smoothed centile curves were generated for SMMI, FMI, BF% and WHtR separately using the Cole and Green (1992) method. This summarises the data into three age-specific smooth curves, named *L* (lambda), *M* (mu), and *S* (sigma). Seven centile curves (2^{nd} - 98^{th}) were generated, each spaced apart by two-thirds of an SD score. The 85th and 95th centile curves were subsequently calculated for FMI and BF%. Contingency tables (3x3 cells) were used to calculate the level of agreement between BF% and FMI centiles for defining adiposity status, with the Kappa statistic being calculated. The alpha value for detecting statistical significance was set at $p<0.05$.

Results

Table 1 displays study population characteristics showing no significant differences in anthropometric and body composition variables between urban and suburban fire station-based participants. Table 2 displays the study sample age distribution, showing the greatest proportion of participants to be aged between 25 y and 55 y. Table 2 also displays mean SMMI, FMI and WHtR values across nine age ranges. Figs. 2-5 display smoothed centile curves which illustrate the age-related 2nd, 9th, 25th, 50th, 75th, 91st and 98th centiles for SMMI, FMI, BF% and WHtR respectively. Figs. 3-4 also display the 85^{th} and 95^{th} centiles. Tables S1-S4 (see Appendix) display the tabulated corresponding centile cut-off values. Figs. 6 and 7 illustrate centile curve comparisons between this study sample and the UK white male general population from age 40 y for SMMI and FMI respectively.

Table 1: Study population characteristics

	Total sample (*N*=497) Mean ± SD	Urban firefighters (*n*=246) Mean ± SD	Suburban firefighters (*n*=251) Mean ± SD	Urban vs Suburban *p* value
Age (y)	40.8 ± 8.6	40.4 ± 8.4	41.1 ± 8.8	NS
Height (m)	1.79 ± 0.07	1.79 ± 0.06	1.8 ± 0.07	NS
Weight (kg)	90.3 ± 13.5	90.1 ± 14.1	90.4 ± 12.9	NS
BMI (kg/m^2)[c]	27.7 ± 4.2	27.5 ± 4.1	27.9 ± 4.3	NS
WC (cm)[ac]	92 ± 12.8	92 ± 14.3	92 ± 12	NS
WHtR	0.52 ± 0.06	0.52 ± 0.06	0.52 ± 0.06	NS
BF (kg)	20.5 ± 7.8	20.4 ± 8.1	20.6 ± 7.5	NS
BF%	22.1 ± 5.4	21.9 ± 5.4	22.2 ± 5.4	NS
FMI (kg/m^2)	6.4 ± 2.3	6.3 ± 2.4	6.4 ± 2.3	NS
ASMM (kg)[b]	30.2 ± 3.6	30.3 ± 3.7	30.2 ± 3.6	NS
SMMI (kg/m^2)[b]	9.4 ± 0.9	9.4 ± 0.9	9.4 ± 0.8	NS

[a]*N*=496 due to missing data, [b]*N*=493 due to missing data. [c]Median ± interquartile range.
Abbreviations: BMI: Body mass index, WC: Waist circumference, WHtR: Waist-to-height ratio, BF: Body fat, FMI: Fat mass index, ASMM: Appendicular skeletal muscle mass, SMMI: Skeletal muscle mass index, NS: Non-significant.

Table 2. Mean SMMI, FMI and WHtR of participants within each age range

Age (y)	N	%	SMMI		FMI		WHtR	
			Mean	SD	Mean	SD	Mean	SD
22-24	16	3.2	9.5	0.7	4.6	1.8	0.46	0.04
25-29	42	8.5	9.3	0.8	5.0[a]	2.7[a]	0.48	0.05
30-34	84	16.9	9.6	0.8	5.8	2.0	0.49[a]	0.06[a]
35-39	93	18.7	9.2	0.8	5.9	1.7	0.50	0.04
40-44	85	17.1	9.4	0.9	6.6	2.3	0.52	0.05
45-49	96	19.3	9.4[a]	1.1[a]	6.8[a]	3.1[a]	0.54[a]	0.07[a]
50-54	69	13.9	9.3[a]	1.0[a]	7.0[a]	3.1[a]	0.55[a]	0.06[a]
55-59	8	1.6	8.9	0.4	6.2[a]	1.8[a]	0.51[a]	0.07[a]
60-62	4	0.8	9.4[a]	2.3[a]	8.5[a]	6.1[a]	0.58[a]	0.17[a]

[a]Median and interquartile range. Abbreviations: SMMI: Skeletal muscle mass index (kg/m^2), FMI: Fat mass index (kg/m^2), WHtR: Waist-to-height ratio (cm/cm), SD: Standard deviation.

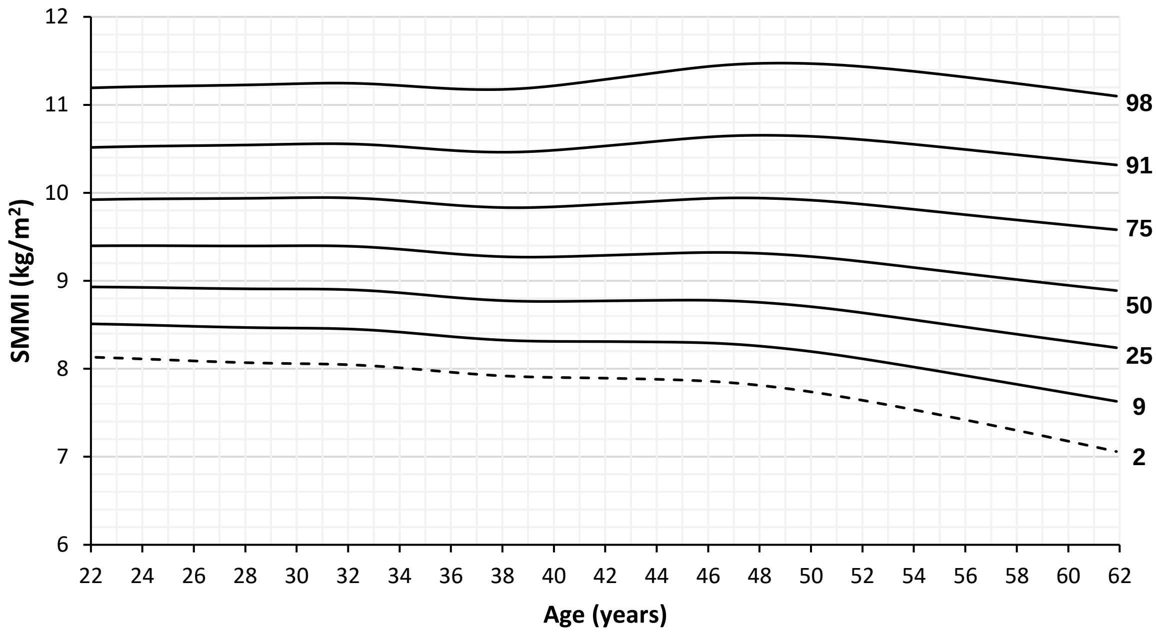

Fig. 2 Male firefighter age-related skeletal muscle mass index reference.
The dotted line (2nd centile) defines the cut-off for low SMM

