ASSESSING BILATERAL AND UNILATERAL SQUAT PERFORMANCE AMONG FIREFIGHTER TRAINEES

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Abstract: Firefighting is a physical demanding job which requires firefighters to operate in potentially dangerous atmospheres. The added weight and movement restriction of the firefighter’s protective equipment may cause movement compensations, increasing the firefighter’s risk of musculoskeletal injury. Breaking down a firefighter’s movement pattern may give indication of any movement dysfunctions that may predispose the firefighter to musculoskeletal injury. Movement screens assess the interaction of the kinetic chain and may help identify compensatory movement patterns. A common denominator of movement screens is a variation of the squat, which allows clinicians to observe the whole lower body kinetic chain in one exercise. The purpose of this study was to determine if significant relationships exist between anthropometric variables, range of motion and squat depth in the body weight and unilateral squat. Bodyweight and unilateral squat data from 31 male firefighter trainees were utilized for this analysis. Range of motion for the ankle, knee, hip, and trunk was measured using a markerless motion analysis system. Squat depth was recorded in inches and calculated as a percentage of the lower body length, based on the distance from iliac crest to the ground. A Pearson’s product correlation was used to examine relationships among the lower body functional tests, height, body mass, and joint range of motion. Significant negative correlations were found between body mass and left (r=-.481; p<.01) and right (r=-.507; p<.01) knee flexion as well as squat depth for the body weight (r=-.475; p<.01) and left (r=-.482; p<.01) and right (r=-.408; p<.01) unilateral squat. A large correlation was found between knee flexion and squat depth for the bodyweight and unilateral squat. No significant correlations were found with ankle, hip, or trunk flexion and squat depth. Likewise, there were no significant differences found between the left and right ankle, knee, or hip range of motion in this group. It is expected that range of motion may decrease later in the firefighters’ career due to age and potential injuries. Routine movement analysis screens should be performed throughout the firefighter’s occupational life span to identify movement dysfunctions and mitigate injury.

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CHAPTER I

INTRODUCTION

Firefighting is a hazardous occupation that requires firefighters to complete physically demanding job tasks in unstable and potentially fatal environments (Campbell & Evarts, 2020). These tasks include, but are not limited to, lifting and carrying heavy objects, victim/casualty extraction, maneuvering water-filled hose lines, and operating for prolonged periods of extreme physical exertion (National Fire Protection Association, 2017). Furthermore, when performing these tasks, firefighters are required to wear personal protective equipment (PPE) (Gledhill, 1992). PPE includes a coat, pants, helmet, boots, and a self-contained breathing apparatus (SCBA) designed to withstand thermal, physical, environmental, and bloodborne pathogen hazards the firefighter may encounter (National Fire Protection Association, 2017). This protective gear adds bulk and up to 37 kg which may have deleterious effects on dynamic balance as well as lower extremity range of motion (ROM) (Bock & Orr, 2015; Games, Csiernik, Winkelmann, True, & Eberman, 2019; National Fire Protection Association, 2017). These impairments may not only hinder performance but increase risk of musculoskeletal injury within this population (Kesler et al., 2018).

According to the Bureau of Labor Statistics (U.S. Department of Labor, 2020), firefighters suffer the greatest number of non-fatal job-related musculoskeletal injuries in the

United States. The National Fire Protection Association (NFPA) estimated 60,825 firefighter injuries occurred in the line of duty in 2019 (Evarts & Campbell, 2020). Sprains, strains, and muscular pains were the leading type of injury both while on the fire ground (41%) and during all firefighter activities (56%) (Evarts & Campbell, 2020). These injuries occurred primarily while performing activities that required lifting, stepping, pushing, or pulling and can lead to significant medical-related costs for the agencies in the form of workman's compensation claims and workdays lost (Burty, Webb, Gilbert, & Taylor, 2019; Frost, Beach, Crosby, & McGill, 2015). Limited ROM or asymmetrical movement patterns can increase the risk of injury due to compensatory movements (Kiesel, Butler, & Plisky, 2014). Previous studies have also found a negative correlation between ROM and body mass (Cornell et al., 2017; Jafari et al., 2020; Mayhew et al., 1993). According to the National Institute of Standards and Technology, the estimated cost for injury and lost time is approximately $50,000 to $200,000 per fire department, or $1500 to $5500 per firefighter per year (Burty et al.,2019). Regardless of these movement inefficacies, firefighters must still complete these tasks as part of their job. Addressing movement constraints within these populations may help reduce the severity and frequency of injuries, as well as lost work time and the medical costs associated with these injuries.

Movement screens are commonly used to identify compensatory movement patterns which may increase an individual's risk of injury (Kiesel, Plisky, & Voight, 2007; Kritz, Cronin, & Hume, 2009). Athletic populations have been using these screens as indicators for potential injury and the use of these screens is growing in popularity among tactical populations (Burton, 2006; Cook, Burton, & Hoogenboom, 2006; Cornell, Gnacinski, Zamzow, Mims, & Ebersole, 2017; Jafari et al., 2020). Cornell et al. (2017) examined the relationship between firefighters' health and fitness measures and their Functional Movement Screen (FMS™) scores. These researchers found FMS™ scores were significantly correlated with Body Mass Index (BMI) (*r*= -.231, p=.042), bilateral lower extremity strength (*r*=.302, *p*=.007) and core muscular endurance (*r*=.320, *p*=.004) (Cornell et al., 2017). Jafari et al. (2020) was able to significantly increase firefighters' functional movement by completing an eight-week training program.

