ENHANCED REHABILITATION TARGETING STRENGTH AND MOVEMENT PATTERN SYMMETRY FOLLOWING HIP FRACTURE

by

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STATEMENT OF DISSERTATION APPROVAL

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ABSTRACT

Asymmetries in movement and muscle function are ubiquitous and long lasting in those who survive after hip fracture. Enduring asymmetries in lower limb muscle function (i.e., strength and power) have been associated with fall frequency and impaired physical mobility among older adults. Lower limb discrepancies in vertical ground reaction forces (vGRFs) are evident during performance of mobility tasks, including ambulation and transfers from a seated to a standing position. Movement asymmetry during a sit-to-stand task (STST) made a small, independent contribution (r^2 = 7%) to stair climb test performance when coupled with gait speed (r^2 = 41%), balance confidence (r^2 = 4%), and self-reported function (r^2 = 4%); while STST asymmetry did not independently predict modified physical performance test score.

To date, there is no specific rehabilitation strategy to restore movement pattern and muscle function symmetry after hip fracture. Thus, the potential impact of specific strategies to improve symmetry in vGRF variables during STST performance, and muscle function after hip fracture is unclear. We examined the feasibility and beneficence of High Intensity Task-Oriented strategies designed to improve Strength and Symmetry (HI-TOSS). We determined that asymmetries in strength, power, and vGRFs evident during STST, were each significantly reduced (i.e., improved) with training.

Finally, improvements in muscle quality and its components with training after hip fracture have not been tested. We identify the surgical limb to be 10%-15% lower in muscle mass and muscle quality compared to the nonsurgical limb after discharge from usual care. Following HI-TOSS, muscle mass in the surgical limb improved by 9%, muscle strength improved by 21%, and muscle quality improved by 14%. Expectedly, physical performance improved significantly with training (~20% improvement); exceeding established clinically meaningful difference values.

In summary, specific strategies to reduce asymmetries in movement and improve muscle function are well-tolerated in community-dwelling older adults after hip fracture and can yield improvements in STST and muscle function symmetry. Substantial improvements in STST performance, muscle function, muscle composition, and physical function are expected with HI-TOSS. Further studies should determine long-term effects and optimal HI-TOSS implementation practices in a restorative effort to enhance recovery after hip fracture.

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LIST OF ABBREVIATIONS

ADLs	Activities of Daily Living
BMI	Body Mass Index
CI	Confidence Interval
HF	Hip Fracture
HI-TOSS	High-Intensity Task-Oriented Strength and Symmetry
IH	Intermountain Healthcare
Peak vGRF	1st Peak Vertical Ground Reaction Force
RCT	Randomized Controlled Trial
RFD	Rate of Force Development
SD	Standard Deviation
SEM	Standard Error of Measurement
STST	Sit-to-Stand Task
UU	University of Utah
vGRF`	Vertical Ground Reaction Force

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CHAPTER 1

INTRODUCTION

Introduction

Hip fracture is a devastating injury, expected to impact more than 350,000 older adults in the U.S. annually,[1] with an estimated direct cost of $14 to $20 Billion per year.[2] Fall-related injuries constitute the leading cause of death and disability among persons 60 years and older, with 30% of older adults reporting a fall in the previous year.[3] Medicare direct costs for fall-related injuries exceeded $19 Billion in 2000, and are projected to surpass $54 Billion annually by 2020.[4] Although less than 35% of nonfatal falls result in fracture, this group incurs nearly 70% of all fall related costs.[4] The most frequent, costly, and disabling *nonlethal* injury from a fall is a hip fracture. Mortality is high in this population, as approximately 20% of older adults who have incurred a hip fracture will die within 3 months and nearly 30% within 1 year after incurring a hip fracture.[5] Those who survive frequently require continued in-home services and are susceptible to recurrent falls, fracture, and hospitalization.[6] Physical function, muscle function, and muscle composition progressively worsen among those who survive, and each is linked to decreased mobility and adverse health outcomes.[7]

Background

The nature and intensity of rehabilitation strategies typically offered following hip fracture have not changed significantly over the last 30 years.[8] These strategies include simple bedside range of motion, light resistance exercises (rarely exceeding 40% of 1-repetition maximum), and basic mobility training to improve safety and balance with gait and transfers. The rehabilitation timeline for “usual care” after hip fracture includes 3-5 days of hospitalization, followed by 6-8 weeks of physical therapy intervention until individuals regain a limited measure of basic mobility and physical function.[8] At least 60% of hip fracture survivors never recover their prefracture physical function,[6] and most become progressively more sedentary.[9] Those who cannot perform basic mobility tasks independently after a few weeks of rehabilitation are destined for institutionalization.[10] Survivors are four times more likely to become dependent in activities of daily living (ADLs) and at least six times more likely to require long-term institutionalization than age-matched peers.[11,12] Current postoperative management does not adequately address what may in-part be reversible muscle and movement deficits; thus, the downward spiral of limited movement and deteriorating muscle conditions persist following the trauma related to a hip fracture and resultant surgery. This has contributed to the notion that long-term deficits in physical function are acceptable, irreversible and unavoidable consequences of a hip fracture.

A modicum of evidence is now suggesting an extended bout of rehabilitation may significantly improve clinical outcomes. Extended high-intensity resistance training strategies designed to improve muscle size and strength are well-tolerated and yield markedly better recovery in strength and physical function than traditional rehabilitation.[13-16] This is important since there is a 50% loss of strength in knee extension in the surgical limb in the first week after hip fracture,[17] and residual strength loss is evident for several years after fracture for many.[18] Recovery of physical function in fact is linked to quadriceps strength recovery, and 30-80% quadriceps strength gain is expected with an extended high-intensity rehabilitation regime over a 3-month period following hip fracture.[15] While neural adaptations may explain some of the strength gain, increased muscle size may also contribute. Regardless of the mechanism, without extended intervention, physical function plateaus approximately 3 months after hip fracture, then gradually declines[6,19] Unfortunately, these individuals have limited muscle and physical function reserves leaving them susceptible to a future catabolic event (e.g., illness, injury, hospitalization) which propagates extended inactivity, muscle loss and subsequent declines in physical function.

With an impaired lower limb, it is not unusual for abnormal movement patterns to emerge after hip fracture. These patterns may also contribute to persistent physical function deficits. Muscle function impairments, such as strength and power deficits of the surgical limb are higher in fallers and mobility-limited individuals than nonfallers,[20-22] and between-limb discrepancies in strength and power are known risk factors for recurrent injurious falls. [21,22] Negative consequences of residual surgical limb muscle deficits among older adults include increased fall risk,[23] decreased mobility,[24-27] and greater likelihood of lower extremity injury.[28] Independent, community-dwelling older adults who have had a hip fracture demonstrate movement pattern asymmetries during an sit-to- stand task (STST) a year after injury.[29,30] The persistent muscle function deficits in the surgical limb may contribute to asymmetrical movement patterns.[20]

Typical Asymmetries and Muscle/Mobility Recovery After Hip Fracture

Young adults demonstrate movement pattern asymmetries and surgical limb strength deficits after orthopedic procedures such as anterior cruciate ligament reconstruction. Muscle function asymmetries in this population are associated with suboptimal postsurgical outcomes including pain, recurrent injury, and elevated incidence of surgical revisions.[28,31,32] Among young adults, strength training alone is inadequate to restore symmetry, and task-specific training strategies combined with balance training are a vital component in recovery after orthopedic surgeries such as anterior cruciate ligament repair.[33-35] These rehabilitation strategies are linked to restored physical function, reduced injury rate, and lower surgical repair incidence.[32,34,36,37]

Though suspected contributors to movement pattern asymmetry have been identified (e.g., surgical limb strength and power deficits, compensated movement strategies), studies examining rehabilitation strategies that might mitigate emerging asymmetrical movement patterns after hip fracture are lacking. Thus it is currently unknown whether extended rehabilitation strategies designed to improve movement pattern symmetry might effectively restore symmetry after a hip fracture.

Lower extremity movement strategies captured during an STST are correlated with self-reported physical function, balance, and fall risk in a community-dwelling hip fracture population.[29,38] Citing the significant, high correlations between surgical limb STST performance, and other observable measures of physical performance, it is suggested that rehabilitation efforts to target the impaired surgical limb, thus reducing lower extremity vGRF asymmetry may inspire significant gains in physical performance.[38] However, whether asymmetries in STST performance can independently predict observed physical performance above other factors known to influence physical function is unknown.

Multiple factors may contribute to unresolved asymmetry in task performance after a hip fracture. An increased hip extensor moment strategy is adopted for sit-to-stand transitions after total knee arthroplasty in response to reduced quadriceps femoris strength, and persists for at least 12 months, even after strength is restored.[39] Similarly, enduring reduced knee extensor power is evident in the surgical limb during STST performance following hip fracture despite strength gains, and is associated with reported difficulty and slower times during stair climbing.[20] STST is a common, yet difficult task for many survivors after hip fracture. STST requires high hip and knee joint moments compared to other common tasks, such as standing, walking, or stair climbing.[40] Thus, individuals frequently require compensations--elevated seat height, elevated arm rests, increased dependency in the nonsurgical limb (specifically a greater knee extensor moment),[38] and higher arm impulse for push-off from armrest[30] to maintain or regain independence in STST performance. For at least a year after hip fracture, STST performance reveals an approximate 30% deficit in lower extremity vGRF impulse during the initiation of STST performance, and a similar between-limb discrepancy in the surgical limb compared to the nonsurgical limb while rising from a seated surface, indicating that compensated movement strategies do not resolve spontaneously after hip fracture. Interestingly, though less force is required from the lower extremities when rising from a chair with arm assistance, vGRF asymmetries remain apparent, regardless of arm use, suggesting that a lack of strength does not fully explain the vGRF asymmetries evident during STST completion.[30] While moderate correlations between strength and STST performance exist,[38,41] additional variables such as muscle power, balance, psychological factors,[42] and learned movement strategies[30] influence STST performance. Since decreased symmetry of lower extremity force application in an STST appears, at least in part, due to learned movement, task-specific training might be a beneficial adjunct to resistance training in restoring movement symmetry.

Early task-oriented training mitigates gait abnormalities, yielding reductions in postoperative pain while improving gait speed, efficiency, and confidence compared to traditional strength and gait training among older adults with compensated gait patterns.[43-45] Following hip replacement, an aggressive daily 3-week intervention initiated within the first week after surgery when integrating task-oriented movement strategies resulted in decreased pain, increased independence, improved physical function, and improved quality of life, compared to a cohort receiving a typical progression of balance, progressive strengthening, and gait training.[43] A task-oriented approach might similarly improve recovery following hip fracture, but results of a similar approach have not yet been reported in a hip fracture population.