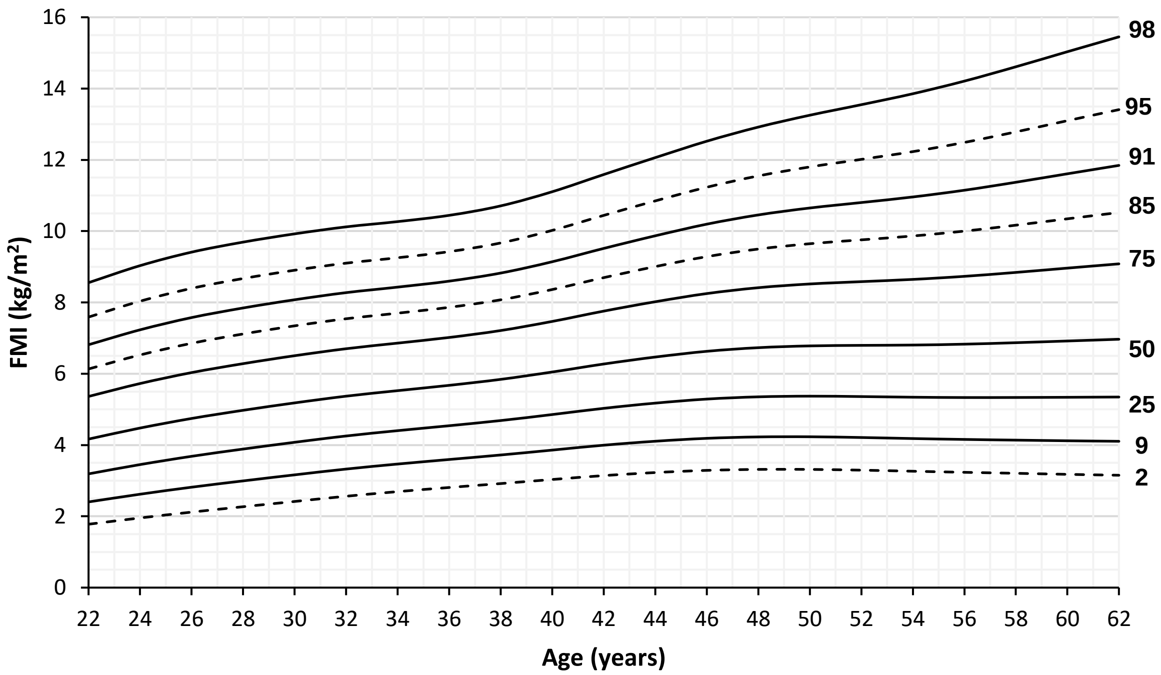

Fig. 3 Male firefighter age-related fat mass index (FMI) reference. Bottom dotted line = Under-fat cut-off, middle dotted line = Overfat cut-off, top dotted line = Obesity cut-off

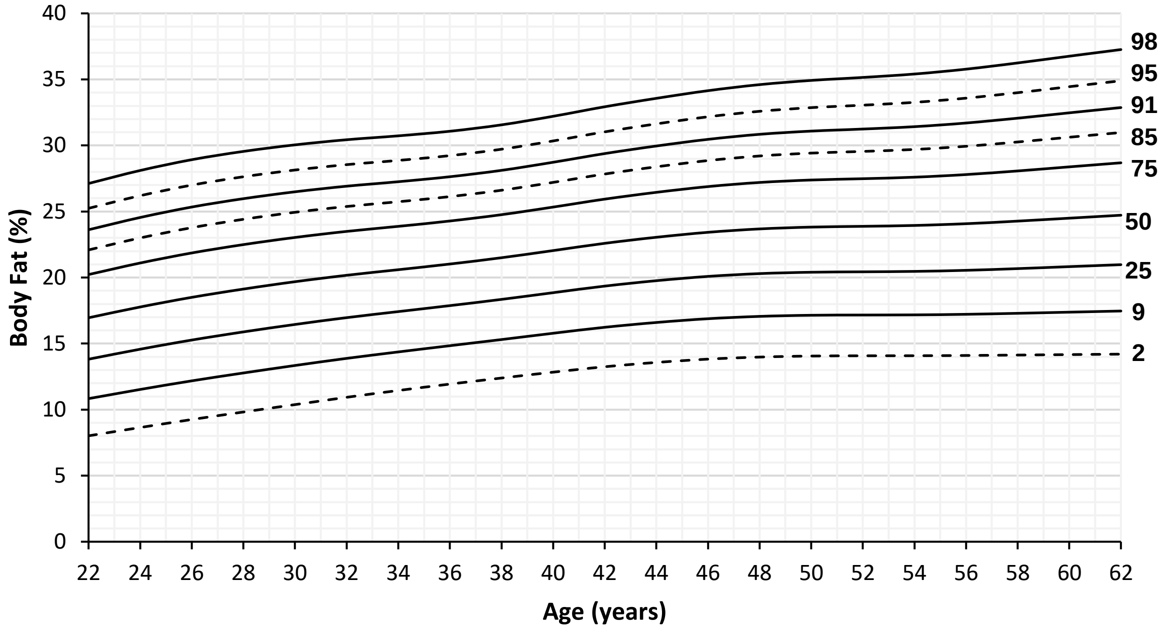

Fig. 4 Male firefighter age-related body fat percentage (BF%) reference. Bottom dotted line = Under-fat cut-off, middle dotted line = Overfat cut-off, top dotted line = Obesity cut-off