While there are many different movement screens, most include a variation of the squat (Beach, Frost, McGill, & Callaghan, 2014; Bock & Orr, 2015; Cornell, et al., 2017; Jafari et al., 2020). The squat can assess lower-body strength, mobility, and motor control (Teyhen et al., 2012). The single leg, or unilateral squat, has a smaller base of support, requiring more balance than the bodyweight squat (Eliassen, Saeterbakken, & Tillarr, 2018; Secomb, Tran, Lundgren, Farley, & Sheppard, 2014). The single leg squat may more accurately reflect movement likely to occur during more complex tasks such as gait (Bailey, Selfe, & Richards, 2010). The single leg squat may also accentuate weaknesses or movement dysfunctions of the lower body kinetic chain (Bailey et al., 2010; Eliassen et al., 2018). Both the body weight and unilateral squat are required in many firefighting tasks such as lifting and carrying heavy equipment or casualty extraction (Bock & Orr, 2015). For these reasons, using the squat exercise, and its variations, may be useful for identifying injury potential within this population.

Firefighters are taught proper lifting and carrying techniques during fire academy training (U.S. Fire Administration, 2021). The inclusion of movement screening as part of a comprehensive fitness testing battery during training academy may provide greater insight into the trainee's current physical abilities and limitations (Burton, 2006) and assist in the development of exercise interventions aimed at improving fitness for duty (Cornell et al., 2017; Jafari et al., 2020). The implementation of such screens and programs may aid in the reduction of injury rates, workman’s compensation claims, and lost workdays related to injuries (Burty et al., 2019).

The primary aim of this study was to determine if significant relationships exist between body mass, joint ROM, and squat depth for two squat variations. This information could be useful in assisting future fire academies by noting the presence of abnormal movement pattens among trainees, while also allowing the trainee and instructors to work toward improving movement quality before graduating from the academy. Unilateral squat depth for each leg was also compared to the ipsilateral.

There were three hypotheses in this study. The first hypothesis was a negative correlation would be found with body mass and ROM and body mass and squat depth. The second hypothesis was there would not be a significant correlation between unilateral squat depth or ROM. The final hypothesis was that no significant differences in ROM or squat depth between the left and right sides in unilateral squat would be found.

CHAPTER II

LITERATURE REVIEW

The National Fire Protection Association (NFPA) provides guidelines on the minimum physical requirements for a structural firefighter in NFPA 1001. This standard states that firefighters should be able to transport and operate hand and power tools to force entry through doors, walls, or windows (4.3.4B); carry, raise, and climb ladders (4.3.6B); and operate and advance charged hose lines of 1.5 inch or larger up and down stairs or ladders (4.3.10B) (NFPA, 2017). Furthermore, these tasks are often performed while wearing PPE and a self-contained breathing apparatus (SCBA), which together can add up to 37 kg of additional load that must be moved (Bock & Orr, 2015) while simultaneously restricting the firefighter’s movement (Smith, 2011). Based on these factors, it is evident that firefighting is a physically demanding occupation that requires strength, endurance, and mobility to perform tasks efficiently and effectively (Beach et al., 2014; Bock & Orr, 2015; Gledhill, 1992).

Firefighting requires high levels of aerobic fitness, anaerobic capacity, and muscular strength and endurance (Smith, 2011). Performing high-intensity tasks in a hot or hazardous environment while wearing heavy and restrictive clothing increases the risk of injury (Bock & Orr, 2015; Gledhill, 1992; Smith, 2011). Sudden cardiac death is the number one killer of firefighters on the job (Fahy, Petrillo, & Molis, 2020). Therefore, the cardiovascular, metabolic, and cardiorespiratory systems have been heavily studied in the firefighting population and target ranges have been set for firefighters to achieve (Durand, Tsismenakis, Jahnke, Baur, Christophi, & Kales, 2011; Michaelides, Parpa, Henry, Thompson, & Brown, 2011; Smith, 2011; Storer et al., 2014). However, while musculoskeletal injuries are the leading type of injury for firefighters due to poor movement technique, overexertion, and strain (Campbell & Everts, 2019), there are no standardized scores, or assessments related to lifting and carrying techniques. Nearly 30,000 firefighters encounter a musculoskeletal injury every year (Campbell & Everts, 2019). Breaking down the lifting and carrying movements to assess for movement dysfunction or training in techniques to reduce the mechanical load on parts of the musculoskeletal system in ergonomically challenging tasks may reduce injuries in firefighters (Peate et al., 2007).

Firefighter trainees typically attend a fire academy where they learn how to perform job tasks using proper form and techniques prior to becoming a certified firefighter. During these academies, trainees are at an increased risk for injury due to the repetitive loads placed on the body while attempting to hone their firefighting skills (Cornell et al., 2017). To help minimize injury risk during this time period, the physical dysfunctions exposing firefighters to injury should first be identified (Jafari et al., 2020). Once these dysfunctions are identified, physical training programs can be implemented to reduce a trainee’s risk of experiencing an on-the-job injury.

Dysfunctional movement patterns may be further exacerbated with the addition of occupational loads (Beach, Frost, & Callaghan, 2014; Sciascia & Kibler, 2011). It has been reported that the additional weight of PPE and SCBA can cause balance deficits (Games et al., 2019), alter walking gait (Kesler et al., 2018), and increase energy expenditure (Hasselquist, Bensel, Corner, Gregorczyk, & Schiffman, 2008). Poor movement patterns are likely to be worsened with the earlier onset of muscle fatigue and increase the risk of injury (Park et al., 2014). For these reasons, identifying faulty movement patterns that may lead to injury is a primary concern for many firefighting agencies (Cornell et al., 2017; Jafari et al., 2020). Thus, to mitigate injury risk, the physical dysfunctions exposing firefighter trainees to injury should first be identified (Jafari et al.,2020). Identifying faulty movement patterns among trainees may reduce their injury potential during training academy, as well as over the occupational life span. Mitigating injury through early identification of compensatory movement patterns may also reduce the financial burdens (i.e., agency, taxpayer, etc.) associated with musculoskeletal injury (Butry et al., 2019).