Hip fractures are devastating injuries that lead to poor health outcomes. Despite growing evidence that supports extended, high-intensity strengthening interventions,[16] current rehabilitation strategies remain suboptimal.[8,46] Usual care results in poor muscle strength and power gains, and does not address asymmetrical movement patterns that are related to poor physical function and may increase risk for future falls. Because muscle function deficits, and learned compensated movements can contribute to asymmetrical movement patterns, rehabilitation after hip fracture should address muscle function and be task-oriented, with specific strategies incorporated to minimize movement asymmetry.

In order to accomplish the specific aims outlined for this study, an intervention strategy designed to improve muscle function and vGRF contributions of the surgical limb, thereby reducing measurable asymmetry after hip fracture, was designed and implemented. The strategies used and their rationale are briefly described below and explained in detail in the chapters that follow.

Enhancing Hip Fracture Physical Function by Targeting Asymmetries

Current intervention strategies are inadequate in restoring muscle structure and function after hip fracture.[47-51] A combined approach of task-specific training instruction with emphasis on restoring symmetrical movement patterns combined with high-intensity unilaterally-biased resistance training is expected to improve muscle function and asymmetrical movement relative to usual care. The HI-TOSS intervention incorporated high-intensity resistance training and multiple strategy components in an effort to reduce weight-bearing asymmetries during common patterns of movement. Individualized gait training was practiced based on deficiencies noted in a quantitative assessment of temporal and spatial gait variables. Tai Chi-inspired strength and balance exercises emphasizing eccentric loading, weight acceptance, and purposeful stepping were incorporated in a progressive manner to enhance mobility performance and confidence.[52] Individualized task-specific training was based on self-identified limitations in physical function. Sit-to-Stand transitions were practiced with emphasis on weight-bearing efforts including bilateral limb contributions during task performance. 6 specific progressive resistance exercises were included: seated knee extension, standing hip extension, standing hip abduction, prone knee flexion, supine hip flexion, and leg press, each performed at 85% of 1RM.[15] An eccentric recumbent stepper was used, with instruction and visual feedback to encourage equal participation of each lower limb during this aspect of training. In general, participants were provided with verbal encouragement and continuous feedback that was gradually withdrawn as they became more familiar with the exercises. More challenging exercises were introduced throughout the intervention period as individuals progressed in strength, balance, and activity tolerance.

Improving Muscle Mass, Quality, and Function After Hip Fracture

Little is known about muscle mass and muscle quality changes in response to high-intensity resistance training following usual care after hip fracture. Though improvements in physical function are expected with extended resistance strategies designed to improve strength and utility of the surgical limb,[16] muscle composition and muscle quality gains are unknown.

Older adults experience significant deleterious effects in muscle strength and muscle mass with inactivity after hip fracture.[17,53] Indeed, as little as 5 days of bed rest among healthy older adults yields a 4% loss in lean leg mass, and 14% loss in knee extension strength.[54] Compared to the typical 1.0-1.5% lean mass loss expected in this aging population, the documented lean mass loss in the year following hip fracture is significantly greater.[55,56] Six percent of total body lean mass loss is evident by 1 year after hip fracture, of which nearly 90% occurs in the legs, specifically quadriceps.[57] In addition, fat mass in the lower extremities occurs in older adults with hip fracture at an annual rate more than five times that of healthy older adults (11.0% vs 1.7%).[55,56]

Ruinous changes in muscle composition have negative effects on strength and physical function and are evident despite usual-care rehabilitation efforts. Moreover, older adults exhibit poor muscle recovery following inactivity and disuse-related muscle loss.[58,59] The effects of extended training strategies on muscle composition after fracture are unknown.

Purpose

The aim of this dissertation was to increase our depth of understanding of asymmetries, which commonly endure after hip fracture, and determine whether a specific strategy to enhance recovery after hip fracture could mitigate identified asymmetries. Further, we desired to identify and document improvements in vGRF variables, muscle function, muscle morphology, and physical function that could be expected with extending a restorative approach to recovery after hip fracture. Specifically, we sought to address the following aims:

1) The aim of the first study was to define the independent ability of vGRF asymmetry identified during rising phase of an STST to predict physical function.

2) In the second study, we determined whether HI-TOSS would result in improved vGRF symmetry during both the preparatory and rising phase of an STST compared to baseline measures. As a secondary aim, we also examined whether improved muscle function (strength, power) symmetry would be evident at ~6 months after fracture in response to HI-TOSS training compared to baseline measures.

3) Finally, in the third study, we described the muscle composition in a subpopulation following hip fracture. In addition, we calculated gains in muscle mass and quality that resulted from HI-TOSS training. As a secondary aim, we also reported physical function improvement evident in this sample after HI-TOSS training.

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CHAPTER 2

DOES WEIGHTBEARING ASYMMETRY AFTER HIP FRACTURE PREDICT PHYSICAL FUNCTION?

Introduction

Enduring asymmetry is evident in both muscle force output and vertical ground reaction (vGRF) forces during a sit-to-stand task (STST) following a hip fracture.[1-4] Since the surgical limb typically experiences long-lasting deficits, lower extremity asymmetries often endure,[1] and have been implicated in gait impairments[3,5] and elevated fall risk[6,7] among frail older adults, particularly after fracture. Asymmetries observed during mobility and physical task completion are thought to result from lower extremity injury and surgical repair, and continue long after pain is minimized and strength has been largely restored.[8-10]

Asymmetries in muscle function (strength and power), and vGRF during the STST need to be mitigated, as mobility impairments and an increased fall risk linked to asymmetries may contribute to poor balance confidence, increased sedentary behavior,[11] and a resulting cascade of health problems. Since half of those who experience a hip fracture will fall within 6 months after hospital discharge,[12] and since hip fracture survivors are up to five times more likely to experience an additional fall-related fracture within 1 year after hip fracture,[13] identifying and integrating strategies to mitigate falls and improve mobility in this vulnerable population is important. Asymmetries in muscle function and vGRFs may be modifiable risk factors following hip fracture and thus could inform new rehabilitation strategies.

Several factors contribute to physical performance among frail older adults, particularly after hip fracture.[14-23] The ability to perform an STST is thought to be due to a number of factors,[24-27] but it is generally agreed to be one of the more difficult tasks older persons may perform each day. Though several other identified variables contribute to a successful STST,[24] strength is a key contributor.[28-34] Knee extension strength predicts the lowest seated surface from which one can rise,[31] while inability to consistently rise from a chair predicts pending disability.[35] Maintaining independence in accomplishing this task is associated with mobility, daily activity level, and preserved independence, while inability to successfully perform STST predicts illness, institutionalization, and mortality.[29,36] As older adults experience an immediate, significant strength decline of up to 50% after hip fracture,[37] it is expected that many will experience a resulting decline in physical function.

One less frequently addressed factor that might impact physical function after hip fracture is weight-bearing asymmetry during physical task performance. Typically, whole body measurements in physical movements are used to quantity physical function after hip fracture (i.e., time required to walk 10 meters or to climb stairs), with little effort to identify individual lower limb contributions to the measured task.[1] Asymmetry has recently been implicated as persistent and apparent in the performance of physical tasks such as STST, for at least a year after fracture,[1-4,38,39] and may never fully recover after a serious injury such as hip fracture. Conflicting evidence exists regarding asymmetry and physical function among older adults. Most researchers agree that asymmetry in muscle function is apparent after hip fracture, with larger asymmetries being associated with injury risk, fall frequency, and mobility impairments.[6,7,40] The magnitude of asymmetry varies across different weight-bearing tasks, with evidence that more complex tasks may be more demonstrative of lower limb deficits and residual asymmetries.[9] While one study suggests that absolute lower limb power, but not power or strength asymmetry, differed significantly between fallers and nonfallers[41] the consensus is that asymmetry apparent during mobility tasks negatively impacts mobility and increases injurious fall risk.[2,3,42]

The purpose of this study was to determine the unique contribution of weight bearing asymmetry during an STST on physical function after recovering from a hip fracture. In order to do this, we examined correlations between vGRF asymmetry variables during an STST, the modified Physical Performance Test (mPPT), a composite nine-item standardized test designed to assess multiple dimensions of physical function and used to classify frailty level among older adults;[43] and the stair climb test (SCT), a physically demanding task that is particularly relevant after hip fracture among those who desire to maintain community-dwelling independence.[44] We hypothesized that asymmetry in vGRF variables during an STST would provide a unique contribution to physical function beyond that identified by known contributors to physical function after controlling for covariates.

Methods

Participants

A convenience sample of 31 community-dwelling older adults, who had recently incurred a hip fracture, participated in this study. Participants (age range: 53 - 90 years, mean 77.7 ± 10.5 years) were recruited from University of Utah (UU) and Intermountain

Healthcare (IH) hospitals in Salt Lake City, Utah between August 2013 and May 2015. To be eligible, participants were required to be able to independently transfer and ambulate at least 50 feet without physical assistance, have incurred a hip fracture in the last 3-8 months, be aged 50 years or older, have minimal cognitive impairments (>23/30 Montreal Cognitive Assessment), and have been discharged from "usual care," typically consisting of 8-10 weeks of physical therapy that included balance, mobility, and strength training in acute, rehabilitation center, and residential settings following hip fracture. Baseline characteristics of the sample are summarized in **Table 2.1**. Exclusion criteria were having a known serious medical or neurological diagnosis (e.g., cancer, COPD, MS), visual impairments, vestibular disorders, bilateral hip fracture, significant range of motion limitations, or painful osteoarthritis in the hip or knee. Exclusion criteria were selected in an effort to minimize factors other than hip fracture that might contribute to asymmetries in task performance. Institutional review boards of the UU and IH both approved the study and all participants provided informed consent before enrollment.

Procedures

All participants completed a series of questionnaires and underwent a battery of physical performance tests. In order to determine the vGRF during the STST, participants were tested performing this task on an instrumented chair (**Figure 2.1**). Muscle function was assessed by unilateral isometric strength of the knee extensors and lower extremity extension power. In order to document physical function, both performance and self-report measures were used. The mPPT, and SCT, were chosen to represent actual physical function, and the Lower Extremity Measure (LEM), and Activities of Balance Confidence Scale (ABC) were used as self-report measures. Additional performance measures (timed up-and-go, gait speed) and demographic information were captured to further describe the sample and for use in statistical analysis.

vGRFs During STST Analysis

A custom-built portable chair (**Figure 2.1**) with an adjustable seat height was used and adjusted to approximate a 90/90 hip/knee flexion angle when the participant was seated. Participants were seated on the front half of the instrumented chair with mid-length of the thighs aligned with the edge of the chair and ankles placed in approximately 15° of dorsiflexion. Using arms to assist in the task, participants were instructed to stand up as "quickly as you safely can." One practice trial was performed before recording data from three separate STST trials, allowing 30-second rest between trials.

