THE INFLUENCE OF AGE ON THE RECOVERY FROM WORKSITE RESISTANCE EXERCISE

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ABSTRACT

Abbie Trivisonno: The Influence of Age on the Recovery from Worksite Resistance Exercise
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Worksite resistance exercise can reduce injuries and improve performance in the fire service. This study examined the influence of age on the recovery from a worksite exercise routine. Nineteen young and 19 older firefighters completed an acute bout of resistance exercise in addition to pre- and post-testing 24, 48, and 72 hours post-exercise. Upper- and lower-body strength, muscle activation, ultrasonography, countermovement jump, and muscle soreness were measured to assess recovery. Linear mixed model (controlling for work-related fatigue) results revealed no (group × time) interactions. Group effects indicated the young firefighters exhibited greater lower-body force, jump performance, and better muscle quality than the older firefighters ($P \leq 0.047$). Time effects indicated that upper-body force, lower-body rapid forces, early muscle activation, and jump performance decreased and muscle soreness and size increased ($P \leq 0.044$). These results suggest that age does not influence recovery from worksite resistance exercise in firefighters.

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LIST OF ABBREVIATIONS

BB	Biceps brachii
BMI	Body mass index
CMJ	Countermovement jump
CK	Creatine kinase
CSA	Cross sectional area
DOMS	Delayed-onset muscle soreness
ECC	Excitation-contraction coupling
EI	Echo-intensity
EIMD	Exercise-induced muscle damage
EMG	Electromyography
MSK	Musculoskeletal
MT	Muscle thickness
MVC	Maximal voluntary contraction
ROM	Range of motion
SFT	Subcutaneous fat thickness
US	Ultrasonography
VAS	Visual analog scale
VL	Vastus lateralis

CHAPTER I: INTRODUCTION

Firefighters provide critical emergency services to communities across the country, despite experiencing one of the highest rates of occupational injuries.[1,2] The National Fire Protection Association reported that there were 68,085 injuries among firefighters in 2015.[3] The primary non-fatal injuries that are commonly reported include strains and sprains[1-3] to the extremities and back[4] and are often attributed to acute overexertion and slips, trips, and falls.[3] These injuries result in above average worker's compensation claims,[5] extended worker absence rates,[1,6] and are the leading cause of early retirement in firefighters.[7]

Exercise has been consistently listed as the primary approach to reducing injuries in the fire service.[8,9] However, more than 75% of firefighters fail to achieve the minimum physical activity recommendations from the American College of Sports Medicine.[10] The workplace (e.g. fire station) may provide an optimal setting to improve the exercise habits of firefighters. For example, worksite exercise programs may offer unique advantages to the employee that include convenience (i.e. less travel, ease of access to equipment), lower associated-costs, and improved camaraderie among co-workers who train together.[11] Previous studies have shown that worksite exercise can improve working physical capacity, musculoskeletal (MSK) pain, and reduce the incidence of injury in a number of occupations.[6,12,13] It is well documented that resistance training improves muscle strength, power, and endurance,[14-16] which are critical to the safe execution of essential firefighter tasks.[13,17-19] Furthermore, resistance training has been shown to target risk factors associated with the primary non-fatal injuries reported among firefighters.[20,21]

These data may demonstrate that worksite resistance exercise can be an important tool to reduce injuries and improve performance in the fire service.

Nearly all United States firefighters are between the ages of 20 – 59 years.[22] Given the large age range of firefighters, it is important to determine if aging influences their recovery from a worksite resistance exercise routine. Previous studies have indicated that age may influence the adaptations following chronic resistance training,[23,24] and it is possible that these alterations may be mediated by a prolonged recovery response.[25,26] Furthermore, an altered recovery response in older firefighters may have unintended consequences that include increases in the risk of strain and sprain injuries and impaired subsequent job performance when performed on-shift. These studies may suggest that future research is needed to examine the influence of aging on the recovery following worksite resistance training to inform future worksite exercise prescription among firefighters.

Purpose

The overall objective of this proposal is to examine the influence of age on recovery, using indirect markers of muscle damage, following an acute bout of worksite resistance training in young and older firefighters.

Research Question

1) Does age impact firefighters' recovery from an acute bout of worksite resistance training?

Research Hypothesis

1) We hypothesize that the older firefighters will have a prolonged recovery response when compared to their younger counterparts.

CHAPTER II: REVIEW OF LITERATURE

Current Health and Fitness of the Fire Service

Firefighters play a critical role in public safety, providing life-saving services. There are currently about 1,160,450 firefighters[22] and, as emergency first responders, they are recognized as one of the most physically demanding, dangerous, and, stressful civilian occupations.[27-29] The dangerous and demanding physical tasks that are required for this occupation (forcible entry, rescues, fire suppression, etc.) result in a high risk for injury and fatality.[28] Firefighters have one of the highest occupational injury rates among emergency responders, accounting for 30% of all injuries and 7.4 injuries per 100 full-time employees.[30] The National Fire Protection Association estimated that over 62,000 firefighter injuries occurred in 2016, with an injury occurring every eight minutes and 28 seconds.[31] The majority of these injuries occur as strains and sprains[1-3,32] to the extremities and back[4,32] and are attributed to slips, trips, and falls and overexertion.[3] In order to reduce these risks, firefighters must maintain high levels of physical preparedness.

Previous research has shown that optimal firefighter health and performance requires high levels of cardiovascular fitness, muscular strength, muscular endurance, power, and flexibility.[33,34] Firefighters must also be conditioned to resist fatigue in poor environmental conditions such as extreme temperatures and smoke-filled air, while wearing heavy personal protective equipment.[9,35,36] Physical fitness variables have consistently been correlated with performance of firefighter specific tasks.[18,37-41] For example, Rhea et al.[18] found that overall task performance in firefighters was significantly correlated with muscular strength, local muscular endurance, and anaerobic endurance. In addition, having greater upper- and lower-body strength and endurance (as determined with resistance exercise testing) was correlated with the efficiency of completing job specific tasks such as hose pulls, dummy drags, stair climbs, and hoists.[18] Michaelides et al.[39] found that 55% of the variation in performance of a firefighter ability test was explained by upper-body strength, upper-body endurance, and body composition. Other studies[37,38,40,41] have found similar results emphasizing the importance of maintaining high levels of physical fitness in the fire service in order to perform their duties effectively. However, it has been reported that more than 75% of firefighters fail to achieve the minimum physical activity recommendations from the American College of Sports Medicine.[10] It has also been estimated that approximately 80% of fire departments do not have physical fitness programs designed to improve or maintain health and fitness.[42] These data may suggest that novel, cost-effective, and more feasible exercise interventions are needed in the fire service.

Many recent studies have suggested that the fire service has an obesity epidemic. For example, recent estimates suggest that 79.5% of career firefighters and 78.4% of volunteer firefighters are obese or overweight.[43] Furthermore, Soteriades et al.[44] found that obesity rates increased from 35% to 40% in a five year period, along with a four-fold increase in the number of firefighters with extreme obesity. Several studies have also found firefighters to gain an average of 1.2-3.4 lbs per year.[44-46] Obesity is also associated with a greater risk of job disability in firefighters, including a 5% increased risk for every one unit increase in BMI above 25.[47] Jitnarin et al.[48] found that the prevalence of obesity in firefighters may be even higher when calculating body fat percentage rather than BMI and waist circumference. These high rates of obesity are a significant problem because obese firefighters are more likely to get injured,[49] have higher rates of disability and absenteeism[47,50] resulting in significant costs to the department,[50] have a greater risk of cardiovascular events,[44,51,52] and perform more poorly during firefighter tasks.[39,41]

Benefits of Resistance Training

Resistance training is a common modality used to improve muscular strength, power, and endurance.[14-16] In addition, the health-related benefits of resistance training are numerous[53] and have been shown to be appropriate for a number of populations.[6,12,13] For example, resistance exercise is effective for increasing muscular strength which reduces the risk of all-cause mortality,[54-56] improves cardiovascular risk factors,[57,58] reduces pain and disability,[12,59] and decreases the risk of developing a MSK disorder.[60] Resistance training is also effective for improving functional capacity[61,62] and body composition.[63,64] All of these factors are important for the health and performance of many populations, and because of this, resistance training has become a popular tool to improve occupational health and performance, and injury outcomes. For example, resistance training has been used in workplace interventions to improve pain in the neck and shoulders,[59,65,66] and low-back.[59] Sundstrup et al.[67] also found that specific strength training improved muscular fatigue resistance, self-rated health, and reduced pain in slaughterhouse workers suffering from chronic upper limb pain. In further support, a one year resistance training worksite intervention resulted in significant decreases in systolic blood pressure, body fat percentage, and pain, as well as an increase in muscular strength.[68] Specifically in firefighters, Pawlak et al.[69] found that a twelve week circuit training program led to significant improvements in body mass, fat mass, BMI, and the completion rate of a simulated fire ground test. Similarly, Peterson et al.[27] found that a traditional linear periodized training program and an undulating training program improved firefighter's upper- and lower-body muscular strength, peak power output, vertical jump, and completion of simulated firefighter tasks. In conclusion, resistance training may be effective for firefighters in order to improve current fitness levels, improve job-related performance,[13,17-19] and ultimately reduce their risk for on-the-job injuries.[6,12,13] However, given the physical nature of their work, it is important to examine recovery from worksite resistance training and consider how age specifically may play a significant role.

Exercise-Induced Muscle Damage (EIMD)

Exercise-induced muscle damage (EIMD) is a condition that includes ultrastructural changes in contractile filaments of the muscle resulting in numerous symptoms (i.e. soreness, swelling, force loss, etc.) when someone engages in unaccustomed, intense exercise.[70] Specifically, exercise related activities that include eccentric or isometric muscle actions at longer muscle lengths have been shown to result in the greatest muscular damage.[71-75] Previous studies have demonstrated histological evidence of ultrastructural changes at the level of the sarcomere,[76,77] which presents as a collection of systemic and symptomatic changes that occur in the days following the exercise bout.[78-81] The subsequent sections will detail how muscle damage occurs, what the consequences are, and why strength is considered the primary outcome variable to examine the magnitude and recovery of muscle damage.

Mechanisms of EIMD

Exercise-induced muscle damage is most prominent when the acute bout of exercise includes repetitive eccentric muscle actions.[77,82] Previous studies have suggested that repetitive eccentric muscle actions may alter skeletal muscle at the level of the contractile units,[76,77] membrane, and connective tissue.[83-85] High volume eccentric muscle actions have been shown to result in myofibrillar disruption, or Z-line streaming.[76,77] Morgan et al.[86] proposed that during the mechanical strain caused by eccentric muscle actions, the nonuniformity of half-sarcomeres results in overstretching and weakening of sarcomeres beyond myofilament overlap. This is known as the "popped sarcomere" theory and suggests that passive tension increases as a result.[86] The continual repetition of these lengthening contractions then begins to impact more sarcomeres and eventually results in damage to the muscle. Another noted disruption from eccentric contractions is damage to the excitation-contraction coupling (ECC) system.[83,84] This hypothesis has been supported through findings in mice where caffeine has been shown to recover post-exercise decreases in tension, supposedly through initiating Ca^{2+} release from the sarcoplasmic reticulum.[83,84] These processes can lead to an acute rightward shift in the length-tension curve due to the over-stretching and mechanical disruption of lengthening sarcomeres.[87-89] However, this shift may only occur when eccentric muscle actions are utilized at longer muscle lengths.[90,91] Recent theories now suggest that the occurrence of damage to the skeletal muscle such as Z-line streaming may not in fact be indicators of damage but rather indicative of the muscle remodeling and adaptation.[92]

Consequences of EIMD

Exercise-induced muscle damage is a multifactorial issue, which results in histologic (i.e. myofibrillar disruptions), systemic (e.g. creatine kinase, inflammatory markers), and symptomatic (e.g. soreness, swelling, force loss) consequences.

Histologic Responses

When investigating muscle damage directly, the examination of muscle tissue harvested from biopsies allows for the study of alterations in muscle structure after damaging exercise bouts,[71,72] revealing myofibrillar disruptions in the form of Z-line smearing.[76,77,93] There is also evidence of a widening of perimysial areas between fascicles and a separation of the muscle fibers within the fascicles, along with alterations to the extracellular matrix components.[85] The culmination of these alterations is likely what triggers the inflammatory response to eccentric exercise.[85,94] Although the use of muscle biopsy techniques allows us to examine ultrastructural changes within the muscle it also requires expertise with the procedure, can be very costly, and is an extremely invasive procedure on participants. It has also been shown that a muscle can take over two weeks to recover from a needle biopsy procedure[95] which prevents the use of frequent, repeated measures to monitor the acute recovery process. Thus, many indirect markers of muscle damage (discussed below) have been established that are easily measured, relatively inexpensive, and are much less invasive for the participants.