Range of Motion

Range of motion (ROM) is commonly used in the clinical setting as a functional parameter to determine the health of a joint and its movement progression over time (Lea & Gerhardt, 1995). Inability to achieve acceptable ranges of motion in specific joints may increase injury risk due to increased reliance or over-compensation, on other certain soft muscle tissues and joints (Bradley & Portas, 2007). Poor flexibility is the leading factor of decreased ROM and has been significantly correlated with an increase in musculoskeletal injuries ($p<.05$) (Bradley & Portas, 2007; Gleim & McHugh, 1997: Witvrouw, Danneels, Asselman, D'Have, & Cambier, 2003). For this reason, one of the first steps in the recovery process following an injury is restoring the affected joint's ROM (Prentice, 2014). Table 1 provides the American College of Sports Medicine (ACSM) standards for joint ROM as measured by a goniometer.

Joint ROM can be measured extrinsically by means of a goniometer or inclinometer or intrinsically using a three-dimensional motion analysis system (Lea & Gerhardt, 1995;

Mundermann et al., 2005; Perrott et al., 2017). The two-arm goniometer is one of the most widely used tools for measuring joint ROM (Lea & Gerhardt, 1995). To measure joint ROM, the fulcrum of the goniometer is placed at the joint line with the stationary arm fixated along the proximal part of the joint while the other arm moves with the distal part of the joint (Lea & Gerhardt, 1995). An inclinometer measures the degree of slope in relation to gravity (Lea & Gerhardt, 1995). The inclinometer is placed along the distal end of the joint, then the clinician calibrates the device, so it is set zero degrees while the joint is at rest. The subject then moves the joint and the change in degree of tilt at the distal end of the joint is measured to determine ROM (Lea & Gerhardt, 1995).

Devices such as the standard goniometer measure one plane of motion at a time (Keogh et al., 2019), but joints such as the ankle (Rome & Cowieson, 1996), hip (Beckman & Buchanan, 1995), and shoulder (Sciascia & Kibler, 2011) are complex motions occurring in multiple planes. The goniometer may be helpful in measuring a specific joint’s ROM for rehabilitation purposes; however, it cannot observe the joint in the full ROM or movement occurring in other planes (Keogh, Hume, Mellow, & Pearson, 2005; Rome & Cowieson, 1996). Despite the common goniometric use in the clinical setting (Keogh et al., 2019; Milanese et al., 2014), previous research has found poor correlations between clinical examination measurements and dynamic motion (Desloovere, Molenaers, Feys, Huenaerts, Callewaert, Walle, 2006). Clinical assessments measure ROM in a mono-articular way, however, bi-articular muscles behave differently during many activities of daily living such as walking (Desloovere et al., 2006). Three-dimensional analysis creates a skeleton and allows the dynamic movement of the whole kinetic chain to be observed at once (Finley, Jelinek, & Misamore, 2015; Keogh et al., 2019; Rome & Cowieson, 1996). A better understanding of dynamic movement and ranges of motion may help clinicians with injury prevention and rehabilitation.

Three-dimensional motion capture systems, such as the Dynamic Athletic Research Institute (DARI) are working to create a standard for joint ranges of motion (A. Morgan, personal communication, March 25, 2021). DARI has the largest biomechanical database in the world, and the clinicians are working to create a normative database to let subjects know how they compare to thousands of others at the data point level (A. Morgan, personal communication, March 25, 2021). The DARI's database has collected ROM for geriatric post-operative patients to elite athletes. Rather than setting unrealistic or overreaching goal ranges of motion for some populations, DARI created a "target" range. DARI's most current target motions can be found in Table 1. Some targets are still being developed, such as the hip abduction.

Table 1 ACSM's Goniometric static and DARI's dynamic ROM.

	Goniometric	DARI's Dynamic Target
Ankle Dorsiflexion	20^{O}	$<5^{O}$ Delta
Knee Flexion	$130\text{-}150^{O}$	$>125^{O}$
Hip Flexion	$115\text{-}125^{O}$	$>109^{O}$
Hip Abduction	45^{O}	--
Lumbar Flexion	60^{O}	$<44^{O}$
Thoracic Flexion	50^{O}	

The DARI system does not differentiate lumbar and thoracic flexion.

Movement Screening

Movement screens have been used in athletic and tactical populations to predict injury potential by assessing movement dysfunction (Bock & Orr, 2015). Movement screens are typically used to assess an individual's ability to perform fundamental movement patterns in a dynamic and functional manner (Bock & Orr, 2015). These screens are meant to observe the selected movement patterns to identify abnormalities, not diagnose the cause of abnormal movements (Balachandran, 2011; McCunn, Funten, Fullagar, McKeown, & Meyer, 2016).

Consequently, movement screens may give an indication of muscular weaknesses or imbalance for the subjects to address via training or reconditioning (Jafari et al., 2020; McCunn et al., 2016). Addressing these issues may improve an individual's overall health, fitness, and performance, as well as reduce injury potential.

There are a variety of screens available to assess movement function, one of the most common being the FMS™. The FMS™ is a screening tool used to present any biomechanical dysfunctions that can be addressed with further diagnosis (Balachandran, 2011). The FMS™ is comprised of seven movement patterns (Frost et al.,2015) which include the deep squat, hurdle step, in-line lunge, shoulder internal and external rotation mobility, active straight leg raise, trunk stability push-up, and rotary stability (Cook et al., 2006). Each movement is rated on a scale of 0-3 based on the whole-body movement quality. If the subject was able to complete the movement exactly as verbally described, the subject receives a three for that movement. If the movement was completed with compensation, the subject is given a two. A scoring of one means the subject was unable to perform the pattern as described, and the subject is given a zero if there is pain in the movement pattern (Teyhen et al., 2012). The scores are then added together, with the highest possible score being 21 (Teyhen et al.,2012). Previous research suggests that individuals who score lower than 14 on this screen may be at an increased risk for injury (Butler et al.,2013; Raleigh et al.,2010; Peate et al.,2007; Zarei, Samani, & Reisi, 2015).

Bonazza, Smuin, Onks, Silvis, and Dhawan (2017) conducted a systematic review and meta-analysis to determine the validity and reliability of the FMS™. The researchers found six studies for reliability and nine studies for the injury predictive value to pool for quantitative synthesis. From their analysis, it was determined the ICC for intra-rater reliability was 0.81 (95% CI, 0.69-0.92) and interrater reliability was 0.81 (95% CI, 0.70-0.92). They also found participants with FMS™ scores of 14 or less were 2.74 times more likely to experience an injury when compared to those with scores greater than 14 (95% CI, 1.70-4.43). While it is demonstrated to be reliable, the validity of the FMS™ is still under review (Bonazza et al., 2017; Teyhen et al., 2012).

