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RESEARCH ARTICLE

The impact of inter-limb leg lean tissue mass asymmetry on stair climb performance in career firefighters

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ABSTRACT

The purpose of this study was to examine the influence of inter-limb leg lean tissue mass (LTM) asymmetry on stair climb (SC) performance in firefighters. Forty-one career firefighters (age = 32.3 ± 8.2 years, body mass = 92.1 ± 18.6 kg, stature = 178.3 ± 7.9 cm) visited the laboratory on one occasion and completed a whole body and leg composition assessment followed by a timed and weighted SC task. Percent body fat (%BF) and leg LTM were determined during a DEXA scan and regional thigh analysis. Asymmetry was assessed by the percent difference between limbs (dominant limb LTM − non-dominant limb LTM)/dominant limb LTM × 100) and a ± 3% cut-off for asymmetry classification. Participants ascended and descended 26 stairs four times as quickly as possible while wearing a weighted (22 kg) vest. Point biserial correlations were used to assess the relationship of inter-limb leg LTM asymmetry and SC performance before and after controlling for age and %BF. Results indicated that inter-limb leg LTM asymmetry was associated with longer SC task time (poorer performance) both before ($r = 0.432$, $P = 0.005$) and after ($r = 0.502$, $P = 0.001$) controlling for age and %BF. Our findings indicated that inter-limb leg LTM asymmetry negatively impacts firefighter SC performance, which may be improved with appropriate exercise interventions.

PRACTITIONER SUMMARY

This study examined the influence of leg inter-limb lean tissue mass (LTM) asymmetry on SC performance in career firefighters. We found that inter-limb leg LTM asymmetry was associated with reduced SC performance, prior to and after controlling for age and percent body fat. Interventions that mitigate these asymmetries may improve occupational performance.

Abbreviation: LTM: lean tissue mass; SC: stair climb; DEXA: dual energy x-ray absorptiometry; ACL: anterior cruciate ligament; %BF: percent body fat; PPE: personal protective equipment; BMI: body mass index

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Tactical; occupational health; body composition; occupational performance; ageing

Introduction

Firefighters are paramount to public safety with over 360,000 career firefighters currently employed in the United States, protecting nearly 70% of the population (Fahy, Evarts, and Stein 2020). Occupational injuries are common within the fire service with over 60,000 firefighters being injured on duty in 2021 (Campbell and Hall 2023). These injuries result in a high economic burden, with subsequent expenses between $2.8 billion and $7.8 billion per year (National Institute of Standards and Technology, 2019). One potential contributing factor is that these individuals are required to perform a number of critical and essential tasks in hazardous conditions while wearing personal protective equipment weighing around 22 kg (Mota et al. 2018). Specifically, the International Association of Fire Chiefs and International Association of Firefighters have identified eight critical firefighter tasks in the Candidate Physical Abilities Test (Sheaff et al. 2010). The stair climb (SC)

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task is often considered one of the most critical and challenging tasks. For example, previous studies have demonstrated a significant cardiometabolic response during the SC including near maximal heart rates and increased oxygen consumption and blood lactate levels (von Heimburg, Rasmussen, and Medbø 2006; Plat, Frings-Dresen, and Sluiter 2010; Taylor, Fullagar, et al. 2015). Further, simulated SC assessments have been shown to be reliable (Plat, Frings-Dresen, and Sluiter 2010) and rated as a highly relevant occupational task among firefighters with a mean response of 3.6 on a 0–4 scale (0 = not relevant at all, 4 = very relevant) (Ryan et al. 2022).