The custom-built chair was instrumented to detect vGRFs measured under each foot, each arm, and the seat **(Figure 2.2)**. Force sensors (NMB Technologies Corporation (Menibia), Chatsworth, CA) mounted in two Wii platforms were amplifiedwith SGA/A signal conditioners (Mantracourt Electronics Ltd., Devon, UK) and fed into a computer using a 16-bit analog to digital converter (Model: USB 1608G. Additional force sensors (Menibia, Chatsworth, CA) were also mounted in each arm and on the seat to record seat off and arm push as well. The arm force signals were also amplified and converted to a 16-bit signal output. During each trial, the vGRF of each force plate was recorded at a sampling rate of 1000 Hz and exported to excel using TracerDAQ 2.2.0 software (Measurement Computing, Norton, MA). Correlations to known weights of each arm and footplate were high (r = 0.99).

Two phases of the STST were identified from the sum of $\text{vGRF}_{\text{INVolved}}$ and $\text{vGRF}_{\text{UNINVolved}}$ ($\text{vGRF}_{\text{Bilateral}}$). [1,26] The preparation phase was initiated by a 5N decrease in vGRF$_{\text{Bilateral}}$. This brief unweighting of the lower limbs is a countermovement, typically occurring just prior to the ensuing rapid lower-limb loading. The end of the preparation phase occurred at seat off, marked as the instant when vGRF$_{\text{Seat}}$ was below 5N. The rising phase began at seat off and ended when vGRF$_{\text{Bilateral}}$ equaled body weight, following the first peak of vGRF$_{\text{Bilateral}}$. The STST time was measured from the beginning of the preparatory phase to the end of the rising phase (**Figure 2.3**).

To capture the vGRF developed by each limb during the preparation phase, the rate of force development (RFD) was calculated. The RFD was calculated as the slope of the vGRF data (vGRF$_{\text{INVolved}}$, and vGRF$_{\text{UNINVolved}}$). The slope of the force between 25%-50% of force at time of seat off (end of preparation phase) was calculated for each limb separately (RFD$_{\text{INVolved}}$, RFD$_{\text{UNINVolved}}$), and summed (RFD$_{\text{Bilateral}}$). Higher slopes indicate more rapid development of force, which correlates to faster rising time.

To capture the vGRF developed by each limb during the rising phase, magnitude impulse (AREA) variables were calculated. The impulse of the vGRF$_{\text{INVolved}}$ and the vGRF$_{\text{UNINVolved}}$ was calculated by obtaining the area under the curve from the beginning to the end of the rising phase (AREA$_{\text{INVolved}}$, AREA$_{\text{UNINVolved}}$, and summed AREA$_{\text{Bilateral}}$). Note that a higher area value arises from either a longer rising period or higher force amplitude over the rising phase. Lower area values are the result of shorter rising periods or lower force amplitudes over the rising phase. An AREA score was calculated as the difference between AREA$_{\text{INVolved}}$ and AREA$_{\text{UNINVolved}}$ to indicate the difference in contribution of each limb to rising. Higher AREA during rising phase suggests lower symmetry or greater reliance on one limb (typically the nonsurgical limb), while a lower AREA suggests relatively equal vGRF under both limbs. Good reliability has been previously established (0.84 – 0.91) for vGRF variables identified during STST performance among older adults who have recently incurred a hip fracture.[25]

The average of three STST trials normalized to body mass (/kg) were recorded for RFD and AREA to represent STST performance during preparatory phase, and rising phase, respectively. Limb symmetry index ratios (involved/uninvolved) were calculated for RFD and AREA to determine the asymmetry, or discrepancy in lower limb contributions during STST performance. AREA was also calculated as the difference between $\text{AREA}_{\text{INVolved}}$ and $\text{AREA}_{\text{UNINVolved}}$ as described above. Perfect symmetry yields an LSI ratio of 1.0, while values less than 1.0 indicate a lesser contribution from the surgical limb.

Muscle Function

An isokinetic dynamometer (KinCom, Chattanooga Inc, USA) was used to determine unilateral knee extension strength. Participants were positioned with their hips at 90 and knee at 60 degrees of flexion. A maximal voluntary isometric contraction (MVIC) of the knee extensors, as well as the average force over a 3-second duration was recorded in Newtons (N). The average of three trials (with 30-second rest between trials) normalized to body mass (/kg) was used for analysis. This method has excellent reliability (.81-.98.).[45] Leg extension power of each limb was unilaterally measured on a Nottingham power rig (Medical Engineering Unit, Nottingham, UK), and recorded in Watts (W). Participants were seated in an upright position with arms folded across their chests. The seat was adjusted until comfortable extension of the knee with full depression of the foot pedal was reached. Participants were instructed to depress the foot pedal as hard and fast as possible. After three warm-up trials at 50%, 75%, and 100% effort, six trials were performed and the average of the three highest trials, normalized to body mass (/kg) was used for analysis. The leg extension power rig is a valid, reliable and feasible means of assessing muscle power across the lifespan in both sexes.[46]

Physical Function

Gait speed was measured over a 50-foot distance at the participant's usual walking pace. Participants were instructed to "walk at your normal daily pace." The average score from two recordings at usual walking speed were used for analysis. Gait speed is a quick, inexpensive, reliable measure of mobility with established predictive value for major health-related outcomes among older adults.[15,47] The ABC scale, a 16-item, validated, reliable self-report scale was used to determine balance confidence. Higher scores indicate greater confidence in balance. Scores below 67 indicate high risk of falling,[48] and fall prevalence for elderly individuals with poor balance confidence (score < 67) is twice that of individuals with balance confidence > 82.[49] The LEM, a validated 29-item self-report scale for assessment of perceived mobility and performance was used as the self-report of physical function. The LEM is reliable, valid, and responsive for assessing changes in performance after hip fracture.[21] Scores of 75-85 indicate moderate limitations in mobility and scores above 85 indicate normal mobility.

The mPPT, a composite nine-item standardized test, is designed to assess multiple dimensions of physical function, mimics ADLs, and includes assessment of various movements such as standing balance, sit-to-stand transitions, light lifting, putting on and removing a jacket, picking up an object from the floor, walking, and stair climbing.[50,51] This composite test categorizes level of frailty, with a score of 17-24 indicating moderate frailty, 25-31 considered mildly frail, and 32-36 indicating no frailty.[43] The stair climb test (SCT) was also performed. Nonstandardized methods of applying this test (e.g., varying number and height of steps, inconsistent arm rail usage, etc.) have resulted in a lack of normative data in an older population; yet the SCT has good construct validity, and is highly reliable.[44,52] The SCT is described as a clinically relevant measure of leg power impairments[53] that is meaningfully associated with mobility performance,[52,54] strength,[55] independence,[55] and self-report of physical function[52] and thus suitable for clinical settings in which impairment-mobility relationships are of interest.

Data Analysis

Data management and statistical analyses were performed with SPSS statistical software (SPSS Version 22). Descriptive data were calculated for demographic variables and dependent measures and are presented as means (SD) (**Table 2.1**). Pearson correlation coefficients were calculated to determine the bivariate relationship between each vGRF asymmetry (RFD, AREA) and physical function (mPPT, SCT) variable. RFD, initial impulse in STST, did not show significant correlation with physical function variables, and was not included in further analysis. All variables showing significant correlation ($r > 0.40$) were retained in the model for further analysis (**Table 2.2**). The relative contribution of each vGRF asymmetry variable to explaining the variability in the physical function outcomes were examined using hierarchal linear regression models, after controlling for covariates (**Table 2.3**). Each of the vGRF variables derived from STST trials as well as the muscle function variables (strength and power) were normalized to body mass (kg). Criterion for entry to the model was a significance level of $p < 0.05$. For each variable entered into the final model, the part correlation was examined to determine the unique amount of variance in the physical function outcomes that was accounted for by the variable. The alpha level was set at $p < 0.05$.

Results

Participant characteristics are presented in **Table 2.1**. The sample is representative of a typical hip fracture population, demonstrating persistent physical function deficits and a high fall risk despite having been discharged from usual care. All participants were community dwelling at the time of their participation.

The bivariate correlations of demographic variables with physical performance variables (mPPT, SCT) revealed age to be the single demographic variable with a significant moderate correlation ($r = -0.43, 0.40$, respectively, $p < 0.05$) (**Table 2.2**). The bivariate correlations of other clinical measures expected to predict physical function showed significant moderate to strong correlations with both mPPT (r range = -0.47-0.86) and SCT (r range = -0.47-0.83) (**Table 2.2**). The direction of the correlations indicates that as age, physical performance, balance confidence, and self-reported function increase, mPPT score increases. Similarly, as physical performance, balance confidence, and self-reported function increase, time to complete SCT decreases. These results support the use of hierarchical regression analyses to examine the unique and shared contributions of AREA towards explaining the variance in mobility measures.

The multiple regression analysis on the AREA during rising phase of an STST revealed that the predictors as a group accounted for 83.4% of the variance in mPPT, with ABC ($p<0.001$), GS ($p<0.001$), and LEM ($p=0.05$) each significantly contributing to the final model ($p < 0.001$). The part correlation of ABC was 0.32, of GS was 0.41, of LEM was 0.20 indicating that ABC, GS, and LEM explained 10.4%, 16.6%, and 4.0% of the variance in the mPPT score, with all other model variables held constant (**Table 2.3**).

The multiple regression analysis on the AREA during rising phase of a STST revealed that the predictors as a group accounted for 78.0% of the variance in SCT, with ABC ($p=0.03$), GS ($p<0.001$), LEM ($p=0.04$), and AREA (0.006) each contributing to the final model ($p<0.001$). The part correlation of ABC was -0.20, of GS was -0.44, of LEM was 0.18, of AREA was 0.27 indicating that ABC, GS, LEM, and AREA explained 3.8%, 19.4%, 3.4%, and 7.1% of the variance in the mPPT score, respectively, with all other variables in the model held constant (**Table 2.3**).

Discussion

The key finding in this investigation is that after accounting for the expected contributors to physical function following hip fracture, asymmetry during the performance of an STST emerged as a significant predictor for SCT performance. Specifically, age, balance confidence, gait speed, normalized muscle strength, and self-reported function were each tested to determine the contribution of these variables to physical function in the 3-8 months after hip fracture. Interestingly, asymmetry did not surface as a significant predictor for a composite physical function score (mPPT), but did emerge as a significant predictor of the more difficult task of climbing stairs. Identifying persisting asymmetries could be important for the clinician in predicting fall risk during high-risk ambulatory activities such as stair climb. Though others have suggested a relationship between asymmetry and physical performance, this is the first study to identify the unique and shared contribution of identified weight-bearing asymmetry during a STST on physical performance after hip fracture.