The Y-balance and Star Excursion Balance (SEB) test are movement screens used to assess for deficits in a subject’s balance and dynamic postural stability (Coughlan, Fullam, Delahunt, Gissame, & Caulfield, 2012). For the SEB test, eight lines extend from the center point at 45-degree increments to look like a star (Hertel, Braham, Hale, & Olmsted-Kramer, 2006). The subject then stands on one leg in the center of the star. With the non-supporting leg, the subject reaches as far as he or she can along the tape, starting with the anterior line and ending anterolaterally of the support leg (Plisky, 2009). The subject must return to an upright and balanced position before moving along the next line. The Y-balance test is similar; however, it only includes three of the eight directions included in the SEB: anterior, posteromedial, and posterolateral. These three directions appear to be the most predictive in identifying subjects with chronic ankle instability and those who have a greater risk of lower extremity injuries (Plisky, Gorman, Butler, Kiesel, Underwood, & Elkins, 2009).

The SEBT and Y-balance test require postural control, strength, ROM, and proprioception to reach in each of the tests’ directions while remaining balanced on one leg (Hertel et al., 2006). Plisky, Rauh, Kaminski, and Underwood (2006) observed a relation between the reach distance during the SEB test and lower extremity injury. The researchers determined females who could not reach 94 percent of their limb length were 6.5 times more likely to sustain a lower extremity injury ($p < .05$) (Plisky et al., 2006). These researchers also reported that individuals with a reach difference between sides of greater than four centimeters were 2.5 times more likely to suffer a lower extremity injury (p <.05) (Plisky et al., 2006). The Y-balance and SEB tests can also show the presence of any asymmetrical ROM (Olmsted, Carcia, Hertel, & Shultz, 2002), another factor which may increase injury risk (Maloney, 2019). Asymmetrical movement patterns are an identifiable risk factor for injury (Kiesel et al., 2014). Training interventions may reduce movement asymmetries, which improve performance (Maloney, 2019) and decrease injury risk (Kiesel et al., 2014).

The Drop Jump Screening Test (DJST), Landing Error Scoring System (LESS), and Tuck Jump Assessment (TJA) are other screening tools used in the clinical setting to observe lower extremity landing and jumping patterns (Chimera & Warren, 2016). During the TJA, subjects complete as many tuck jumps as possible during 10 second intervals (Read, Oliver, Croix, Myer, & Lloyd, 2016). Subjects are instructed to jump as high as they can while pulling their knees to their chest (Myer, Ford, & Hewett, 2008). Cameras are placed in the frontal and sagittal plane of the subject to assess lower body kinetic chain function while landing and jumping (Myer et al., 2008; Read et al., 2016). Observing the kinetic chain during jumping and landing techniques may indicate areas of muscular weakness, movement abnormalities, or asymmetries (Myer et al., 2008; Read et al., 2016).

The DJST and LESS use video cameras and three-dimensional motion analysis system to observe the knee valgus motion and the lower body kinetic chain response while the subject steps off a 30-inch box and jumps up (Padua et al., 2009). Kinematic analysis defines the changes in position or orientation of body segments in terms of displacements, velocities, and accelerations during a movement (Arslan, Karabulut, Ortes, & Popovic, 2019). Three-dimensional kinematic analysis may be necessary to better observe biomechanical ROM and the presences of any movement compensations. Three-dimensional kinematic measures have gained popularity as a reliable analysis of motion (Perrott, Pizzari, Cook, & McClelland, 2017). Reflective markers are placed along the joint line and other specified landmarks of the subject. Cameras placed around the subject relay the marker locations to the computer system where the researcher uses the information to build a three-dimensional character (Davis, Ounpuu, Tyburski, & Gage, 1991). During the LESS test, the subject is instructed to jump off the box onto force plates approximately 50% of the subject's height away from the box (Padua et al., 2009), while the DJST does not specify a distance (Nilstad et al., 2014). The three-dimensional motion analysis system allows for measurements throughout the whole exercise, which may more accurately detect movements which have a greater risk of injury (Padua et al., 2009; Perrott et al., 2017).

When conducting the DJST, reflective markers are placed on the subject's left and right greater trochanter, lateral malleolus, and on the center of the patella (Noyes, Barber-Westin, Fleckenstein, Walsh, & West, 2005). The subject is positioned in front of the camera and instructed to jump down off the 30-inch box and explode up, jumping as high as possible (Noyes et al., 2005). At the completion of the test, the change in position of the subject's lower extremity joints during landing and take-off is analyzed (Noyes et al., 2005). The valgus motion of the knee and compensation by the rest of the lower body joints is evaluated between these frames and on the three-dimensional character, which may indicate a greater potential for injury ($p<.001$) (Nilstad et al., 2014; Young, Wilson, & Byrne, 1999). Observing each joint of the kinetic chain during these movement screens may give insight into weaknesses or other movement dysfunctions to address to reduce the risk of injury.

Markerless Motion Capture

Marker-based systems provide valid kinematic data, but require more time for set up, calibration, and data processing (McLean, Walker, & Bogert, 2005). In recent years, the use of markerless motion capture systems have increased in popularity (Perrott et al.,2017). Mundermann, Anguelov, Corazza, Chaudhari, & Andracchi (2005) found that human kinematics could be accurately estimated in virtual environments. Mundermann et al. (2005) found image processing modules results using background separation, visual hull, and iterative closest point methods were comparable to that of marker-based systems. Markerless motion analysis systems, such as the DARI Motion Analysis system, require less participant preparation and reduce time to process collected data. Other markerless motion analysis systems that use algorithms to detect and quantify movements include Organic Motion^{TM}, SimiShape^{TM}, and BioMotion^{TM}.