Inter-limb leg lean tissue mass (LTM) asymmetries occur when there are inter-limb differences in skeletal muscle mass. These asymmetries have been examined in various populations ranging from athletes to older adults (Bell et al. 2014; Hart et al. 2014; Lepley et al. 2020; Mertz et al. 2019). Previous studies have found leg inter-limb asymmetries adversely impact counter-movement jump height (Bell et al. 2014), contribute to greater leg inter-limb strength differences (Hart et al. 2014), and are associated with reduced performance in common functional tasks (i.e. chair sit-to-stands, walking, timed-up-and-go) (Lee et al. 2019). Previous authors have suggested inter-limb leg LTM asymmetries are influenced by performing various tasks on a favoured side over time (Hides et al. 2010; Krzykała 2010; Lijewski et al. 2021; Stewart et al. 2010). For example, Australian football players tend to have larger psoas muscle size in their kicking (favoured) limb, when compared to their stance leg (Hides et al. 2010; Stewart et al. 2010). It is possible firefighters are exposed to occupational tasks that are performed on a favoured side such as specific victim drag techniques and/or asymmetric load carriage (Alvar et al. 2017; Hides et al. 2010; Stewart et al. 2010). Due to the unilateral limb demands during a SC task (Portegijs et al. 2008), inter-limb leg LTM asymmetries may negatively impact SC performance. For instance, previous authors (Portegijs et al. 2008) have indicated that inter-limb leg asymmetry adversely affects SC speed more than gait speed in older adults due to the higher demand on unilateral leg function. These previous studies indicate a need to assess and examine the relationship between inter-limb leg asymmetries and occupational performance in career firefighters. Therefore, the purpose of this study is to examine the relationship between inter-limb leg LTM differences and SC performance in career firefighters. We hypothesise that firefighters with greater LTM asymmetries will have reduced performance (longer time to completion) during a timed SC task.

Materials and methods

Participants

Forty-one career male firefighters (all demographic data are in Table 1) volunteered for this investigation. All participants were apparently healthy and free of any known cardiovascular, neuromuscular, or metabolic diseases and indicated that they had not sustained any recent musculoskeletal injuries. Participants were excluded if they were a current smoker or had a history of surgery to the low back (e.g. spinal fusion) or lower extremities (e.g. joint replacement, ligament reconstruction). This study was approved by the University institutional review board (IRB #18-1458) for the protection of human subjects.

Experimental design

Participants reported to the laboratory on one occasion following an eight-hour fast (excluding water). They were instructed to refrain from caffeine and smokeless tobacco for a minimum of 12 hours and abstain from vigorous lower-body exercise for a minimum of 48 hours prior to the visit. Each participant completed an informed consent document, a health history questionnaire, a body composition assessment, and a timed SC task with a weighted vest. Prior to the SC task, participants consumed a standardised meal (Carnation Breakfast Essentials High Protein 8 fl oz) to break their fast.

Body composition

Stature and body mass were assessed using a calibrated clinical scale (Health o metre 2101 KL, Bridgeview, IL). Percent body fat (%BF) and leg lean tissue mass (LTM) were assessed using a daily calibrated dual energy x-ray absorptiometry (DEXA; GE Lunar iDXA, General Electric Medical Systems

Table 1. Mean ± standard deviation (SD) and range values for the demographic and performance variables.

	Mean ± SD	Range
Age	32.3 ± 8.2	20.0–50.0
Stature (cm)	178.3 ± 7.9	159.2–194.6
Body mass (kg)	92.1 ± 18.6	65.0–132.5
BMI (kg/m^2)	28.8 ± 5.3	20.9–41.2
% BF (%)	24.1 ± 7.9	9.9–39.4
Dominant leg mass (kg)	11.9 ± 2.1	8.3–17.0
Non-Dominant leg mass (kg)	11.9 ± 2.0	8.7–16.7
Leg asymmetry (%)	0.5 ± 2.5	−4.9–5.9
SC time (seconds)	74.7 ± 13.4	61.0–129.0

BMI: body mass index; % BF: percent body fat; SC: stair climb.
N = 41 male career firefighters.

Ultrasound & Primary Care Diagnostics, Madison WI, USA) scan. Participants wore athletic clothing and removed any metal prior to the scan. Participants were instructed to lie supine and remain still throughout the duration of the scan per the manufacturer's guidelines. Leg LTM was determined by outlining both legs into regions of interest as described similarly in previous studies (Giuliani et al. 2021; Mota, Stock, and Thompson 2017). Tracings for each leg started lateral to the iliac crest and moved diagonally through the femoral neck, continuing down the leg and below the foot, and connecting to the initial tracing at the iliac crest (see Figure 1). Asymmetry was assessed by subtracting the non-dominant limb LTM from the dominant limb LTM and then dividing by the LTM of the dominant limb and expressed as a percentage. Dominant limb was determined by asking participants which leg they would kick a ball with. A ± 3% LTM cut-off was used as it has been shown to result in significant inter-limb leg strength differences (Hart et al. 2014).