Our results are in partial agreement with previous reports. Relationships between asymmetry and physical function have been proposed with asymmetry during an STST showing moderate to high correlations with gait speed, balance, and self-reported function in the year following hip fracture.[1,2] Asymmetry is common among independent community-dwelling women over age 65 and large asymmetries in leg extension power between limbs have been linked to falls.[6] This is clinically relevant as over 50% experience a fall within 6 months of hospital discharge after hip fracture[12] vs. a 14% post-discharge fall rate among the general population over age 70.[56] Mobility impairments are more prevalent among individuals with higher asymmetry,[3] and Portegijs et al. previously identified that large asymmetries in power correlate with slower stair climb—but not gait speed--at week 1 and week 13 after hip fracture.[3]

Climbing stairs is among the most challenging tasks of daily living for older individuals. Stair ambulation requires as much as three-fold greater peak knee extensor strength than level walking[44] and also requires coordinated unilateral limb contributions. Requiring nearly 90% of maximum capacity for many[57] compared to 40% for younger, nonimpaired adults, there may be little strength reserve to cope with unexpected perturbations,[44] contributing to a high fall risk during stair ambulation among frail elderly. Falls on stairs are the single leading cause of accidental death, annually contributing to over 10% of all fatal falls among individuals over age of 65,[44] a large number considering adults spend only a small fraction of their day performing stair ambulation. Women and those living alone are most at risk for stairway falling, with hip fracture being the most common nonlethal result.[58] Marottoli et al. reported that only 8% of hip fracture patients could independently climb a flight of stairs 6 months after hip fracture compared to 63% before fracture.[59] Similarly, Magaziner et al. described stair climb as one of the most daunting tasks after hip fracture, with only 10% achieving complete independence (no hand on stair rail) in stair climbing 2 years after fracture,[51] with less than 50% of ever able to regain stair climb capacity even with use of handrails or other assistive devices.[44]

Asymmetry did not surface as a significant predictor for physical function as defined by the mPPT. This was an unexpected finding, as mPPT provides a valid, reliable and responsive measure of physical function. In this composite physical performance test, climbing stairs has been identified as the most difficult single item.[50] Many of the simpler tasks of the mPPT (e.g., donning/doffing jacket, reaching to a shelf, static balance measurements) do not unilaterally challenge individuals to the extent that SCT does providing a potential explanation for the inability of asymmetry during STST performance to predict mPPT score. Clinically, this provides support for a closer examination of individual limb muscle contributions rather than typical whole-body assessments prior to discharge. It should also be considered that prior to the inclusion of stair climb, 83% of the variance was explained leaving little unexplained variance remaining for asymmetry to contribute.

ABC, GS, and LEM all emerged as significant predictors of physical function. This is expected, as each has been reported to provide moderate to high correlations with physical performance among older adults. Considering the strength requirements of the SCT, it is surprising that our sample demonstrated no significant predictive value from normalized strength. However, strength and power are curvilinear.[60] Thus, it is likely that a wider variety of older adults, including a more frail subset, may have yielded a higher percentage of explained variance from normalized knee extension strength.

There is wide variation in aging populations with respect to mobility, strength, and physical performance particularly following hip fracture. Deficits in muscle function and identifiable asymmetries have been suggested to impact frail older adults more adversely than other populations as frail older adults require a higher relative percentage of their maximum capacity collectively, and from each limb in order to accomplish a specified task.

Despite the ability of variables included in our model to predict over 70% of the variance in stair climbing prior to the inclusion of an asymmetry measure, AREA uniquely explained over 7% of the SCT performance. The identified asymmetry provided a higher unique contribution than either self-reported function (3.4%) or balance confidence (4%). This suggests that asymmetry may be important to challenging tasks that require fluid unilateral limb contributions that may predispose one to falls. Examples of this include stair ascent and descent, stepping off a curb, walking on uneven surfaces, recovering balance after perturbation, and recovering from a misstep, each of which significantly contributes to the number of injurious falls each year. Rehabilitation methods that reduce asymmetries may contribute to preserving mobility after hip fracture.

The results of the study should be considered in light of some limitations. Our convenience sample of older adults with hip fracture, by virtue of their interest and ability to volunteer for this study may have had better physical function than others, who with a higher incidence of cognitive impairments and other comorbidities, may have been more limited in their postfracture recovery and performance. Our sample showed limb symmetry in the STST to be approximately 0.77, though even higher weight-bearing asymmetry (>30%) is commonly reported after hip fracture.[1,2,38] In addition each participant in our sample was able to climb stairs without manual assistance, with use of a handrail while the literature suggests that relatively few can perform this task at 3-6 months after fracture.[51,59] These issues should be considered when generalizing our results. However, there is the possibility that a sample with lower physical performance capacity may demonstrate an even more dramatic influence of asymmetry on physical function. A strong relationship ($r > 0.70$) between mPPT and asymmetry that we noted in a subgroup of 12 participants scoring less than 24 on the mPPT lends further support to this notion. Finally, while we identified the unique contribution of asymmetry of STST on SCT performance, this study was underpowered to more thoroughly explain the variance in mPPT and SCT from predictor variables and to explore potential interactions.

Conclusion

Asymmetry during an STST is a significant and unique contributor to predicting stair climb performance after hip fracture. Despite having been discharged from usual care physical therapy and being independent community-dwelling older adults, individuals who demonstrate asymmetry remain at high fall risk. As asymmetry provides a unique contribution to explain variance in SCT performance, interventions aimed at improving symmetry should be tested. With potential impact for reducing fall risk and improving gait mobility, there is a need for higher intensity intervention(s) addressing surgical limb deficits after hip fracture in an effort to reduce persisting asymmetries.

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Figure 2.1. Instrumented Chair Designed for Sit-to-Stand Trials.
The portable, instrumented chair incorporated four imbedded force plates to measure vertical ground reaction forces (vGRF) of individual lower extremity and individual upper extremity, in addition to timing of seat off. For full description of procedures, see methods section of this chapter.

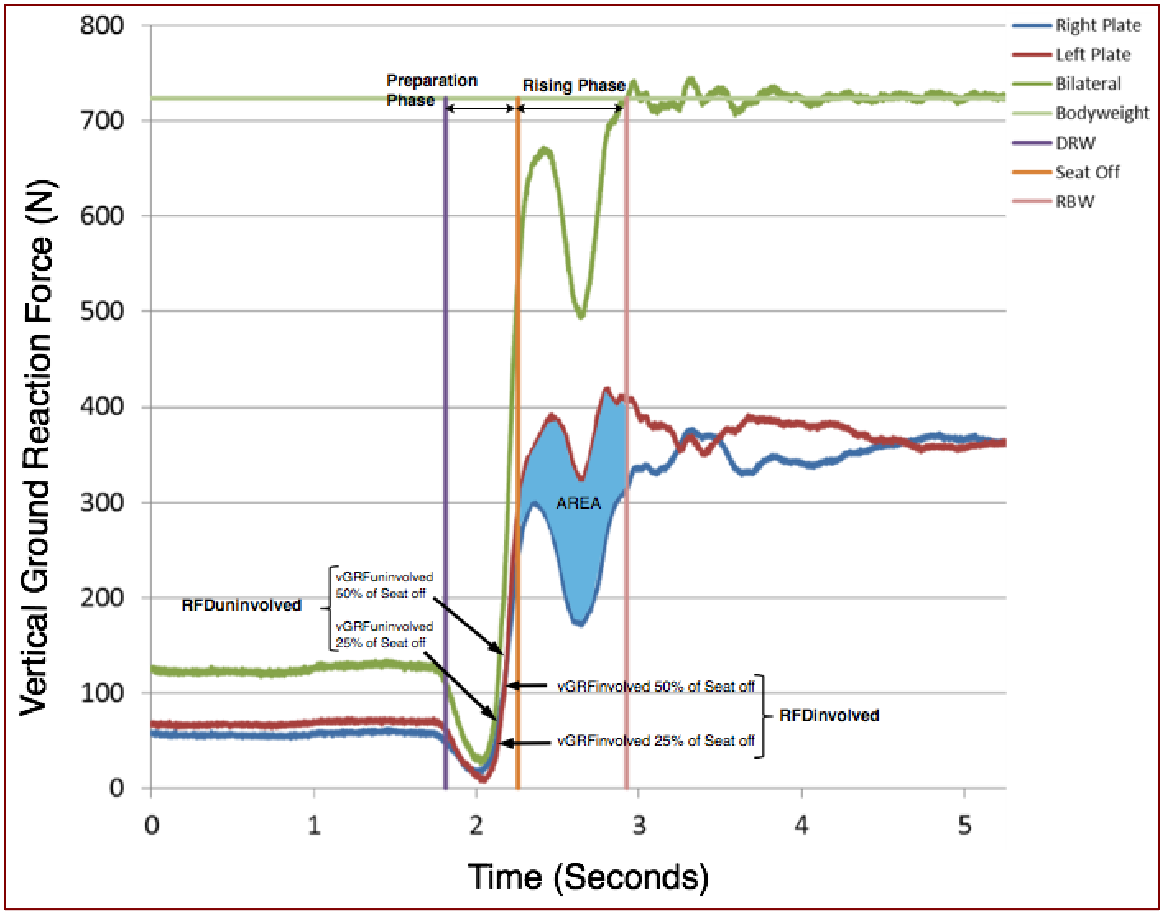

Figure 2.2. Graphical Display of Sit-to-Stand Task Trial Output.
The figure above is an example of a single participant trial of the sit-to-stand task with graphical depiction of the resulting vGRF output. Two phases of the sit-to-stand movement are identified: preparation phase and rising phase. The moment of seat off, measured by the seat force plate ($\text{vGRF}_{\text{seat}}$), determines transition from preparation to rising phase. The RFD during the preparation phase was calculated as the slope from 25% to 50% of the force value at seat-off for each lower extremity. The arms impulse is area under $\text{vGRF}_{\text{arms}}$. The unilateral measures of $\text{vGRF}_{\text{involved/uninvolved}}$ were determined from the left and right force plates. Symmetry during the rising phase was calculated as AREA between the $\text{vGRF}_{\text{involved/uninvolved}}$ throughout rising phase. Note: each trial was recorded over a 10-second duration as described, but this graph output is abbreviated to show task completion over the initial 5 seconds.