Systemic Responses

The inflammatory response to EIMD is an extremely complex process that aims to repair damage and reestablish homeostasis, and may also contribute to the remodeling and adaptation of skeletal muscle.[96,97] The basic inflammatory response includes an accumulation of leukocytes as evidenced in muscle biopsies after eccentric exercise.[98-100] There appears to be accumulations of neutrophils within the 24 hours post-exercise[98,101] while monocytes and macrophages tend to accumulate beyond 48 hours post-exercise.[94,102,103] These leukocytes are mobilized within the circulation[104,105] and then proceed toward the site of damage where they begin the processes of breakdown, repair, and remodeling.[106,107] Previous studies have suggested that the severity of leukocyte accumulation correlates with the severity of force reduction and the timelines of recovery exhibit similar patterns.[101,108] Several other inflammatory agents such as mast cells, T-lymphocytes, eosinophils, and cytokines are recruited to the site of muscle damage and contribute to the repair and remodeling processes as further described by Peake et al.[109]

Another commonly measured systemic response to EIMD includes the measurement of serum proteins such as creatine kinase.[79,110-112] High levels of creatine kinase (CK) within the bloodstream have typically been used to indicate severe muscle damage such as myocardial infarctions[113,114] or exertional rhabdomyolysis.[115,116] However, it is now well known that elevated levels of CK can been seen in response to eccentric exercise.[79,110-112] Creatine kinase was once thought of as a primary marker of muscle damage, but has since been questioned due to its variability within subjects.[111,117] Other serum proteins and blood constituents such as myoglobin, alanine aminotransferase, and lactate dehydrogenase have shown significant increases after strenuous eccentric exercise, however they typically respond less drastically than CK.[81,118] Although the presence of blood markers, such as CK, typically increase significantly after eccentric exercise, the timeline of these increases may not consistently correlate with changes in muscle function[78] or evidence of muscle damage.[119]

Symptomatic Responses

Several other measurements have been used as indirect indicators of muscle damage such as soreness, swelling, and neuromuscular function. As with other measurements of muscle damage, these indicators vary due to the type of damaging protocol (i.e. volume, intensity) and the characteristic of the subject (i.e. training status, sex, age).[120] Delayed-onset muscle soreness (DOMS) typically peaks 24-48hrs post-exercise[112,121] and resides within 8-10 days,[112] however the presence or absence of DOMS does not correlate well with the muscle's functional ability.[80] Ultrasonography has been used to assess muscle thickness and muscle quality via echo-intensity. Muscle thickness has increased as a result of swelling from eccentric contractions[79] and echo-intensity tends to increase,[79,110,122] which is believed to be a marker of interstitial edema.[123] Electromyography has been used to demonstrate that greater muscle activation may be required to produce the same force up to 48hrs after eccentric exercise.[121,124,125] This neuromuscular inefficiency has also been shown in performance related tasks such as jumping[126] and endurance exercise[127,128] which are negatively impacted following exercise-induced muscle damage. Strength testing has become one of the most frequent and reliable measurements of monitoring muscle damage recovery,[78,129] often done with isometric maximal voluntary contractions (MVC). Typically, muscle function following eccentric muscle actions of the elbow flexors has resulted in an immediate strength decrease of 30-60% from baseline MVC.[80,110,130-132] It has been suggested that eccentric exercise of the elbow flexors may have a recovery half-time as long as 5-6 weeks,[133] and full recovery has been shown to take up to 12 weeks.[130] Strength decrements are typically less for the lower-body compared to the upper-body[122,134] possibly due to constant loading and frequent use. Typically, the knee extensors have shown strength decreases of 20-40% from baseline MVC,[126,135-138] recently however, Damas et al.[78] found decreases of up to 80% of baseline MVC in a large sample size. There is some evidence that lower body muscle function may return to or near baseline levels around seven days post-exercise.[126,136-138]

The Significance of Strength as an Indirect Marker of EIMD

Recently, the measurement of isometric strength has been established as the primary indicator of muscle damage.[78,129] Decreases in force production have been proposed to result from mechanical damage of the sarcomeres[71,76] and ECC dysfunction,[83,84] and thus provide a good representation of the extent and recovery from muscle damage. Damas et al.[78] examined the recovery from an acute bout of EIMD in a large sample of young men following 30 maximal eccentric muscle actions of the elbow flexors. A cluster analysis was used to stratify subjects based on their decrease in MVC post-exercise and the groups that responded with the largest decreases in MVC corresponded with those experiencing the largest decreases in all other measured variables (i.e. soreness, CK activity, range of motion, and circumference). Thus, the extent to which strength is impaired tends to represent the extent of muscle damage incurred.

Damas et al.[78] and others[109,139] have previously suggested that mild EIMD was considered a reduction of <20% in force output, moderate damage was considered >20% decline in force output, and severe damage was considered a reduction in strength >50%. Many factors such as the exercise protocol, training status, and age play a role in the extent of strength reduction and the recovery timeline.

Impact of Training Status on EIMD Recovery

Research examining EIMD has utilized subjects with a variety of training statuses. Because of the phenomenon known as the "repeated bout effect",[110,112] there has been speculation that resistance trained individuals may have a blunted response to muscle damaging exercise. This hypothesis was supported by Newton et al.[140] who compared resistance trained and untrained men after eccentric exercise of the elbow flexors. The resistance trained group showed significantly smaller changes in maximal isometric and isokinetic torque, range of motion (ROM), circumference, and plasma CK.[140] Muscular strength was recovered to baseline levels after three days in the trained group while the untrained group still showed a 40% decrease in MVC, indicating there may be a greater degree of damage and a longer recovery timeline in untrained subjects. Furthermore, Gibala et al.[72] found that strength trained men experienced only half of the fiber damage of untrained men who were examined in their previous work.[71] Although no statistical significance can be applied to these data, it is also interesting to note that the strength trained men appeared to approach full recovery of contractile damage five days after eccentric damage[72] whereas previous work in untrained men showed significantly reduced muscle function at five days post-eccentric exercise.[71] This supports previous data in which muscle biopsies at seven and twelve days after eccentric exercise in untrained men showed signs of fiber disruption.[94] However, these findings are in contrast to Vincent et al.[141] who examined the effect of training status on muscle damage recovery from an acute bout of resistance training. Subjects completed a training session focusing on the knee extensors on day one and the knee flexors on day two to simulate a split training program. There were no significant differences in groups for maximal isometric torque, circumference, ROM, or DOMS, however the creatine kinase response was significantly higher for the untrained group on days 2-5. It should be noted that the exercise program differed between groups as the untrained group used a smith machine instead of free weights for squat and completed one less set. The trained group also completed four sets of stiff-leg deadlift while the untrained group did none and untrained group completed three more sets of lying leg curl. This translated to a total workload of 2,735,220 N for the trained group and 1,620,449 N for the untrained group which may have impacted the degree of muscle damage experienced by the groups. It is also possible that the use of eccentric contractions at a single joint such as those used by Newton et al.[140] and Gibala et al.[71,72] caused more severe localized muscle damage than Vincent et al.[141] In conclusion, there is evidence to support that resistance trained subjects may be more resistant to EIMD and this should be noted as a significant factor when examining the muscle damage in specific populations.

The Impact of Sex on EIMD Recovery

There has been considerable debate whether EIMD is impacted by sex. Specifically, estrogen has been proposed as one of the protective mechanisms for muscle damage[142,143] which potentially indicates females may have a reduced response to exercise-induced damage. However, the research in this field varies considerably. Hubal et al.[144] found no significant differences in the relative changes of MVC between males or females after isokinetic eccentric contractions of the elbow flexors. Although there appears to be no differences in DOMS between males and females after EIMD,[145-147] differences have been found in other factors of recovery. For example, Flores et al.[148] found sex differences in muscle swelling and peak torque recovery after a concentric/eccentric resistance training protocol of the elbow flexors which indicated a longer recovery timeline for females. In contrast, Sayers et al.[130] examined differences in EIMD in males and females after eccentric contractions of the elbow flexors. Although they found similar decrements in isometric strength, there was a much larger number of females who experienced force reductions >70% of baseline MVC and they tended to recover force production quicker than males who experienced similar decrements in force.[130] Similarly, Sewright et al.[145] found that more females experienced strength losses >70% after eccentric exercise, but females also experienced significantly greater strength losses immediately post-exercise compared to males. Furthermore, Hakkinen et al.[149] found that females recovered maximal force to a greater extent than males in the first hour after a heavy resistance training session. However, no differences existed in their recovery at two hours, one day, and two days post-exercise. Due to the inconsistencies within this research, it is possible that sex may impact the recovery response, and this should be considered in future research.

Impact of Aging on EIMD

It is well-known that the aging process is associated with declines in functional capacity,[62] however the relationship between age and EIMD recovery is less clear. Between the second and seventh decades there are significant decreases in muscle size,[150-152] strength,[150,153,154] and proportion of type II muscle fibers.[152,153,155] When considering these age-related changes in skeletal muscle, it is often assumed that older individuals would have a prolonged recovery from EIMD due to an increased susceptibility to damage and an elongated repair process. The proposed mechanisms behind this assumption include differences in muscle fiber composition,[156] dysfunction in the ECC process,[157,158] and an altered inflammatory response.[159]

One of the possible mechanisms of increased susceptibility to EIMD in older individuals involves the well documented loss of type II fibers in aging individuals.[152,153,155] There is evidence that muscle damage resulting from eccentric exercise is predominant within type II muscle fibers.[76,136,160] Choi et al.[156] found that type IIa and type IIa/IIx muscle fibers from elderly subjects were much more susceptible to muscle damage than type I fibers. This is in contrast to what has been observed in younger subjects [161] and it was proposed that elderly adults experience deterioration of the myofilament lattice in type IIa and type IIa/IIx fibers.[156] This increase in susceptibility to muscle damage in type II fibers could be a result of greater mechanical strain across fewer fibers because of the loss of type II fibers in older individuals. There is also evidence that ECC dysfunction occurs in fast-twitch fibers of older individuals.[157,158] A decrease in dihydropyridine receptor activity in elderly muscles results in a reduced release of calcium which may impact muscle contractions. This occurrence, along with potential decrements in ECC function as a result of muscle damage,[83,84] may further impact the recovery from muscle damage in the elderly. There may also be an impaired recovery in older individuals because of a decrease in the number of satellite cells, specifically in type II muscle fibers.[162,163] Satellite cells have been shown to contribute to muscle repair and regeneration,[164,165] and the reduced number in older individuals could potentially impact this process.

Another possible mechanism involves alterations in the inflammatory response. Hamada et al.[159] found that elderly subjects experienced a dysfunction in the inflammatory response to EIMD compared to younger subjects. There was a reduced recruitment of leukocytes in older compared to younger subjects, indicated by changes in CD18, along with a lesser accumulation of IL-6, an anti-inflammatory cytokine. These dysfunctions indicate an abnormal inflammatory response to muscle damage which may have negative implications. Although all of these potential mechanisms provide evidence that aging may impact the recovery process, many other factors, such as sex and training status, as well as the methods and devices used to measure EIMD vary greatly between studies and these inconsistencies have resulted in conflicting findings in the literature.

EIMD Recovery in Old v. Young

Previous studies have indicated that aging may influence the adaptations following chronic resistance training,[23,24] and it is possible that these alterations may be mediated by a prolonged recovery response.[26,78] The majority of research examining the impact of age on muscle damage recovery compares groups of young and elderly subjects,[26,111,166,167] which are typically termed as ≥65 years old. Results from Lavender et al.[167] suggest that elderly subjects may be less susceptible to muscle damage compared to younger subjects. After completing six sets of five eccentric actions of the elbow flexors the young subjects had significantly larger decreases in isometric strength and range of motion along with greater increases in DOMS, CK, and myoglobin compared to the older subjects. However, this study allowed for voluntary completion of the eccentric movements as opposed to using dynamometry to control for speed and range of motion through the movement. Because the older subjects had significantly smaller baseline ROM it is likely that they completed the eccentric contractions through a shorter ROM which has been shown to result in less muscular damage.[137,168] Furthermore, Nikolaidis[169] found no differences between young and elderly men when examining isometric torque, ROM, DOMS, CK activity, and oxidative stress after eccentric-biased squats. However, measurements were only taken before and 48hrs after exercise.

In contrast to these findings, Manfredi et al.[111] compared levels of CK activity in older and younger subjects and took muscle biopsies of the vastus lateralis in older subjects after completing three 15-minute eccentric cycling periods at power outputs of 90, 80, and 70% of VO_2max. There appeared to be no relationship between CK activity and muscle damage which led to speculation of the use of CK as an indirect marker. There was also evidence of ultrastructural muscle damage in greater than 90% of fibers in the older men immediately after the exercise bout.[111] However, muscle biopsies were not taken from the young subjects so direct statistical comparison is not possible. Other research utilizing a cycle ergometer eccentric muscle damage protocol found fiber disruption in 5-10 % of young subjects,[170] which suggests that older subjects may exhibit greater levels of muscle damage, although no biopsies were taken from the younger subjects in the study by Manfredi et al.[111]

When examining age differences in females, Dedrick et al.[171] found that physically active older females had a slower recovery of isometric strength after eccentric muscle actions of the elbow flexors. Younger subjects experienced their greatest decrease in strength on day one post-exercise and returned to baseline strength on day three. However, the older subjects experienced a continual decrease in isometric strength until two days post-exercise and remained significantly below baseline on the 5th day post-exercise. In addition, Clarkson et al.[166] examined differences in CK activity, flexed and relaxed elbow angle, and pain in older and younger females following eccentric exercise of the forearm flexors. The authors[166] found no differences between changes in CK activity, flexed elbow angle, or pain, however, the older subjects did experience a significant reduction in relaxed arm angle compared to the younger group on day two after the exercise bout.

EIMD Recovery in Middle-age v. Young

It has been suggested that age-related changes in skeletal muscle begin to occur during the later years of the second decade,[151] whereas other evidence supports skeletal muscle retention until the fifth decade.[172,173] Currently, there is little research examining how middle-aged men are impacted during the early years of physiological alterations and whether these effects impact their ability to recover from EIMD.[174-176] While the majority of the fire service is 20-59 years, nearly half of the fire service is over 40 years old.[22] Thus, because they compose a significant portion of the firefighter population, it is extremely important to specifically examine the physiological responses of the middle-aged population. Lavender et al.[176] compared the recovery responses in young and middle-aged men after six sets of five eccentric contractions of the elbow flexors using 40% of their maximal isometric strength. No significant differences existed between groups for maximal isometric strength, arm circumference, or range of motion. Surprisingly, the younger men had significantly higher levels of muscle soreness compared to middle-age men. It was proposed that perhaps the middle-aged men had experienced more pain in their life and so perceived the muscular soreness as less severe, however that is just one proposed theory.[176] Gordon et al.[174] examined recovery differences in recreationally trained young and middle-aged men after eight sets of ten repetitions of knee extension on an isokinetic dynamometer at 60°/sec. No differences were found between groups for peak torque, average torque, or rate of torque development at 200ms. Similarly, no differences between groups were found in myoglobin, CK, C-reactive protein, or interleukin-6 suggesting that the recovery response from high-volume isokinetic exercise may be similar for young and middle-aged recreationally trained men. However, the sample size was small (n=9 and n=10) and measurements were only taken up to 48hrs post-exercise. The authors also acknowledged that the use of a single-joint isokinetic protocol to elicit damage is not specific to the types of exercise-induced damage experienced by lifters and future studies may use multi-joint, dynamic exercises to observe the recovery response.

To the best of our knowledge, there is currently only one study that utilized a practical acute bout of resistance training to compare the recovery response in young and middle-age men.[175] McLester et al.[175] compared muscular endurance recovery between young (18 to 30 years) and middle-aged men (50 to 65 years) as they completed three sets of repetitions to failure for eight exercises at a predetermined ten repetition maximum load. They found that repetitions completed at 24 and 48hrs apart were not significantly different between groups, but after 72hrs of rest, the younger group completed significantly more repetitions than the middle-aged group. At 96hrs there were no statistically significant differences between groups, although P=0.06 which may be noted as a trend for the groups to differ. However, it should be noted that the results of this study were underpowered and although the use of repetitions to failure was further validated as a reliable measurement[177] the were no previously validated indirect markers of muscle damage used to assess the subjects' recovery. Thus, a gap in the literature still remains to examine the impact of aging on EIMD recovery using a practical resistance training protocol.