Stair climb performance

All participants performed a timed SC task wearing a weighted vest as described previously (Ryan et al. 2022). Prior to the assessment, participants were familiarised with the protocol by ascending 26 steps once without the weighted vest. After the familiarisation, participants were fitted with a 22.73 kg weighted vest (Z Fitness Inc., San Jose, CA, USA) to simulate the weight of their personal protective equipment (PPE) and self-contained breathing apparatus (SCBA) (Ryan et al. 2022). The vest was securely fastened around the torso and chest via Velcro straps to assure movement was minimised during the SC task. Following the verbal command (i.e. 3-2-1-GO), a timer started and participants began to ascend and descend 26 stairs that included a floor, followed by three separate flights of stairs (i.e. nine steps, nine steps, five steps) and a landing for each flight. Firefighters completed this four times for a total of 104 steps. They were instructed to touch each step (stair height – 18.5 cm) with one foot as quickly as possible without stopping or holding onto the railing. The timer stopped once both feet touched the floor of the bottom of the stairs.

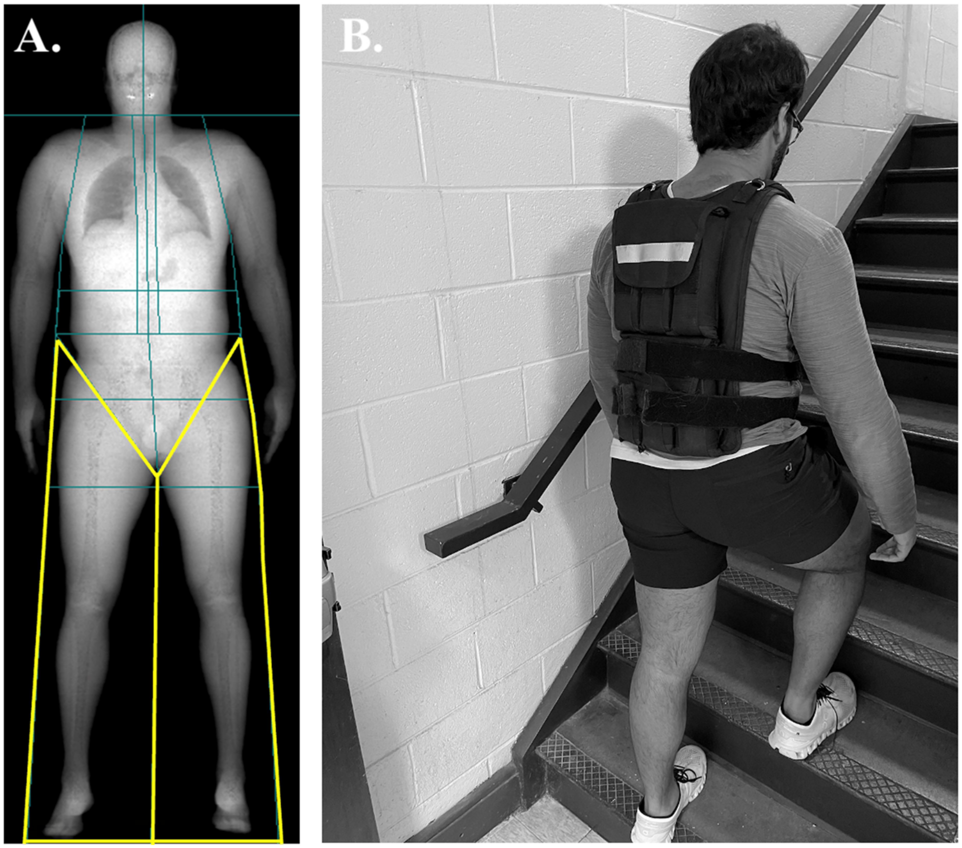

Figure 1. Examples of the boundaries (highlighted in yellow) used for the limb lean tissue mass analysis from a dual energy x-ray absorptiometry scan (A) and of the stair climb task with weighted vest (B).

