NEUROMUSCULAR DETERMINANTS OF FUNCTIONAL BALANCE PERFORMANCE IN CAREER FIREFIGHTERS

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ABSTRACT

TIMOTHY J. BARNETTE JR.: Neuromuscular Determinants of Functional Balance Performance in Career Firefighters 
(Under the direction of Eric Ryan)

Slips, trips, and falls (STFs) are one of the most common injuries in the fire service. The purpose of this study was to examine the relationship between biceps femoris (BF) neuromuscular function [rate of torque development (RTD), rate of electromyographic rise (RER), muscle size (CSA), and muscle quality (EI)], and functional balance performance during a simulated firefighting activity. Rate of torque development and RER were examined during a maximal isometric strength assessment with surface electromyography and ultrasonography was used to examine CSA and EI in 44 career firefighters. The functional balance performance index was significantly related to age ($r = 0.423, P < 0.01$), $\%$BF ($r = 0.378, P < 0.05$), and RTD ($r = -0.327, P < 0.05$). After accounting for age and $\%$BF, increases in RTD remained related to improved functional balance performance, which was influenced by the RER, but not the size or quality of the BF.
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CHAPTER I
INTRODUCTION

Firefighters face many inherent dangers associated with their occupation and are at a high risk of injury (Cloutier & Champoux 2000). The National Fire Protection Association (NFPA) reported nearly 70,000 injuries to firefighters occurring in the line of duty in 2013 (Karter Jr & Molis 2014). Approximately half of these injuries occurred during fireground operations with the leading causes of injury including overexertion or strain, and slips, trips, and falls (STFs) (Karter Jr & Molis 2014). Over a five year period, STF related injuries were the leading cause of moderate and severe injuries in United States firefighters (Karter Jr 2013). The National Institute of Occupational Safety and Health (NIOSH) has recognized STF research as one of the most needed areas of injury prevention research. Environmental factors associated with fireground operations and the added burden of protective gear increase the risk of STF related injuries (Hsiao 2014). Furthermore, STF related injuries result in the longest work absences in this population (Cloutier & Champoux 2000) and above average workers compensation costs (Walton et al. 2003).

A number of factors contribute to STF related injuries in firefighters. These include both extrinsic (i.e. wet surfaces), and intrinsic or physiological (i.e. neuromuscular function) variables (Kong et al. 2013). Although the environment is often unpredictable, physiological variables are readily modifiable. For example, previous authors (van den Bogert et al. 2002; Kong et al. 2013) have suggested that a firefighter’s ability to recover from a fall may be significantly associated
with how rapidly they can generate muscle actions. This has been demonstrated in a number of studies (Bento et al. 2010; LaRoche et al. 2010; Crozara et al. 2013; Palmer et al. 2015; Palmer et al. 2015) which have shown that the rate of torque development (RTD) contributes to balance recovery and fall prevention. Specifically, the early phase of torque production (i.e. 0-100 ms from contraction onset), appears to be an important variable associated with lower extremity performance and fall prevention (Palmer et al. 2015). This time period is considerably less than the time required to produce maximal torque (~300 ms) (Aagaard 2003). Furthermore, recent findings have also suggested that the rate of muscle activation has been correlated with the ability to recover one’s balance after tripping (Pijnappels et al. 2005) and may be an additional risk factor for STF injuries. The rate of muscle activation is often quantified by the slope of the EMG signal during an isometric muscle action and represents the neuromuscular contribution to rapid torque development (Clark et al. 2011; Thompson et al. 2014).

Previous authors (Janssen et al. 2002; Visser et al. 2005; Addison et al. 2014; Kleinberg et al. 2015) have also suggested both muscle size and quality are important variables that contribute to lower extremity performance, mobility, and balance. Muscle quality is a variable indicative of the amount of intramuscular adipose tissue or connective tissue found within a muscle (Pillen et al. 2009; Addison et al. 2014). A recent study by Kleinberg et al. (2015) demonstrated that both the size and quality of the vastus lateralis and rectus femoris muscles were significant contributors to weighted stair-climb performance in career firefighters. These findings are in agreement with previous studies that have demonstrated that muscle size is associated with strength (Maughan et al. 1983), power (Mangine et al. 2014), functional capacity (Visser et al. 2002), and mobility (Visser et al. 2005). Decreased muscle mass has been directly linked to an increased risk of falls (Landi et al. 2012). Furthermore, decreased muscle mass
relative to total body mass has been correlated with functional impairment and disability (Janssen et al. 2002). In addition, a number of studies (Visser et al. 2005; Fukumoto et al. 2012; Addison et al. 2014; Straight et al. 2015) have demonstrated that the quality of skeletal muscle (i.e. amount of intramuscular fat and/or connective tissue) is an important predictor of lower extremity performance and falls risk. For example, Straight et al. (2015) determined that muscle quality was the best predictor of lower extremity physical function in men and women.

Decreased muscle quality of the thigh musculature has also been correlated with slower walking speeds, decreased performance in a sit to stand task, and mobility limitations (Visser et al. 2002; Visser et al. 2005). Furthermore, it was recently demonstrated that muscle quality of the lower extremity negatively impacts balance performance which has important implications for the risk of falls (Addison et al. 2014).

Several researchers have recently used functional balance assessments in various occupational groups to assess factors associated with STF related injuries (Punakallio 2003; Kong et al. 2012; Hur et al. 2013). For example, Punakallio et al. (1997) developed a reliable functional balance assessment that required participants to walk forward and backward along a narrow beam as fast as possible while committing minimal mistakes. Using this assessment, Punakallio and associates (2003; 2004) examined occupational differences in functional balance, the effects of aging on functional balance, and the work ability index (WAI) and the perceived work ability (PWA) of firefighters. More recently, Hur and colleagues (2013) modified the functional balance test developed by Punakallio et al. (1997) to more closely mimic fireground operations. These collective tasks included stepping up and down from raised platforms, walking along a narrow wooden beam, and ducking under an overhead obstacle intended to simulate cautious movement in a confined space (Hur et al. 2013). The authors examined the
effects of fatigue and personal protective equipment (PPE) on functional balance performance and concluded that both of these factors significantly reduced performance measures (Hur et al. 2013). The detrimental effects of PPE on functional balance are likely attributed to its added weight and bulkiness as well as the limiting effects on vision when wearing the self-contained breathing apparatus (SCBA) (Kong et al. 2012; Hur et al. 2013).