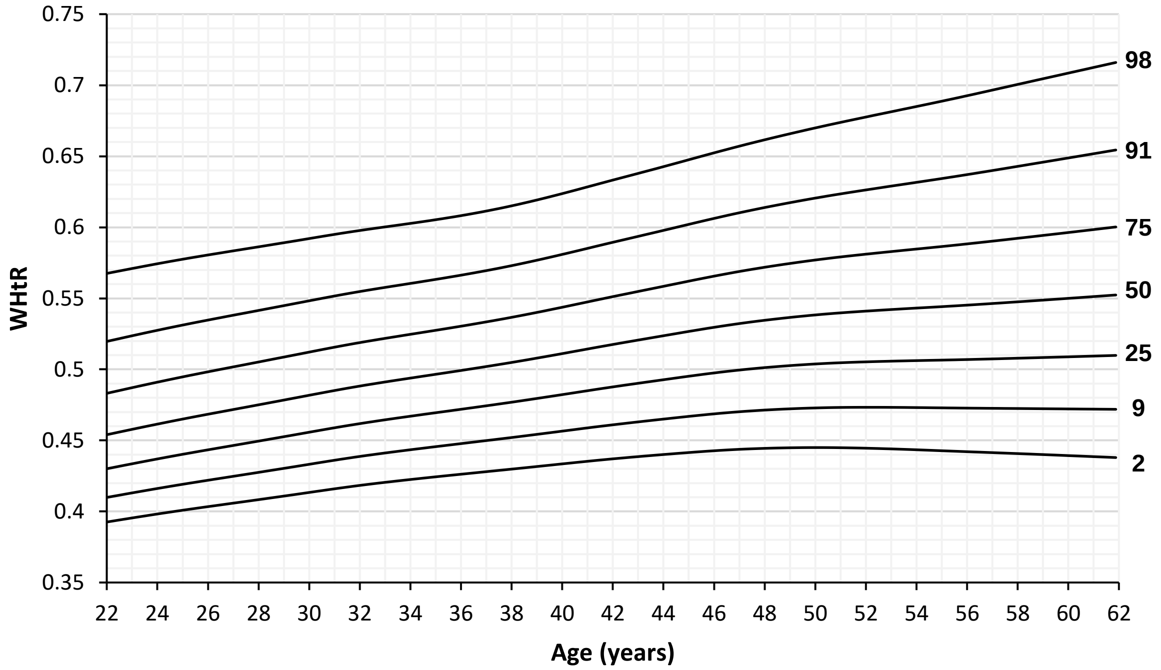

Fig. 5 Male firefighter age-related waist-to-height ratio (WHtR) reference

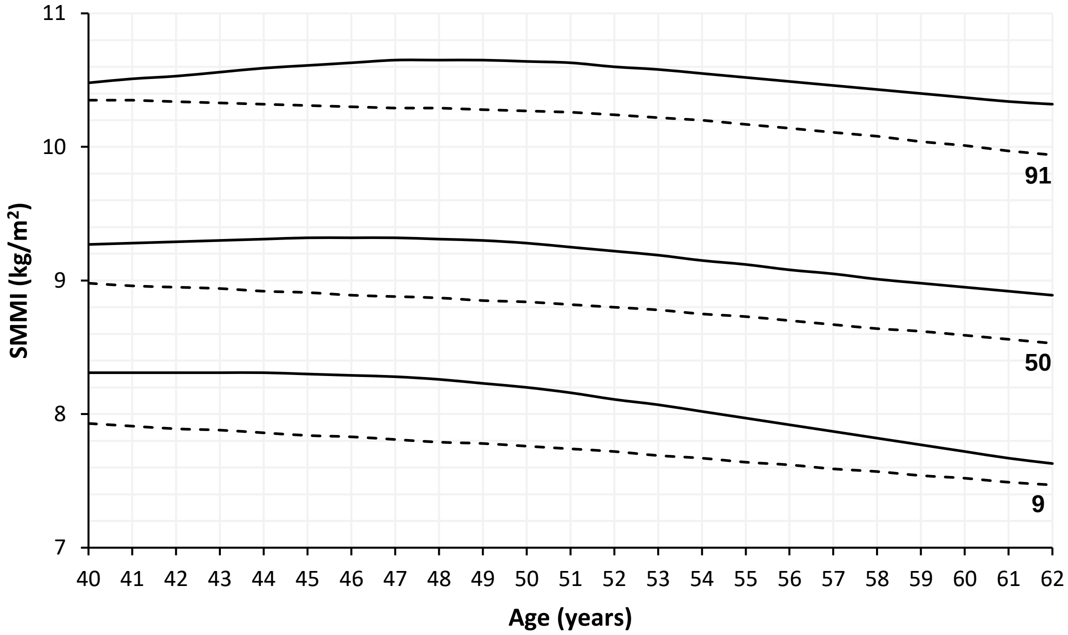

Fig. 6 Firefighter age-related skeletal muscle mass index 9th, 50th and 91st centiles (solid curves) with corresponding English white male centiles (dotted curves) between 40 and 62 y (Lee et al., 2020)