Statistical analysis

All descriptive data are presented as mean ± standard deviation. A point biserial correlation was used to assess the relationship between leg inter-limb asymmetry and SC task performance. Due to the large age range (Fahy, Evarts, and Stein 2020) and high prevalence of obesity among firefighters (Poston et al. 2011), an additional partial correlation controlling for age and %BF was employed to assess the relationship between inter-limb leg LTM asymmetry and SC task performance. As previous studies (Bohannon 1997) have reported taller participants walk faster, we also examined the potential relationship of stature on SC performance. Outliers were identified and removed if they were greater than three standard deviations above the mean. All data were analysed using R statistical language (version 4.1.2 R Core Team, 2022). An alpha level of 0.05 was utilised a priori to determine statistical significance.

Results

All mean and standard deviation values for limb LTM, asymmetry, and SC variables are presented in Table 1. Our participants age and %BF were similar to and representative of career firefighters reported in previous studies (Fahy, Evarts, and Stein 2020; Poston et al. 2011). One participant was identified as an outlier (> 4 SD above the mean) for the SC time and was removed prior to analyses. The point biserial correlation indicated LTM asymmetry was associated with longer SC task time (poorer performance) (Figure 2; $r = 0.432$, $P = 0.005$). When adjusting for age and %BF, a similar positive relationship was observed between LTM asymmetry and SC time ($r = 0.502$, $P = 0.001$). Lastly, there was no significant relationship between participant stature and SC time ($r = -0.095$, $P = 0.562$).

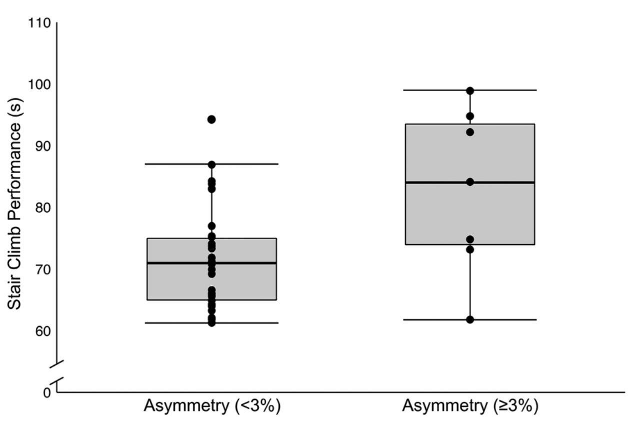

Figure 2. Box-and-whisker plots for asymmetry classification and stair climb time. Median values are marked with a bold line within the boxes. The lower and upper boundaries represent the 25th (Q1) and 75th (Q3) percentiles. The lower and upper whiskers indicate the value for (Q1 – [1.5 * Interquartile Range]) and (Q3 + [1.5 * Interquartile Range]), respectively. N = 40 male career firefighters.

Discussion

Firefighters are required to perform a number of essential occupational activities (Sheaff et al. 2010), however, the SC is often considered one of the most critical and challenging tasks (Taylor, Dodd, et al. 2015). The current study examined the impact of lower body LTM asymmetry on simulated SC performance in career firefighters. The primary findings of the current study indicated that inter-limb leg LTM asymmetry is significantly associated with impaired SC task performance (longer completion times) in career firefighters before and after accounting for age and %BF.

The finding that greater inter-limb leg LTM asymmetry is associated with reduced performance is in agreement with previous research in both athletic and older adult populations (Bell et al. 2014; Hart et al. 2014; Lee et al. 2019; Mertz et al. 2019). For example, investigators have reported that greater inter-limb leg LTM asymmetries are associated with poorer countermovement jump height (Bell et al. 2014), greater inter-limb strength differences (unilateral isometric back squat on force plates) (Hart et al. 2014), poorer performance during common functional tasks (chair sit-to-stands, walking, timed-up-and-go) (Lee et al. 2019), and reduced lower-extremity function (400 m walk test, 30 sec chair sit-to-stands) (Mertz et al. 2019). These authors (Lee et al. 2019; Mertz et al. 2019) also noted that inter-limb leg LTM asymmetries likely contribute to limb strength/power capabilities that may impact subsequent performance. For example, Bell et al. (Bell et al. 2014) reported LTM asymmetry accounted for 20% of the variance in leg inter-limb force differences in collegiate athletes. Thus, it is possible that the inter-limb leg LTM asymmetry reported in the current study may have contributed to strength/power asymmetries whereby the weaker limb is unable to maintain the unilateral demands required during the weighted SC climb (Nadeau, McFadyen, and Malouin 2003; Portegijs et al. 2008). This may be supported by Portegijis et al. (Portegijs et al. 2008) who reported leg inter-limb asymmetry adversely affects SC speed more than gait speed in older adults, given that the SC is a more challenging mobility task requiring a higher demand on unilateral leg function.