Although the incidence and magnitude of STF related injuries in firefighters is well documented, we are aware of no laboratory based studies that have specifically examined the influence of neuromuscular factors on firefighter specific functional balance performance. Recent studies (Bento et al. 2010; Palmer et al. 2015) have suggested that the leg flexors (i.e. hamstring musculature) are specifically important for fall prevention as they “may allow a rapid control of the lower limb arrangement and recover balance after a trip (Bento et al. 2010)”.

Several authors have suggested that neuromuscular characteristics associated with this muscle group are important for preventive strategies associated with STFs (Pijnappels et al. 2005; Bento et al. 2010; Palmer et al. 2015). Therefore, the purpose of this study was to examine the relationship between leg flexion neuromuscular function and muscle architecture, and functional balance performance in career firefighters.

**Research Questions**

1. Are leg flexion RTD, RER and biceps femoris CSA and EI related to functional balance performance in career firefighters?

2. Which parameters are most predictive of functional balance performance in career firefighters?
Hypothesis

1. Biceps femoris CSA, EI, RER, and RTD are related to performance in a functional balance test in career firefighters.

Delimitations

1. Participants were current career firefighters within the age range of 18-50 years old.
2. Statistical analyses accounted for differences in body composition and age.

Limitations

1. Participant recruitment took place throughout various fire stations in the local area and included volunteers, therefore participant selection was not truly random.

Theoretical Assumptions

1. Participants provided an accurate health and exercise history on the enrollment questionnaire.
2. All participants gave maximal effort during the isometric strength testing.
3. Each participant’s right leg was completely relaxed during all US assessments.
4. All equipment was calibrated and accurate for all testing sessions.

Statistical Assumptions

1. The population from which the sample was drawn is normally distributed.
2. The data is based on a parametric scale, either interval or ratio.
3. The within-group variability of the samples in the experiment is equal or nearly so (homogeneity of variance).
Operational Definitions

1. Surface Electromyography (EMG) – an electrical recording of the muscle action potentials that sweep across the sarcolemma and pass through the surface electrode recording areas during a skeletal muscle action; representative of motor unit recruitment and firing frequency; the raw signal is expressed in microvolts (µV).

2. Maximum Voluntary Contraction (MVC) – the maximum voluntary torque produced by a muscle or group of muscles under isometric conditions.

3. Rate of Torque Development (RTD) – The peak slope of the torque versus time curve during an isometric muscle action.

4. Panoramic Ultrasound (US) – an image fitting method that extends the field of view of the ultrasound probe through real-time generation of a cross-sectional image.

5. Echo Intensity (EI) – an index of muscle quality obtained through computer aided gray-scale analysis of the individual pixels within an ultrasound image; representative of the amount of adipose and/or connective tissue in a given cross-sectional scan of skeletal muscle.
CHAPTER II

REVIEW OF LITERATURE

Firefighter Injuries

Slipping, tripping, or falling accidents are attributed to a large percentage of work related injuries. According to the USA Bureau of Labor Statistics in 1998, falls accounted for 16.8% of non-fatal injuries and 11.9% of job-related deaths (Cham & Redfern 2001). Furthermore, a national health survey in 1997 indicated that 64% of work-related falls were attributed to slipping, tripping, or stumbling (Cham & Redfern 2001). The National Institute of Occupational Safety and Health (NIOSH) has indicated that slip, trip, and fall (STF) related research has long been recognized as one of the most important and needed areas of occupational and non-occupational injury prevention research (Hsiao 2014).

Firefighters face many inherent dangers due to their occupation and run a high risk of job related injury (Cloutier & Champoux 2000). Environmental factors associated with fireground operations as well as the added difficulties associated with personal protective equipment (PPE) increase the risk of STFs in this population. These injuries also present a large economic burden and often result in above average worker’s compensation claims (Walton et al. 2003). For example, Walton et al. (2003) suggested that STF related injuries resulted in an average medical cost of $3,147, and a worker’s compensation cost of $8,662 per individual.
According to the National Fire Protection Association, there were a total of 65,880 firefighter injuries that occurred in the line of duty in 2013 and an additional 97 fatalities (Karter Jr & Molis 2014). Nearly half of the injuries (45.2%) occurred during fireground operations and the leading causes were overexertion, or strain (26.5%) and fall, slip, or jump (22.7%) (Karter Jr & Molis 2014). Other injuries occurred while responding to calls, during non-fire emergencies, during training, or from miscellaneous on-duty tasks (Karter Jr & Molis 2014). Over a four year span from 2007-2011, minor injuries in the STF category accounted for 22% of the total, or 5,200 injuries (Karter Jr 2013). Approximately half of these were reported to have occurred on an uneven, icy, or otherwise slippery surface (Karter Jr 2013). During the same time period, an annual average of 3,375 (33%) moderate to severe injuries were a result of slipping, tripping, or falling compared to 2,845 (28%) of injuries resulting from overexertion or strain (Karter Jr 2013). Furthermore, a recent study by Britton et al. (2013) found that STF related accidents were the predominant source of injuries in wildland firefighters, accounting for 28% of total injuries and 34% of severe injuries. There may be an elevated exposure to fall risk associated with wildland firefighting due to hazardous terrain; however, these injuries were the most costly among suburban structural firefighters according to worker’s compensation claims (Britton et al. 2013). Seventy-one percent of STF related injuries were specifically to the lower extremity. Sprains and strains were the most frequent type of injury resulting from falls as well as one third of all fractures and dislocations (Britton et al. 2013).

Kong et al. (2013) recently described the contributing factors to STF related injuries as either extrinsic or intrinsic in nature. Extrinsic factors including firefighter PPE, impaired vision, surface conditions, and heat are often inherent to the situation and outside of the PPE, are often not modifiable. Intrinsic factors include age, balance, work experience, muscular strength,
fitness, fatigue, and body mass (Kong et al. 2013). Many of these are physiological in nature and readily modifiable through diet and exercise. The paper by Kong et al. (2013) emphasizes the necessity of studying factors associated with fall related injury rather than simply reporting the injury associated data. Hsiao (2014) explains that “the majority of human falls can be regarded as loss-of-balance incidents” (p. 388). Thus it is likely that neuromuscular function may be of primary importance for the prevention of STFs (Kong et al. 2013). Other research supports this notion in populations where STF accidents are common (van den Bogert et al. 2002; Bento et al. 2010; Crozara et al. 2013; Palmer et al. 2015).