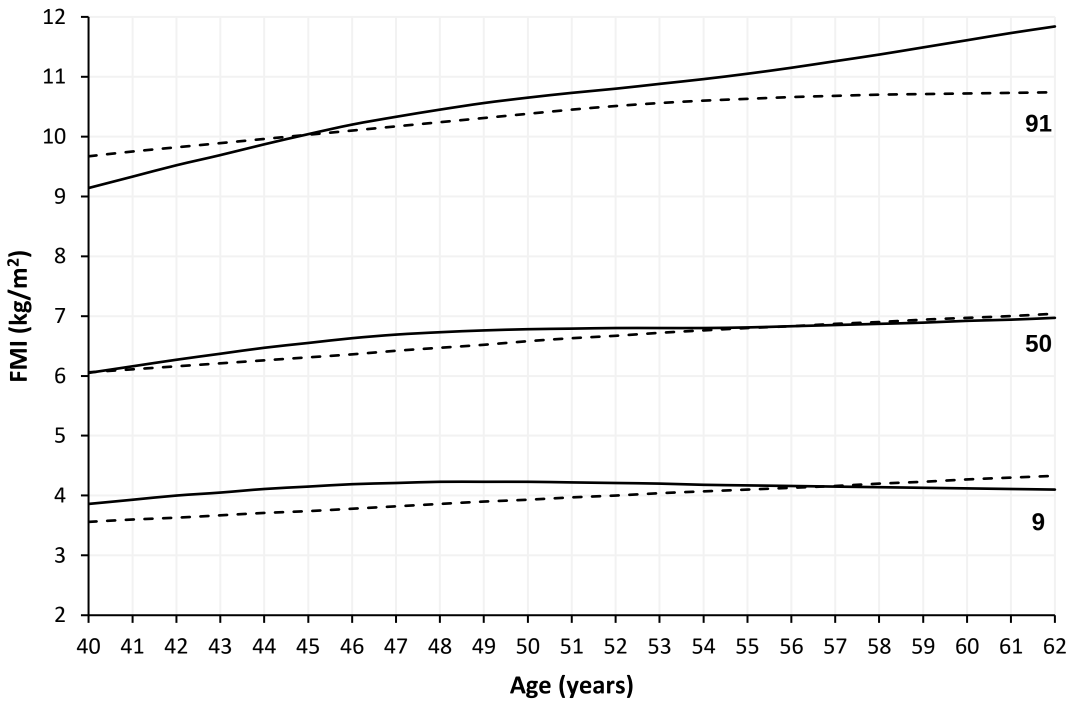

Fig. 7 Firefighter age-related fat mass index 9th, 50th and 91st centiles (solid curves) with corresponding English white male centiles (dotted curves) between 40 and 62 y (Lee et al., 2020)

Centile curve trajectories

Skeletal muscle

The 50th centile for SMMI (Fig. 2) shows a stable value of 9.4 for the first decade. Between 32 y and 38 y a decline occurs equating to an average of 0.02 units/y. This is followed by a brief period of stability at 9.27 until 41 y, at which point a very gradual SMMI rebound begins equating to 0.01 units per year, reaching 9.3 at 45 y. This stabilises briefly until 48 y which marks the beginning of a visibly steep decline equating to a mean of 0.03 units/y, reaching an SMMI of 8.9 at 62 y. This decline is estimated to equate to an average ASMM of 183 g/y.

Adiposity

Fig. 3 displays the FMI centile curves. The 50^{th} centile begins at FMI 4.2 and steadily increases at a mean rate of 0.1 units/y until reaching 6.6 at 46 y. This curve then levels out, showing a very gradual small total increase of 0.34 units over the following 16 years, equating to an annual mean increase of 0.02 units whilst the 2^{nd} and 9^{th} FMI centile curves show a steady gradual descent from 50 to 62 y.

This contrasts with BF% (Fig. 4) where all centiles continue to gradually increase until 62 y. The 50^{th} centile begins at 17% and steadily increases to intercept 19.7% at 30 y, before continuing upward to reach 22% at 40 y. This curve continues on its trajectory, reaching 23.6% at 47 y which marks the beginning of a more gradual increase toward an apex of 24.7% at 62 y.

Fig. 5 displays the WHtR centile curves, showing a broad distribution ranging from 0.39 at the beginning of the 2^{nd} centile to 0.72 at the upper end (62 y) of the 98^{th} centile. The 50^{th} centile begins at a WHtR of 0.45 at 22 y. This steadily escalates to reach the beginning of the first cardiometabolic disease risk threshold of 0.5 at 35 y. This is exceeded at age 39 y and continues on the same trajectory until reaching a WHtR of 0.54 at 49 y, which marks the start of a more gradual increase toward 0.55 at 62 y.

Firefighter reference centile cut-offs

Low SMM was defined at the 2^{nd} centile which is illustrated by the dotted curve in Fig. 2. Male firefighters possessing extremely low SMM are therefore identified if they fall below the 2^{nd} centile curve on the SMMI chart. This equates to >2 SD below the mean SMMI and is consistent with other British growth charts which also use the 2^{nd} centile to define low values (Cole, Freeman and Preece, 1995; McCarthy et al., 2006).

To identify individuals at the highest health risks in terms of adiposity, cut-offs were defined for classification of firefighters into under-fat, healthy, overfat and obese categories. The 2nd centile was selected to identify under-fat firefighters. The 85th centile was selected to define overfat firefighters and the 95th centile was selected to define obese firefighters. Overfat and obesity were defined at these centiles due to 97% of the firefighters being classified into the same risk categories by both FMI and BF% at the 85th and 95th centiles (Kappa: 0.86, $p< 0.001$), showing good agreement and a low rate of misclassification.

Discussion

In this study we developed novel firefighter-specific body composition references. The charts produced represent the very first firefighter body composition reference centile curves globally. They illustrate the variations and changes in the body compartment proportions across a fire service career and can provide a more detailed body composition assessment against a reference population compared with other commonly used references such as BMI.

Representativeness of the study population

497 male firefighters participated in this study with a mean age of 40.8 y, which is almost identical to the mean age of 41 y across the English fire services (Home Office, 2019). The median BMI of 27.7 kg/m^2 in this study sample is also very close to the BMI of the average London firefighter (27.6 kg/m^2 measured in 2018 - statistic provided by the London Fire Brigade [LFB] occupational health service). These similarities in age and BMI, coupled with the even spread of urban and suburban fire stations from which the study population were derived, strengthens the external validity of these reference charts.

Firefighters from ethnicities other than white Caucasian were not included in this study as this demographic accounts for 4.3% of the English fire service (Home Office, 2019) and, obtaining sufficient data to generate ethnicity specific centile references remains unfeasible. With only 6.4% of firefighters in England being female (Home Office, 2019), the same limitation applied for creating sex specific references.

The present limitation of a relatively smaller sample size for the subjects over 55 y is due to firefighters generally retiring by this age. Indeed, the UK Fire and Rescue Services (FRSs) pension review by Williams et al. (2013) analysed data on 7,550 male firefighters from four English FRSs, which showed a similar age group distribution to that seen in this study. External validity of the reference curves is further strengthened by this similarity in age distribution. The Cole and Green (1992) method accounts for skewness and goes some way toward overcoming the less well represented age categories. It therefore provides a representative illustration of body composition differences across the age ranges. As this workforce is an aging population group being required to work longer to obtain a full pension, the older firefighters will represent a greater proportion of the workforce over time, and will be required to perform the same operational duties to the same standard as their younger colleagues (Williams et al., 2013).

<u>SMMI reference curves</u>

The age-related SMM decline from 48 to 62 y which is clearly visible in Fig. 2, equates to a mean decline of 0.03 SMMI units/y. Whilst mean SMMI in this age group is greater than UK white males by a mean of 0.35 units, the rate of decline in this study is slightly steeper than that seen in UK white males between 48 and 62 y (Fig. 6), equating to a mean decline of 0.024 SMMI units/y in the firefighters. This is estimated to translate to a mean decline of approximately 0.6% of ASMM per year between 48 y and 62 y.