Previous studies have suggested inter-limb leg LTM differences occur as a result of the mechanical stress stimulating increases in muscle mass on the favoured limb through chronic exposure to asymmetric tasks, and is commonly seen in athletic populations (Hides et al. 2010; Krzykała 2010; Lijewski et al. 2021; Stewart et al. 2010). For example, Australian football athletes tend to have greater psoas major muscle size in their dominant (kicking) leg compared to their contralateral (stance) limb, and field hockey athletes exhibit lower extremity asymmetries between their lead side and contralateral limb (Hides et al. 2010; Krzykała 2010; Stewart et al. 2010). We are unaware of any previous studies that have examined the impact of inter-limb leg LTM asymmetries on occupational performance in firefighters. Based on previous studies examining LTM in athletic populations (Bell et al. 2014; Hart et al. 2014), the muscle atrophy that occurs following injury (Lepley et al. 2020), and recent work demonstrating the impact of firefighter demographics on performance during other simulated occupational tasks (Mota et al. 2018; Ryan et al. 2022), it is possible that these asymmetries may exist due to chronically performing various firefighter tasks, injury history, age, and/or %BF.

Previous injury (i.e. ACL tear) can cause prolonged underloading resulting in muscle atrophy of the injured limb and the development of inter-limb leg LTM asymmetry (Lee et al. 2019; Lepley et al. 2020). However, inter-limb leg LTM asymmetry reported in the current study may occur from repetitively performing occupational tasks targeting the favoured side given that we excluded participants with any major musculoskeletal surgeries in the lower leg and back, any recent injuries, and found no impact of age and %BF when controlled for our in our analyses. For example, firefighters perform many occupational duties including specific victim drag techniques and asymmetric load carriage that may impact inter-limb leg LTM asymmetries. However, future work (e.g. occupational analysis) is needed to identify specific issues that cause LTM asymmetries in firefighters. Additionally, it is important to note that inter-limb leg LTM asymmetry accounted for 18.7 – 25.2% of the variance in SC time, which aligns with previous studies (Bell et al. 2014). Along with LTM asymmetries, it is likely additional physiological parameters such as lower extremity strength and power (Ryan et al. 2022), aerobic capacity (von Heimburg, Rasmussen, and Medbø 2006; Huang et al. 2009; O'Connell et al. 1986), and/or steadiness (Ryan et al. 2022) may also be important contributors to SC performance. Therefore, future studies are needed to identify additional variables that further explain the remaining variance in firefighter SC performance. Lastly, it is important to note that previous investigations have utilised different percent asymmetry calculations (Bell et al. 2014; Hart et al. 2014). However, when using these calculations (Bell et al. 2014; Hart et al. 2014) to determine the ±3% threshold, there were no differences in the outcome ($r = 0.432$, $P = 0.005$, 7 asymmetry cases identified) between these methods and the asymmetry calculation used in the current paper.

Limitations and future research considerations

Previous research has shown simulated SC performance to be reliable (Plat, Frings-Dresen, and Sluiter 2010) and that using a weighted vest to simulate the impact of wearing firefighter PPE and SCBA during a SC task is occupationally relevant (Ryan et al. 2022). However, given that prior investigations have noted wearing PPE or a SCBA results in minimal to significant alterations in balance performance (Colburn et al. 2019; Garner et al. 2013; Kong et al. 2012; Hur et al. 2013), future investigations are needed to determine the impact of wearing PPE and/or SCBA versus a weighted vest on SC performance. While the aim of the current study examined the impact of inter-limb leg LTM asymmetries on performance, additional work is needed to determine the impact of asymmetries on firefighter injuries. Further, to increase the ability to test more firefighters at their departments, future studies are required to determine if field-based assessments of inter-limb leg LTM (e.g. bioelectrical impedance analysis) are suitable alternatives to examine asymmetries when compared to the DEXA-based assessments used in the current study.