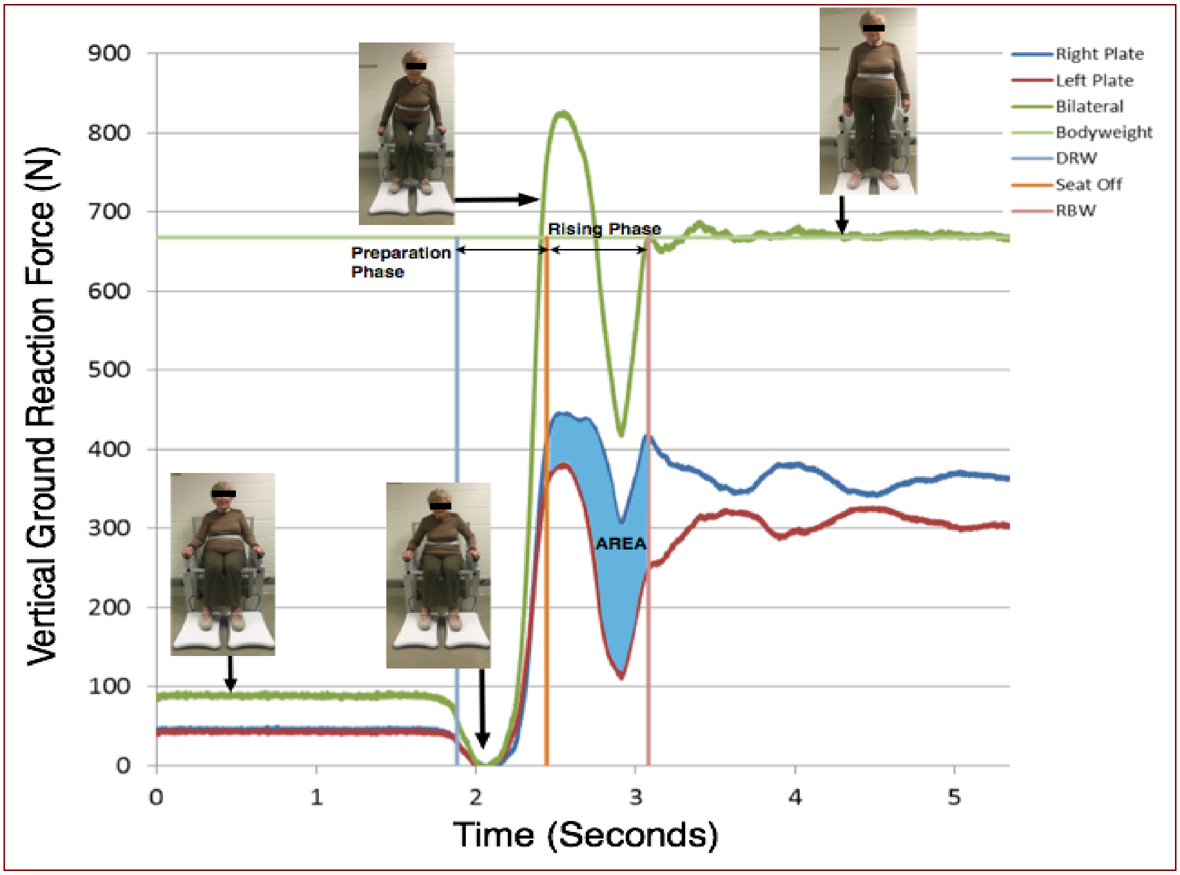

Figure 2.3. Sit-to-Stand Task Performance on Instrumented Chair.
Depicted is an individual performing a sit-to-stand trial and corresponding movement during recorded trial. Typical post-hip fracture vGRF output of bilateral and unilateral lower extremity contributions during a sit-to-stand trial is presented. Red line corresponds with (left) involved lower extremity. Blue line corresponds with (right) uninvolved lower extremity. Green line corresponds with summation of vGRF output from both lower extremities. RFD is recorded by 25-50% of vGRF at seat off divided by time (not labeled). AREA and 1st peak vGRF after seat off (not labeled) are key time points during sit-to-stand movement as labeled. AREA is identified as the difference between the lower extremities*Time during rising phase. Each vGRF variable is normalized for body mass (/kg). Note: arm impulse measurement removed on this image for clarity of lower extremity, though individuals did use arms during sit-to-stand task performance.

Table 2.1. Descriptive Characteristics of Eligible Participants.

Variable	Hip Fracture (n=31)
Age (yr)	77.7 (10.5)
Sex	21F / 10M
Height (in)	65.4 (4.2)
Weight (kg)	70.3 (18.0)
BMI	25.3 (5.6)
Time since Fracture (mo)	4.1 (1.4)
Fracture Type	17C/14T
Normalized Peak Strength (N/kg)	3.1 (1.5)
Gait Speed (m/s)	0.9 (0.3)
ABC	68.7 (17.0)
LEM	75.1 (11.4)
AREA	1.3 (0.8)
mPPT	25.7 (5.5)
Stair Climb (sec)	12.3 (6.2)

BMI, body mass index; Fx, fracture; ABC, Activities of Balance Confidence scale; LEM, Lower Extremity Measure (self-report function), AREA (asymmetry during rising phase); mPPT, modified physical performance test.
All data are presented as means (SD).

Table 2.2. Bivariate Correlations Between Selected Variables Expected to Influence Function and Measured Physical Function.

Variable	**mPPT**	**SCT**
Age	**-0.43** ($p<0.05$)	**0.40** ($p<0.05$)
Sex	0.33 ($p=0.08$)	-0.28 ($p=0.12$)
BMI	0.05 ($p=0.78$)	-0.09 ($p=0.65$)
GS	**0.86** ($p<0.001$)	**-0.83** ($p<0.001$)
ABC	**0.77** ($p<0.001$)	**-0.65** ($p<0.001$)
Peak Strength$_{INV}$ (N/kg)	**0.55** ($p<0.005$)	**-0.53** ($p<0.005$)
LEM	**0.55** ($p<0.005$)	**-0.47** ($p<0.01$)
AREA	**-0.47** ($p<0.01$)	**0.60** ($p<0.001$)

Bold indicates significant correlations, () = p-values. All variables listed above were considered for inclusion in the regression model(s). Only significant correlations were included for further analysis.

Table 2.3. Results of Hierarchical Regression Examining Association Between Asymmetry in Sit-to-Stand Task Performance and Physical Function.

Variable	Regression Coefficient (95% CI)	Standardized Coefficient (Beta)	p-value	Part Correlation	R^2
mPPT					83.4
Age	0.02 (-0.08-0.12)	0.04	0.69	0.03	
ABC*	0.20 (0.10-0.29)	**0.61**	**<0.001**	0.32	
GS*	11.47 (7.15-15.18)	**0.64**	**<0.001**	0.41	
Strength	0.06 (-0.64-0.76)	-0.02	0.86	0.01	
LEM*	-0.17 (-0.30- -0.04)	**0.06**	**<0.05**	-0.20	
AREA	-0.46 (-1.23-0.32)	-0.11	0.23	-0.09	
SCT					78.0
Age	-0.03 (-0.15-0.10)	-0.05	0.65	-0.04	
ABC*	-0.14 (-0.26- -0.01)	-0.37	<0.05	-0.20	
GS*	-14.1(-19.64- -8.40)	-0.69	<0.001	-0.44	
Strength	0.04 (-0.88-0.95)	0.01	0.94	0.01	
LEM*	0.17 (0.01-0.34)	0.32	<0.05	0.18	
AREA	1.52 (0.51-2.53)	0.31	<0.005	0.27	

Bold* Indicates variable is a significant predictor ($p<0.05$) in the regression model. mPPT = modified Physical Performance Test, ABC = Activities of Balance Confidence, GS = Gait Speed, LEM = Lower Extremity Measure, AREA = asymmetry measure during rising phase of STST, SCT = stair climb test.

CHAPTER 3

TRAINING REDUCES ASYMMETRIES IN SIT-TO-STAND TASK PERFORMANCE FOLLOWING HIP FRACTURE: A PILOT STUDY

Introduction

Hip fracture (HF) is a costly injury frequently contributing to deteriorating health and societal consequences. While HF accounts for 14% of all fractures among older adults, 72% of fracture-related health care costs are allocated to HF treatment and recovery.[1] Despite a slight decrease in HF incidence rate in recent years, the prevalence continues to rise as the aging population increases.[2,3] Further, costs for HF management are significant despite shorter acute hospital stays since postacute care is the most rapidly rising cost driver of medical care,[4] and older adults who have incurred an HF are one of the top five groups utilizing postacute care.[5] Escalating costs of postacute care, combined with reduced mobility, increased sedentary behavior, and poor quality of life among survivors,[6] make HF a major public health concern. Moreover, complications (e.g., hospital acquired infections and revision requirements), hospital readmittance, institutionalization, and disability, continue to climb, while 1-year mortality rate remains stable at ~30%.[7-9] Of the 70% who survive HF, less than 20% recover full mobility function within 1 year of fracture.[10] Following HF, older adults experience significant rapid losses of muscle mass,[11] knee extension muscle strength,[12,13] and physical function;[14-16] each of which persists despite multimodal rehabilitation efforts.[12,15,17-19] Therapeutic interventions after HF remain largely unchanged over the last several decades,[20] and this may be one of the reasons deficits in muscle and mobility persist. There seems to be an underlying sense of resignation that HF will result in significant decreases in strength, vitality, and function and these aspects are recalcitrant to change. Improved rehabilitation strategies are clearly necessary in order to facilitate a more complete recovery in confidence, mobility, and function following hip fracture.

Functional weight-bearing asymmetry has been suggested as an important variable to target during HF rehabilitation[21] and may serve as a novel rehabilitation program outcome. An important functional task necessary for independence in older adults is moving from a sitting to a standing position. Older adults demonstrate side-to-side asymmetry in vertical ground reaction force (vGRF) application during the sit-to-stand task (STST) following a hip fracture.[22,23] Importantly, vGRF during the STST demonstrates significant associations with standing balance, gait speed, balance confidence, and self-report of function in this population.[21] Asymmetries in vGRFs during an STST 4-12 months after HF have been recorded as high as 40% favoring the uninvolved lower extremity, while age-matched controls demonstrate less than 10% asymmetry.[22,23] We have recently identified vGRF asymmetry during rising phase of an STST as a significant and unique contributor to stair climb performance after HF. Whether a rehabilitation program targeting muscle function and movement asymmetries after HF can reduce asymmetries during STST performance is unknown.

Therefore, the purpose of this study was to describe vGRF asymmetry changes during an STST after an extended high-intensity, task-oriented strength and symmetry training (HI-TOSS) implemented between 3 and 6 months after HF. Muscle function asymmetry changes occurring after HI-TOSS were also described. A secondary purpose was to describe recruitment, retention, and treatment adherence in anticipation of a larger clinical trial. We hypothesized that asymmetry in vGRF variables and muscle function would improve with targeted intervention.