Rate of Torque Development and the Rate of Muscle Activation

The ability to produce torque rapidly is related to multiple factors including efferent neural drive, muscle size and architecture, fiber type, and muscle tendon unit properties (Aagaard et al. 2002; Aagaard 2003; Andersen & Aagaard 2006). Explosive muscle force is characterized by the rate of torque (or force) development (RTD) during the early onset of a muscle action, (i.e. 0-200 ms), and is associated with rapid movement ability (Aagaard et al. 2002; Folland et al. 2014). Aagaard et al. (2002) explains that rapid movements may occur within the 50-200 ms timeframe which is shorter than the amount of time required for maximal isometric strength production (~300 ms). Furthermore, rapid torque production has been suggested to be more important than maximal strength in athletic activities (Thompson et al. 2013; Palmer et al. 2015), balance (Pijnappels et al. 2005; Palmer et al. 2015), reaction time (Reeves et al. 2003; Morcelli et al. 2015), and complex movement strategies (McLellan et al. 2011; Waugh et al. 2013).

In vivo, RTD represents the slope of the torque vs. time curve during isometric muscle actions (Andersen & Aagaard 2006). The contribution of the aforementioned characteristics associated with RTD appear to be relative to the time frame considered. Andersen and Aagaard
demonstrated that during time intervals after 90 ms from contraction onset, maximal strength accounted for 52-81% of the variance in voluntary RTD. For the very early phase of contraction (0 – 40 ms), MVC strength and evoked twitch RTD accounted for 18-31% and 32-35% of the variance in voluntary RTD respectively. Similarly, Folland et al. (2014) found that MVC strength explained 55-90% of the variance from 75-150 ms and electromyographic (EMG) activity contributed significantly to the early phase of RTD, accounting for 17-37% of the variance from 25-75 ms respectively (Folland et al. 2014). Specifically, motor unit discharge rate (or motor unit firing frequency) appears to be a primary contributor to the early phase of RTD (Van Cutsem et al. 1998; Andersen & Aagaard 2006; Duchateau & Baudry 2014).

Aagaard (2003) suggests that supramaximal firing rates may be attributed to increases in RTD more so than maximal force at the onset of muscle action. Supramaximal firing may be in part due to an increase in discharge doublet firing which has been shown to increase along with RTD in individual motor units after ballistic type training (Van Cutsem et al. 1998; Aagaard 2003). In a recent study, Duchateau and Baudry (2014) were able to demonstrate that initial motor unit discharge rates heavily influenced RTD at the onset of a fast muscle action. Furthermore, Folland et al. (2014) suggested that muscle activation was at or near maximal activity at 50 ms, and muscle tendon unit properties likely contributed to rising force during the 50-100 ms time frame. The stiffness of the muscle-tendon unit has also been shown to be an important factor in the RTD (Bojsen-Moller et al. 2005; Waugh et al. 2013). For example, Waugh et al. (2013) determined that tendon stiffness and neural drive together were able to account for 45% of the variance in normalized RTD. These findings collectively suggest that for the early phase of contraction, a combination of factors including intrinsic muscle contractile properties, muscle tendon properties, and the neural drive to the muscle influence RTD (Andersen & Aagaard 2006; Folland et al. 2014).
As mentioned previously, STFs occur as the result of many factors including both extrinsic and intrinsic variables. Falls specifically appear to be related to a loss of balance or the inability to adequately recover from a trip (Hsiao 2014). Following a STF, rapid activation of the ankle musculature (LaRoche et al. 2010), hip flexors (Morcelli et al. 2015), and hip extensors (LaRoche et al. 2010; Morcelli et al. 2015; Palmer et al. 2015) are important for regaining balance. Studies focusing on aging populations have specifically examined the association of RTD on mobility limitations and the history of falls. The RTD appears to decline with age (Thompson et al. 2014) and contribute to the incidence of falls in this population (Bento et al. 2010). Thompson et al. (2014) found a significant reduction in RTD (46.2%) of the plantar flexors in older men when compared to young men. With regard to timing, it appears that the early phase (0-50 ms) of force production is of most importance regarding the risk of falls (Palmer et al. 2015). Palmer et al. (2015) identified a significant correlation between RTD of the hip extensor muscles and fall history in the first 50 ms after contraction onset suggesting the importance of early phase torque development for fall prevention. Furthermore, the hamstrings, which serve as both hip extensors and leg flexors, have been shown to potentially best discriminate balance recovery and the likelihood of falls (Cham & Redfern 2001; Pijnappels et al. 2005; Pijnappels et al. 2005; Bento et al. 2010; Palmer et al. 2015). Bento et al. (2010) suggests that the improvements in RTD of the hamstring muscles are a relevant strategy for fall prevention.

The rate of muscle activation has been shown to be an important component of lower extremity performance (Aagaard et al. 2002; Cormie et al. 2010; Clark et al. 2011; Mitchell et al. 2011) and is often quantified from the rate of EMG rise (RER) expressed as a percentage of a maximal reference muscle action (Cormie et al. 2010; Thompson et al. 2014). For example,
Cormie et al. (2010) found increased muscle activation coincided with improved speed and power production in individuals exposed to ballistic type training. Mitchell et al. (2011) also reported increased rates of muscle activation in power trained males vs. endurance trained or control subjects. Additional studies have determined that the rate of muscle activation is an important component of functional performance in older adults. For instance, decreased RER has been shown to partially determine performance declines in functional tasks (Clark et al. 2011; Clark et al. 2013). Decreased rate of muscle activation was correlated with poorer scores in the Short Physical Performance Battery (SPPB) and indicative of mobility limitations in older adults (Clark et al. 2011). The rate of muscle activation was also found to be a principle determinant in maximal walking speed which may be an indicator of functional decline (Clark et al. 2013). Furthermore, the RER appears to be associated with balance recovery after tripping (Pijnappels et al. 2005), and has been shown to be 30% higher during the initial phase of EMG activity (0-50 ms) in the biceps femoris muscles of younger adults compared to older individuals with a history of falls (Crozara et al. 2013). Clark et al. (2011) suggests that the decline in neuromuscular activation is not purely due to age alone as studies have shown that physically active older adults maintain higher rates of activation and RER can also be increased with resistance training (Barry et al. 2005).