Conclusion

The primary findings of the current study indicated that inter-limb leg LTM asymmetry (≥3%) is significantly associated with poorer SC task performance in career firefighters. These results highlight the importance of 1) monitoring inter-limb leg LTM over time to identify firefighters who have significant asymmetries that may impact performance and potential injury risk (Helme et al. 2021), and 2) implementing training strategies to minimise inter-limb leg asymmetries (Bishop et al. 2023; Gonzalo-Skok et al. 2017).

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Disclosure statement

No conflicts of interests were reported by the authors.

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References

Alvar, B. A., K. Sell, P. A. Deuster, and National Strength & Conditioning Association (U.S.), eds. 2017. *NSCA's Essentials of Tactical Strength and Conditioning*. Champaign, IL: Human Kinetics.

Bell, D. R., J. L. Sanfilippo, N. Binkley, and B. C. Heiderscheit. 2014. "Lean Mass Asymmetry Influences Force and Power Asymmetry during Jumping in Collegiate Athletes." *Journal of Strength and Conditioning Research* 28 (4): 884–891. doi:10.1519/JSC.0000000000000367.

Bishop, C., K. L. De Keijzer, A. N. Turner, and M. Beato. 2023. "Measuring Interlimb Asymmetry for Strength and Power: A Brief Review of Assessment Methods, Data Analysis, Current Evidence, and Practical Recommendations." *Journal of Strength and Conditioning Research* 37 (3): 745–750. doi:10.1519/JSC.0000000000004384.

Bohannon, R. W. 1997. "Comfortable and Maximum Walking Speed of Adults Aged 20—79 Years: reference Values and Determinants." *Age and Ageing* 26 (1): 15–19. doi:10.1093/ageing/26.1.15.

Campbell, R., and S. Hall. 2023. United States Firefighter Injuries in 2021. National Fire Protection Association. https://www.nfpa.org/education-and-research/research/nfpa-research/fire-statistical-reports/firefighter-injuries-in-the-united-states

Colburn, D., L. Russo, R. Burkard, and D. Hostler. 2019. "Firefighter Protective Clothing and Self Contained Breathing Apparatus Does Not Alter Balance Testing Using a Standard Sensory Organization Test or Motor Control Test in Healthy, Rested Individuals." *Applied Ergonomics* 80: 187–192. doi:10.1016/j.apergo.2019.05.010.

Fahy, R., B. Evarts, and G. P. Stein. 2020. "US Fire Department Profile."

Garner, J. C., C. Wade, R. Garten, H. Chander, and E. Acevedo. 2013. "The Influence of Firefighter Boot Type on Balance." *International Journal of Industrial Ergonomics* 43 (1): 77–81. doi:10.1016/j.ergon.2012.11.002.

Giuliani, H. K., M. R. Laffan, A. J. Trivisonno, G. R. Gerstner, J. A. Mota, L. R. Arieta, and E. D. Ryan. 2021. "Measuring Muscle Quality: Associations between Echo Intensity and Normalized Strength and Power." *Physiological Measurement* 42 (3): 03NT01. doi:10.1088/1361-6579/abea24.

Gonzalo-Skok, O., J. Tous-Fajardo, L. Suarez-Arrones, J. L. Arjol-Serrano, J. A. Casajús, and A. Mendez-Villanueva. 2017. "Single-Leg Power Output and between-Limbs Imbalances in Team-Sport Players: Unilateral versus Bilateral Combined Resistance Training." *International Journal of Sports Physiology and Performance* 12 (1): 106–114. doi:10.1123/ijspp.2015-0743.