Methods

Participants

A convenience sample of 24 community-dwelling elderly adults recovering from HF, and recently discharged from approximately 10-12 weeks of usual-care (e.g., acute care, postacute rehabilitation, and homecare) physical therapy, participated in the study. Each of the participants had incurred an HF in the past 2 to 6 months (mean = 3.60±1.1 months), and was discharged from usual-care physical therapy in the preceding 1-12 weeks. Sample characteristics are shown in **Table 3.1.**

Participants were recruited from University of Utah (UU) and Intermountain Healthcare (IH) hospital systems over a 21-month period between July 2013 and March 2015. Individuals identified through the Enterprise Data Warehouse (EDW) as having undergone surgical repair for HF in the preceding 2-6 months were sent a letter and recruitment flyer informing them of this study. Individuals identified through UU were contacted by phone approximately 2 weeks after receiving invitation letter (unless they opted out via prestamped postcard), while individuals identified by IH received phone interview screening only if they contacted the study coordinator in response to the invitation letter. This procedure of EDW identification and letter recruitment occurred quarterly over the 21-month duration for UU, and a 9-month duration for IH.

Additionally, potential participants were referred directly by physical therapists following usual-care home health intervention. Also, 10 local rehabilitation facilities were visited monthly by the study coordinator, at which time residing candidates expressing interest were informed of the study, and invited to participate following discharge from subsequent home health. Flow diagram of the recruitment pool is included (**Figure 3.1**).

Participants in the HF group were eligible if they had incurred a unilateral HF in the past 6 months, were functionally independent, had returned to community-dwelling, and had completed a course of usual-care to include acute, subacute, and/or home health interventions. Participants were excluded based on significant osteoarthritis (taking regular medications for joint pain), obvious lower extremity range of motion impairments, and various known medical conditions, (e.g., neurological, cardiovascular, respiratory diseases, or cancer), which would likely limit their ability to safely and effectively participate in high-intensity resistance training. Participants underwent cognitive screening, and individuals scoring less than 24/30 on the Montreal Cognitive Assessment (MoCA) were considered ineligible due to cognitive impairment potentially limiting their recall and informed consent signing competency. The MoCA is a standardized, clinically researched, cognitive screening test with high sensitivity (90%), and specificity (87%) for distinguishing individuals with mild cognitive impairment (MCI) from those with normal cognition,[24] with reportedly less ceiling effect and higher sensitivity to detect MCI than other cognitive screening tools.[25,26] All participants enrolled in the study successfully completed the MoCA (mean = 27.7, range = 24 - 30).

Once candidates were screened and approved for study admittance, the participant’s physician was notified of the individual’s study enrollment intentions. After medical clearance, participants were scheduled to attend the Skeletal Muscle Exercise Research Facility at University of Utah for physical and muscle function testing. Institutional review boards at UU, and IH approved the study and recruitment procedures, and all participants provided informed consent.

Baseline and Posttesting

Prior to initiating the 12-week HI-TOSS intervention program, all participants completed a series of questionnaires and underwent a battery of physical performance tests. In order to determine the vertical ground reaction forces (vGRF) during the STST, participants were tested while performing STST on an instrumented chair (**Figure 2.1**). Muscle function was assessed with unilateral isometric strength of the knee extensors and lower extremity extension power. In order to document physical function, both performance and self-report measures were used. Usual gait speed and the modified physical performance test (mPPT) were selected to represent physical performance, while the lower extremity measure (LEM), provided a measure of self-report.

vGRF During STST

A custom-built portable chair with an adjustable seat height was used and adjusted to approximate a 90/90 hip/knee flexion angle when the participant was seated. Participants were seated on the front half of the instrumented chair with mid-length of the thighs aligned with the edge of the chair and ankles placed in ~15° of dorsiflexion. Arm use for task completion was required. Participants were instructed to stand up as “quickly as you safely can.” One practice trial was performed prior to recording data from three separate STST trials, allowing 30-second rest between trials.

The custom built chair was instrumented to detect vGRFs measured under each foot, each arm, and the seat. Force sensors (NMB Technologies Corporation (Menibia), Chatsworth, CA) mounted in two Wii platforms were amplified with SGA/A signal conditioners (Mantracourt Electronics Ltd., Devon, UK) and fed into a computer using a 16-bit analog to digital converter (Model: USB-1608G, Measurement Computing, Norton, MA). Additional Force sensors (NMB Technologies Corporation (Menibea), Chatsworth, CA) were also mounted in each arm and on the seat to record seat off and arm push as well. The arm force signals were also amplified and converted to a 16-bit digital signal using the same instrumentation. During each trial, the vGRF of each force plate was recorded at a sampling rate of 1000 Hz and exported to excel using TracerDAQ 2.2.0 software (Measurement Computing, Norton, MA). Correlation to known weights of each arm and footplate were high (r = 0.99).

Two phases of the STST were identified from the sum of $vGRF_{INVolved}$ and $vGRF_{UNINVolved}$ ($vGRF_{Bilateral}$)[23,27] The preparation phase was initiated by a 5N decrease in $vGRF_{Bilateral}$. This brief unweighting of the limbs is a countermovement, typical just prior to the ensuing rapid loading of the limbs. The end of the preparation phase occurred at seat off, marked as the instant when $vGRF_{Seat}$ was below 5N. The rising phase began at seat off and ended when $vGRF_{Bilateral}$ equaled body weight, following the first peak of $vGRF_{Bilateral}$. The STST time was measured from the beginning of the preparatory phase to the end of the rising phase (**Figure 2.2**).

To capture the vGRF developed by each limb during the preparation phase the rate of force was calculated. The rate of force development (RFD) was calculated as the slope of the vGRF data ($vGRF_{INVolved}$, and $vGRF_{UNINVolved}$). The slope of the force between 25%-50% of force at time of seat off (end of preparation phase) was calculated for each limb separately ($RFD_{INVolved}$, $RFD_{UNINVolved}$), and summed ($RFD_{Bilateral}$). Higher slopes indicate more rapid development of force, which correlates to faster rising.

To capture the vGRF developed by each limb during the rising phase magnitude (peaks) and impulse (AREA) variables were calculated. The 1st peak force of the $vGRF_{INVolved}$ and 1st peak of the $vGRF_{UNINVolved}$ was calculated. Additionally, the impulse of the $vGRF_{INVolved}$ and the $vGRF_{UNINVolved}$ was calculated by obtaining the area under the curve from the beginning to the end of the rising phase ($AREA_{INVolved,}$ $AREA_{UNINVolved}$, and summed $AREA_{Bilateral}$). Note that a higher area value arises from either a longer rising period or higher force amplitude over the rising phase. Lower area values are the result of shorter rising periods or lower force amplitudes over the rising phase. An AREA score was calculated as the difference between $AREA_{INVolved}$ and $AREA_{UNINVolved}$ to indicate the difference in contribution of each limb to rising. Higher AREA during rising phase suggests lower symmetry or greater reliance on one limb (typically the nonsurgical limb postfracture), while a lower AREA suggests relatively equal vGRF under both limbs (**Figure 3.3**). Good test-retest reliability has been previously demonstrated (.84-.91).[23]

The average of three STST trials normalized to body mass (/kg) were recorded for three identified vGRF variables: RFD, 1st Peak vGRF, and AREA. Representative improvement in STST performance after 3 months Hi-Toss training is displayed (**Figure 3.2, Figure 3.3**). Limb symmetry index ratios (involved/uninvolved) were calculated for each of the three vGRF variables, as well as muscle function variables (strength, power) to determine asymmetry before and after 3-months training. Perfect symmetry yields a ratio of 1.0, while values less than 1.0 indicates less involved limb contribution.

Muscle Function

An isokinetic KinCom dynamometer (Chattanooga Inc, Hixon, TN) was used to determine unilateral knee extension strength. Participants were positioned with their hips at 90 and knees at 60 degrees of flexion. A maximal voluntary isometric contraction (MVIC) of the knee extensors, as well as the average force over a 3-second duration was recorded (N). The average of three trials (with 30-second rest between trials) normalized to body mass (kg) was used for analysis. This method has excellent reliability (.81-.98).[28] Leg extension power was measured on a Nottingham power rig (Medical Engineering Unit, Nottingham, UK). Participants were seated in an upright position with arms folded. The seat was adjusted until comfortable extension of the knee with full depression of the foot pedal was reached. Participants were instructed to depress the foot pedal as hard and quickly as possible. After three warm-up trials at 50%, 75%, and 100% effort, six trials were performed and the average of the three highest trials (W), normalized to body mass (kg) was used for analysis. The leg extension power rig is a valid, reliable and feasible means of assessing muscle power across the lifespan in both sexes.[29]

Physical Function

Functional measures were collected at baseline and post-training. Usual gait speed was measured by having participants walk a 50-foot distance at their preferred walking pace. The average of two recordings was used for analysis. The mPPT, a composite nine-item standardized test designed to assess multiple dimensions of physical function, was used to assess overall physical function.[15,30] The lower extremity measure (LEM), a validated 29-item scale, was provided for self-assessment of functional mobility. The LEM is reliable, valid, and responsive for assessing changes in performance post-HF. Scores of 75-85 indicate moderate limitations in functional mobility and scores above 85 indicate normal functional mobility.[31]

Training

High-Intensity, Task-Oriented Strength and Symmetry training consisted of a 3-month exercise program designed to improve muscle function, confidence, and balance to determine training impact on reducing asymmetry. Participants attended three 60- to 80-minute supervised exercise sessions per week for 12 weeks for a total of 36 sessions. The group sessions included a 5-minute warm-up on a recumbent ergometer (Nustep Inc, Ann Arbor, MI) or task-specific gait training on a treadmill or over ground, six lower extremity resistance exercises (straight leg raise, prone knee flexion, standing hip abduction, standing hip extension, seated knee extension, and seated leg press) performed for 3 sets of 8 repetitions at a resistance of 85% of the involved limb one repetition maximum (1-RM), balance/mobility exercises (group Tai-Chi, sit-to-stand repetitions, task-oriented balance and gait training) with emphasis on restoring confidence and movement pattern symmetry, and 1x/weekly 5- to 10-minute lower extremity eccentric ergometer resistance training (Eccentron, BTE Tech, Hanover, MD), followed by a protein-rich drink for purposes of maximizing strength and promote muscle growth in response to resistance training.[32,33] The eccentric ergometer was linked to a monitor and provided instant visual feedback regarding eccentric force exhibited by each limb with each successive push. Participants were encouraged to put equal pressure through each limb, and a target bar was progressively increased as tolerated, while maintaining 16-17/20 perceived rate of exertion. Six Tai-Chi inspired exercise movements were performed with progressively increasing angle and decreasing speed of joint movement to maximize the eccentric phase of the exercise. Four of the six movements were included in each group session, with individuals cued for appropriate weight-bearing and movement patterns, particularly over the involved limb. Primary movements encouraged shift of body weight onto and away from the involved limb, lunging and reaching movements, and efforts to improve confidence in performing whole-body movements. Task-oriented balance exercises were individualized to address deficits such as stepping over a curb, walking up/down stairs, and bending over to pick up objects from the floor. 1-RM values were measured and recorded after the initial 3 weeks of training, then retested every 3 weeks to maximize resistance training stimuli.