**Muscle Cross Sectional Area and Echo Intensity**

It is well documented that muscle size significantly influences muscle strength (Maughan et al. 1983), power (Mangine et al. 2014), and functional capacity (Visser et al. 2002). Previous authors have reported significant relationships between muscle size and lower extremity performance (Fukumoto et al. 2012; Mangine et al. 2014). In young healthy populations, muscle size has been shown to be related to muscle strength (Maughan et al. 1983; Maughan et al. 1984)
and jump and sprint performance (Mangine et al. 2014). In addition, studies incorporating resistance training have also reported significant correlations between the improvements in performance and subsequent increases in muscle size (Aagaard et al. 2002; Ronnestad et al. 2010). In a classic study by Aagaard et al. (2002), the authors suggested that the increases in absolute RTD following resistance training were in part due to increases in muscle size. Furthermore, improved cycling performance following heavy resistance training has also been significantly correlated with the increases in muscle size (Ronnestad et al. 2010). Reduced muscle size with age (sarcopenia) is thought to be a contributing factor to impaired lower extremity performance (Janssen et al. 2002; Visser et al. 2002; Thompson et al. 2013). For example, Visser et al. (2002) found decreased muscle mass resulted in poorer lower extremity performance in a timed walking test and repeated chair stands. More recently, Fukumoto and associates (2012) reported a significant relationship between isometric strength and quadriceps muscle thickness in older individuals. In addition, Thompson et al. (2013) suggested that sarcopenia may be a common factor for decreased rapid force production in this population.

Muscle tissue quality is traditionally defined as a measure of muscle function (strength or power) per unit of muscle size (mass or CSA) (Straight et al. 2015). This has been demonstrated by Goodpaster and colleagues (2006) who showed that the age-related decline in muscle strength (dynapenia) and power occur at a faster rate than the loss of muscle mass (sarcopenia). Changes in muscle quality are likely due to altered muscle composition including the infiltration of fatty and connective tissues (Goodpaster et al. 2000; Visser et al. 2002). More recently, imaging techniques like computed tomography (CT) and ultrasound (US) have been used to quantify a measure of muscle quality. For example, Goodpaster et al. (2000) used CT to demonstrate a correlation between reduced muscle attenuation values (Hounsfield units) and increased
intramuscular lipid content. Ryan et al. (2015) recently determined that US derived measures of muscle quality (echo intensity) are a valid tool to examine muscle quality. Echo intensity is based on the echogenicity of a tissue and is determined from the mean gray scale value of a particular region of interest (Ryan et al. 2015; Young et al. 2015). Fatty and fibrous tissues have a higher echogenicity resulting in a whiter image and a higher EI value indicating poorer muscle quality (Reimers et al. 1993; Pillen et al. 2009; Young et al. 2015). This method has been shown to be reliable and is generally more feasible than other methods such as CT (Rosenberg et al. 2014; Ryan et al. 2015).

Muscle quality has been shown to contribute to strength and performance independent of muscle size (Goodpaster et al. 2001; Fukumoto et al. 2012). For instance, Goodpaster et al. (2001) determined that muscle quality was indicative of strength after adjusting for muscle size in older subjects. Fukomoto et al. (2012) also determined that muscle quality was independently correlated with isometric strength in middle-aged and older adults. Diminished muscle quality seen with aging is significantly correlated with poor functional performance and mobility limitation (Visser et al. 2002; Visser et al. 2005). Visser et al. (2002) determined that individuals with greater fat and fibrous tissue infiltration were 50 to 80 percent more likely to develop mobility limitations. Furthermore, those with poorer muscle quality also performed worse in a repeated chair stand and a six meter walk test (Visser et al. 2005). The influence of increases in intramuscular fat and subsequent reduction in muscle quality have been examined recently by Choi et al. (2015) and these authors reported that muscular fat content adversely affected contraction speed, force, and power development in obese individuals. Furthermore, in a finite-element modeling study, Rahemi et al. (2015) suggested that the reduction in muscle performance is due to a stiffer base material composing the muscle itself due to the inclusion of
fatty tissue. Compared to the lean model, the fatty model had stiffer base properties, produced less force, and the transverse bulging capability of the muscle was reduced (Rahemi et al. 2015). It was also suggested that the connective tissue within the muscle serves to increase its overall stiffness thereby reducing its performance capacity (Rahemi et al. 2015).

Functional Balance Testing

Balance abilities are of high importance in various occupational groups that have physically demanding jobs (Punakallio 2003). Previous authors have utilized unique functional balance assessments to examine the influence of many factors that may lead to STF injuries (Punakallio et al. 2004; Kong et al. 2012; Hur et al. 2013). There are many contributions to balance which include vestibular senses, visual feedback, and physiological determinants such as muscular size and strength. These factors may be individually tested; however, a functional balance assessment may be the most relevant tool to provide information regarding specific occupational balance abilities. For example, Punakallio and colleagues (Punakallio 2003; Punakallio 2004) originally developed a functional balance assessment that included walking forward and backward on a wooden plank as fast as possible. Errors committed during the test resulted in a one second penalty added to the total time of each trial and a total of six trials were completed. A follow up study found good to excellent reliability of the functional balance test among a professional firefighter population (ICC = 0.77) (Punakallio 2004). It was also recommended that a familiarization trial and a minimum of 3 official trials be completed and the best score taken for analysis to further improve the test’s reliability (Punakallio 2004).

The functional balance test developed by Punakallio et al. (2003) was used to initially suggest that particular occupational populations (construction workers and firefighters) had better balance capacities than others (home care workers and nurses), likely due to the demands
of their working conditions. Within these four subgroups, it was also determined that firefighters performed more slowly and made more errors than construction workers. Furthermore, in all four groups, functional balance performance decreased with age (Punakallio 2003). In a subsequent study using only professional firefighters, Punakallio et al. (2004) found a significant relationship between functional balance performance and working ability. A work ability index (WAI) as well as a perceived work ability index (PWA) were utilized and both were significantly correlated with performance in the functional balance test (Punakallio et al. 2004). In a similar study using career firefighters, Kong et al. (2012) determined that PPE negatively impacted performance time and errors committed in the functional balance test. A key finding in this study was that subjects who reported regular strength training performed better in the functional balance test than those who did not report physical activity (Kong et al. 2012).