Hart, N. H., S. Nimphius, T. Spiteri, and R. U. Newton. 2014. "Leg Strength and Lean Mass Symmetry Influences Kicking Performance in Australian Football." *Journal of Sports Science & Medicine* 13 (1): 157–165.

Helme, M., J. Tee, S. Emmonds, and C. Low. 2021. "Does Lower-Limb Asymmetry Increase Injury Risk in Sport? A Systematic Review." *Physical Therapy in Sport: Official Journal of the Association of Chartered Physiotherapists in Sports Medicine* 49: 204–213. doi:10.1016/j.ptsp.2021.03.001.

Hides, J., T. Fan, W. Stanton, P. Stanton, K. McMahon, and S. Wilson. 2010. "Psoas and Quadratus Lumborum Muscle Asymmetry among Elite Australian Football League Players." *British Journal of Sports Medicine* 44 (8): 563–567. doi:10.1136/bjsm.2008.048751.

Huang, C.-J., R. S. Garten, C. Wade, H. E. Webb, and E. O. Acevedo. 2009. "Physiological Responses to Simulated Stair Climbing in Professional Firefighters Wearing Rubber and Leather Boots." *European Journal of Applied Physiology* 107 (2): 163–168. doi:10.1007/s00421-009-1092-8.

Hur, P., K. S. Rosengren, G. P., Horn, D. L. Smith, and E. T. Hsiao-Wecksler. 2013. "Effect of Protective Clothing and Fatigue on Functional Balance of Firefighters." *Journal of Ergonomics* S2 (02): 1–7. doi:10.4172/2165-7556.S2-004.

Kong, P. W., J. Suyama, R. Cham, and D. Hostler. 2012. "The Relationship between Physical Activity and Thermal Protective Clothing on Functional Balance in Firefighters." *Research Quarterly for Exercise and Sport* 83 (4): 546–552. doi:10.1080/02701367.2012.10599144.

Krzykała, M. 2010. "Dual Energy X-Ray Absorptiometry in Morphological Asymmetry Assessment among Field Hockey Players." *Journal of Human Kinetics* 25 (2010): 77–84. doi:10.2478/v10078-010-0034-1.

Lee, E. J., S. A. Lee, Y. Soh, Y. Kim, C. W. Won, and J. Chon. 2019. "Association between Asymmetry in Lower Extremity Lean Mass and Functional Mobility in Older Adults Living in the Community: Results from the Korean Frailty and Aging Cohort Study." *Medicine* 98 (45): e17882. doi:10.1097/MD.0000000000017882.

Lepley, L. K., S. M. Davi, J. P. Burland, and A. S. Lepley. 2020. "Muscle Atrophy after ACL Injury: Implications for Clinical Practice." *Sports Health* 12 (6): 579–586. doi:10.1177/1941738120944256.

Lijewski, M., A. Burdukiewicz, J. Pietraszewska, J. Andrzejewska, and A. Stachoń. 2021. "Asymmetry of Muscle Mass Distribution and Grip Strength in Professional Handball Players." *International Journal of Environmental Research and Public Health* 18 (4): 1913. doi:10.3390/ijerph18041913.

Mertz, K. H., S. Reitelseder, M. Jensen, J. Lindberg, M. Hjulmand, A. Schucany, S. Binder Andersen, R. L. Bechshoeft, M. D. Jakobsen, T. Bieler, N. Beyer, J. Lindberg Nielsen, P. Aagaard, and L. Holm. 2019. "Influence of between-Limb Asymmetry in Muscle Mass, Strength, and Power on Functional Capacity in Healthy Older Adults." *Scandinavian Journal of Medicine & Science in Sports* 29 (12): 1901–1908. doi:10.1111/sms.13524.

Mota, J. A., T. J. Barnette, G. R. Gerstner, H. K. Giuliani, A. J. Tweedell, C. R. Kleinberg, B. J. Thompson, B. Pietrosimone, and E. D. Ryan. 2018. "Relationships between Neuromuscular Function and Functional Balance Performance in Firefighters." *Scientific Reports* 8 (1): 15328. doi:10.1038/s41598-018-33555-z.