Data Analysis

The three STST trials normalized to body mass were averaged and used to represent all vGRF variables. The average of three knee extension strength trials and three leg extension power measures were averaged and normalized to body mass to represent muscle function. Descriptive statistics were used to evaluate for normality and characterize the sample (**Table 3.1**). Means and 95% CIs of the main outcome variables between pretraining and post-training were tested with paired-sample t-tests. Analyses included paired comparisons for descriptive and clinical data including biomechanical vGRF variables (RFD, $\text{vGRF}_{\text{peak}}$, and AREA), muscle function, and asymmetry indexes (**Table 3.2, Table 3.3**), before and after training, and between-limb differences in vGRF and muscle function measures. Effect sizes were calculated for vGRF and muscle function changes observed with training. Statistical analysis was completed using SPSS version 22 and p-value was set at 0.05.

Results

Baseline Characteristics

Sixteen of 24 participants in this sample were female, an average of 3.6 months postsurgery, were 78.4 years old, and had an average BMI of 26.3. Average strength and power were significantly poorer in the surgical limb ($p < .001$) yielding an average 223.7N (± 129.8N) and 88.7W (± 55.3W), respectively; and an average 309.8N (±145.9N), 116.7W (± 66.1W) in the nonsurgical limb. Functionally, baseline scores of 0.9 m/s GS, 25.4 mPPT score, and LEM of 74.2 indicate a mildly frail group of community-dwelling older adults post-HF with residual mobility deficits (**Table 3.1**).

Asymmetry Changes

Limb symmetry indexes demonstrated improved symmetry for vGRF variables during STST performance as well as muscle function after training (**Figure 3.4, Figure 3.5**). RFD asymmetry improved from 0.78 to 0.85, $p < .05$, mean change 0.07, 95% CI [0.01, 0.13]. 1st Peak vGRF asymmetry improved from 0.78 to 0.87, $p < .005$, mean change 0.07, 95% CI [0.02, 0.11]. Area asymmetry improved from 0.78 to 0.87, $p < .005$, mean change 0.09, 95% CI [0.04, 0.14]. Strength asymmetry improved from 0.74 to 0.88, $p < .001$, mean change 0.14, 95% CI [0.08, 0.20]. Power asymmetry improved from 0.75 to 0.82, $p < .005$, mean change 0.07, 95% CI [0.02, 0.11].

vGRF Variables

vGRF, collectively, and particularly in the surgical limb changed significantly with training (**Table 3.2**). RFD_{INV} increased from 17.0 (N/s)/kg to 22.2 (N/s)/kg, $p < .001$, with training. RFD_{UNINV} increased from 21.5 (N/s)/kg to 26.3 (N/s)/kg, $p<.001$, with training. 1st peak vGRF_{INV} increased from 4.3N/kg to 4.5 N/kg, $p < .05$, with training, while 1st peak $\text{VGRF}_{\text{UNINV}}$ did not change with training 5.4 N/kg (0.5), $p = 0.37$. $\text{Area}_{\text{UNINV}}$ decreased more than Area_{INV}, $p < .005$; while AREA asymmetry decreased by nearly 50% from 1.3 to 0.7.

Muscle Function Variables

Normalized knee extension strength improved significantly in the weaker leg, from 3.1 to 3.7, $p < .001$, but no significant change in strength in the stronger leg was identified with training, 4.2 N/kg, $p = 0.95$. Normalized leg extension power improved bilaterally with training. $\text{Power}_{\text{INV}}$ increased from 1.2 W/kg to 1.5 W/kg, $p < .001$ with training; while $\text{Power}_{\text{UNINV}}$ increased from 1.6 W/kg to 1.8 W/kg, $p < .05$ (**Table 3.3**). All vGRF and muscle function variables indicated weakness in the surgical limb compared to the nonsurgical limb both before and after training ($p < .005$).

Adherence and Feasibility

Adherence and feasibility were high. All participants who attended at least two clinic visits were retained for the 3-month intervention. Training adherence averaged 92% ± 5% (range: 71-100%). Conflicting medical appointments, vacations, and physical ailments (i.e., urinary tract infection, influenza, etc.) accounted for > 85% of all missed visits, while muscle soreness or exercise-related pain was not cited as reason for a missed visit once training was initiated.

Adverse events in this study were few. One individual experienced a near fall during the first of 10 STST repetitions. While recovering balance (with assistance), this individual brushed his forearm and dorsal wrist against a wall, resulting in a small abrasion. The abrasion was treated conservatively in-clinic and healed over ~2 weeks. Four participants cited knee joint discomfort at some point during training. Specifically, bilateral squatting movement during Tai-Chi inspired exercise, and eccentric ergometer training were described as contributing to occasional discomfort among individuals who had previously experienced intermittent knee pain. No individual missed a session due to pain or injury.

Discussion

Results of this preliminary study suggest that those who have incurred an HF can achieve more symmetrical vGRF during a STST and symmetrical muscle function after high-intensity targeted strength training designed to restore impaired lower limb function. Additionally, we identified that such training is feasible, and can be successfully completed after HF, with excellent tolerance and minimal adverse events among mildly frail older individuals living in their community. This is the first longitudinal study to determine the impact of training on weight-bearing asymmetry after HF.

Similar to prior studies, the majority of our participants demonstrated marked deficits in the surgical limb compared to the nonsurgical limb despite after discharge from usual-care physical therapy.[16,18,21,34] Collectively, 95% of participants demonstrated surgical limb deficits in strength, power, and vGRF variables, while only one individual had a LSI of greater than 1.0 for vGRF variables at baseline. Not surprisingly, the majority (>90%) of participants improved muscle function and vGRF values in the surgical limb with HI-TOSS, while 70-80% improved scores in the nonsurgical limb, albeit to a lesser extent. The larger improvement in the surgical limb contributed to improved symmetry for all variables.

Not all individuals improved their symmetry with training, but 90% improved their strength LSI score, 83%, 75%, and 71% improved their AREA, power, and RFD asymmetry scores, respectively. Importantly, those with large baseline asymmetries tended to improve most with training. Large asymmetries in muscle function are related to mobility limitation and frequent,[35] injurious falls[36] among healthy older women, and are often evident up to 7 years after HF.[12] Of 12 individuals who had larger than 0.75 asymmetry at baseline, 11 of 12 improved in AREA, while each improved in power, strength, and RFD, with an average LSI improvement of 0.13 – 0.22, nearly double that of the overall average in our sample. Those with less asymmetry at baseline generally showed smaller gains with training. For instance, three of the four participants who did not improve significantly in AREA had baseline LSI > 0.90. This observation suggests the possibility that there is a subgroup that might benefit most from training that targets asymmetrical performance.

Improvements in vGRF symmetry variables were phase-dependent and correlated with measures of muscle and physical performance. An individual who improved symmetry in one phase of STST often, but not always, improved symmetry in another phase. Similarly, individuals who improved muscle function symmetry frequently also improved symmetry in vGRF variables. This was supported by moderate to high correlations (r = 0.58 to 0.76) among limb symmetry indexes for biomechanical and muscle function variables (**Table 3.4**), indicating a potential relationship between asymmetries of muscle function and vGRF asymmetries. Despite the correlations between vGRF symmetry and muscle function symmetry, there was still sufficient variability to question the meaningfulness of the symmetry-function relationship.

We observed that some individuals with poor muscle function demonstrated less asymmetry in vGRF and muscle function variables than their stronger counterparts. These individuals with lower capacity generally require more output from their surgical limb to successfully complete functional tasks, and were thus more symmetrical. However, the vGRF variables indicated low performance (i.e., lower RFD and peak force). Thus, for some, spontaneous recovery of symmetrical lower-limb muscle function may be an indication of poor bilateral limb function, rather than optimal recovery.[12]

Some evidence indicates that a combination of minimum capacity (i.e., muscle function) and asymmetrical lower limb force development may optimize the association with physical performance.[12] For instance, participants with low lower limb power and poor symmetry in one recent study were significantly less stable during tandem stance. In contrast, participants with very high lower limb power, yet maintaining poor symmetry, demonstrated relatively good stability during tandem stance.[18] This same pattern is seen in the vGRF measures of symmetry in our data. For example a few of the stronger individuals displayed evidence of medium to large vGRF and muscle function asymmetries despite significant bilateral muscle function improvements with training. For most ADLs and daily activities, strong individuals may have ample functional reserve to demonstrate good physical performance, despite enduring asymmetry.

Although improvements in vGRF symmetry measures frequently followed improvements in muscle function, clinical improvements in muscle function alone were insufficient to explain changes in vGRF symmetry values. Our data and previous reports observed high correlations between surgical limb vGRF parameter magnitude (e.g., RFD during preparatory phase, AREA during rising phase) and physical function as compared to symmetry of vGRF variables. This indicates that rehabilitation efforts to improve the magnitude of the vGRF parameters might be more critical than symmetry gains for improving physical function.

These results should be taken in light of some limitations. Our results are specific to community-dwelling elderly participants recovering from HF who were generally healthy, motivated, cognitively intact, and who volunteered for a physical therapy exercise program. Recruiting this patient population is feasible, yet future researchers should note that our recruitment yield, after accounting for inclusion and exclusion criteria, deaths, transportation, and desire to participate was only 10%, once contacted by letter or in person. Whether these results are generalizable to other older adults who have incurred an HF is not known. Since monitoring fall frequency following this training program was beyond the scope of the current project, we do not know whether reducing asymmetries during STST impacts fall frequency.

Despite significant mean symmetry improvements in weight-bearing STST and muscle function; the participants in this sample demonstrate larger asymmetries than those of the healthy aged population.[21,23,35-37] It is unknown what level of asymmetry existed in this cohort prior to HF. Though asymmetry is typically higher during challenging tasks such as STST than during static stance or walking,[38] whether improved symmetry in a STST is associated with improved symmetry in other functional tasks is unknown. Recent evidence suggests that earlier implementation of resistance training and injured limb weight-bearing may enhance mobility,[39] perhaps before habitual movement patterns are established. Future studies can examine whether other training strategies, such as earlier implementation, or high-velocity training, might be even more influential.