More recently, Hur et al. (2013) incorporated the use of personal protective equipment (PPE) into a study investigating the effects of fatigue on functional balance in firefighters. While utilizing a similar structure and testing procedure as described previously, the authors chose to incorporate two raised platforms as well as a simulated overhead obstacle in order to more closely resemble the working environments firefighters often encounter. Each of the two platforms included a defined space inside of which the firefighters were instructed to maintain their footing during each trial. The overhead obstacle, placed at 75% of the participant’s height, was included to mimic the necessity to pass through a confined space with low clearance in potentially hazardous conditions. Minor errors were counted similar to previous studies (Punakallio 2003; Kong et al. 2012) and a major error was counted if the overhead obstacle was contacted and fell. This study concluded that both PPE and fatigue resulted in significantly decreased functional balance performance (Hur et al. 2013).
CHAPTER III

METHODOLOGY

Participants

Forty-four career firefighters ages 18-50 years were recruited for this study. Local career firefighters were solicited from fire departments in the central North Carolina region. Participants were excluded if they had a neuromuscular or metabolic disease, if they were pregnant or trying to become pregnant, or had a current or recent (within the past 3 months) joint or muscle problem of the lower body or lower back that would not allow them to complete the testing. Due to the physiological changes that occur with pregnancy and the potential risk of falling during the functional balance test, if a female participant was pregnant, she would have been withdrawn from the study. Urine dipsticks were used to determine pregnancy status during their first visit. G-Power software was used according to the procedures presented by Beck (2013) to estimate sample size using an effect size ($f^2 = 0.38$) as determined by Kleinberg et al. (2015) required to reach a statistical power ($1-\beta$) of 0.8 with four predictors, and resulted in an estimated total sample size of 37. We recruited a sample of 47 participants and three subjects did not fully complete the study.

Experimental Design

Participants visited the Neuromuscular Research Laboratory in the Exercise and Sport Science department three separate times at the same time of day. Visit two occurred two to ten
days after visit one, and visit three occurred two to ten days following visit two. Upon arrival for visit one, participants were asked to read and sign an informed consent document stating the experimental protocol with the potential risks and benefits associated with participation in the study. They then completed a health history and exercise status questionnaire, and practiced the isometric strength assessments.

During visit two, each participant had their stature, body mass, body composition, muscle size and quality of the hamstrings (biceps femoris) examined, and performed the leg flexion isometric strength assessment. Following all assessments, participants then practiced the functional balance assessment. All participants then completed the functional balance assessment during their third visit.

**Body Composition**

Participants were asked to come to the lab for their second visit following a minimum of a four hour fast (except water) with no exercise performed 24 hours prior to testing. Stature was measured to the nearest 0.5 cm with a calibrated stadiometer (Perspectives Enterprises, Portage, MI USA) and body mass (BM) was measured to the nearest 0.01 kg using a calibrated clinical scale (BOD POD®, Life Measurement, Inc., Concord, CA.). Percent body fat (%BF) was assessed using dual energy X-ray absorptiometry (DEXA, Hologic Discovery W, Bedford, MA). Subjects were positioned supine and centered on the table after removing all personal items and instructed to remain still while the scan was performed.
Ultrasound

Prior to the ultrasound (US) assessment, participants rested on a padded table for 10 minutes to allow adequate time for any potential changes in body fluid shifts (Berg et al. 1993). Measures of muscle size and quality were assessed using a portable brightness mode (B-mode) US imaging device (LOGIQ e 5, General Electric Company, Milwaukee, WI, USA) and a multi-frequency linear-array probe (12L-RS; 5-13 MHz; 38.4 mm FOV) (General Electric Company, Milwaukee, WI, USA). The musculoskeletal mode with standardized settings for gain (68 dB), depth (4.5 cm), and frequency (10 MHz) was used to optimize image quality and was maintained across all participants. All ultrasound measures were assessed with the panoramic (extended field of view) function on the hamstring muscles (biceps femoris) of the right leg, with the participants in a relaxed prone position, and the lower leg propped at 50 degrees of flexion. A cross sectional scan perpendicular to the longitudinal axis of the thigh was performed at half the distance between the greater trochanter and the articular cleft of the knee (Kleinberg et al. 2015). Transmission gel was applied to the skin to enhance acoustic coupling (Rosenberg et al. 2014). A custom foam guide was fixed to the thigh to ensure movement of the probe in the transverse plane and the scan was performed from the medial to lateral aspects of the biceps femoris muscle. Care was taken to ensure steady mild pressure was applied to the skin during the scan without compression of the muscle.

Image Analysis

All images were analyzed using Image-J software (version 1.46r, National Institutes of Health, USA) to obtain a measure of muscle size [cross sectional area (CSA)] and muscle quality [echo intensity (EI)] values. Prior to analysis, each individual image was scaled from pixels to
centimeters using the straight line function. The polygon function was used to assess CSA by outlining the entire muscle while excluding the fascial border. The same region of interest was analyzed with a computer aided gray scale standard histogram function to obtain a mean EI value. Values for muscle quality index are reported as mean gray scale values ranging from 0-255 arbitrary units (a.u.) (black = 0; white = 255) (Rosenberg et al. 2014). Subcutaneous fat was measured using the straight line function from the skin to the superficial aponeurosis at the midpoint of the muscle measured between the medial and lateral borders. The EI values were then corrected for subcutaneous fat thickness by using the method outlined by Young and colleagues (2015).

**Isometric Strength Testing**

The rate of torque development (RTD) was assessed from the torque curves of the isometric maximal voluntary contractions (MVC) of the leg flexors using a calibrated HUMAC Norm dynamometer (Computer Sports Medicine Inc., Stoughton, MA, USA). Participants were seated in the dynamometer with the right leg extended to 60º below horizontal and their lower leg secured to the dynamometer lever arm using a padded Velcro strap (90mm width) placed five cm proximal to the lateral malleolus of the ankle. The dynamometer axis of rotation was aligned with the center of the subject’s knee joint. The seat belt was used to stabilize the subject’s torso and a Velcro strap across the thigh aided in isolation of the leg flexor muscles. Subjects were instructed to cross their arms across their chest during each maximal effort. Participants performed three submaximal isometric warm-up muscle actions followed by three MVCs with a two minute recovery period between MVCs. They were asked to flex their leg as hard and fast
as they could against a stationary lever arm for 3-4 seconds (Thompson et al. 2013). Participants were given strong verbal encouragement during each muscle action.