CHAPTER III: METHODOLOGY

Participants

Twenty young and 21 older active-duty male career firefighters volunteered to take part in this study. Demographic data are displayed in Table 1. Three participants withdrew from the study due to experiencing low back musculoskeletal pain following testing (2 older firefighters) or a lack of follow-up contact following testing (1 younger firefighter), therefore, 38 participants completed all testing visits (19 young and 19 older firefighters). The firefighters were solicited from local departments near the University of North Carolina at Chapel Hill. All participants provided written and dated informed consent (IRB# 18-0025) to participate in the research study. Additionally, the participants agreed to abstain from vigorous exercise (48 hours) or any exercise (24 hours) prior to all testing visits as well as abstain from any recovery strategies (i.e. massage, ice baths, ibuprofen, etc.) for the duration of the study. Participants also abstained from food and drinks (except water) four hours prior to their first visit and abstained from caffeine, tobacco, and alcohol (8 hours) prior to all testing visits. None of the participants reported any neuromuscular, cardiovascular, or metabolic disease (i.e., diabetes); had a current or recent (within the past three months) musculoskeletal injury of the upper- or lower-body and/or lower back that would not allow them to complete the testing; were involved in an active workers' compensation or personal injury case; currently performed more than three sessions per week of resistance training (on average) over the last three months. The average reported hours of resistance training per week for all participants was 2.00 ± 2.15 hours/wk..

Experimental Design

The experimental design is depicted in Figure 1. The participants completed five days of testing at local fire stations that included; a familiarization (visit one), pre-testing and an acute resistance exercise bout (visit two), and post-testing at 24, 48, and 72 hours following the bout of resistance exercise (visits 3-5). All visits were completed in the morning around the same time of day (± 2 hrs).

Familiarization (Visit One)

Each firefighter reported for visit one immediately after a shift, at least four days (mean ± SD: 7.53 ± 3.19 days) prior to visit two. All participants read and signed an informed consent document stating the experimental protocol with the potential risks and benefits associated with participation in the study, as well as a health history questionnaire. Participants first had their height and weight measured and their body mass index (BMI) calculated. Height (HT) was measured to the nearest 0.1 cm with a calibrated stadiometer. Body mass (BM) was measured to the nearest 0.01 kg using a calibrated clinical scale (Seca 769, Hamburg, Germany). Body mass index was calculated using the equation $BMI=BM\ (kg)/HT^2\ (m^2)$. Participants were then familiarized with ultrasonography (US) imaging, a countermovement vertical jump (CMJ) assessment, isometric strength assessments, and the resistance training exercises. To prescribe the appropriate loads for the resistance exercise bout, each firefighter performed a multi-repetition maximum assessment for each exercise (deadlift, shoulder press, lunge, and upright row) similar to procedures described by the National Strength and Conditioning Association.[178] Participants were initially instructed how to complete each exercise safely using proper form. The deadlift was completed using a kettlebell handle (KettleClamp, In The Box RX, LLC) and a commercially available plate-loaded dumbbell (ODH-20, Ader Sporting Goods, Dallas, TX, USA). The shoulder press and lunges were completed using adjustable dumbbells (PowerBlock Inc., Owatonna, MN, USA) and the upright row was completed using a single adjustable dumbbell with a kettlebell handle (PowerBlock Inc., Owatonna, MN, USA). They performed a weighted warm-up for each exercise, with progressively heavier loads, for sets of 8-10 and 4-6 repetitions with one minute of rest between sets. After completing the warm-up sets, participants were given two minutes of rest. An estimated weight that the participant could lift for six repetitions was then selected for the participant to perform one set of as many repetitions as possible to failure. Using the weight and number of repetitions the participant completed, the participant's one repetition maximum (1RM) was estimated using the following modified equation:[179]

$$1\text{RM} = \frac{\text{Repetition Weight}}{0.522 + 0.419e^{(-0.055\text{xRTF})}}$$

The repetition weight is the load (kg) used for each exercise and RTF is the number of repetitions completed to failure. This calculation was used to estimate the 1RM for each exercise.

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Visit two (PRE) occurred following a participant's shift. Visits 3-5 occurred 24, 48, and 72 hours (P24, P48, P72, respectively) after visit two as participants were coming on- or off-shift. All testing included a comprehensive neuromuscular assessment commonly used to examine recovery from exercise.[78] Each testing visit included 1) a questionnaire to assess the participant's current level of fatigue, 2) a visual analog scale (VAS) to determine subjective perceived muscle soreness, 3) ultrasonography to determine the size and echogenicity of the vastus lateralis (VL) and biceps brachii (BB), 4) a CMJ test to measure jump height and average velocity, 5) an upper-body (UB) maximum isometric strength assessment, and 6) a lower-body

(LB) maximum and rapid isometric strength assessment using a calibrated custom isometric dynamometer with pre-amplified electromyographic (EMG) electrodes placed over the VL to examine muscle activation.

Fatigue Scale

To account for the unanticipated changes in work schedules, variability in occupational demands, and/or volume of calls that firefighters may experience on shift, a work-related fatigue (WRF) questionnaire[180] was used to determine WRF prior to testing during visits 2-5. The questionnaire asked participants: 'How tired are you right now as a result of your previous workday in: 1) your body in general; 2) your back; 3) your neck/shoulders; 4) your arms/wrists; and 5) your lower limbs?'. Participants were instructed to circle one answer for each of the five questions. The answer options included: 1) Not tired; 2) A little tired; 3) Somewhat tired; 4) Very tired; or 5) Completely exhausted. As described previously,[180] an average WRF score from all five questions was calculated for each participant on each visit and used in the analyses.

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A separate VAS was used to determine the participant's perceived muscle soreness for their lower- and upper-body during visits 2-5. The scale ranged from 0 (no discomfort at all) to 100 (worst imaginable pain) and asked the participants to rate their muscle soreness by placing a vertical mark on the line given.

Ultrasonography

A B-mode US (Logiq-e, General Electric Company, Milwaukee, WI, USA) with a multi-frequency linear-array probe (12L-RS; 5-13 MHz; 38.4 mm FOV, General Electric Company, Milwaukee, WI, USA) was used to determine muscle size (cross-sectional area; CSA) and muscle quality (echo-intensity; EI) of the VL and muscle thickness (MT) and EI of the BB. All imaging was performed on the right limbs and the settings for all scans were held constant at: gain (56 dB), depth (6 cm), frequency (10.0 MHz). Muscle size and EI of the VL were determined from a transverse panoramic scan of the thigh, as described previously.[181] Prior to the VL imaging, the participants were positioned supine with the right leg relaxed and supported at 50 degrees of flexion, which was verified using a goniometer (Model G300, Whitehall Manufacturing, City of Industry, CA, USA). A piece of foam padding was strapped to the participant's leg in line with the transverse plane at mid-thigh (approximately halfway between the greater trochanter and lateral femoral epicondyle) so that the probe slid along the skin surface in a straight line perpendicular to the longitudinal axis of the thigh. The probe was moved from the medial to lateral portion of the muscle at a consistent speed using non-allergenic ultrasound gel (Aquasonic 100, Parker Laboratories Inc, Fairfield, NJ, USA) to improve acoustic coupling. Muscle thickness of the BB was determined from a transverse scan at approximately 66% of the distance from the acromion of the scapula to the fossa cubit, as described previously.[182] During the scan, participants were positioned with their arm extended, abducted, relaxed, and supported on a table. All US scans were completed by the same researcher.

All US imaging analyses were performed by the same investigator using ImageJ software (National Institute of Health, MD, USA, Version 1.37). The straight-line function was used to convert each image from pixels to centimeters. To determine CSA, the same technician used the polygon function to trace the outline of the VL for each participant's scan along the fascia border as close as possible to capture only the muscle. This traced region was then analyzed within ImageJ to determine CSA (cm^2). The same ImageJ software was also used to determine muscle thickness of the BB using the straight-line function to measure the distance (cm) from the deep to superficial border of the BB at the mid-point of the muscle. The rectangle function was used to measure the largest possible internal area of the BB, without including any surrounding fascia, which was then used for analysis of EI. Echo-intensity was determined for the VL and BB with a standard mean gray scale analysis, ranging from 0 – 255 units (black = 0, white = 255). Subcutaneous fat thickness (SFT) was measured by using the straight-line function to measure the depth of the subcutaneous fat layer from the average of the mid-point, medial, and lateral borders of the muscle for the VL[183] and from the mid-point of the BB.[182]

Countermovement Vertical Jump

For the CMJ, participants were positioned with feet shoulder-width apart and were instructed to jump vertically, as high as possible, and return to the same position with both feet landing at the same time. A jump mat (Just Jump or Run, Probotics, Inc., Huntsville, AL, USA) was placed beneath the participant's feet and was used to measure jump height. A linear transducer (Tendo Weightlifting Analyzer, Tendo Sports Machines, Trencin, Slovak Republic) was used to measure average velocity (m/s) in accordance with the manufacturers' guidelines (Tendo Weightlifting Analyzer, Microcomputer User's Manual, Trencin, Slovak Republic). The unit cord was attached to the posterior aspect of a belt placed just below the participant's umbilicus with the linear transducer on the floor behind them, as previously described.[184] Participant's completed 3-4 total jumps separated by 30 seconds of rest and the greatest jump height (and associated velocity) of all three jumps was used for analysis.

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Upper-body peak force (PF) was determined from an upper-body strength assessment that was performed as an isometric upright row utilizing a calibrated load cell (TSD121C, Hand Dynamometer, Biopac Systems Inc., Goleta, CA, USA). The load cell was attached to a flat metal platform (on which the participants stood on) and an adjustable chain which connected to a metal bar. Participants grasped the bar with a pronated grip, hands in line with their shoulders, their shoulders abducted, and elbows flexed. The chain was adjusted to one chain link below the level of the umbilicus. Following three submaximal warm-up contractions (50% - 75% of perceived maximum effort), participants performed three isometric maximal voluntary contractions (MVCs) with a two-minute recovery period in between each muscle contraction. Participants were instructed to pull the bar submaximally to remove the slack in the chain immediately prior to the start of the MVC, as determined with visual feedback of force production. During the three MVCs, participants were given a consistent, strong, verbal encouragement to pull as hard and as fast as possible during each contraction of 3-4s. If the participant utilized a countermovement or did not explosively produce force during the MVC, an additional MVC was performed.

Lower body peak and rapid force variables were examined with a custom-built, calibrated, isometric dynamometer during an isometric maximal voluntary contraction. Participants were seated in the dynamometer chair with their right knee fixed at 60-degrees below full extension[185,186] as verified with a goniometer. The load cell (Model 41, Honeywell Inc., Columbus, OH, USA) was positioned approximately two centimeters above the lateral malleolus. A strap was placed across the participant's waist and their left leg to prevent extraneous movements during leg extension. They were also instructed to place their arms across their chest during testing. All of the chair adjustments were recorded and replicated for each testing session. Following three submaximal warm-up contractions (50% - 75% of perceived maximum effort), participants performed three MVCs with a two-minute recovery period in between contractions. Participants were instructed to kick their right leg out as hard and as fast as possible against a stationary padded lever arm for 3-4 seconds to produce maximal force. If the participants did not remain relaxed (i.e. performed a countermovement) before the MVC or did not explosively produce force during the MVC, an additional MVC was performed.

All MVCs were visually inspected for any countermovement and pretension as described by Gerstner et al.[187] There was a noticeable countermovement or pretension for 11 MVCs (PRE: 2 participants; P24: 2 participants; P48: 3 participants; P72: 4 participants). The mean ± standard deviation (SD) of the baseline slope (200ms prior to contraction onset) for these excluded MVCs were $-14.44 \pm 11.41\ \mathrm{N \cdot s^{-1}}$. The baseline slopes for all remaining values were $-0.72 \pm 2.88\ \mathrm{N \cdot s^{-1}}$. The MVC with the highest peak force value was used for all subsequent analyses.

Surface Electromyography

A bipolar, pre-amplified, surface electromyographic (EMG) electrode (TSD150B, Biopac Systems Inc., Goleta, CA, USA; gain = 350 and interelectrode distance of 20 mm) was placed on the VL in accordance with recommendations from the Surface EMG for the Non-Invasive Assessment of Muscles (SENIAM) project.[188] Specifically, the electrode was placed two-thirds the distance from the anterior superior iliac spine to the superior aspect of the lateral patella on the right leg. Additionally, a reference electrode was placed on the tibial tuberosity. Prior to placing the EMG and reference electrodes, the skin was shaved, lightly abraded, and cleansed with rubbing alcohol.

Signal Processing

The force and EMG signals were sampled at 2 kHz with a Biopac data acquisition system (MP150WSW, Biopac Systems Inc., Goleta, CA, USA) and stored on a personal computer (ThinkPad T420; Lenovo, Morrisville, NC). Custom-written software (LabView 17; National Instruments, Austin, TX) was used to process all of the signals offline. The force signals were filtered using a fourth order, zero phase shift low pass Butterworth filter with a 150 Hz cutoff frequency. The EMG signals were filtered using a fourth order, zero phase shift bandpass filter (10 – 500 Hz).

Force and EMG onsets were manually determined by the same investigator using previously established guidelines.[187] The last trough/peak before signal deflection from baseline was manually selected as the force or EMG signal onset. Isometric PF was determined as the highest 500ms epoch during the 3- to 4-s MVC for UB and LB PF. Absolute rapid force variables for the LB were calculated from the force-time curve at 50 (F_{50}), 100 (F_{100}), 150 (F_{150}), and 200ms (F_{200}) from onset. The EMG signal was simultaneously analyzed during the same time epoch as used to determine PF, using the root mean squared (RMS) calculation. The EMG amplitude calculated during the PF epoch (EMG_{MVC}) during each post-testing visit was then normalized to the pre-testing values. In addition, similar to previous work,[187] EMG amplitude variables were quantified at 0-100 (EMG_{0-100}) and 100-200ms ($EMG_{100-200}$) following contraction onset, to represent early and late muscle activation timepoints, and were subsequently normalized to the RMS obtained during PF on each respective day.

Resistance Exercise (Visit Two)

The resistance exercise bout occurred on the same day as pre-testing, following all pre-testing data collection. Participants first completed a brief warm-up set using 40% of their predicted 1RM, which was also used to reinforce proper lifting form. Each firefighter then performed three sets of 8 – 10 repetitions at 80% of their predicted 1RM of the deadlift, shoulder press, lunge, and upright row exercises. The load was selected as 80% 1RM because this has been shown to induce muscular hypertrophy and strength adaptations[189] and is recommended by the American College of Sports Medicine for untrained populations.[190] This load and repetition range has also been previously shown to induce muscle damage.[175,177] These exercises were selected because they are multi-joint movements that engage major muscle groups and can be performed with minimal equipment. The exercises were performed in a circuit style using an adjustable dumbbell set (same as testing) and there was one minute of rest between exercises and two minutes of rest between sets. If participants completed more or less than 8-10 repetitions the loads were increased or decreased by 10%. An experienced member of the research team was present at all times to ensure safe execution of the lifts. Total training volume (load x repetitions) was calculated for each participant to assess any training volume differences between groups.