Most marker-based systems use reflective markers placed on the anterior and superior iliac spine in order to recognize the anterior tilt of the pelvis, whereas the markerless systems identify the pelvis as the bottom 25 percent of the trunk (Perrott et al., 2017). Perrott et al (2017) compared the analysis of the Vicon Motion System and Helen Hayes marker and Organic Motion and DARI Motion markerless capture systems and determined there was no significant difference between nine of the 13 clinically relevant joints in single leg squat. Significant differences were detected in trunk flexion and rotation of the trunk, pelvis, and knee. These differences are attributed to the variance of the marker-based system defining the tilt of the pelvis ($p \leq 0.05$) (Perrott et al.,2017). Based on this research it appears that the validity of markerless systems may be sufficient to collect data outside the lab and for large groups in a timely manner.

Motion analysis systems may allow researchers to quantify the change in movement as the subjects age. Adaptive strategies and their long-term consequences may become more noticeable with age (Chimera & Warren, 2016; Junge, Jespersen, Wedderkopp, & Juul-Kristensen, 2013). The markerless systems may eliminate some of the human error associated with marker placement (Mundermann et al.,2005), therefore increasing repeatability (Perrott et al., 2017). The DARI system has different applications for populations with varying activity levels, allowing it to assess ROM limitations, muscular imbalances, and asymmetrical movement tendencies (Grube, Nill, & Miller). One such population DARI was developed to observe is the tactical athlete (Glaeser, 2021).

The development of various systems to meet the needs of different populations should not be overlooked. Post-operative rehabilitation patients may need different analysis than the high-speed capture used to observe professional athletes' performances (DARI Motion, 2021). Subjects in the same fitness level population may also see differences in ROM outcomes. Clinicians may use a subject's contralateral side for a post-injury target ROM (Finley et al., 2015). Likewise, a motion analysis system can be used to compare the dynamic movements bilaterally and over time.

The DARI motion analysis system recognized the absence of a standardized ROM analysis, as well as the difficulty of developing a standard for diverse populations (DARI Motion, 2020). DARI clinicians developed systems to target the spread of activity levels from professional athletes, tactical professionals, and rehabilitative patients. DARI also has the largest biomechanical database in the world (A. Morgan, personal communication, March 25, 2021). The researchers at DARI have created a normative database and they can determine how each subject compares to others at the same data point level. This is not completed by a ROM standard for joints. Instead, a “target” measurement in the 60th percentile has been developed (A. Morgan, personal communication, March 25, 2021). This tells the subject to aim for an above average performance while not making the goal unattainable for geriatric or post-operative patients (A. Morgan, personal communication, March 25, 2021). The DARI research team is continuing to collect data for some joints; however, the DARI motion analysis system has been validated against other measurement methods (A. Morgan, personal communication, March 25, 2021). The DARI ROM outputs are reliable; however, they should not be compared to outputs of other systems in dynamic tests.

The Squat

Motion analysis systems and the added equipment to complete movement analysis such as the DJST and LESS can be costly. Ugalde, Brockman, Bailowitz, and Pollard (2015) recognized the difficulty of performing DJST outside of a lab, so they compared the single leg squat performance to the subjects’ DJST performance. Ugalde et al. (2015) determined subjects who displayed any abnormal responses during the squat motion such as arms flailing, Trendelenburg sign, or collapse of the supporting knee into valgus had a significantly lower knee-hip ration, indicating greater dynamic knee valgus ($p=.02$) (Sciascia & Kibler, 2011). While observing the single leg squat in this way may not provide data for intrasubject comparison, it can still be used as a valid movement analysis screen. Almost all whole body or lower extremity movement screens include a variation of the squat, where the whole lower body can be observed interacting as a part of the kinetic chain. The kinetic chain is comprised of the musculoskeletal joints and body segments working together to perform movements.

The squat variations involve the ankle, knee, hip, lumbar, and thoracic spine, allowing clinicians to observe the lower body kinetic chain function in one exercise (Kritz et al., 2009).

The bilateral squat is one of the most prevalent exercises used in strength training, and it is considered a foundational exercise for many activities of daily living (Kapandii, 1982; Kritz et al., 2009). Kritz et al. (2009) recommend the bodyweight squat be used as a potential method of screening an athletes' movement competencies. For these reasons, squat technique and ROM is a component of all these functional screens. Variations of the squat can be incorporated to focus on aspects of the lower body kinetic chain. Restricting the knee from moving anteriorly beyond the toes, for example, will require more movement from the hip and increased ROM for thoracic curvature (List, Gulay, Stoop, Lorenzetti, 2013) Not restricting knee movement will require more movement from the knees and ankles, decreasing the stress placed on the thoracic and lumbar spine (List et al., 2013; Lorenzetti, Stoop, Ukelo, Gerber, Stacoff, & Stussi, 2012). Anterior motion of the knees past the toes increases the shear and compressive forces experienced at the knees and the knee also experiences excessive torque when the center of rotation for knee flexion is altered during the deep squat (Kritz et al., 2009). The deep squat relies more on hip dynamic ROM, making it more desirable for movement screens of the hip, however, the increased stress placed on the knees may not be suitable for all populations (McKean, Dunn, & Burkett, 2010; Scaglioni-Solano, Song, & Salem, 2005). Deep squatting is important for activities on the ground (Kim, Kwon, Park, Jeon, & Weon, 2015), which firefighters incur frequently with patient and equipment lifts. Kritz et al. (2009) noted subjects may employ poor movement patterns or malalignment to achieve the deep squat, and therefore recommended using the parallel squat, when the top of the thigh is parallel with the ground, for movement screening purposes. Subjects in this study were instructed to perform the squat movement in one smooth motion, while dropping the hips as low as possible and returning to the starting position.