**Electromyography Measures**

Each participant had pre-amplified, bipolar surface electrodes (EL254S Biopac Systems, Santa Barbara, CA, USA; gain = 350; interelectrode distance = 20 mm) placed over the biceps femoris muscle of the right leg. Electrode placement was determined immediately following the US assessments while the subject was lying in the prone position. The muscle was visually identified and palpated while the leg was flexed. Before placement of the electrode, the skin was shaved, mildly abraded, cleaned with alcohol, and allowed to dry to reduce skin impedance. The electrode was then be taped to the predetermined position on the subject’s thigh at half the distance between the greater trochanter of the femur and the articular cleft of the knee. The electrode was placed parallel to muscle fiber orientation in accordance with the recommendations of the SENIAM project (Hermens et al. 2000). A custom foam pad was secured around the electrode to the subject’s thigh to aid in maintaining proper positioning during testing while in the seated position. A single, pre-gelled, disposable electrode (Ag Cl Quinton Prep; Quinton Instruments Co, Bothell, WA, USA) was placed over the tibia tuberosity to serve as a reference electrode.

**Signal Processing**

The torque (Nm), and EMG (μV) signals were sampled simultaneously at 2.0 kHz with a Biopac MP150WSW data acquisition system and Acqknowledge software (Biopac Systems Inc., Goleta, CA, USA) during each of the MVCs. All signals were stored on a personal computer.
(Lenovo IBM ThinkPad T420, Morrisville, NC, USA) and processed offline with custom written software (Labview 2014, National Instruments, Austin, TX, USA). Torque signals were filtered with a low pass zero-phase shift fourth order Butterworth filter (50 Hz). The raw EMG signals were filtered with a bandpass zero-phase shift fourth order Butterworth filter (20-400 Hz.), de-biased (mean set to zero), rectified, and smoothed with a low pass filter (10 Hz) to create a linear envelope, and then normalized to the peak EMG amplitude of the EMG-time curve. Identification of the torque and EMG onsets were manually determined by the same investigator. For the torque and EMG onset, a horizontal cursor was used as a guide to identify the point where the signal amplitude was just higher than the collective baseline (at least 2,000 data points). The onset for both signals was determined from the last trough of the torque signal before it deflected from baseline. Rate of torque development was determined from the slope of the torque vs. time curve from 0 - 100 ms following manual onset and then normalized to body mass. The RER values were calculated from the slope of the normalized EMG linear envelope from 0 – 100 ms following manual onset.

**Functional Balance Assessment**

Functional balance was examined using a test similar to that recently developed by Hur et al. (2013). The simulated firefighting task required firefighters to step down from a raised platform, walk along a narrow beam, pass under an overhead obstacle, step up to a raised platform, and repeat this walking backward as fast as possible while wearing their standard personal protective equipment and self-contained breathing apparatus. A lightweight wooden rod (overhead obstacle) was placed at 75% of the participant's height and designed to fall away if the rod was hit, rather than being a rigid structure. Subjects completed two practice trials and five timed trials with a one minute rest period between each trial. Three researchers were present
during the balance assessment. Two of the researchers were responsible for timing each trial using a stopwatch, (Robic SC-505W, Marshall-Browning Int’l Corp, Oxford, CT) and monitored the participant during the testing, and a third researcher was responsible for the verbal commands to start and stop each trial. The command “three, two, one, GO” was given and the time started on ‘GO’. Time was stopped when the subject had both feet back in the original starting position on the first platform. The average of the times recorded by each of the two researchers was used as the performance time for each individual trial.

The number of errors (minor and major) and performance time were calculated to determine a performance index (PI) similar to that described by Hur et al. (2013). A minor error was counted when: 1) a foot or hand contacted the ground, 2) a hand contacted a platform, 3) the subject stepped outside of the defined space on the platforms, or 4) the obstacle was touched but did not fall. A major error was counted when: 1) the obstacle was contacted and the rod fell, 2) both feet contacted the ground, or 3) the subject tripped or fell during the trial. A minor error counted as a one second penalty and a major error equaled a two second penalty which was added to the total time of each trial. The PI was determined by the following equation: $\text{PI} = \text{[time to complete trial (seconds)]} + \text{[number of minor errors x 1]} + \text{[number of major errors x 2]}$ (Hur et al. 2013). Each functional balance test was videotaped and the minor and major errors were analyzed after testing by the same investigator. Each subject’s best PI score was used for all analyses (Punakallio et al. 2004). A similar functional balance assessment as described by Punakallio et al. (2004) produced good to excellent test-retest reliability with an intra-class correlation coefficient ranging from 0.78 to 0.96 increasing with number of trials completed.
Statistics

Descriptive data are summarized in Table 1. Variables collected from all assessments are 1) RTD, 2) RER, 3) muscle size (CSA), 4) muscle quality (EI), and 5) functional balance performance. All analyses were performed with SPSS version 20.0 (SPSS, Inc., Durham, NC, USA) with an alpha level set *a priori* at $P \leq 0.05$. A Pearson correlation analysis was used to determine the relationship between the functional balance PI, age, %BF, and each neuromuscular variable (Table 2). Because of the impact of age and %BF, a partial correlation was used to assess the relationship between the PI and each neuromuscular variable while controlling for age and %BF. A final correlation analysis was used to assess the relative association of RER, CSA, and EI with RTD.
CHAPTER IV

RESULTS

Thirty-nine male firefighters (age 35.5 ± 7.9 yrs., stature 180.6 ± 6.3 cm., %BF 24.8 ± 5.0%) and five female firefighters (age 34.8 ± 6.5 yrs., stature 167.3 ± 3.7 cm., %BF 27.3 ± 3.8%) were used for statistical analyses. The Pearson product moment correlation analysis revealed a significant relationship ($P < 0.05$) between the functional balance PI and age, %BF, and RTD ($r = 0.423$, $P = 0.004$, $r = 0.378$, $P = 0.012$, $r = -0.327$, $P = 0.030$, respectively, Table 2). When controlling for age and %BF, the partial correlation analyses indicated a significant negative association between RTD and functional balance performance ($r = -0.342$, $P = 0.027$), but no relationship with RER ($r = -0.246$, $P = 0.117$), BF CSA ($r = 0.190$, $P = 0.228$), or corrected EI ($r = -0.040$, $P = 0.812$). A secondary correlation analysis was used to determine the relative contribution of neuromuscular variables to RTD. This analysis revealed a significant relationship between RTD and RER values ($r = 0.505$, $P < 0.001$) but not with BF CSA ($r = -0.178$, $P = 0.247$) or EI ($r = -0.015$, $P = 0.927$).
CHAPTER V