Heart Rate and Rating of Perceived Exertion

Heart rate (HR) was recorded prior to and during the resistance training session using a Polar HR monitor (H10, Polar Electro Oy, Finland) which was worn around the participant's chest. The participant's resting HR was recorded during the ultrasound assessments in the supine position. Heart rate was also recorded at the completion of the warm-up and immediately after each of the three exercise sets. Each participant's working intensity was calculated as the percentage of heart rate reserve ($\%HRR = ((HR_{exercise} - HR_{rest})/(HR_{max} - HR_{rest}))$ at the end of each set. The participant's rating of perceived exertion (RPE) was assessed with the OMNI resistance training RPE scale.[191] The participants' RPE was recorded at the same time as HR at the completion of the warm-up and after each of the three exercise sets.

Statistical Analysis

Descriptive data were summarized using mean ± standard deviation (SD). An independent T-test was employed to examine baseline group differences in age, stature, body mass, BMI, SFT of the VL and BB, and total training volume. A linear mixed model was employed to examine the mean change in RPE and %HRR during the training session. The same model was used to examine changes in reported WRF over time for both groups.

A linear mixed model, with fixed effects for group (young v. older) and time (PRE v. P24 v. P48 v. P72), while covarying for WRF, was employed to examine the mean and longitudinal changes in maximal strength (PF). The interaction was tested first; if non-significant, a reduced model was used without the interaction. Contrasts were then used to test for differences between time and/or group and only if overall contrasts were significant, pairwise comparisons were completed. The same methods were used to compare groups' self-reported soreness for the upper- and lower-body (VAS), CMJ height and velocity, CSA and EI of the VL, MT and EI of the BB, rapid forces of the lower body (F_{50}, F_{100}, F_{150}, and F_{200}) and EMG amplitude (EMG_{0-100}, $EMG_{100-200}$, EMG_{MVC}). The subjects were chosen as the random effect within the linear mixed model because of expected variation and this was significant for all analyses ($P<0.001$). Outliers were defined as values being at least three times greater than the interquartile range and were removed from analyses. All analyses were performed with SAS (Version 9.4, SAS Institute Inc., Cary, NC, USA) with an alpha level set a priori at $P \leq 0.05$.

CHAPTER IV: MANUSCRIPT

Introduction

Firefighters provide critical emergency services to communities across the country, despite experiencing one of the highest rates of occupational injuries.[1,2] The National Fire Protection Association reported that there were 58,835 injuries among firefighters in 2017.[192] The primary non-fatal injuries that are commonly reported include strains and sprains[1,2,192] to the extremities and back[4] and are often attributed to acute overexertion and slips, trips, and falls.[192] These injuries result in above average worker's compensation claims,[5] extended worker absence rates,[1,6] and are the leading cause of early retirement in firefighters.[7]

Exercise has been consistently listed as the primary approach to reducing injuries in the fire service.[8,9] However, more than 75% of firefighters fail to achieve the minimum physical activity recommendations from the American College of Sports Medicine.[10] The workplace (e.g. fire station) may provide an optimal setting to improve the exercise habits of firefighters. For example, worksite exercise programs may offer unique advantages to the employee that include convenience (i.e. less travel, ease of access to equipment), lower associated-costs, and improved camaraderie among co-workers who train together.[11] Previous studies have shown that worksite exercise can improve working physical capacity, musculoskeletal (MSK) pain, and reduce the incidence of injury in a number of occupations.[6,12,13] It is well documented that resistance training improves muscle strength, power, and endurance,[14-16] which are critical to the safe execution of essential firefighter tasks.[13,17-19] Furthermore, resistance training has been shown to target risk factors associated with the primary non-fatal injuries reported among firefighters.[20,21] These data may demonstrate that worksite resistance exercise can be an important tool to reduce injuries and improve performance in the fire service.

Nearly all United States firefighters are between the ages of 20 – 59 years.[22] Given the large age range of firefighters, it is important to determine if aging influences their recovery from a worksite resistance exercise routine. Previous studies have indicated that age may influence the adaptations following chronic resistance training,[23,24] and it is possible that these alterations may be mediated by a prolonged recovery response.[25,26] Furthermore, an altered recovery response in older firefighters may have unintended consequences that include increases in the risk of strain and sprain injuries and impaired subsequent job performance when performed on-shift. These studies may suggest that future research is needed to examine the influence of aging on the recovery following worksite resistance training to inform future worksite exercise prescription among firefighters. Therefore, the purpose of this study is to examine the influence of age on the recovery from a feasible, worksite resistance exercise in firefighters that includes minimal free weight equipment.

Methods

Participants

Twenty young and 21 older active-duty male career firefighters volunteered to take part in this study. Demographic data are displayed in Table 1. Three participants withdrew from the study due to experiencing low back musculoskeletal pain following testing (2 older firefighters) or a lack of follow-up contact following testing (1 younger firefighter), therefore, 38 participants completed all testing visits (19 young and 19 older firefighters). The firefighters were solicited from local departments near the University of North Carolina at Chapel Hill. All participants provided written and dated informed consent (IRB# 18-0025) to participate in the research study. Additionally, the participants agreed to abstain from vigorous exercise (48 hours) or any exercise (24 hours) prior to all testing visits as well as abstain from any recovery strategies (i.e. massage, ice baths, ibuprofen, etc.) for the duration of the study. Participants also abstained from food and drinks (except water) four hours prior to their first visit and abstained from caffeine, tobacco, and alcohol (8 hours) prior to all testing visits. None of the participants reported any neuromuscular, cardiovascular, or metabolic disease (i.e., diabetes); had a current or recent (within the past three months) musculoskeletal injury of the upper- or lower-body and/or lower back that would not allow them to complete the testing; were involved in an active workers' compensation or personal injury case; currently performed more than three sessions per week of resistance training (on average) over the last three months. The average reported hours of resistance training per week for all participants was 2.00 ± 2.15 hours/wk.

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Upper-body peak force (PF) was determined from an upper-body strength assessment that was performed as an isometric upright row utilizing a calibrated load cell (TSD121C, Hand Dynamometer, Biopac Systems Inc., Goleta, CA, USA). The load cell was attached to a flat metal platform (on which the participants stood on) and an adjustable chain which connected to a metal bar. Participants grasped the bar with a pronated grip, hands in line with their shoulders, their shoulders abducted, and elbows flexed. The chain was adjusted to one chain link below the level of the umbilicus. Following three submaximal warm-up contractions (50% - 75% of perceived maximum effort), participants performed three isometric maximal voluntary contractions (MVCs) with a two-minute recovery period in between each muscle contraction. Participants were instructed to pull the bar submaximally to remove the slack in the chain immediately prior to the start of the MVC, as determined with visual feedback of force production. During the three MVCs, participants were given a consistent, strong, verbal encouragement to pull as hard and as fast as possible during each contraction of 3-4s. If the participant utilized a countermovement or did not explosively produce force during the MVC, an additional MVC was performed.

Lower body peak and rapid force variables were examined with a custom-built, calibrated, isometric dynamometer during an isometric maximal voluntary contraction. Participants were seated in the dynamometer chair with their right knee fixed at 60-degrees below full extension[185,186] as verified with a goniometer. The load cell (Model 41, Honeywell Inc., Columbus, OH, USA) was positioned approximately two centimeters above the lateral malleolus. A strap was placed across the participant's waist and their left leg to prevent extraneous movements during leg extension. They were also instructed to place their arms across their chest during testing. All of the chair adjustments were recorded and replicated for each testing session. Following three submaximal warm-up contractions (50% - 75% of perceived maximum effort), participants performed three MVCs with a two-minute recovery period in between contractions. Participants were instructed to kick their right leg out as hard and as fast as possible against a stationary padded lever arm for 3-4 seconds to produce maximal force. If the participants did not remain relaxed (i.e. performed a countermovement) before the MVC or did not explosively produce force during the MVC, an additional MVC was performed.

All MVCs were visually inspected for any countermovement and pretension as described by Gerstner et al.[187] There was a noticeable countermovement or pretension for 11 MVCs (PRE: 2 participants; P24: 2 participants; P48: 3 participants; P72: 4 participants). The mean ± standard deviation (SD) of the baseline slope (200ms prior to contraction onset) for these excluded MVCs were -14.44 ± 11.41 $\text{N}\cdot\text{s}^{-1}$. The baseline slopes for all remaining values were -0.72 ± 2.88 $\text{N}\cdot\text{s}^{-1}$. The MVC with the highest peak force value was used for all subsequent analyses.

Surface Electromyography

A bipolar, pre-amplified, surface electromyographic (EMG) electrode (TSD150B, Biopac Systems Inc., Goleta, CA, USA; gain = 350 and interelectrode distance of 20 mm) was placed on the VL in accordance with recommendations from the Surface EMG for the Non-Invasive Assessment of Muscles (SENIAM) project.[188] Specifically, the electrode was placed two-thirds the distance from the anterior superior iliac spine to the superior aspect of the lateral patella on the right leg. Additionally, a reference electrode was placed on the tibial tuberosity. Prior to placing the EMG and reference electrodes, the skin was shaved, lightly abraded, and cleansed with rubbing alcohol.

Signal Processing

The force and EMG signals were sampled at 2 kHz with a Biopac data acquisition system (MP150WSW, Biopac Systems Inc., Goleta, CA, USA) and stored on a personal computer (ThinkPad T420; Lenovo, Morrisville, NC). Custom-written software (LabView 17; National Instruments, Austin, TX) was used to process all of the signals offline. The force signals were filtered using a fourth order, zero phase shift low pass Butterworth filter with a 150 Hz cutoff frequency. The EMG signals were filtered using a fourth order, zero phase shift bandpass filter (10 – 500 Hz).

Force and EMG onsets were manually determined by the same investigator using previously established guidelines.[187] The last trough/peak before signal deflection from baseline was manually selected as the force or EMG signal onset. Isometric PF was determined as the highest 500ms epoch during the 3- to 4-s MVC for UB and LB PF. Absolute rapid force variables for the LB were calculated from the force-time curve at 50 (F_{50}), 100 (F_{100}), 150 (F_{150}), and 200ms (F_{200}) from onset. The EMG signal was simultaneously analyzed during the same time epoch as used to determine PF, using the root mean squared (RMS) calculation. The EMG amplitude calculated during the PF epoch (EMG_{MVC}) during each post-testing visit was then normalized to the pre-testing values. In addition, similar to previous work,[187] EMG amplitude variables were quantified at 0-100 (EMG_{0-100}) and 100-200ms ($EMG_{100-200}$) following contraction onset, to represent early and late muscle activation timepoints, and were subsequently normalized to the RMS obtained during PF on each respective day.

Resistance Exercise (Visit Two)

The resistance exercise bout occurred on the same day as pre-testing, following all pre-testing data collection. Participants first completed a brief warm-up set using 40% of their predicted 1RM, which was also used to reinforce proper lifting form. Each firefighter then performed three sets of 8 – 10 repetitions at 80% of their predicted 1RM of the deadlift, shoulder press, lunge, and upright row exercises. The load was selected as 80% 1RM because this has been shown to induce muscular hypertrophy and strength adaptations[189] and is recommended by the American College of Sports Medicine for untrained populations.[190] This load and repetition range has also been previously shown to induce muscle damage.[175,177] These exercises were selected because they are multi-joint movements that engage major muscle groups and can be performed with minimal equipment. The exercises were performed in a circuit style using an adjustable dumbbell set (same as testing) and there was one minute of rest between exercises and two minutes of rest between sets. If participants completed more or less than 8-10 repetitions the loads were increased or decreased by 10%. An experienced member of the research team was present at all times to ensure safe execution of the lifts. Total training volume (load x repetitions) was calculated for each participant to assess any training volume differences between groups.

Heart Rate and Rating of Perceived Exertion

Heart rate (HR) was recorded prior to and during the resistance training session using a Polar HR monitor (H10, Polar Electro Oy, Finland) which was worn around the participant's chest. The participant's resting HR was recorded during the ultrasound assessments in the supine position. Heart rate was also recorded at the completion of the warm-up and immediately after each of the three exercise sets. Each participant's working intensity was calculated as the percentage of heart rate reserve ($\%HRR = ((HR_{exercise} - HR_{rest})/(HR_{max} - HR_{rest}))$ at the end of each set. The participant's rating of perceived exertion (RPE) was assessed with the OMNI resistance training RPE scale.[191] The participants' RPE was recorded at the same time as HR at the completion of the warm-up and after each of the three exercise sets.

Statistical Analysis

Descriptive data were summarized using mean ± standard deviation (SD). An independent T-test was employed to examine baseline group differences in age, stature, body mass, BMI, SFT of the VL and BB, and total training volume. A linear mixed model was employed to examine the mean change in RPE and %HRR during the training session. The same model was used to examine changes in reported WRF over time for both groups.

A linear mixed model, with fixed effects for group (young v. older) and time (PRE v. P24 v. P48 v. P72), while covarying for WRF, was employed to examine the mean and longitudinal changes in maximal strength (PF). The interaction was tested first; if non-significant, a reduced model was used without the interaction. Contrasts were then used to test for differences between time and/or group and only if overall contrasts were significant, pairwise comparisons were completed. The same methods were used to compare groups' self-reported soreness for the upper- and lower-body (VAS), CMJ height and velocity, CSA and EI of the VL, MT and EI of the BB, rapid forces of the lower body (F_{50}, F_{100}, F_{150}, and F_{200}) and EMG amplitude (EMG_{0-100}, $EMG_{100-200}$, EMG_{MVC}). The subjects were chosen as the random effect within the linear mixed model because of expected variation and this was significant for all analyses ($P<0.001$). Outliers were defined as values being at least three times greater than the interquartile range and were removed from analyses. All analyses were performed with SAS (Version 9.4, SAS Institute Inc., Cary, NC, USA) with an alpha level set a priori at $P \leq 0.05$.

Results

Demographics

All demographic data are presented in Table 1. There was a significant difference in age ($P<0.001$) and stature ($P=0.033$), but not body mass ($P=0.885$), BMI ($P=0.104$), or VL and BB SFT ($P\geq0.303$) between the young and the older firefighters.

WRF

The raw means for all dependent variables are presented in Table 2. For WRF, there was a significant group × time interaction ($P=0.002$, Figure 2). The older firefighters reported greater and less ($P\leq0.041$) WRF at PRE and P48, respectively, when compared to the young firefighters. There were no differences in WRF between groups at P24 ($P=0.121$) or P72 ($P>0.999$). For the young, WRF at P24 and P48 was greater than both PRE and P72 ($P<0.001$). For the older firefighters, WRF at P72 was less than PRE and P24 ($P\leq0.008$), and P48 was less than P24 ($P=0.033$).