Of more potential concern is the conclusion of a review by Mitchell et al. (2012), which found that a loss of 1% SMM is associated with a loss of muscular strength of 3-4%, suggesting strength to decline more rapidly, at a rate 2-5 times faster than SMM. The implications of this rate of SMM decline and potentially even greater concomitant losses of muscular strength are potentially concerning for an aging workforce which relies heavily upon muscular strength to successfully perform strenuous life-saving activity whilst minimising risk to themselves and others in hazardous situations. Within this context, the SMMI centile reference curves can be used as a sarcopenic surveillance tool, indicating rates of age-related SMM decline and informing appropriate physical activity and nutritional interventions. Potential aetiology for this indicated steeper decline of SMM in firefighters could be the combined deleterious physiological effects of shift work (Choi et al., 2019), sleep interruption (Lucassen et al., 2017) and elevated levels of psychological stress. In this context, sleep deprivation could be driving dual pathologies, acting both as a mediator for increased cortisol production, possibly leading to SM catabolism (Braun and Marks, 2015), whilst simultaneously suppressing testosterone production (Andersen and Tufik, 2008), leading to anabolic resistance (Bremner, 2010). More research is required to elucidate the physiological mechanisms behind the perceived rapid decline in firefighter SMM. Another potential reason for this decline could be that, to date there has been a paucity of fitness testing in UK fire brigades (Williams, 2014). An occupation which was once highly active has become steadily more sedentary due to increases in computer-based training and advances in fire prevention technology leading to fewer fires to fight, and ultimately lower levels of occupational-related physical activity (Home Office, 2018; 2020). This is currently being addressed via the recent introduction of periodic fitness testing within the UK fire services (Siddall et al., 2016), however, this solely tests cardiorespiratory fitness. It does not test muscular strength. Within this context the SMMI reference chart has potential to act as a proxy for muscular strength to cover this shortfall.

Adiposity

The average FMI from 40-49 y within this sample was 6.7 which is 0.1 units greater than UK white males within the same age range (Lee et al., 2020). Within the 50-54 y age range the average FMI of 7.0 in this sample is the same as 50-54 y UK white males (Lee et al., 2020). Given the established high prevalence of overweight and obesity within the UK general population (Organisation for Economic Co-operation and Development, 2017), these comparisons indicate a similar concerning level of adiposity for UK firefighters. In this instance, the same exposures of firefighting as a highly stressful occupation (Rodrigues et al., 2018), combined with shift work and sleep deprivation contributing to SMM decline, could simultaneously be contributing to increased adiposity through a complex combination of deleterious mechanisms, leading to increased food intake (Spiegel et al., 2004) being possible mechanisms for sleep curtailment being a risk factor for obesity and type-2 diabetes (Van Cauter et al., 2008). This is further compounded by the fire station food environment which has been characterised as obesogenic (Dobson et al., 2013).

Figure 3 illustrates the 50th FMI centile curve increasing on a steady trajectory between the ages of 22 and 46 y. From 47 y, a levelling off of FMI at the 50th centile is observed, with a total marginal gain of 0.28 units up to the age of 62 y. FMI would be expected to increase at a faster rate between these ages, as illustrated by the FMI trajectory of the average English white male displayed in Figure 7. The attenuated FMI increase in firefighters could potentially be related to the fact that older firefighters can still currently retire and collect a full pension at around 50 years of age. Whilst this policy has changed for firefighters recruited after 2006, who are now required to work until 60 y, the majority of firefighters within the older age range were employed on a different contract (Williams et al., 2013). This may imply that the personnel who currently decide to remain working beyond 50 y are doing so because of superior health/physical fitness, reflected by attenuation of FM increase. Future generations of firefighters will not have this choice available to them. The implications of an aging, physically deteriorating workforce brings widespread adverse implications in terms of safety, health and financial outcomes (Williams et al., 2013).

The opposing trajectories of the FMI and SMMI centile curves further highlights a key limitation of BMI, being intrinsically unable to detect these important changes in body composition, with the opposing effects of FM gain and SMM loss possibly cancelling each other out resulting in little weight change.

Whilst BF% is a more valid measure of adiposity than BMI, it is a proportional measure i.e. BF% is affected by both FM and FFM. Thus, if BF% is relied upon without FMI, increased BF% could be the product of a decline in SMM as opposed to an increase in FM. This is illustrated in Figs. 3 and 4 by the contrasting trajectories of the FMI and BF% lower centile curves, highlighting a limitation of BF%, which in this instance may be masking SMM decline at the lower centiles. At the opposite end of the spectrum, a clear contrast is observed between FMI and BF% at the upper centile curves. In this instance, the 75th, 91st and 98th FMI curves show progressively greater divergence from the 50th centile curve whilst the corresponding BF% centile curves are less steep, suggesting that a relatively high amount of SMM at the upper centiles may be reducing the gradient of the upper BF% centile curves.

When used in conjunction, the FMI and SMMI charts provide a more valid reference tool for assessing body composition changes across age ranges than the traditional methods of BMI and BF%. Smoothed centile curves can be also be considered as being more reflective of the gradual age-related transitional nature of risk, as opposed to the currently used arbitrary cut-offs which apply to age groups spanning two decades. The notion of risk suddenly increasing at a specific age lacks credibility, an issue which can be overcome via the application of smoothed centile curves.

Consistent with previous research by Munir et al. (2012) and Lessons and Bhakta (2018), this study suggests that a population of firefighters possessing an optimal body composition may not currently exist within the UK. As overfat and obesity were highly prevalent in this sample, the cut-offs defining overfat and obesity had to be applied at a lower level than most British growth charts (Cole, Freeman and Preece, 1995; McCarthy et al., 2001). They are however consistent with the UK child BF% reference curve cut-offs (McCarthy et al., 2006).