DISCUSSION

The primary findings of this study indicated that age ($r = 0.423$), %BF ($r = 0.378$), and leg flexion RTD ($r = -0.327$) were significantly related to functional balance performance in our sample of career firefighters. However, muscle size and quality of the BF, and RER were not significantly related ($r = 0.217, 0.105, -0.264$, respectively) to the functional balance assessment. When controlling for age and %BF, RTD remained a significant predictor of functional balance performance ($r = -0.342$). A recent review by Kong et al. (2013) has suggested that both age and obesity may be independent risk factors for STF related injuries in firefighters. Previous studies by Punakallio and colleagues (Punakallio 2003; Punakallio et al. 2005) have reported contrasting findings on functional balance performance using a similar assessment as in the current study. For example, Punakallio (2003) determined that age was a significant variable associated with functional balance among several occupational groups including firefighters. However, Punakallio et al. (2005) found no statistical difference between age groups of firefighters in slip distance under four separate surface conditions. Although the older group experienced a greater number of slips and generally more severe slips than the younger group, the groups were not significantly different ($P > 0.05$). Our results support the initial findings by Punakallio et al. (2003) and are in agreement with previous authors who reported that injuries specifically related to STFs were highest among firefighters aged 40-44 years (Cloutier & Champoux 2000), similar to the peak age in our study. Obesity has also been shown to be an important risk factor for STF
injuries. For example, Chau et al. (2004) has demonstrated in various occupational populations (i.e. masons, roofers, and construction workers) that falls are more frequent among overweight and obese individuals compared to those of normal BMI. In addition to the increased frequency of falls, Michaelides et al. (2011) have demonstrated that increased %BF is related to poor performance in a physical abilities test comprised of simulated firefighting tasks. In contrast, a recent study by Kong et al. (2012) reported no relationship between functional balance performance and adiposity, however the authors utilized BMI vs %BF, and the study cohort was comprised of volunteer rather than career firefighters, which may not adequately represent our study population. Our results add to these findings and demonstrate that %BF negatively influences functional balance performance in career firefighters.

Muscular strength and endurance have been suggested to be important risk factors for STF related injuries (Kong et al. 2013). However, Punakallio et al. (2005) reported no significant relationships between various measures of muscular fitness (maximum repetition squatting and sit-ups, maximum leg and trunk extension strength) and the risk for STF injuries. They determined that approximately half of all firefighters tested experienced slip distances indicative of an unavoidable fall which was also related to poor performance in a dynamic stability test. Although not statistically significant \( P > 0.05 \), the group with less severe slips (< 5 cm) performed better than the group with greater slip severity (> 5 cm) in all muscular fitness assessments except for trunk extension strength. In relation to balance and STF risk factors, it has been proposed that response time and the ability to rapidly produce torque rather than maximal strength are key variables to consider. For example, a number of previous studies (Bento et al. 2010; LaRoche et al. 2010; Crozara et al. 2013; Morcelli et al. 2015; Palmer et al. 2015) have demonstrated that RTD was a discriminatory variable between fallers and non-fallers.
in older adults. Interestingly, Bento et al. (2010) found that RTD rather than peak torque of the hamstring muscles was significantly related to the occurrence of falls. Furthermore, a study by Morcelli et al. (2015) demonstrated a general trend toward decreased hip extension RTD at 50 and 100 ms (29% and 26% lower, respectively) in the elderly with a history of falls compared to those without a history of falling. The findings by Morcelli et al. (2015) are in agreement with time periods used by other researchers (Palmer et al. 2015) for the assessment of balance and fall related risk. For example, Palmer et al. (2015) illustrated that early RTD (50 ms), but not later RTD (100-200 ms), of the hip extensor musculature was significantly related to fall history. Furthermore, Palmer and colleagues (2015) concluded that increased early rapid torque production of the hip extensor muscles would likely contribute to improved balance recovery and reduce the risk of fall related injuries. The influence of early phase (≤ 100 ms) RTD on balance and fall risk demonstrated in these studies is in line with our current findings. It is likely that the rapid development of torque in the hamstrings of the stance leg assists in reduction of forward angular momentum following a trip (Pijnappels et al. 2005) and allows for the rapid rearrangement of the swing leg (Bento et al. 2010) to regain balance and avoid a STF.

The RTD variable in the current study was calculated during the initial 100 ms from contraction onset, which has been considered an early RTD variable (Blazevich et al. 2009; Thompson et al. 2013; Morcelli et al. 2015; Palmer et al. 2015) and within a similar time period needed to recover from a STF (Pijnappels et al. 2008). Pijnappels et al. (2008) have suggested that this early time frame (≤ 100 ms) is particularly important for rapid movements including balance recovery compared to later time periods (> 100 ms) which are more closely associated with maximal strength capacity (Aagaard et al. 2002). Our data suggest that the RER (r = 0.505), and not the size and quality of the BF musculature (r = 0.178, r = -0.015, respectively), is
related to early RTD. These findings are in agreement with many previous studies that demonstrated that early RTD variables are related to the rate of muscle activation (Mitchell et al. 2011; Crozara et al. 2013; Waugh et al. 2013; Folland et al. 2014; Morcelli et al. 2015). For example, Folland et al. (2014) showed that during the initial 150 ms of contraction time, neuromuscular activation rate contributed significantly to the explained variance in rapid force production. Furthermore, the rate of muscle activation was significantly correlated with relative rate of force development at 50 and 100 ms ($r = 0.71$, $r = 0.37$, respectively). Folland and colleagues (2014) concluded that neuromuscular activation is an important determinant of early RTD and likely has important implications for stabilization following a loss of balance. The differences in the rate of muscle activation may be attributed to increased motor unit recruitment and/or motor unit discharge rate (firing frequency) as described by previous authors (Van Cutsem et al. 1998; Aagaard et al. 2002; Mitchell et al. 2011; Duchateau & Baudry 2014). For example, Aagaard et al. (2002) demonstrated a parallelism between increased early phase RTD and the rate of muscle activation following training, and concluded that differences in RTD were likely due to increases in motor unit firing frequency. A classic paper by Van Cutsem et al. (1998) using indwelling EMG electrodes also concluded that increases in rapid force production were primarily due to earlier motor unit recruitment, increased discharge doublet firing rates (interspike intervals 2 – 5 ms), and increased maximal firing frequency following training. Duchateau and Baudry (2014) have recently summarized these findings in a review paper which concluded that during fast muscle actions, maximal motor unit firing frequency is the primary mechanism responsible for increases in early RTD. Collectively, these findings and the results from the current study, support that functional performance including balance and STF recovery is likely limited by RTD, which is influenced by RER.
In the present study, the size and quality of the BF were not related to RTD. Previous studies have shown that thigh CSA is positively correlated with maximal strength (Maughan 1984; Harridge et al. 1996; Thompson et al. 2013). However, due to the time required to reach peak strength (~300 ms) (Aagaard et al. 2002) and the association between CSA and maximal strength, CSA may be more closely associated with later time periods (> 100 ms) in muscle force development. Furthermore, Thompson et al. (2013) has demonstrated that leg flexor CSA was not correlated with early RTD and may be in part due to the small relative CSA of the hamstrings compared to the quadriceps muscles. In addition, Hakkinen et al. (1998) showed that thigh CSA was positively correlated with maximal strength following a training protocol in young and older men; however, no correlation existed between CSA and RTD. These previous studies and the results of the current study may suggest that muscle CSA is more related to maximal strength as opposed to early RTD.