VAS

When controlling for WRF, there was no significant group × time interaction ($P=0.251$) or main effect for group ($P=0.268$) for upper-body VAS values. However, there was a main effect for time ($P<0.001$, Figure 3). When collapsed across groups, upper-body VAS values increased from PRE to P24 and P48 (*P*<0.001), but not at P72 (*P*=0.142). Upper-body VAS values at P24 and P48 were also greater than P72 values (*P*≤0.025).

When controlling for WRF, there was no significant group × time interaction (*P*=0.991) or main effect for group (*P*=0.545) for lower-body VAS values. However, there was a main effect for time (*P*<0.001, Figure 4). When collapsed across groups, lower-body VAS values increased from PRE to P24 and P48 (*P*<0.001), but not at P72 (*P*=0.400). Lower-body VAS values at P24 and P48 were also greater than P72 values (*P*<0.001).

<u>US</u>

When controlling for WRF, there was no significant group × time interaction (*P*=0.277) or main effect for group (*P*=0.313) for VL CSA. However, there was a main effect for time (*P*=0.006, Figure 5). When collapsed across groups, VL CSA increased from PRE to P24, P48, and P72 (*P*≤0.036).

When controlling for WRF, there was no significant group × time interaction (*P*=0.586) or main effect for time (*P*=0.711) for VL EI. However, there was a main effect for group (*P*=0.006, Figure 6) with older firefighters having a greater VL EI when compared to young firefighters.

When controlling for WRF, there was no significant group × time interaction (*P*=0.470) or main effect for group (*P*=0.473) for BB MT. However, there was a main effect for time (*P*=0.002, Figure 7). When collapsed across groups, BB MT increased from PRE to P24, P48, and P72 (*P*≤0.041).

When controlling for WRF, there was no significant group × time interaction (*P*=0.171) or main effect for time (*P*=0.169), however the main effect for group approached significance

(*P*=0.069) for BB EI with the older firefighters having greater EI values when compared to the young firefighters.

CMJ

When controlling for WRF, there was no significant group × time interaction (*P*=0.910) for CMJ height. However, there was a main effect for time (*P*=0.022, Figure 8A) and a main effect for group (*P*<0.001, Figure 8B). When collapsed across groups, CMJ height decreased from PRE to P24 (*P*=0.006), but not at P48 or P72 (*P*≥0.092). Countermovement jump height then increased from P24 to P48 (*P*=0.019). When collapsed across time, CMJ height was greater in the young compared to the older firefighters.

When controlling for WRF, there was no significant group × time interaction (*P*=0.945) for CMJ velocity. However, there was a main effect for time (*P*=0.005, Figure 9A) and a main effect for group (*P*=0.020, Figure 9B). When collapsed across groups, CMJ velocity decreased from PRE to P24 (*P*=0.007), but not at P48 or P72 (*P*≥0.416). Countermovement jump velocity then increased from P24 to P48 and P72 (*P*≤0.003). When collapsed across time, CMJ velocity was greater for young when compared to the older firefighters.

Isometric Strength

When controlling for WRF, there was no significant group × time interaction (*P*=0.384) or main effect for group (*P*=0.138) for UB PF. However, there was a main effect for time (*P*=0.027, Figure 10). When collapsed across groups, UB PF decreased from PRE to P24 and P48 (*P*≤0.035), but not at P72 (*P*=0.132).

When controlling for WRF, there was no significant group × time interaction (*P*=0.185) or main effect for time (*P*=0.279) for LB PF. However, there was a main effect for group

(*P*=0.004, Figure 11) with young firefighters having greater LB PF when compared to the older firefighters.

When controlling for WRF, there was no significant group × time interaction (*P*=0.970), main effect for time (*P*=0.420), or main effect for group (*P*=0.849) for F_{50}.

When controlling for WRF, there was no significant group × time interaction (*P*=0.579) or main effect for group (*P*=0.435) for F_{100}. However, there was a main effect for time (*P*=0.002, Figure 12). When collapsed across groups, F_{100} decreased from PRE to P24, P48, and P72 ($P \leq 0.044$).

When controlling for WRF, there was no significant group × time interaction (*P*=0.685) or main effect for group (*P*=0.137) for F_{150}. However, there was a main effect for time ($P<0.001$, Figure 13). When collapsed across groups, F_{150} decreased from PRE to P24, P48, and P72 ($P \leq 0.011$).

When controlling for WRF, there was no significant group × time interaction (*P*=0.615) for F_{200}. However, there was a main effect for time ($P<0.001$, Figure 14A) and group (*P*=0.047, Figure 14B). When collapsed across groups, F_{200} decreased from PRE to P24, P48, and P72 ($P \leq 0.006$). Furthermore, when collapsed across time, F_{200} was greater for the young when compared to older firefighters.

EMG

When controlling for WRF, there was no significant group × time interaction (*P*=0.216), main effect for group (*P*=0.637), or main effect for time (*P*=0.230) for EMG_{MVC}.

When controlling for WRF, there was no significant group × time interaction (*P*=0.590) or main effect for group (*P*=0.895) for EMG_{0-100}. However, there was a main effect for time (*P*=0.021, Figure 15). When collapsed across groups, EMG_{0-100} decreased from PRE to P72

(P=0.002). In addition, P24 and P48 time points were lower than PRE and approached significance (P≤0.075).

When controlling for WRF, there was no significant group × time interaction (P=0.812) or main effect for group (P=0.638) for $EMG_{100-200}$. However, there was a main effect for time (P=0.014, Figure 16). When collapsed across groups, $EMG_{100-200}$ decreased from PRE to P48 and P72 (P≤0.008), but not P24 (P=0.282).

Training

There was no significant difference (P=0.256) between young and older firefighters in total training volume during the resistance training session (4371.58 ± 908.10 kg and 4000.57 ± 1067.37 kg, respectively). Rating of perceived exertion (RPE) and %HRR data are presented in Table 3.

For RPE, there was no significant group × time interaction (P=0.937) or main effect for group (P=0.214). However, there was a main effect for time (P<0.001, Figure 17). When collapsed across groups, RPE increased across all time point comparisons (WU < Set 1< Set 2 < Set 3, P<0.001).

For %HRR there was no significant group × time interaction (P=0.899). However, there was a main effect for time (P<0.001, Figure 18A) and group (P=0.023, Figure 18B). When collapsed across time, the young firefighters trained at a greater %HRR when compared to older firefighters. When collapsed across groups, %HRR increased over time (WU < Set 1 < Set 2 and Set 3, P<0.001), but the increase only approached significance from Set 2 to Set 3 (P=0.058).

Discussion

The primary findings of the present study indicated that, when accounting for WRF differences between groups, the young and older firefighters demonstrated a similar recovery following a bout of worksite resistance exercise, as none of the indirect markers of muscle damage revealed an interaction effect. It is important to note that resistance training volume and perceived exertion were similar between groups, whereas %HRR was slightly higher in the young firefighters (Table 3). The similar recovery between groups is supported by Gordon et al.[174] who found no differences in the recovery response of young (21.8±2.0 yrs) and older (47.0±4.4 yrs) recreationally active adults of similar ages as in the current study, following a high-volume isokinetic resistance training session. In addition, McLester et al.[175] utilized a traditional resistance training session to examine recovery responses in young (22.6±4.6 yrs) and older men (56.4±5.0 yrs) and found that both groups exhibited similar recovery responses up to 48 hours after exercise. However, at 72 and 96 hours post-exercise, the older group-maintained baseline performance while the younger group began to exceed baseline performance. Furthermore, Lavender et al.[176] compared the recovery responses in young (19.4±0.4 yrs) and older (48.0±2.1 yrs) men after eccentric exercise of the elbow flexors and found that no significant differences existed between the groups' recovery for maximal isometric strength, arm circumference, or range of motion.

The results of the present study indicated that young firefighters exhibit greater lower-body strength (PF and F_{200}) than older firefighters. This is not surprising considering that losses of muscle strength may begin as early as the second decade[151] and similar findings that older men exhibit decreased lower-body strength are well-documented.[174,187,193] However, the present study indicated no group differences in upper-body strength. This is supported by previous research examining firefighters[194,195] and suggests that upper-body strength may be preserved with aging in this population. This may be due to the physical nature of their job which requires significant upper-body strength and endurance to perform daily tasks.[18,39]

Within the present study, age-related differences were evident in CMJ height and velocity as young firefighters exhibited greater jump height and velocity than older firefighters. These results are supported by previous data in tactical populations indicating that the aging process negatively influences both of these performance measures.[196,197] Specifically in firefighters, Perroni et al.[196] reported a 13% difference in CMJ height between young (<30 yrs) and older (>45 yrs) firefighters.

No age-related differences existed between groups in the present study for VL CSA or BB MT. However, older firefighters exhibited higher EI values of the VL and non-significantly higher EI values of the BB (*P*=0.069), indicating that older firefighters may have poorer muscle quality. This finding is supported by Gerstner et al.[193] who found no age-related differences in the CSA of the medial gastrocnemius, although the older men exhibited higher EI values. Similarly, Gordon et al.[174] found that young and older men exhibited similar CSA values for the VL but did not report EI values. These results may suggest that muscle size is maintained, however older muscles have a greater infiltration of non-contractile tissue (i.e. fat and fibrous tissues),[183,193] which may be a contributor to the age-related differences that were found in lower-body strength and CMJ performance.

In the present study, CMJ height and velocity decreased significantly at 24 hours and returned to baseline values by 48 hours post-exercise. Byrne et al.[126] found that CMJ height decreased significantly after 100 barbell squats and did not fully return to baseline values until four days post-exercise. In addition, lower body power output has been shown to decrease up to three days after an eccentric exercise session.[136] This difference in the recovery period observed in the present study is likely explained by the type of exercise that was utilized (i.e. eccentric v. traditional resistance training) and the total volume.

In the present study, there was no evidence of EIMD in lower-body PF. Similarly, Gordon et al.[174] found that high volume isokinetic exercise did not cause decrements in peak torque up to 48 hours post-exercise for young or older men. However, studies utilizing eccentric exercise found significant decreases in lower-body strength for 3-7 days post-exercise.[136,137] Since it is well documented that eccentric exercise leads to greater EIMD[77,82] it is also possible that the resistance training exercise bout utilized in the current study, as well as the high-volume isokinetic session utilized by Gordon et al.,[174] did not induce significant muscle damage in the lower-body. This is further supported by a lack of change in EMG_{MVC}. It has previously been shown that muscle activation may be depressed as a result of EIMD[138,198] and thus may reflect the lack of change in lower-body PF.

Unlike lower-body PF, several lower-body rapid strength variables (F_{100}, F_{150}, and F_{200}) decreased across all time points. These rapid strength variables have been shown to be more sensitive to EIMD as evidenced by Peñailillo et al.[199] In addition, Crameri et al.[200] found that the relative decrease in the rate of force development was greater than the relative decrease in peak torque after eccentric exercise. Furthermore, the present study also showed a continued decrease in early and late muscle activation of the VL up to 72 hours post-exercise. However, as previous studies have shown rapid strength is related to CMJ performance,[16,201] we would expect these variables to respond similarly. The prolonged decrease in rapid force and the associated muscle activation variables, beyond the recovery of CMJ height and velocity, may suggest that the firefighters could have been impacted by accumulated fatigue over the course of their shift cycle. Although we attempted to account for physical fatigue using the WRF questionnaire, we did not quantify the mental/emotional fatigue that firefighters may experience over the course of their shift cycle that may reflect their overall workload. For example, previous studies have shown rapid force production to decrease as a result of accumulated fatigue during shiftwork in other populations.[202,203] Therefore, future studies should aim to quantify perceived workload in a more holistic manner using validated questionnaires (e.g. NASA-TLX) in order to examine its possible effects on firefighters' performance and recovery from exercise during a shift cycle.

In the present study, upper-body strength decreased significantly at 24 and 48 hours post-exercise but returned to baseline by 72 hours. This follows previous research that shows upper-body strength decreases 24-48 hours after an unaccustomed bout of exercise,[79,133,176] however these studies show much longer decreases after eccentric exercise of the elbow flexors. It has also been suggested that the upper-body is more susceptible to EIMD than the lower-body as evidenced by larger and prolonged decreases in maximal strength,[122,134] which may explain differences observed between UB and LB PF in the current study. This may also be a result of participants utilizing the upright row as an exercise during the resistance training session and assessment of upper-body strength. It is possible that since participants were being directly tested in the same manner that they were trained during the exercise bout, they exhibited greater decrements in this task.

Firefighters reported that lower- and upper-body soreness increased significantly at 24- and 48-hours post-exercise. This aligns with previous research that suggests delay-onset muscle soreness (DOMS) peaks around 24-48 hours after eliciting muscle damage.[112,121] This is supported by Gordon et al.[174] who found that reported soreness increased at 24 and 48 hours post-exercise in young and older men after high volume isokinetic resistance training. The majority of previous studies evaluate DOMS after eccentric-based exercise which is likely why symptoms are commonly reported to persist several days longer than what was observed in the present study utilizing resistance training.[78,112,133]

In the present study, VL CSA and BB MT increased and remained significantly greater than baseline up to 72 hours post-exercise. These data suggest there may have been an inflammatory response, as evidenced by swelling, within the muscles as a result of the exercise bout and this is supported by previous research.[79,204] For example, Sbricolli et al.[204] showed that muscle thickness of the elbow flexors increased after eccentric exercise and the largest increases were experienced 2-4 days after eccentric exercise. In addition, Nosaka et al.[79] found increases in elbow flexor thickness 4-5 days after eccentric exercise. However, in the present study, there were no significant changes in EI over time which differs from previous studies[79,110,122] that have shown increased EI typically accompanies increases in CSA as a result of EIMD. This may be a result of differences in the type of exercise (i.e. eccentric) and thus the extent of EIMD. However, Chen et al.[122] found that EI increased as a result of eccentric exercise-induced muscle damage in the elbow flexors and extensors and the leg flexors, but not for leg extensors. They suggested that the leg extensors may be accustomed to eccentric contractions as a result of daily activities and are thus less susceptible to experiencing muscle damage than other muscle groups. However, because there were no changes in EI in the present study, changes in CSA and MT should be interpreted cautiously.

Practical Applications

In summary, the primary findings of the current investigation suggest that age did not influence the firefighters' recovery from an acute bout of on-site, circuit based, free weight resistance exercise. These findings may be impactful to fire departments, indicating that they can implement resistance training programs that are uniform to the broad age range within the fire service. It appears that firefighters experience the majority of performance and symptomatic decrements between 24 and 48 hours post-exercise after a bout of worksite resistance exercise, however muscle swelling may persist up to 72 hours. In addition, rapid force production and muscle activation may be decreased up to 72 hours-post exercise, which may be further impacted by fatigue accumulated during the shift cycle. However, future studies are needed to test this hypothesis. Fire administrators should be cognizant of this when implementing a new training program.