Mota, J. A., M. S. Stock, and B. J. Thompson. 2017. "Vastus Lateralis and Rectus Femoris Echo Intensity Fail to Reflect Knee Extensor Specific Tension in Middle-School Boys." *Physiological Measurement* 38 (8): 1529–1541. doi:10.1088/1361-6579/aa791a.

Nadeau, S., B. J. McFadyen, and F. Malouin. 2003. "Frontal and Sagittal Plane Analyses of the Stair Climbing Task in Healthy Adults Aged over 40 Years: what Are the Challenges Compared to Level Walking?" *Clinical Biomechanics (Bristol, Avon)* 18 (10): 950–959. doi:10.1016/s0268-0033(03)00179-7.

National Institute of Standards and Technology. 2019 "The Economic Consequences of Firefighter Injuries and Their Prevention."

O'Connell, E. R., P. C. Thomas, L. D. Cady, and R. J. Karwasky. 1986. "Energy Costs of Simulated Stair Climbing as a Job-Related Task in Fire Fighting." *Journal of Occupational Medicine: Official Publication of the Industrial Medical Association* 28 (4): 282–284.

Plat, M.-C. J., M. H. W. Frings-Dresen, and J. K. Sluiter. 2010. "Reproducibility and Validity of the Stair-Climb Test for Fire Fighters." *International Archives of Occupational and Environmental Health* 83 (7): 725–731. doi:10.1007/s00420-010-0518-2.

Portegijs, E., S. Sipilä, T. Rantanen, and S. E. Lamb. 2008. "Leg Extension Power Deficit and Mobility Limitation in Women Recovering from Hip Fracture." *American Journal of Physical Medicine & Rehabilitation* 87 (5): 363–370. doi:10.1097/PHM.0b013e318164a9e2.

Poston, W. S. C., C. K. Haddock, S. A. Jahnke, N. Jitnarin, B. C. Tuley, and S. N. Kales. 2011. "The Prevalence of Overweight, Obesity, and Substandard Fitness in a Population-Based Firefighter Cohort." *Journal of Occupational and Environmental Medicine* 53 (3): 266–273. doi:10.1097/JOM.0b013e31820af362.

Ryan, E. D., M. R. Laffan, A. J. Trivisonno, G. R. Gerstner, J. A. Mota, H. K. Giuliani, and B. G. Pietrosimone. 2022. "Neuromuscular Determinants of Simulated Occupational Performance in Career Firefighters." *Applied Ergonomics* 98: 103555. doi:10.1016/j.apergo.2021.103555.

Sheaff, A. K., A. Bennett, E. D. Hanson, Y.-S. Kim, J. Hsu, J. K. Shim, S. T. Edwards, and B. F. Hurley. 2010. "Physiological Determinants of the Candidate Physical Ability Test in Firefighters." *Journal of Strength and Conditioning Research* 24 (11): 3112–3122. doi:10.1519/JSC.0b013e3181f0a8d5.

Stewart, S., W. Stanton, S. Wilson, and J. Hides. 2010. "Consistency in Size and Asymmetry of the Psoas Major Muscle among Elite Footballers." *British Journal of Sports Medicine* 44 (16): 1173–1177. doi:10.1136/bjsm.2009.058909.

Taylor, N. A. S., M. J. Dodd, E. A. Taylor, and A. M. Donohoe. 2015. "A Retrospective Evaluation of Injuries to Australian Urban Firefighters (2003 to 2012): Injury Types, Locations, and Causal Mechanisms." *Journal of Occupational and Environmental Medicine* 57 (7): 757–764. doi:10.1097/JOM.0000000000000438.

Taylor, N. A. S., H. H. K. Fullagar, B. J. Mott, J. A. Sampson, and H. Groeller. 2015. "Employment Standards for Australian Urban Firefighters: Part 1 the Essential, Physically Demanding Tasks." *Journal of Occupational and Environmental Medicine* 57 (10): 1063–1071. doi:10.1097/JOM.0000000000000525.

von Heimburg, E. D., A. K. R. Rasmussen, and J. I. Medbø. 2006. "Physiological Responses of Firefighters and Performance Predictors during a Simulated Rescue of Hospital Patients." *Ergonomics* 49 (2): 111–126. doi:10.1080/00140130500435793.