In older adults, muscle quality, a measure of intramuscular adipose (Goodpaster et al. 2000) and connective tissue (Pillen et al. 2009) infiltration, has been correlated with maximal (Fukumoto et al. 2012) and rapid (Rech et al. 2014; Wilhelm et al. 2014{Rech, 2014 #2370}) strength characteristics. For example, Fukumoto et al. (2012) found that muscle quality assessed via EI was independently associated with maximal isometric strength in middle aged and older adults. Wilhelm and colleagues (2014) reported that of the four quadriceps muscles, only the vastus intermedius EI was associated with early RTD in older adults. Interestingly, EI from all four quadriceps muscles were significantly related to all other performance variables including countermovement jump, peak torque, one repetition maximum, and the late phase of RTD (200 ms). Moreover, Rech and colleagues (2014) reported significant correlations between vastus lateralis and rectus femoris EI, and early phase RTD in an active older female population. These
findings in conjunction with the current study suggest that EI may be more related to RTD in older adults (> 65 years) who have significant changes in muscle quality than the sample in the current study (mean age 35.4 years). Finally, the EI values in the current study have been corrected for subcutaneous fat as described by Young et al. (2015), a consideration not previously accounted for in other studies, which may provide better insight into the relationship between muscle quality and RTD.

In conclusion, the results of the present study indicated that functional balance performance in career firefighters is negatively influenced by aging and increased levels of %BF. Furthermore, when accounting for age and %BF, increases in RTD remained significantly related to faster times during the functional balance test which was influenced by RER, but not the size or quality of the BF muscle. These findings and previous research indicate that early RTD of the leg flexor musculature may be an important variable to help reduce STF-related injuries in the fire service.
<table>
<thead>
<tr>
<th>physical characteristic or outcome variable</th>
<th>Mean ± SD</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (yrs.)</td>
<td>35.4 ± 7.7</td>
<td>20.0 - 50.0</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>179.1 ± 7.4</td>
<td>163.0 - 194.0</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>94.3 ± 20.3</td>
<td>54.1 - 145.4</td>
</tr>
<tr>
<td>%BF (%)</td>
<td>25.1 ± 5.0</td>
<td>12.9 – 33.5</td>
</tr>
<tr>
<td>PI (s)</td>
<td>11.3 ± 3.0</td>
<td>5.6 - 16.7</td>
</tr>
<tr>
<td>BF CSA (cm²)</td>
<td>10.2 ± 2.4</td>
<td>5.9 - 16.8</td>
</tr>
<tr>
<td>BF EI (a.u.)</td>
<td>110.1 ± 14.8</td>
<td>71.1 - 142.2</td>
</tr>
<tr>
<td>BF RTD (Nm·s⁻¹·kg⁻¹)</td>
<td>5.4 ± 3.8</td>
<td>0.04 - 15.9</td>
</tr>
<tr>
<td>BF RER (% PEMG·s⁻¹)</td>
<td>722.6 ± 324.6</td>
<td>88.8 – 1205.0</td>
</tr>
</tbody>
</table>

%BF percent body fat, PI functional balance performance index, BF CSA biceps femoris cross sectional area, BF EI biceps femoris echo intensity, BF RTD biceps femoris rate of torque development, BF RER biceps femoris rate of EMG rise
Table 2. Correlation coefficients between functional balance performance index, demographic data, and each separate neuromuscular variable

<table>
<thead>
<tr>
<th></th>
<th>PI</th>
<th>Age</th>
<th>%BF</th>
<th>BF CSA</th>
<th>BF EI</th>
<th>RTD</th>
<th>RER</th>
</tr>
</thead>
<tbody>
<tr>
<td>PI</td>
<td>-</td>
<td>0.423**</td>
<td>0.378*</td>
<td>0.217</td>
<td>0.105</td>
<td>-0.327*</td>
<td>-0.264</td>
</tr>
<tr>
<td>Age</td>
<td>0.170</td>
<td>-</td>
<td>0.015</td>
<td>-0.152</td>
<td>0.011</td>
<td>0.018</td>
<td></td>
</tr>
<tr>
<td>%BF</td>
<td>0.165</td>
<td>-</td>
<td>-0.138</td>
<td>-0.178</td>
<td>-0.164</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BF CSA</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-0.015</td>
<td>-0.117</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BF EI</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-0.015</td>
<td>-0.117</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RTD</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.505**</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RER</td>
<td></td>
<td>-</td>
<td>-</td>
<td></td>
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</tbody>
</table>

*PI* functional balance performance index, *%BF* percent body fat, *BF CSA* biceps femoris cross sectional area, *BF EI* biceps femoris echo intensity, *RTD* rate of torque development, *RER* rate of EMG rise

Statistical significance: *P* < .05, **P** < .01
Figure 1. Functional balance test
REFERENCES


van den Bogert, A. J., M. J. Pavol, et al. (2002). "Response time is more important than walking speed for the ability of older adults to avoid a fall after a trip." J Biomech 35(2): 199-205.