CHAPTER V: SUMMARY

Worksite resistance exercise can be an important tool to reduce injuries and improve performance in the fire service. Given the large age range of firefighters, it is important to determine if aging influences their recovery from a worksite resistance exercise routine. The purpose of this study was to determine whether age influences the recovery from a feasible worksite resistance exercise routine. Nineteen young (25.47 ± 3.36 yrs) and 19 older firefighters (50.32 ± 3.53 yrs) completed five testing visits at their fire station as they were coming on- or off-shift. The first visit included a familiarization of the assessments and a multiple repetition maximum (RM) assessment to determine appropriate loads for their training session. The second visit included pre-testing and a circuit-style, resistance training session where they completed three sets of 8-10 repetitions of the deadlift, shoulder press, lunges, and upright row at 80% of their predicted 1RM. Visits 3-5 included post-testing at 24, 48, and 72 hours post-exercise (P24, P48, and P72, respectively). Prior to all testing on visits 2-5, firefighters completed a work-related fatigue (WRF) questionnaire to account for potential differences in previous shiftwork over the past 24 hours. Recovery assessments included reported muscle soreness (VAS), ultrasonography to quantify muscle size and quality of the vastus lateralis (VL) and biceps brachii (BB), countermovement jump (CMJ) height and velocity, upper- and lower-body strength testing, and electromyography (EMG) of the vastus lateralis. All recovery variables were analyzed using a linear mixed model, controlling for WRF. Results revealed no (age × time) interactions for any variable and similar training volumes completed between groups ($P \geq 0.171$

and *P*=0.256, respectively). Group effects indicated that the young firefighters exhibited greater CMJ height and velocity, lower-body peak force, force at 200ms, and better muscle quality than the older firefighters for the VL ($P \leq 0.047$). When collapsed across groups, upper- and lower-body VAS increased at P24 and P48, muscle size for the VL and BB increased across all time points, CMJ height and velocity decreased at P24, and upper-body force decreased at P24 and P48 ($P \leq 0.041$). Also, lower-body rapid force (100, 150, and 200ms) and early and late muscle activation variables remained depressed at P72 ($P \leq 0.044$). The unique responses of the rapid force variables and CMJ and UB strength may suggest a potential accumulation of fatigue due to the firefighters' shift cycle. These results suggest that age does not influence the recovery from an acute bout of worksite resistance exercise in firefighters.

Table 1: Demographics

Mean ± standard deviation (SD) values for demographics in younger and older firefighters

	Young Firefighters	Older Firefighters
Age (years)	25.45 ± 3.27	50.57 ± 3.79*
Stature (cm)	181.00 ± 6.40	176.49 ± 6.65*
Body Mass (kg)	92.58 ± 18.26	93.30 ± 12.87
BMI (kg/m^2)	28.01 ± 5.51	30.66 ± 4.64
VL SFT (cm)	1.08 ± 0.39	0.99 ± 0.29
BB SFT (cm)	0.24 ± 0.15	0.29 ± 0.15

BMI body mass index, VL vastus lateralis, SFT subcutaneous fat thickness, BB biceps brachii, * $P < 0.05$, significant age group difference

Note: (Young: n=20, Older: n=21), SFT (n=19 per group)

Table 2: Unadjusted raw means for the dependent variables

Pre- (i.e. PRE) and post-exercise (i.e. P24, P48, P72) unadjusted raw values (mean ± SD) for all dependent variables

	Age group	PRE	P24	P48	P72
WRF (AU)	Y	1.52 ± 0.41	2.31 ± 0.74	2.06 ± 0.57	1.52 ± 0.37
	O	1.94 ± 0.69	2.01 ± 0.68	1.67 ± 0.56	1.52 ± 0.52
Upper-body VAS (AU)	Y	10.37 ± 10.93	33.63 ± 20.75	30.47 ± 18.64	11.68 ± 10.71
	O	14.42 ± 18.05	24.40 ± 19.53	16.32 ± 14.33	12.84 ± 16.22
Lower-body VAS (AU)	Y	10.22 ± 10.46	40.95 ± 26.06	34.63 ± 22.54	12.68 ± 13.18
	O	16.26 ± 18.33	33.53 ± 22.32	25.63 ± 24.27	9.79 ± 13.28
CMJ Height (cm)	Y	43.51 ± 6.15	42.21 ± 6.30	43.36 ± 6.22	42.88 ± 6.02
	O	34.75 ± 6.35	32.74 ± 6.96	34.37 ± 5.97	34.09 ± 6.53
CMJ Velocity (m/s)	Y	1.30 ± 0.13	1.26 ± 0.19	1.29 ± 0.17	1.31 ± 0.16
	O	1.17 ± 0.18	1.13 ± 0.20	1.18 ± 0.18	1.19 ± 0.18
VL CSA (cm^2)	Y	32.12 ± 7.22	32.20 ±7.20	32.54 ± 7.62	32.28 ± 7.08
	O	28.68 ± 4.62	30.19 ± 5.85	29.79 ± 4.80	30.50 ± 5.91
VL EI (AU)	Y	57.35 ± 4.20	56.80 ± 5.23	57.77 ± 4.87	56.80 ± 4.76
	O	61.81 ± 7.72	62.52 ± 6.96	62.40 ± 6.92	62.01 ± 6.06
BB MT (cm)	Y	2.83 ± 0.45	2.91 ± 0.43	2.92 ± 0.44	2.88 ± 0.43
	O	2.75 ± 0.42	2.77 ± 0.40	2.84 ± 0.38	2.79 ± 0.42
BB EI (AU)	Y	73.60 ± 5.98	72.18 ± 7.41	71.13 ± 9.19	72.09 ± 8.07
	O	74.81 ± 7.77	72.90 ± 5.71	74.53 ± 6.31	78.54 ± 6.72
Upper-body PF (N)	Y	879.23 ± 100.38	841.55 ± 103.89	848.52 ± 96.03	848.70 ± 114.34
	O	812.46 ± 107.91	785.77 ± 122.83	801.40 ± 123.33	814.28 ± 123.71
Lower-body PF (N)	Y	745.51 ± 221.67	706.27 ± 181.10	697.82 ± 172.54	741.42 ± 214.51
	O	589.71 ± 115.33	564.75 ± 138.23	582.28 ± 146.38	554.90 ± 147.27
Lower-body F_{50} (N)	Y	46.44 ± 21.89	39.83 ± 24.97	36.80 ± 16.11	41.75 ± 28.02
	O	41.39 ± 15.58	40.69 ± 22.07	39.76 ± 17.11	36.65 ± 20.02
Lower-body F_{100} (N)	Y	250.09 ± 93.86	205.74 ± 96.91	188.65 ± 77.85	205.19 ± 96.80
	O	212.06 ± 79.83	185.59 ± 73.64	200.97 ± 72.13	166.85 ± 82.96
Lower-body F_{150} (N)	Y	384.00 ± 119.58	332.39 ± 111.11	318.65 ± 94.02	334.58 ± 123.24
	O	321.95 ± 99.69	286.31 ± 80.19	304.98 ± 93.70	267.43 ± 105.79
Lower-body F_{200} (N)	Y	471.90 ± 142.41	409.63 ± 115.16	394.74 ± 109.37	424.75 ± 144.84
	O	382.73 ± 106.09	348.07 ± 89.52	357.50 ± 100.97	329.29 ± 120.05
EMG_{0-100} (%)	Y	121.02 ± 80.90	91.60 ± 33.92	91.03 ± 49.98	83.22 ± 29.57
	O	103.61 ± 33.18	97.57 ± 51.77	99.40 ± 34.12	81.68 ± 54.00
$EMG_{100-200}$ (%)	Y	106.28 ± 38.77	100.87 ± 39.84	86.74 ± 41.99	85.01 ± 23.60
	O	101.69 ± 32.31	90.39 ± 26.95	84.14 ± 27.36	84.58 ± 34.07
EMG_{MVC} (%)	Y	100.00 ± 0.00	94.07 ± 19.91	104.59 ± 35.32	117.35 ± 58.01
	O	100.00 ± 0.00	105.23 ± 11.66	114.14 ± 28.23	99.85 ± 26.59

Y Young, O old, WRF work-related fatigue, VAS visual analog scale, CMJ countermovement jump, VL vastus lateralis, CSA cross sectional area, EI echo-intensity, BB biceps brachii, MT muscle thickness, PF peak force, F_{50-200} force at specific time point (ms), EMG_{0-100} electromyography amplitude at 0-100ms, $EMG_{100-200}$ electromyography amplitude at 100-200ms, EMG_{MVC} electromyography amplitude during MVC, AU aribitrary units

Note: (n=18) WRF: Y-P24; LB VAS: Y-PRE; CMJH: O-P24; VL CSA: O-PRE & P48; BB EI: O-P48; F_{50}: Y-P48; F_{100}, F_{150}, F_{200}, EMG_{0-100}, $EMG_{100-200}$, EMG_{MVC}: Y-PRE & P48, O-PRE

Note: (n=17) F_{50}: Y-PRE & P72, O-PRE, P24 & P72; F_{100}, F_{150}, F_{200}, EMG_{0-100}, $EMG_{100-200}$, EMG_{MVC}: Y-P72, O-P24, P48, P72

Note: (n=16) F_{50}: O-P48

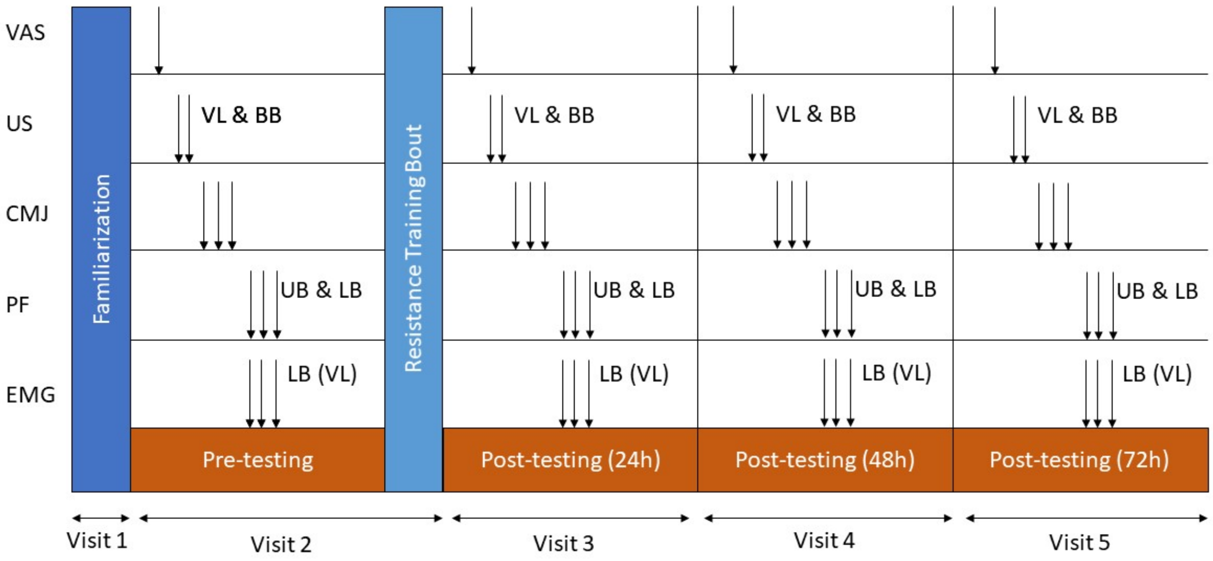
Table 3: Unadjusted raw means for the training session

Mean ± standard deviation (SD) raw values for training session descriptives in younger and older firefighters

	Group	WU	Set 1	Set 2	Set 3	Contrasts
RPE	Y	2.79 ± 1.08	6.25 ± 1.45	7.58 ± 1.22	8.95 ± 1.13	**Time effect:** WU < 1 < 2 < 3 (*P* <0.001)
	O	3.28 ± 1.13	6.72 ± 1.36	8.00 ± 1.14	9.17 ± 0.79	
%HRR	Y	46.55 ± 14.63	75.03 ± 13.78	82.95 ± 9.52	86.81 ± 9.94	**Group effect:** Y > O (*P* =0.023) **Time effect:** WU < 1 < 2, 3 (*P* <0.001)
	O	36.55 ± 11.97	67.50 ± 17.22	73.76 ± 16.08	76.88 ± 16.89	

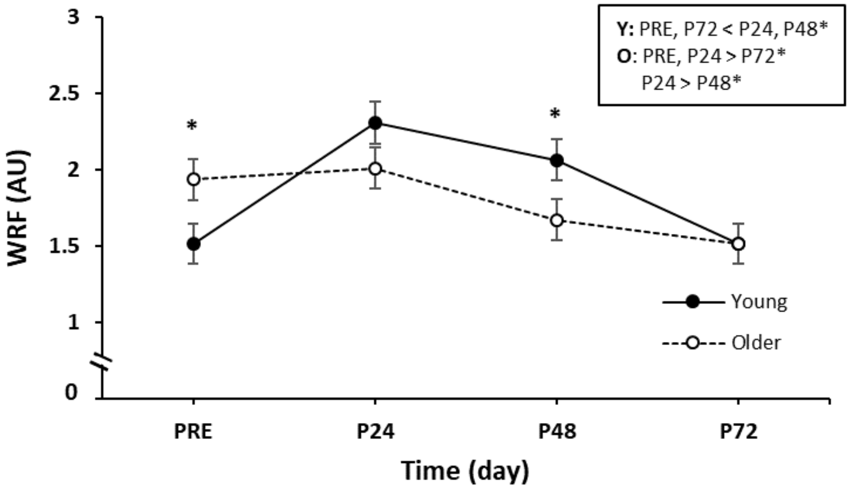
Y young, O older, RPE rating of perceived exertion, %HRR percent of heart rate reserve, WU warm-up
Note: (n=18) RPE: O-Set 3

Figure 1: Experimental design



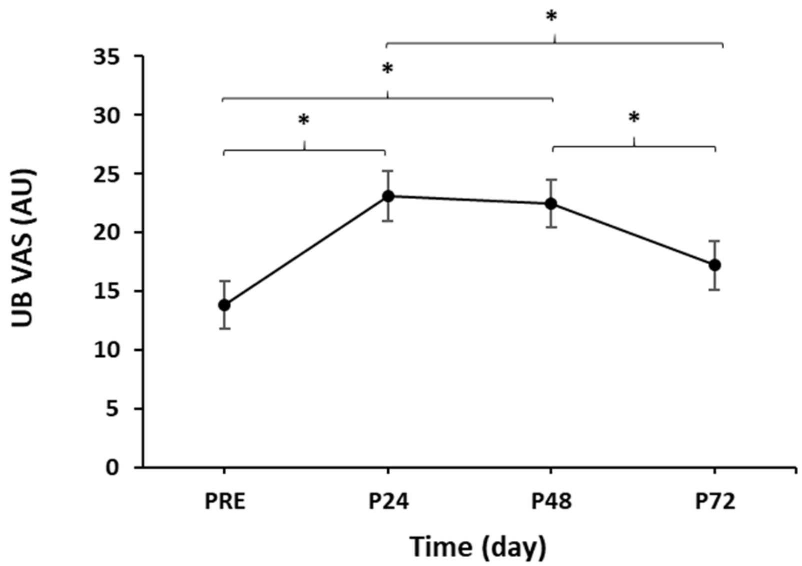
Experimental Protocol: The dependent variables are shown on the left as VAS (visual analog scale), US (ultrasonography), CMJ (countermovement vertical jump), PF (peak force), and EMG (electromyography). The specific visits and sessions are noted on the horizontal axis. The arrows (↓) represent measurements taken, VL=Vastus Lateralis, BB=Biceps Brachii, UB=Upper-body, and LB=Lower-body.