Injuries and pain in the lower extremities may affect the kinetic chain, increasing the risk of further injury (Haddas, James, & Hooper, 2015; McKean et al., 2010). Firefighters rely heavily on their lower body strength and ROM to perform their jobs (National Fire Protection Association, 2017). Therefore, if the firefighter has limited ROM in their hips, knees, or ankles, they may rely on other parts of the kinetic chain to compensate, further increasing their risk of injury (Kritz et al., 2009; Powers, 2010). For instance, Reiman, Bolgla, and Lorenz (2009) analyzed 51 articles that provided epidemiological, neuromuscular, and biomechanical evidence to better understand the lower body kinetic chain and compensation. From their systematic review, these researchers confirmed movement dysfunction of the hip may contribute to knee or ankle injuries (Reiman et al., 2009) Beckman and Buchanan (1995) observed a significant latency decrease of hip activation following chronic ankle sprains. This finding presents a compensatory mechanism where it must be decided if the compensation should be addressed or accepted as an adaptive strategy (Beckman & Buchanan, 1995). However, one must consider these adaptive strategies may have long-term consequences that may affect functionality.

This purpose of this research study was to use the DARI markerless motion analysis system to determine if significant relationships exist with the body weight and unilateral squat and lower body kinetic chain ROM and squat depth of firefighter trainees. The presence of asymmetries could give insight into movement dysfunction that may predispose the firefighters to injury. Firefighters require lower body strength and mobility to adequately perform their necessary tasks, and an accurate indicator of lower extremity performance is the squat. Firefighter trainees were the subjects of this study because they are exposed to a greater amount of repetitive load carriages through the duration of their fire academy.

CHAPTER III

METHODOLOGY

Experimental Approach to the Problem

A retrospective analysis of data was conducted to analyze the bilateral difference in ROM of the ankle, knee, hip, thoracic, and lumbar spine in firefighter trainees.

Subjects

Archived data for one female and thirty-one (n=31) male (age: 28.4 ± 5.47 years; height: 181.1 ± 5.18 cm; body mass: 189.6 ± 24.58 kg; BMI: 26 ± 3) firefighter trainees was used for this analysis. In an attempt to minimize the confounding variables, the female firefighter's data were eliminated from statistical analysis in this study.

Instrumentation

Data was collected using the Dynamic Athletic Research Institute (DARI) motion capture system. (Motion Platform, version 3.2-Denali from Scientific Analytics Inc., Kansas City, KS, USA). This system uses 8 high-speed cameras (120 Hz) placed around the room and a computer-based software. The subject stands in the middle of the room with their feet shoulder width apart, shoulders laterally abducted, and elbows and wrists flexed to accentuate the subject's joints. The subjects also performed a couple lunges to complete the lower body skeleton. Markerless data systems such as DARI rely on the visual hole created by background subtraction for data collection (Perrott et al., 2017). The motion capture system calculated the center of the joint and

26 segments between those joints (Elhayek, et al., 2012). Data collected from this motion capture was then analyzed via a software package that uses specialized biomechanical algorithms.

Procedures

Trainees reported to testing wearing their physical training attire. Subjects self-reported height and weight to help establish the locations of joint centers. Subjects were then instructed to stand in the middle of the room with their feet shoulder width apart, their arms outstretched to the side with elbows and wrists flexed to allow the DARI system to create a biometric skeleton.

Once the silhouette was completed, the trainee was instructed to complete a list of movements as described below. The motion capture system measured the terminal point of the ROM for each exercise in degrees. The movements were performed in the following order.

Bodyweight Squat: Trainees began with the feet shoulder width apart and toes pointing forward. The trainees were instructed to keep their arms extended with their hands over their head. In one fluid motion, trainees were instructed to squat as low as possible, and then return to the starting position. Eccentric hip abduction and flexion, knee flexion, ankle flexion, knee valgus angle, and knee torsion angles were measured in degrees. Squat depth was recorded in inches and calculated as a percentage of the lower body, based on the distance from the iliac crest to the ground. The weight percentage of the force will shift as the trainee begins the eccentric phase of the squat and the center of gravity lowers. Observing the trainee's valgus and torsion angles will give some insight to the presence of any weight shift (Fry, Herda, Sterczala, Cooper, & Andre, 2016).

Unilateral Squat: Trainees were instructed to transfer their weight to one leg and lift the opposite foot off the ground behind their body. In one fluid motion, trainees were instructed to squat as low as possible, keeping the non-weight bearing foot off the ground, trunk upright, and arms extended out to the sides of the body to aid in the maintenance of balance. This process was then repeated using the opposite leg. Similar to the bodyweight squat, eccentric hip abduction and flexion, knee flexion, ankle flexion, knee valgus angle, and knee torsion angles were measured in degrees. Unilateral squat depth was record in inches and calculated as a percentage of the lower body, based on the distance from the iliac crest to the ground.

Statistical Analyses

All statistical analysis were performed using IBM statistical package for the social sciences (SPSS) statistics (Version 26.0; IBM Corporation, New York, USA). Pearson's product movement correlations were used to examine relationships among the selected lower body functional tests, height, body mass and joint ROM. The strengths of each correlation value were graded as follows: 0 to 0.30, or 0 to -0.30 was considered small; 0.31 to 0.49, or -0.31 to -0.49 was considered moderate; 0.50 to 0.69 or -0.50 to -0.69 was considered large; 0.70 to 0.89 or -0.70 to -0.89 was considered very large; and 0.90 to 1.0 or -0.90 to -1.0 a near perfect correlation (Cohen, Cohen, West, & Aiken, 2013). Table 3 shows the correlations among unilateral squat, unilateral squat knee flexion, and body mass. Furthermore, paired samples t-tests were used to determine if significant differences existed between single-leg squat depth between the right and left legs. Significance for all statistical analysis was set at a priori $p \leq 0.05$.