The WHtR centile reference curves were generated, at this point, for use as an academic research tool as opposed to a clinical assessment tool. This is because the WHtR health risk cut-offs do not shift with age. This reference is however useful as a nutritional surveillance tool to indicate health risks (Browning, Hsieh and Ashwell, 2010; Martin et al., 2013; Jayedi et al., 2020) of this occupational group via analysis of the distribution, trajectories and interceptions of the centile curves. When comparing the WHtR chart with the FMI chart using the respective 50th centile curves, it is visible that whilst FMI remains relatively stable from 47 y, WHtR continues to increase. This observed difference indicates a possible shift in the propensity to store FM, from the relatively benign subcutaneous FM depots to the more pathogenic visceral adipose tissue storage site. The stress and sleep curtailment associated with firefighting may be risk factors involved in this pathogenesis via a combination of insulin and increased cortisol secretion promoting triglyceride accumulation mostly in visceral adipocytes, leading to an increase in central adiposity (Hirotsu, Tufik and Andersen, 2015). This continued accumulation of central adiposity accompanied by the observation that the WHtR boundary value of 0.5 is exceeded around midway through the third decade is of concern. This has important implications considering that firefighters are at significantly increased risk of acute myocardial infarction (MI) due to their occupational exposure to intense heat, increasing vascular thrombogenicity (Hunter et al., 2017), and do indeed suffer significantly greater mortality rates from CHD and MI compared with police and paramedics (Kales et al., 2007). Furthermore, they are exposed to an occupational environment which has been characterised as obesogenic (Dobson et al., 2013). As WHtR provides a simple and inexpensive indicator of intra-abdominal visceral adipose tissue (Ashwell, 2011), this measure is recommended as an important risk assessment method to be added to the FMI and SMMI body composition reference charts. This combination of measures further enables the detection of firefighters with a deleterious combination of an elevated WHtR and low SMM.

Study Strengths

This study population was representative of the LFB and the English fire services in terms of BMI and age. A variety of objective measures were administered by the same researcher thereby eliminating inter-measurer error. BIA measurements were conducted within a limited timeframe on each study day in a concerted effort to mitigate diurnal variation in participant hydration status. Furthermore, the pre-test guideline of bladder emptying was adhered to. This study utilised the Tanita MC-780 MA multi-frequency segmental body composition analyser for collecting BIA measurements. This is more recent and accurate than the model used in the most recent and comparable study by Lee et al., (2020) which analysed body composition data obtained using the Tanita BC-418 MA. Because BIA algorithms for the estimation of body composition vary, it is advisable to use these reference centile charts in conjunction with a Tanita MC-780 MA system. Nevertheless, a few studies have found only small differences in BF% prediction between different analysers by this manufacturer, equating to an

FMI difference of 0.3-0.8 units (Hemmingsson, Uddén and Neovius, 2009; Ramírez-Vélez et al., 2016; Lee et al., 2017). This suggests that regardless of the analyser used, a subject would probably fall into the same percentile channel, considering that the narrowest margin between FMI centiles in this study was observed between the 2nd and 9th centiles which averaged at 0.83 units. Whether the same applies to SMMI, whereby the differences between the 2nd and 9th centiles are smaller (averaging 0.44 units) is unclear and therefore requires further research.

Study Limitations

This is a cross-sectional study and therefore assumes that the contemporary young sample of this study population is a valid proxy for their aged sample at a previous time point. This study could therefore be confounded by secular changes such as intergenerational differences reflecting changes in population characteristics as opposed to age-related changes which would be measurable in a longitudinal cohort study. This is a common limitation of body composition centile charts including those created by McCarthy et al. (2006; 2014), as a longitudinal cohort study would be of high logistical burden, relying upon annual measurements of a minimum sample of 500 subjects, taken over several decades. The duration of such a study would likely lead to a high attrition rate rendering this option unfeasible. The cross-sectional design of the current study is a reminder to interpret the centile reference charts with a degree of caution.

The SMMI reference curves were not validated against SMM strength assessment. Although this association has been identified in other populations, without directly assessing muscular strength of the subjects in the current study, no firm associations can be made between age related decline in SMM and loss of muscular strength within this reference population.

Conclusion

These pioneering centile references offer a novel improvement upon the limitations of BMI and BF%, especially when being applied to firefighters, who require greater levels of physical fitness and skeletal muscle mass and strength than the general population. The Firefighter SMMI centiles indicate that whilst firefighters generally possess greater SMM, this may be declining at a slightly faster rate than the UK general population, even at an age when they will still be working. The FMI centiles indicate a prevalence of overfat and obesity similar to the UK general population. The references could therefore be utilised both as risk screening tools and individual education intervention tools to show a firefighter their personal level of SMM and FM relative to the reference sample. This could therefore help motivate behaviour change toward improvement of body composition.

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Appendix. Centile cut-off values Table S1: SMMI Centiles *n*=493

Age	C2	C9	C25	C50	C75	C91	C98
21.465	8.14	8.51	8.93	9.40	9.92	10.51	11.19
22	8.13	8.51	8.93	9.40	9.92	10.52	11.19
23	8.12	8.51	8.93	9.40	9.93	10.52	11.20
24	8.11	8.50	8.93	9.40	9.93	10.53	11.21
25	8.10	8.49	8.92	9.40	9.93	10.53	11.21
26	8.09	8.48	8.92	9.40	9.93	10.54	11.22
27	8.08	8.48	8.91	9.40	9.94	10.54	11.22
28	8.07	8.47	8.91	9.40	9.94	10.54	11.23
29	8.06	8.47	8.91	9.40	9.94	10.55	11.23
30	8.06	8.46	8.91	9.40	9.94	10.55	11.24
31	8.05	8.46	8.91	9.40	9.95	10.56	11.25
32	8.05	8.45	8.90	9.39	9.94	10.56	11.25
33	8.03	8.44	8.89	9.38	9.93	10.54	11.24
34	8.01	8.42	8.86	9.36	9.91	10.53	11.22
35	7.99	8.39	8.84	9.33	9.89	10.50	11.20
36	7.96	8.37	8.81	9.31	9.86	10.48	11.18
37	7.94	8.34	8.79	9.29	9.84	10.47	11.17
38	7.92	8.33	8.78	9.27	9.83	10.46	11.18
39	7.91	8.32	8.77	9.27	9.83	10.47	11.19
40	7.90	8.31	8.77	9.27	9.84	10.48	11.22
41	7.90	8.31	8.77	9.28	9.86	10.51	11.25
42	7.89	8.31	8.77	9.29	9.87	10.53	11.29
43	7.89	8.31	8.77	9.30	9.89	10.56	11.33
44	7.88	8.31	8.78	9.31	9.91	10.59	11.37
45	7.87	8.30	8.78	9.32	9.92	10.61	11.40
46	7.86	8.29	8.78	9.32	9.94	10.63	11.44
47	7.84	8.28	8.77	9.32	9.94	10.65	11.46
48	7.81	8.26	8.76	9.31	9.94	10.65	11.47
49	7.78	8.23	8.73	9.30	9.93	10.65	11.47
50	7.74	8.20	8.71	9.28	9.92	10.64	11.47
51	7.69	8.16	8.67	9.25	9.90	10.63	11.45
52	7.64	8.11	8.64	9.22	9.87	10.60	11.43
53	7.59	8.07	8.60	9.19	9.84	10.58	11.41
54	7.53	8.02	8.56	9.15	9.81	10.55	11.38
55	7.48	7.97	8.52	9.12	9.78	10.52	11.35
56	7.42	7.92	8.47	9.08	9.75	10.49	11.31
57	7.36	7.87	8.43	9.05	9.72	10.46	11.28
58	7.30	7.82	8.39	9.01	9.69	10.43	11.24
59	7.24	7.77	8.35	8.98	9.66	10.40	11.21
60	7.18	7.72	8.31	8.95	9.63	10.37	11.17
61	7.11	7.67	8.27	8.92	9.61	10.34	11.13
61.878	7.06	7.63	8.24	8.89	9.58	10.32	11.10