Figure 2: Changes in work-related fatigue



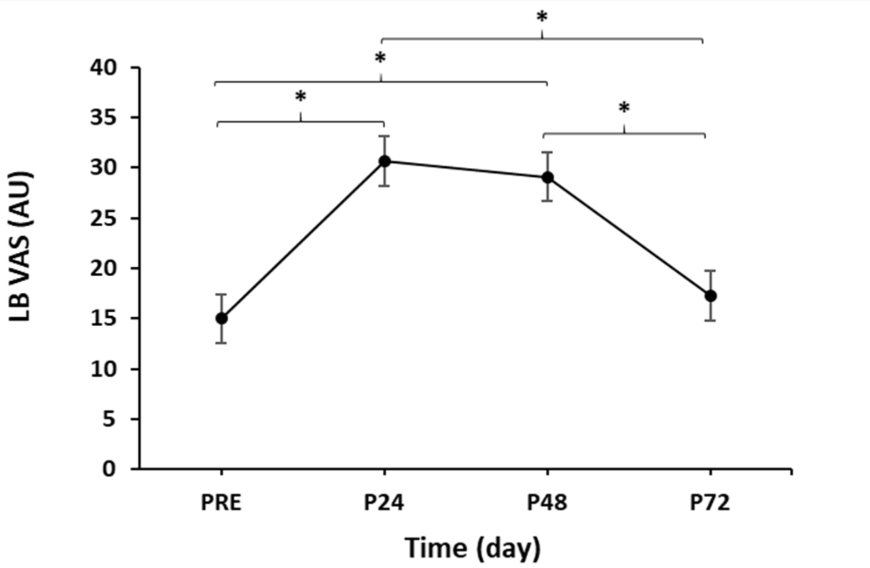
Changes in work-related fatigue (WRF) over the testing period (mean ± SE). (*) significant difference (*P*<0.05) between groups.

Figure 3: Marginal mean changes in upper-body soreness



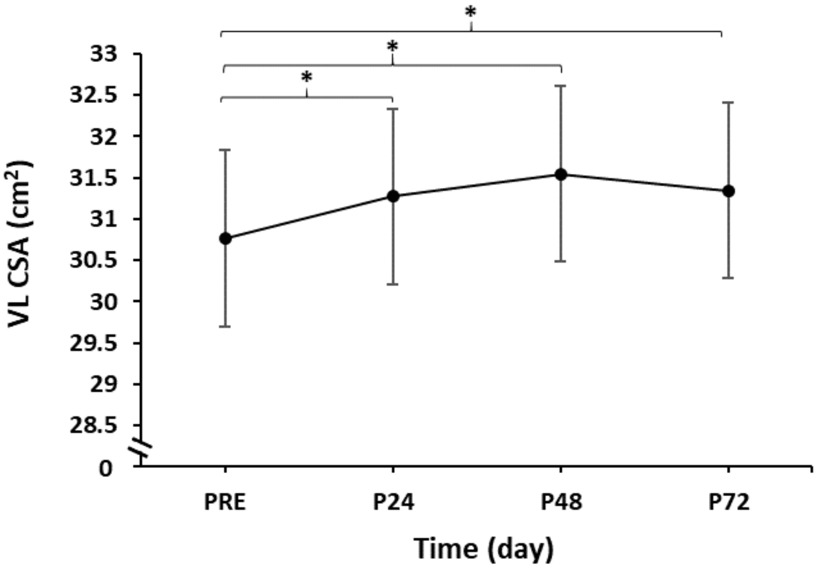
Adjusted marginal mean changes (mean ± SE) in upper-body soreness (UB VAS) over the testing period. (*) significant difference (*P*<0.05) between time points.

Figure 4: Marginal mean changes in lower-body soreness



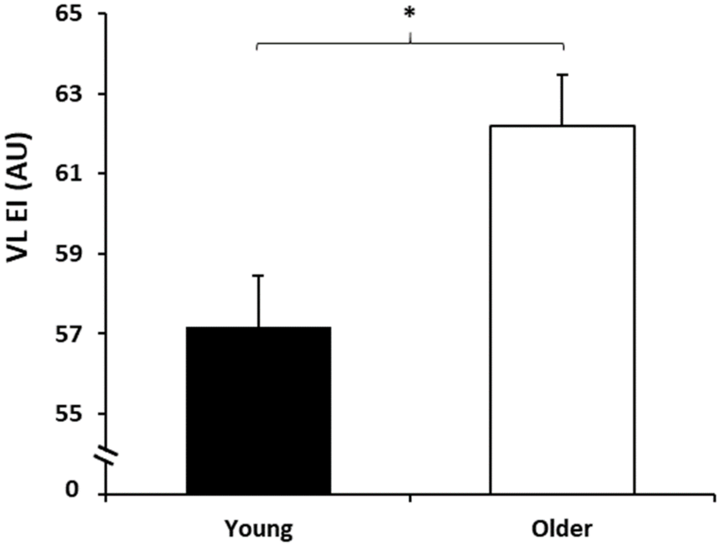
Adjusted marginal mean changes (mean ± SE) in lower-body soreness (LB VAS) over the testing period. (*) significant difference (*P*<0.05) between time points.

Figure 5: Marginal mean changes in vastus lateralis cross-sectional area



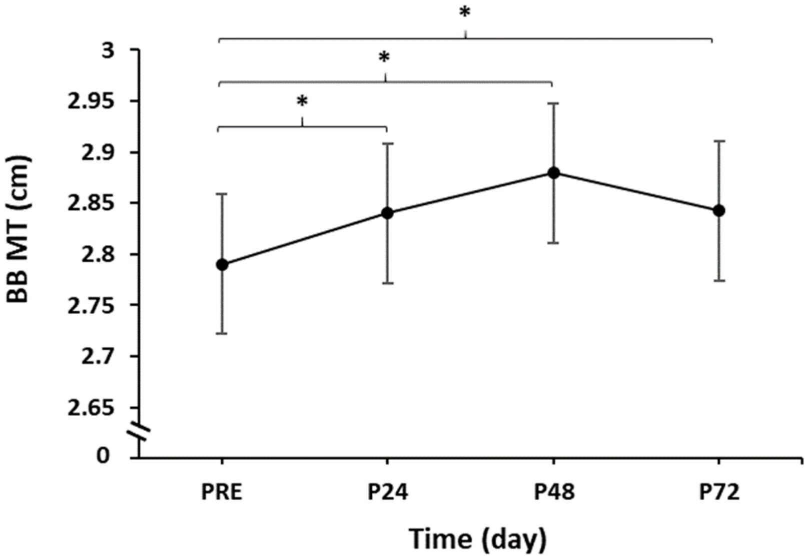
Adjusted marginal mean changes (mean ± SE) in vastus lateralis cross-sectional area (VL CSA) over the testing period. (*) significant difference (P<0.05) between time points.

Figure 6: Marginal means for young and older groups' vastus lateralis echo-intensity



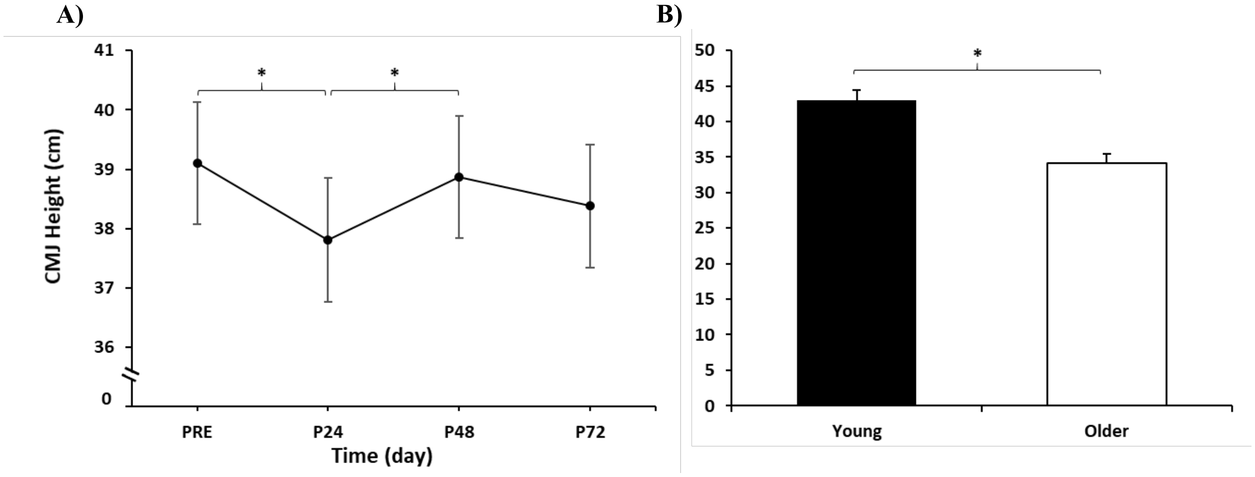
Adjusted marginal means (mean ± SE) for young and older firefighters' vastus lateralis echo-intensity (VL EI). (*) significant difference (*P*<0.05) between groups.

Figure 7: Marginal mean changes in biceps brachii muscle thickness



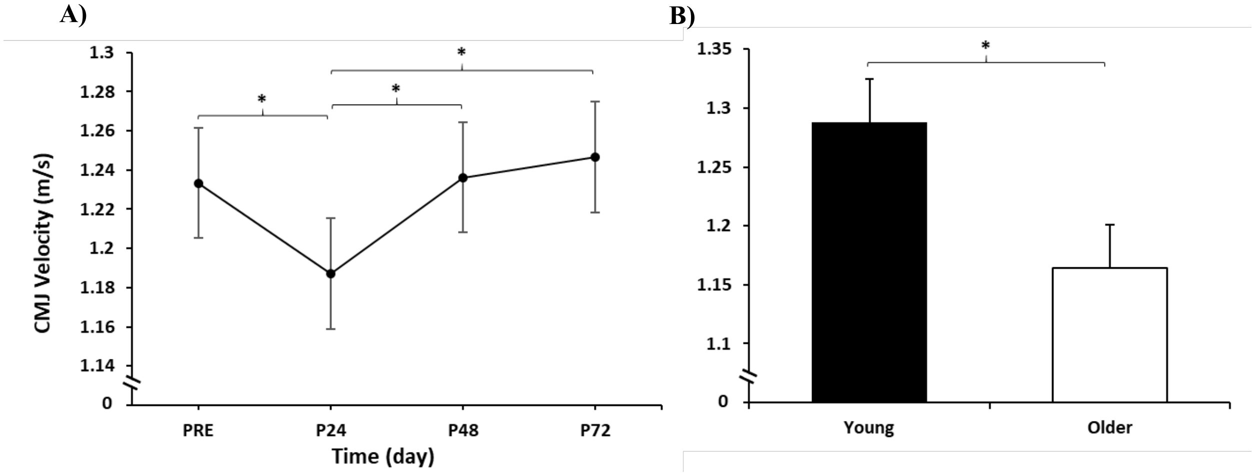
Adjusted marginal mean changes (mean ± SE) in biceps brachii muscle thickness (BB MT) over the testing period. (*) significant difference ($P<0.05$) between time points.

Figure 8: Marginal means for countermovement jump height



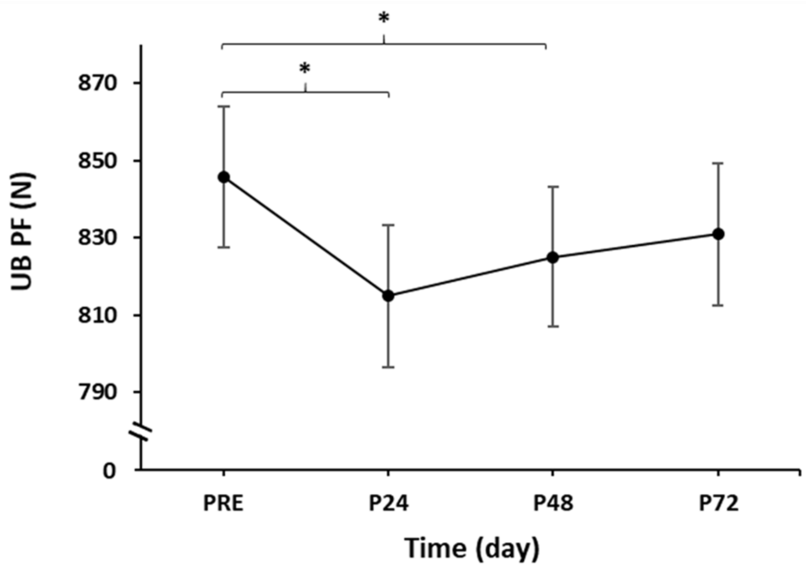
- **A)** Adjusted marginal mean changes (mean ± SE) in countermovement jump (CMJ) height over the testing period. (*) significant difference (*P*<0.05) between time points.
- **B)** Adjusted marginal means (mean ± SE) for young and older firefighters' countermovement jump (CMJ) height. (*) significant difference (*P*<0.05) between groups.