CHAPTER IV

FINDINGS

Descriptive data of the 31 male participants are shown in Table 2. Correlations among body mass, body weight squat depth, and left and right knee flexion are found in Table 3. Table 4 shows correlations among the left and right unilateral squat depth, left and right knee flexion, and body mass. There was a significant negative correlation between body mass and left (r=-.481; p<.01) and right (r=-.507; p<.01) knee flexion as well squat depth for the bodyweight (r=-.475; p<.01) and unilateral left (r=-.482; p<.01) and right (r=-.408; p<.01) squat. A large correlation was found between knee flexion and squat depth for the bodyweight (left r=.660; right r=.592; p<.01) and unilateral squat (left knee flexion to left unilateral squat: r=.901; left knee flexion to right unilateral squat: r=.701; right knee flexion and left unilateral squat: r=.816; right knee flexion and right unilateral squat: r=.864; p<.01). No significant correlations were found with ankle, hip, or trunk flexion and squat depth. Likewise, there were also no significant differences found between the left and right ankle, knee, or hip ROM.

Results of the paired samples t-tests are showed in Table 5. These results revealed no significant differences (t=.028, p<.05) between single-leg squat depth between the right and left legs.

Table 2. Descriptive Data for Firefighter Trainees (n=31).

	Minimum	Maximum	Mean ± SD
Age	21	39	28.4 ± 5.5
Height(cm)	167.6	190.5	181.1 ± 5.2
Body Mass (kg)	150	245	189.6 ± 24.6
BMI	21	33	26 ± 3
Squat Depth (in)	8.6	27.3	20.2 ± 5.1
Squat Depth (% of lower body)	17.2	72.4	53.1 ± 12.8
Thoracic Flexion (degrees during squat)	5.9	32.7	21.7 ± 6.3
Hip Abduction (L)	10.1	35.8	19.9 ± 6.7
Hip Abduction (R)	9.7	45.9	23.2 ± 8.3
Hip Abduction (Delta)	.0	27.4	6.4 ± 6.2
Hip Flexion (L)	77.5	142.2	107.8 ± 14.6
Hip Flexion (R)	68.2	137.4	104.1 ± 15.9
Hip Flexion (Delta)	.5	13.4	5.8 ± 3.8
Knee Flexion (L)	90.8	149	128.9 ± 14.6
Knee Flexion (R)	92.4	148.9	128 ± 14.1
Knee Flexion (Delta)	.1	7.3	3.7 ± 2.2
Ankle Flexion (L)	22.5	57.3	37.4 ± 7.5
Ankle Flexion (R)	24.2	58.4	38.1 ± 7.9
Ankle Flexion (Delta)	.2	23	5 ± 4.9
Knee Valgus (L)	1	8	4.9 ± 1.6
Knee Valgus (R)	.6	7.8	4.6 ± 1.8
Knee Valgus (Delta)	.0	4.2	1.1 ± 1.7
Knee Torque (L)	1.1	10.2	2.6 ± 1.5
Knee Torque (R)	1.2	5.8	2.8 ± 0.9
Knee Torque (Delta)	.0	4.4	0.6 ± 0.8
Unilateral Squat Depth (L) (in)	6.5	18.2	10.8 ± 2.7
Unilateral Squat Depth (R) (in)	4.2	20.3	10.8 ± 3.5
Unilateral Squat Depth (Delta)	.0	7.4	1.8 ± 1.8
Unilateral Squat (L) (% of lower body)	16	50.7	27.6 ± 7.5
Unilateral Squat (R) (% of lower body)	11.3	51.7	27.4 ± 8.5
Unilateral Squat (Delta) (% of lower body)	.0	15.5	4 ± 3.9
Unilateral Squat Hip Flexion (L)	42.1	98.7	70.4 ± 14.9
Unilateral Squat Hip Flexion (R)	47.2	95	71 ± 13.1
Unilateral Squat Hip Flexion (Delta)	.1	19.9	7.3 ± 5.6
Unilateral Squat Knee Flexion (L)	55.1	136.8	88.1 ± 16.3
Unilateral Squat Knee Flexion (R)	57	138.1	86.5 ± 14.8
Unilateral Squat Knee Flexion (Delta)	.0	16.8	5.8 ± 4.5
Unilateral Squat Ankle Flexion (L)	18.5	57.6	43.5 ± 9.3

Unilateral Squat Ankle Flexion (R)	26.1	57.5	41.5 ± 8.7
Unilateral Squat Ankle Flexion (Delta)	.3	20.3	5.9 ± 4.9
Unilateral Squat Knee Valgus (L)	.1	5.2	3.4 ± 1.8
Unilateral Squat Knee Valgus (R)	.7	5.4	4 ± 1.3
Unilateral Squat Knee Valgus (Delta)	.0	3.7	0.9 ± 1.1
Unilateral Squat Knee Torque (L)	1.3	4.9	2.6 ± 0.8
Unilateral Squat Knee Torque (R)	1.3	4.3	2.7 ± 0.6
Unilateral Squat Knee Torque (Delta)	.0	1.8	0.6 ± 0.5

[a] BMI = body mass index. [b] R = Right. L = Left. [c] Measurements in degrees unless otherwise stated

Table 3. Correlation between body mass, body weight squat depth, and left and right knee flexion.

	Body Mass	Squat Depth	Knee Flexion (L)	Knee Flexion (R)
Body Mass	-	-.475**	-.481**	-.507**
Squat Depth	-.475**	-	.660**	.592**
Knee Flexion (L)	-.481**	.660**	-	.957**
Knee Flexion (R)	-.507**	.592**	.957**	-

**=p<0.01

Table 4. Correlation between left and right unilateral squat, left and right unilateral knee flexion, and body mass.

	Unilateral Squat (L)	Unilateral Squat (R)	Unilateral Squat Knee Flexion (L)	Unilateral Squat Knee Flexion (R)	Body Mass
Unilateral Squat Depth (L)	-	.695**	.901**	.816**	-.482**
Unilateral Squat Depth (R)	.695**	-	.710**	.864**	-.408*
Unilateral Squat Knee Flexion (L)	.901**	.710**	-	.896**	-.489**
Unilateral Squat Knee Flexion (R)	.816**	.864**	.896**	-	-.437*
Body Mass	-.482**	-.408*	-.489**	-.437*	-

*= p < 0.05, **= p<0.01

Table 5. Paired t-test for left and right unilateral squat depth.

	Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference		t	df	Sig. (2-tailed)
				Lower	Upper			
Unilateral Squat Left - Unilateral Squat Right	.0129	2.556	.459	-.9246	.951	.028	30	.978

CHAPTER V

DISCUSSION

This purpose of this study was to use a motion analysis system to determine if significant relationships exist with the body weight and unilateral squat and lower body kinetic chain ROM and squat depth of firefighter trainees. Significant positive correlations were found between knee flexion and squat depth in both the bodyweight and unilateral squat. Mild negative correlations were found between bodyweight and unilateral squat depth and body mass. No statistically significant differences were observed between the right and left legs when performing the unilateral squat exercise. These results suggest that limited knee flexion and higher levels of body mass may negatively impact a trainee's ability to squat. Therefore, focusing on knee ROM and maintaining a healthy body mass enhance performance and mitigate injury risk.

The quality of the squat is often measured by the degree of knee flexion an individual is able to achieve (Cook et al., 2006). Cook et al. (2006) determined the inability to perform a bodyweight squat at or below 90 degrees of knee flexion with symmetry and control may indicate restricted joint mobility or stability. Ugalde et al. (2015) concluded the single leg squat was a reasonable tool to assess for dynamic knee valgus. These researchers did not observe the body weight squat or squat depth. Execution of a proper squat requires mobility of the ankle, hip, and thoracic spine, and stability of the foot, knee, and lumbar spine (Kritz et al, 2009). Kim et al. (2015) determined the knee can compensate for ROM dysfunction in other joints of the kinetic chain. This study found significant correlations only with the knee ROM and squat depth. Kim et al. (2015) found a negative relation with passive hip flexion, internal rotation, and ankle dorsiflexion and squat depth (r=-.623; p<.05). Different motion analysis systems may contribute to the discrepancies. The markerless and marker-based motion analysis systems understand the pelvis differently, which may affect the ROM outputs (Perrott et al., 2017). Subject's passive ROM was not measured in this study, so dynamic knee flexion may be the only correlation with squat depth.

A moderate negative correlation (r=-.475, p<.01) was noted between bodyweight squat depth and body mass. Previous studies have found a similar negative correlation with ROM and body mass (Bollinger, 2017; Friesen, Anz, Dugas, Andrews, & Oliver, 2021), although the relationship is not completely understood. Mayhew et al. (1993) and Keogh et al. (2019) observed the relation between anthropometrics and bodybuilders. These researchers found the athletes with greater girth tended to have less ROM. Jeong, Heo, Lee, and Park (2018) observed the passive ROM for normal-weight, pre-obese, and obese subjects. The researchers found decreased ROM in the pre-obese and obese groups. The negative correlation was found with knee flexion more often than other joint motions. Jeong et al. (2018) attribute the decrease of ROM to greater amount of fat deposits obstructing movement. Similar decrease in squat ROM have been found with bodybuilders as well (Mayhew et al., 1993; Perez, Martinez-Sanz, Ferriz-Valero, Gomez-Vicente, & Auso, 2021, Vigotsky et al., 2019), indicating fat-free mass may have a similar effect. The additional girth may require movement compensations such as more movement from other aspects of the kinetic chain to reach full squat depth, placing additional loads on other joints (McKean et al., 2010; Scaglioni-Solano et al., 2005). Firefighters may be at an even greater risk of injury due to the restrictive nature of their PPE. Compensation due to the decreased ROM could increase the risk of injury (Kritz et al., 2009; Powers, 2010).

The subjects in this study revealed no statistically significant asymmetries in the unilateral squat. This includes unilateral squat depth and ROM in the observed joints during the single leg squat. The absence of asymmetries may indicate the lack of lower extremity injury and compensation (Donajkowski, 1993; Robert, 1980). Kiesel et al. (2014) observed athletes performing the FMS^{TM} and noted those with an asymmetrical movement displayed a relative risk of 1.8 times more likely to be injured (p=.05). This does not make the firefighters exempt from injury, but it confirms these subjects are not entering the academy with a predisposed movement dysfunction. As these subjects begin their firefighting career and continue to age, it is expected that their ROM will decrease, and asymmetries may begin to appear. Conducting annual movement analysis screens will allow early detection to slow or reverse the movement dysfunctions.

This study is not without limitations. The sample size was relatively small, and the subjects were just beginning their firefighting career. These subjects were relatively young, and they have not yet experienced the sprains, strains, and muscular pains that long-term firefighters are likely to encounter. While movement screens are suggested at the beginning of the firefighter’s career for a baseline mobility measurement and throughout the years to assess for trends, it is expected that ROM will trend downward later in firefighters’ careers. Future research should be conducted to test this hypothesis.

A second limitation of this study was the failure to acknowledge the role of balance and strength in the subjects' squat depth. Negative correlations were found between body mass and squat depth for both the bodyweight and unilateral squats. However, no strength or balance tests were conducted to decipher any correlations.

Firefighting is a dynamic occupation that should not be measured solely by a static movement. Many fire departments complete annual physical fitness screens. In 2000, the NFPA released NFPA Standard 1582: the Standard on Comprehensive Occupational Medical Program for Fire Departments (NFPA, 2017) to provide further guidance for the physician when conducting annual physical examinations. This standard recommends the inclusion of muscular strength, endurance, and flexibility assessments as part of the annual physical. While all of these are components of the firefighter's daily tasks, the physician is not observing the functional movements from which each of these tests builds. Including a functional test would allow the clinicians to monitor for any movement dysfunctions to further investigate.

Motion analysis systems such as the one used in this study require little time to set up, and the data collection is minimally invasive to firefighters. These three-dimensional systems have demonstrated high reliability (A. Morgan personal communication, March 25, 2021; Perrott et al., 2017), and subjects would be able to accurately compare their annual results. Much like the department physician observing trends in the firefighter's health, this will give an indication of movement dysfunction for further diagnosis. Detecting and addressing a movement dysfunction may save money, but more importantly, it may save the firefighter's career.

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