Table S2: FMI centiles *n*=497

Age	C2	C9	C25	C50	C75	C85	C91	C95	C98
21.46	1.73	2.34	3.12	4.08	5.26	6.02	6.69	7.46	8.42
22	1.78	2.40	3.19	4.17	5.36	6.13	6.81	7.59	8.55
23	1.87	2.51	3.32	4.32	5.55	6.34	7.03	7.82	8.80
24	1.95	2.62	3.45	4.48	5.73	6.53	7.23	8.03	9.03
25	2.04	2.72	3.57	4.62	5.89	6.70	7.41	8.23	9.24
26	2.12	2.82	3.68	4.74	6.03	6.85	7.57	8.39	9.41
27	2.19	2.91	3.79	4.86	6.16	6.99	7.72	8.54	9.56
28	2.27	2.99	3.89	4.97	6.28	7.12	7.84	8.67	9.69
29	2.34	3.08	3.98	5.08	6.40	7.23	7.96	8.79	9.81
30	2.42	3.16	4.08	5.18	6.50	7.34	8.08	8.90	9.92
31	2.49	3.25	4.17	5.28	6.61	7.45	8.18	9.01	10.03
32	2.56	3.33	4.25	5.37	6.70	7.54	8.27	9.10	10.12
33	2.63	3.40	4.33	5.45	6.78	7.62	8.35	9.18	10.20
34	2.69	3.47	4.40	5.53	6.86	7.70	8.43	9.25	10.27
35	2.75	3.53	4.47	5.60	6.93	7.78	8.51	9.33	10.35
36	2.81	3.59	4.54	5.67	7.02	7.86	8.60	9.42	10.44
37	2.86	3.66	4.61	5.75	7.11	7.96	8.70	9.53	10.56
38	2.92	3.72	4.69	5.84	7.21	8.07	8.82	9.67	10.71
39	2.98	3.79	4.77	5.94	7.33	8.21	8.97	9.83	10.89
40	3.03	3.86	4.85	6.05	7.47	8.36	9.14	10.02	11.11
41	3.09	3.93	4.94	6.16	7.61	8.53	9.33	10.23	11.34
42	3.14	4.00	5.03	6.27	7.76	8.70	9.52	10.44	11.59
43	3.19	4.05	5.11	6.37	7.89	8.85	9.69	10.65	11.83
44	3.23	4.11	5.18	6.47	8.02	9.01	9.87	10.85	12.06
45	3.26	4.15	5.24	6.55	8.14	9.15	10.04	11.04	12.30
46	3.29	4.19	5.29	6.63	8.25	9.28	10.20	11.23	12.52
47	3.31	4.21	5.33	6.69	8.34	9.40	10.33	11.40	12.73
48	3.32	4.23	5.35	6.73	8.41	9.50	10.45	11.55	12.92
49	3.32	4.23	5.37	6.76	8.47	9.58	10.56	11.68	13.09
50	3.32	4.23	5.37	6.78	8.52	9.65	10.65	11.80	13.25
51	3.31	4.22	5.37	6.79	8.55	9.70	10.73	11.91	13.40
52	3.29	4.21	5.36	6.80	8.58	9.76	10.80	12.01	13.55
53	3.28	4.20	5.35	6.80	8.61	9.81	10.88	12.12	13.70
54	3.26	4.18	5.34	6.80	8.65	9.86	10.96	12.23	13.85
55	3.25	4.17	5.33	6.81	8.69	9.93	11.05	12.35	14.02
56	3.23	4.16	5.33	6.83	8.73	10.00	11.15	12.49	14.21
57	3.22	4.15	5.33	6.85	8.79	10.08	11.26	12.63	14.41
58	3.21	4.14	5.33	6.87	8.84	10.17	11.37	12.78	14.61
59	3.19	4.13	5.34	6.89	8.90	10.26	11.49	12.94	14.82
60	3.18	4.12	5.34	6.92	8.96	10.35	11.61	13.10	15.03
61	3.16	4.11	5.34	6.94	9.03	10.44	11.73	13.26	15.25
61.88	3.15	4.10	5.35	6.97	9.08	10.52	11.84	13.41	15.45