Figure 9: Marginal means for countermovement jump velocity



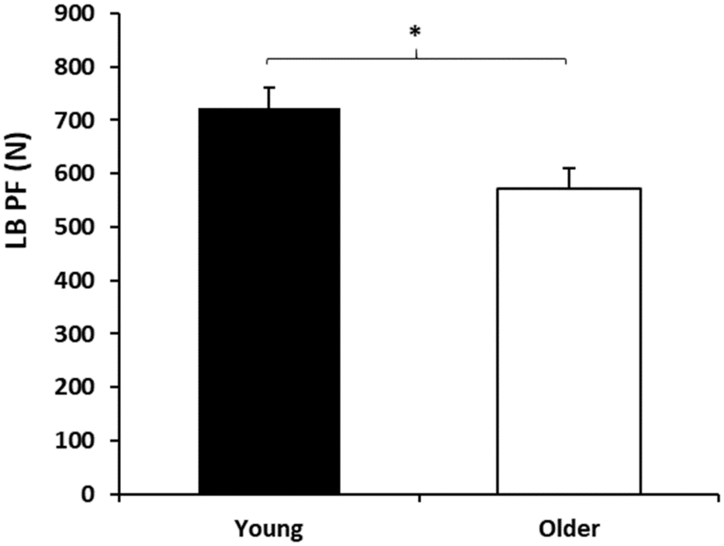
- **A)** Adjusted marginal mean changes (mean ± SE) in countermovement jump (CMJ) velocity over the testing period. (*) significant difference (*P*<0.05) between time points.
- **B)** Adjusted marginal means (mean ± SE) for young and older firefighters' countermovement jump (CMJ) velocity. (*) significant difference (*P*<0.05) between groups.

Figure 10: Marginal mean changes in upper-body peak force



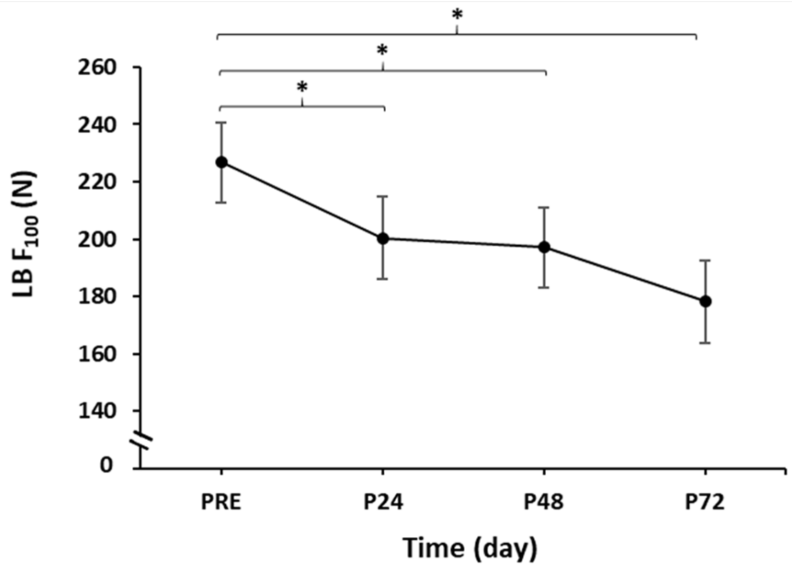
Adjusted marginal mean changes (mean ± SE) in upper-body peak force (UB PF) over the testing period. (*) significant difference (*P*<0.05) between time points.

Figure 11: Marginal means for young and older groups' lower-body peak force



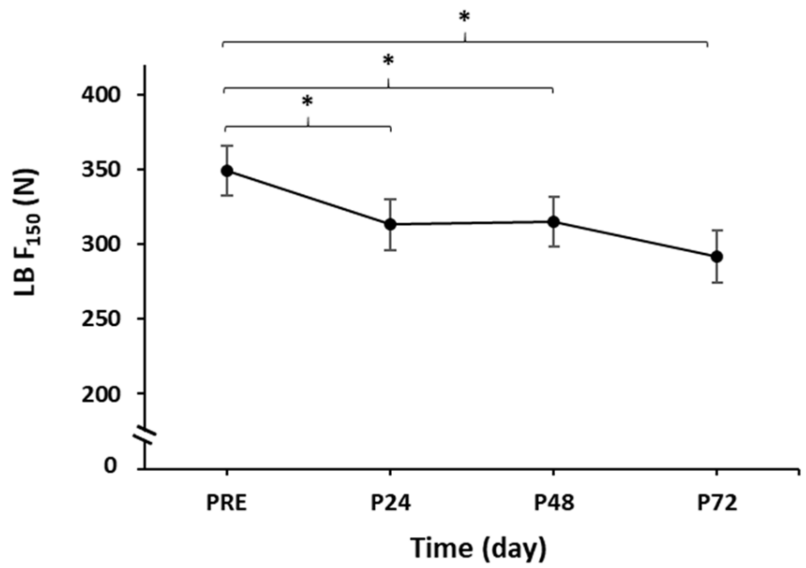
Adjusted marginal means (mean ± SE) for young and older firefighters' lower-body peak force (LB PF). (*) significant difference (*P*<0.05) between groups.

Figure 12: Marginal mean changes in lower-body force at 100ms



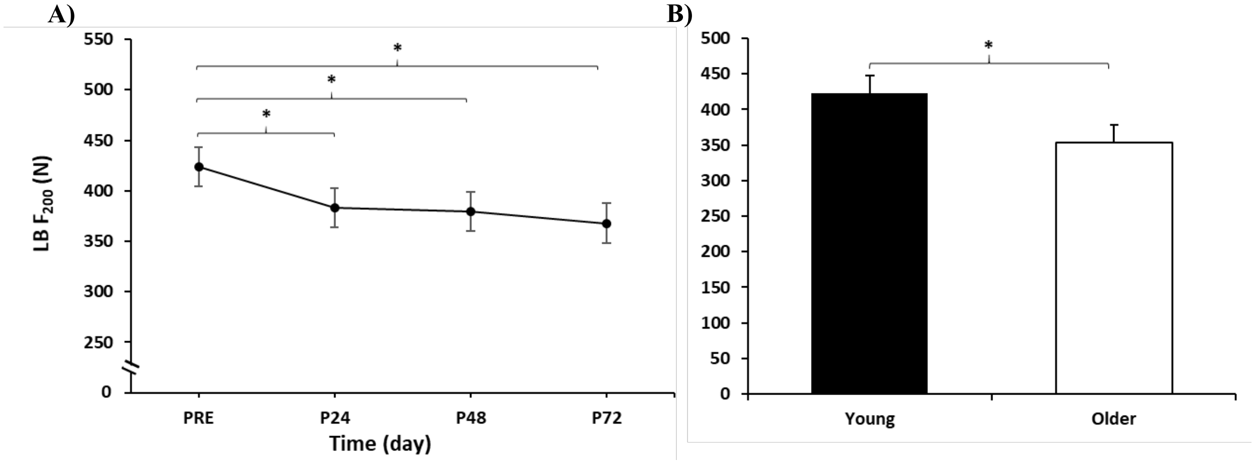
Adjusted marginal mean changes (mean ± SE) in lower-body force at 100ms (LB F_{100}) over the testing period. (*) significant difference (P<0.05) between time points.

Figure 13: Marginal mean changes in lower-body force at 150ms



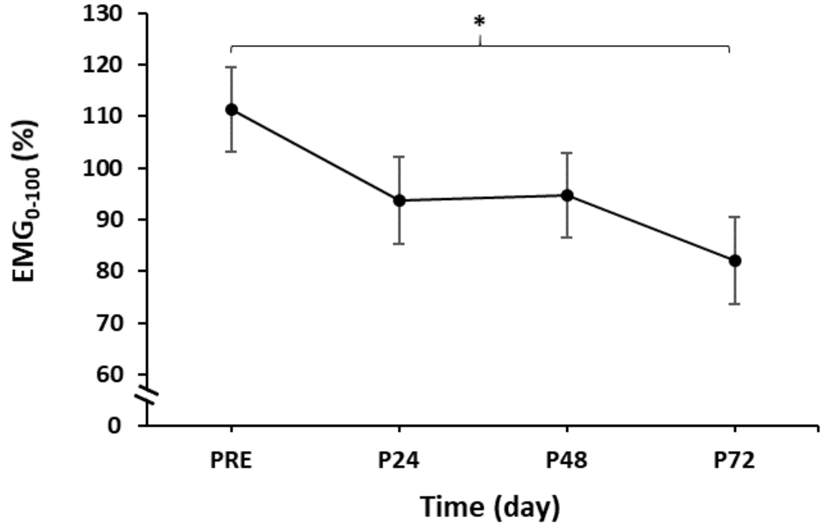
Adjusted marginal mean changes (mean ± SE) in lower-body force at 150ms (LB F_{150}) over the testing period. (*) significant difference ($P<0.05$) between time points.

Figure 14: Marginal means for lower-body force at 200ms



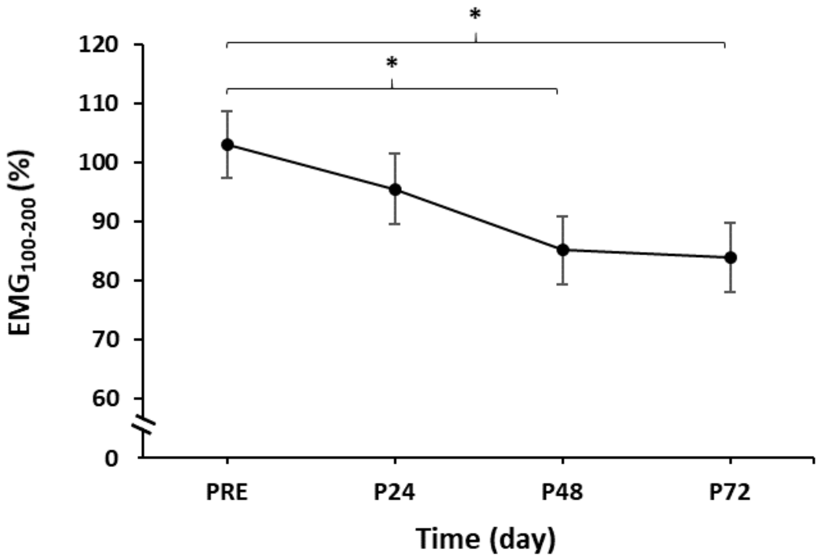
- **A)** Adjusted marginal mean changes (mean ± SE) in lower-body force at 200ms (LB F_{200}) over the testing period. (*) significant difference ($P<0.05$) between time points.
- **B)** Adjusted marginal means (mean ± SE) for young and older firefighters' lower-body force at 200ms (LB F_{200}). (*) significant difference ($P<0.05$) between groups.

Figure 15: Marginal mean changes in EMG amplitude at 0-100ms



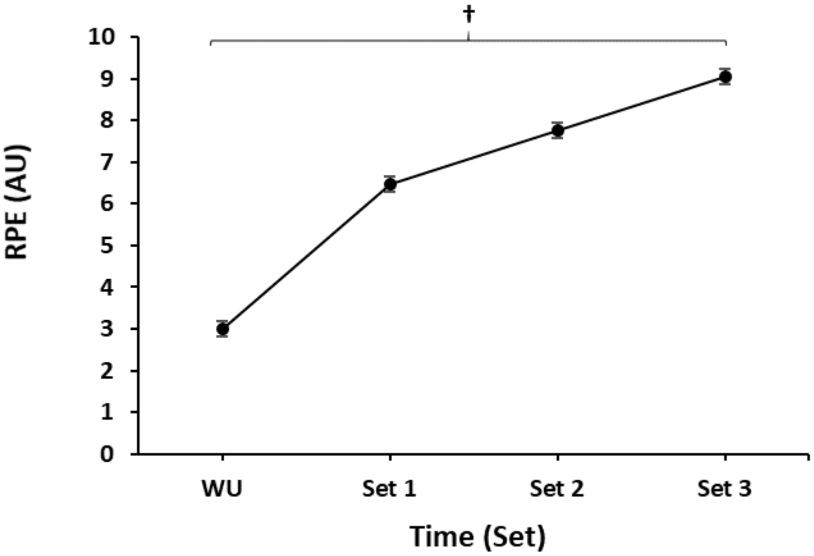
Adjusted marginal mean changes (mean ± SE) in EMG amplitude at 0-100ms (EMG_{0-100}) over the testing period. (*) significant difference (*P*<0.05) between time points.

Figure 16: Marginal mean changes in EMG amplitude at 100-200ms



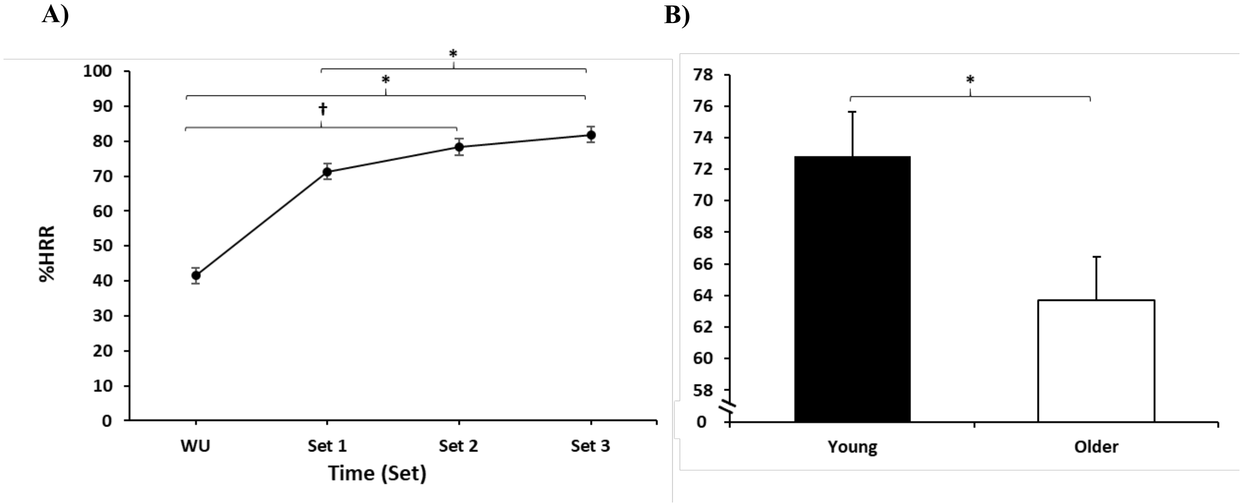
Adjusted marginal mean changes (mean ± SE) in EMG amplitude at 100-200ms ($EMG_{100\text{-}200}$) over the testing period. (*) significant difference (*P*<0.05) between time points.

Figure 17: Marginal mean changes in rating of perceived exertion



Adjusted marginal mean changes (mean ± SE) in rating of perceived exertion (RPE) over the testing period. (†) significant difference (*P*<0.05) between all time points.

Figure 18: Marginal means for percent of heart rate reserve



A) Adjusted marginal mean changes (mean ± SE) in percent of heart rate reserve (%HRR) over the testing period. (†) significant difference ($P<0.05$) between all time points. (*) significant difference ($P<0.05$) between time points.

B) Adjusted marginal means (mean ± SE) for young and older firefighters' percent of heart rate reserve (%HRR). (*) significant difference ($P<0.05$) between groups.

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