Table S3: WHtR centiles *n*=496

Age	C2	C9	C25	C50	C75	C91	C98
21.465	0.39	0.41	0.43	0.45	0.48	0.52	0.57
22	0.39	0.41	0.43	0.45	0.48	0.52	0.57
23	0.40	0.41	0.43	0.46	0.49	0.52	0.57
24	0.40	0.42	0.44	0.46	0.49	0.53	0.57
25	0.40	0.42	0.44	0.47	0.49	0.53	0.58
26	0.40	0.42	0.44	0.47	0.50	0.53	0.58
27	0.41	0.42	0.45	0.47	0.50	0.54	0.58
28	0.41	0.43	0.45	0.48	0.51	0.54	0.59
29	0.41	0.43	0.45	0.48	0.51	0.54	0.59
30	0.41	0.43	0.46	0.48	0.51	0.55	0.59
31	0.42	0.44	0.46	0.49	0.52	0.55	0.60
32	0.42	0.44	0.46	0.49	0.52	0.55	0.60
33	0.42	0.44	0.46	0.49	0.52	0.56	0.60
34	0.42	0.44	0.47	0.49	0.52	0.56	0.60
35	0.42	0.45	0.47	0.50	0.53	0.56	0.61
36	0.43	0.45	0.47	0.50	0.53	0.57	0.61
37	0.43	0.45	0.47	0.50	0.53	0.57	0.61
38	0.43	0.45	0.48	0.50	0.54	0.57	0.62
39	0.43	0.45	0.48	0.51	0.54	0.58	0.62
40	0.43	0.46	0.48	0.51	0.54	0.58	0.62
41	0.44	0.46	0.48	0.51	0.55	0.59	0.63
42	0.44	0.46	0.49	0.52	0.55	0.59	0.63
43	0.44	0.46	0.49	0.52	0.55	0.59	0.64
44	0.44	0.47	0.49	0.52	0.56	0.60	0.64
45	0.44	0.47	0.50	0.53	0.56	0.60	0.65
46	0.44	0.47	0.50	0.53	0.57	0.61	0.65
47	0.44	0.47	0.50	0.53	0.57	0.61	0.66
48	0.44	0.47	0.50	0.53	0.57	0.61	0.66
49	0.44	0.47	0.50	0.54	0.57	0.62	0.67
50	0.44	0.47	0.50	0.54	0.58	0.62	0.67
51	0.44	0.47	0.50	0.54	0.58	0.62	0.67
52	0.44	0.47	0.51	0.54	0.58	0.63	0.68
53	0.44	0.47	0.51	0.54	0.58	0.63	0.68
54	0.44	0.47	0.51	0.54	0.58	0.63	0.69
55	0.44	0.47	0.51	0.54	0.59	0.63	0.69
56	0.44	0.47	0.51	0.55	0.59	0.64	0.69
57	0.44	0.47	0.51	0.55	0.59	0.64	0.70
58	0.44	0.47	0.51	0.55	0.59	0.64	0.70
59	0.44	0.47	0.51	0.55	0.59	0.65	0.70
60	0.44	0.47	0.51	0.55	0.60	0.65	0.71
61	0.44	0.47	0.51	0.55	0.60	0.65	0.71
61.878	0.44	0.47	0.51	0.55	0.60	0.65	0.72

Table S4: BF% centiles *n*=497

Age	C2	C9	C25	C50	C75	C85	C91	C95	C98
21.465	7.85	10.64	13.61	16.73	19.98	21.84	23.36	24.97	26.84
22	8.02	10.83	13.82	16.95	20.23	22.09	23.62	25.24	27.12
23	8.33	11.18	14.20	17.37	20.67	22.56	24.10	25.73	27.63
24	8.65	11.53	14.57	17.77	21.10	23.00	24.55	26.20	28.11
25	8.95	11.86	14.93	18.15	21.50	23.41	24.96	26.62	28.54
26	9.25	12.18	15.27	18.50	21.86	23.78	25.34	27.00	28.92
27	9.54	12.48	15.59	18.83	22.19	24.11	25.67	27.34	29.26
28	9.82	12.78	15.88	19.13	22.49	24.41	25.97	27.63	29.55
29	10.10	13.06	16.17	19.41	22.77	24.68	26.24	27.90	29.81
30	10.38	13.34	16.45	19.68	23.04	24.94	26.49	28.14	30.05
31	10.66	13.62	16.72	19.94	23.28	25.18	26.72	28.36	30.26
32	10.93	13.88	16.96	20.17	23.49	25.38	26.92	28.55	30.43
33	11.20	14.13	17.20	20.39	23.69	25.56	27.09	28.71	30.58
34	11.45	14.37	17.42	20.59	23.87	25.74	27.26	28.87	30.73
35	11.69	14.60	17.65	20.80	24.07	25.92	27.43	29.04	30.89
36	11.93	14.84	17.87	21.02	24.28	26.13	27.63	29.23	31.08
37	12.17	15.07	18.11	21.25	24.51	26.35	27.86	29.45	31.30
38	12.39	15.31	18.35	21.50	24.76	26.61	28.11	29.71	31.56
39	12.62	15.54	18.60	21.76	25.04	26.89	28.41	30.01	31.87
40	12.84	15.78	18.85	22.04	25.33	27.20	28.73	30.34	32.21
41	13.05	16.02	19.11	22.32	25.64	27.53	29.06	30.69	32.57
42	13.25	16.23	19.35	22.59	25.94	27.84	29.39	31.03	32.93
43	13.42	16.43	19.57	22.83	26.20	28.12	29.68	31.34	33.26
44	13.57	16.60	19.76	23.05	26.45	28.38	29.96	31.63	33.57
45	13.71	16.75	19.94	23.25	26.68	28.63	30.22	31.91	33.87
46	13.82	16.88	20.09	23.42	26.89	28.86	30.46	32.17	34.15
47	13.91	16.98	20.21	23.57	27.06	29.05	30.67	32.40	34.39
48	13.98	17.06	20.30	23.68	27.20	29.20	30.84	32.59	34.61
49	14.03	17.11	20.36	23.76	27.30	29.33	30.98	32.74	34.78
50	14.06	17.14	20.40	23.82	27.38	29.42	31.09	32.86	34.92
51	14.07	17.16	20.42	23.85	27.44	29.49	31.17	32.96	35.04
52	14.08	17.16	20.43	23.88	27.48	29.55	31.24	33.05	35.15
53	14.08	17.17	20.44	23.90	27.53	29.61	31.32	33.15	35.27
54	14.08	17.17	20.47	23.94	27.60	29.70	31.42	33.26	35.41
55	14.09	17.19	20.50	24.00	27.69	29.81	31.55	33.41	35.58
56	14.10	17.22	20.55	24.08	27.80	29.94	31.70	33.58	35.78
57	14.11	17.25	20.61	24.17	27.93	30.09	31.87	33.78	36.00
58	14.13	17.29	20.68	24.27	28.07	30.26	32.07	34.00	36.25
59	14.15	17.33	20.75	24.38	28.22	30.44	32.26	34.22	36.50
60	14.17	17.38	20.82	24.50	28.38	30.62	32.47	34.45	36.76
61	14.18	17.42	20.90	24.61	28.54	30.81	32.68	34.68	37.02
61.878	14.20	17.47	20.97	24.72	28.69	30.98	32.87	34.89	37.26