Conclusion

Participation in a 12-week high-intensity, task-oriented resistance training program after discharge from usual-care physical therapy after HF resulted in improved symmetry in weight-bearing vGRF variables during a STST. Muscle function asymmetries were also improved. Older adults tolerated the training program without significant adverse events and demonstrated excellent adherence to the program. The results of this pilot study can inform a larger randomized control trial to compare benefits of this program with other training strategies designed to reduce asymmetries, and further identify the impact of symmetry improvements on functional outcomes.

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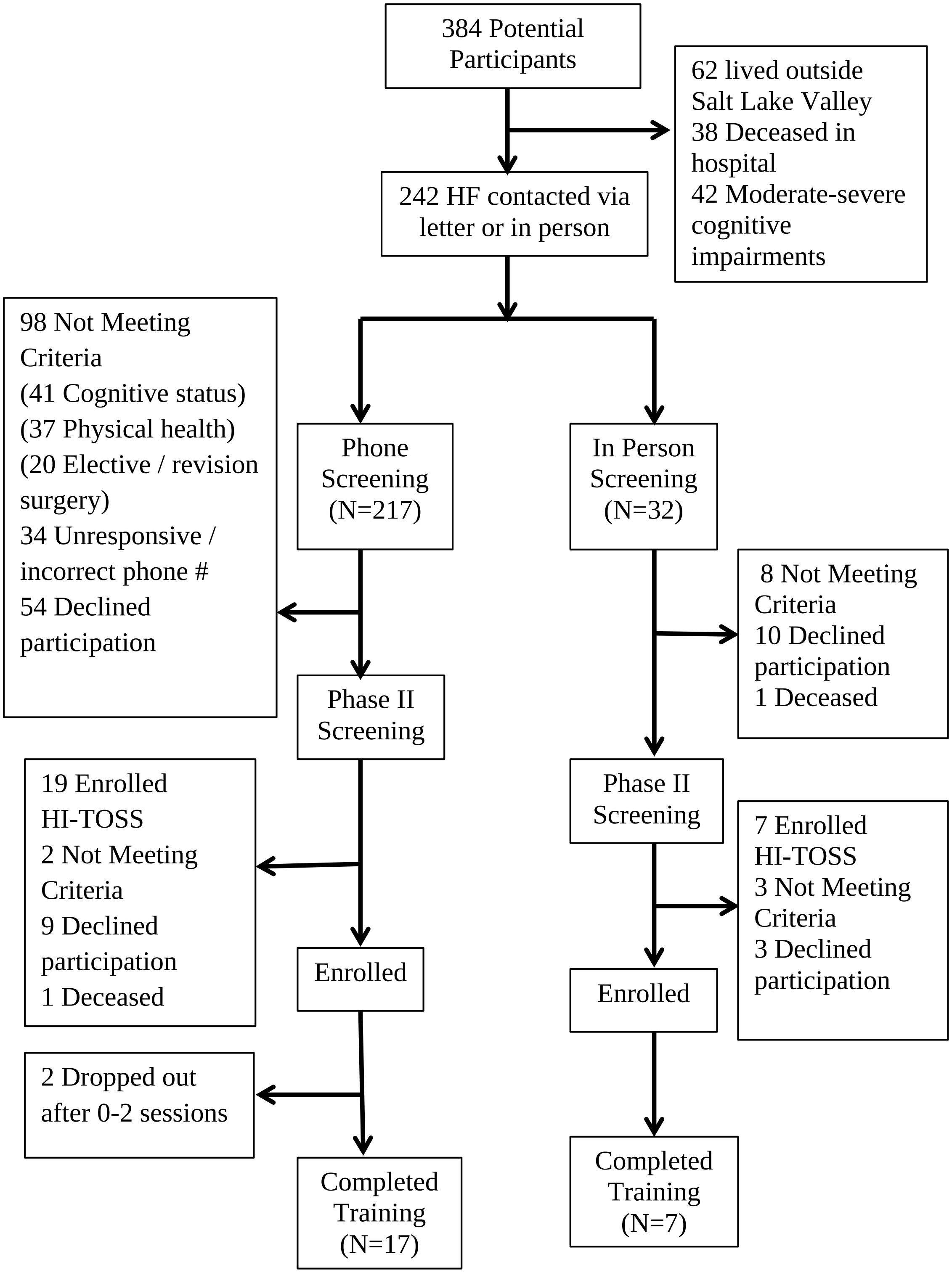

Figure 3.1. Flow Diagram of Recruitment

Table 3.1. Baseline Physical and Functional Characteristics of HI-TOSS Participants.

Characteristics	Training Group (n=24)
Age (y)	78.4 ±10.4
Sex	16F / 8M
Height (in)	65.4 ± 4.4
Weight (kg)	72.6 ± 18.5
BMI	26.3 ± 5.7
Time since fracture (mos)	3.6 ± 1.2
Fracture Side	13R / 11L
mPPT	25.4 ±5.2
Habitual GS (m/s)	0.9 ± 0.3
LEM	74.2 ± 9.0
$\text{Strength}_{\text{INV}}$ (N)	223.7 ± 129.8
$\text{Strength}_{\text{UNINV}}$ (N)	309.8 ± 145.9
$\text{Power}_{\text{INV}}$ (W)	88.7 ± 55.3
$\text{Power}_{\text{UNINV}}$ (W)	116.7 ± 66.1

Note: Values are Mean +/- SD. mPPT = modified Physical Performance Test, GS = Gait Speed, LEM = Lower Extremity Measure

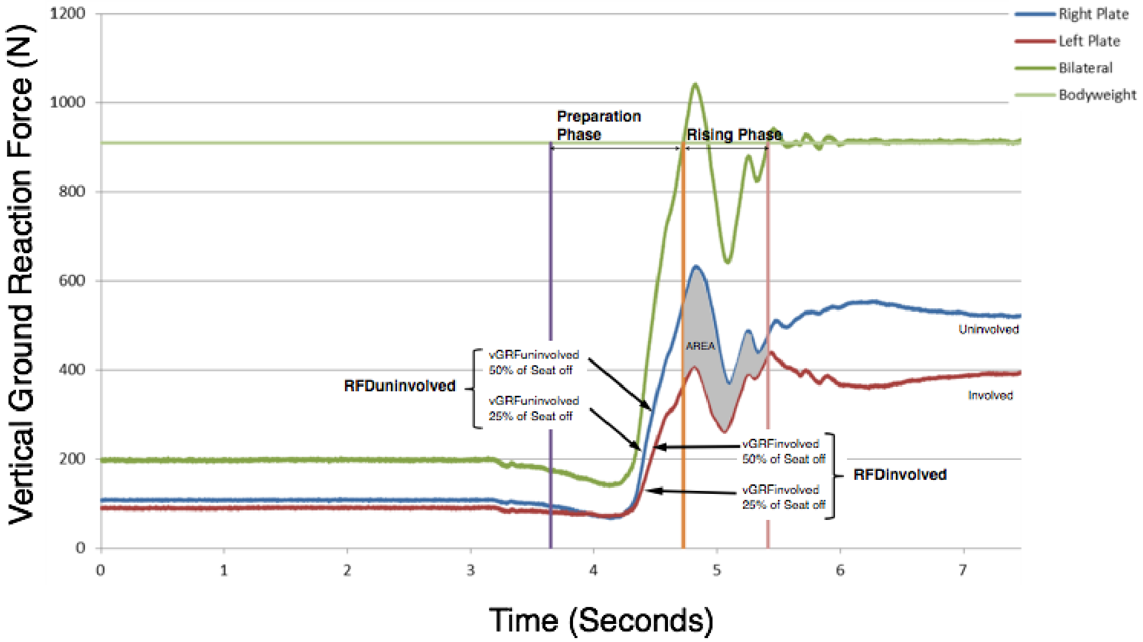

Figure 3.2. Pretraining Sit-to-Stand Performance.
Pretraining bilateral and unilateral lower extremity output from timed STST for one participant. This representative participant shows typical post-HF asymmetry during pretraining STST performance. The red line represents the involved (left) limb in this trial. The blue line represents the uninvolved (right) limb. Note that the involved limb (red line) yields lower vGRF output throughout the trial than the uninvolved limb (blue line). In this case, limb symmetry index (involved/uninvolved limb) performance for RFD identified during preparation phase = 0.66, while limb symmetry index for AREA = 0.73. LSI of 1.0 indicates perfect symmetry (i.e., equal contribution from each limb).

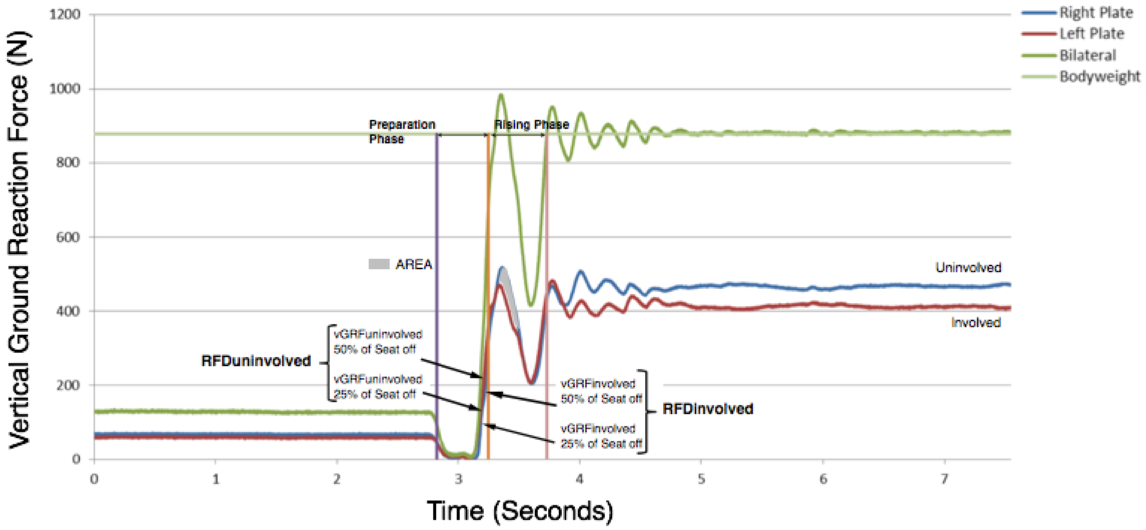

Figure 3.3. Post-Training Sit-to-Stand Performance.
Post-training bilateral and unilateral lower extremity output from timed STST is displayed. This representative participant improved significantly in symmetry during preparatory and rising phase of the STST trial. The red line represents the involved (left) limb in this trial. The blue line represents the uninvolved (right) limb. Note length of STST trial appears shorter in duration than pretraining trial. Also note that each limb contributes more equally post-training compared to pretraining. This results in each limb demonstrating similar slope (RFD) post-training, while AREA is significantly smaller post-training vs. pretraining. In this case, RFD LSI = 0.91, while AREA LSI = 0.93.

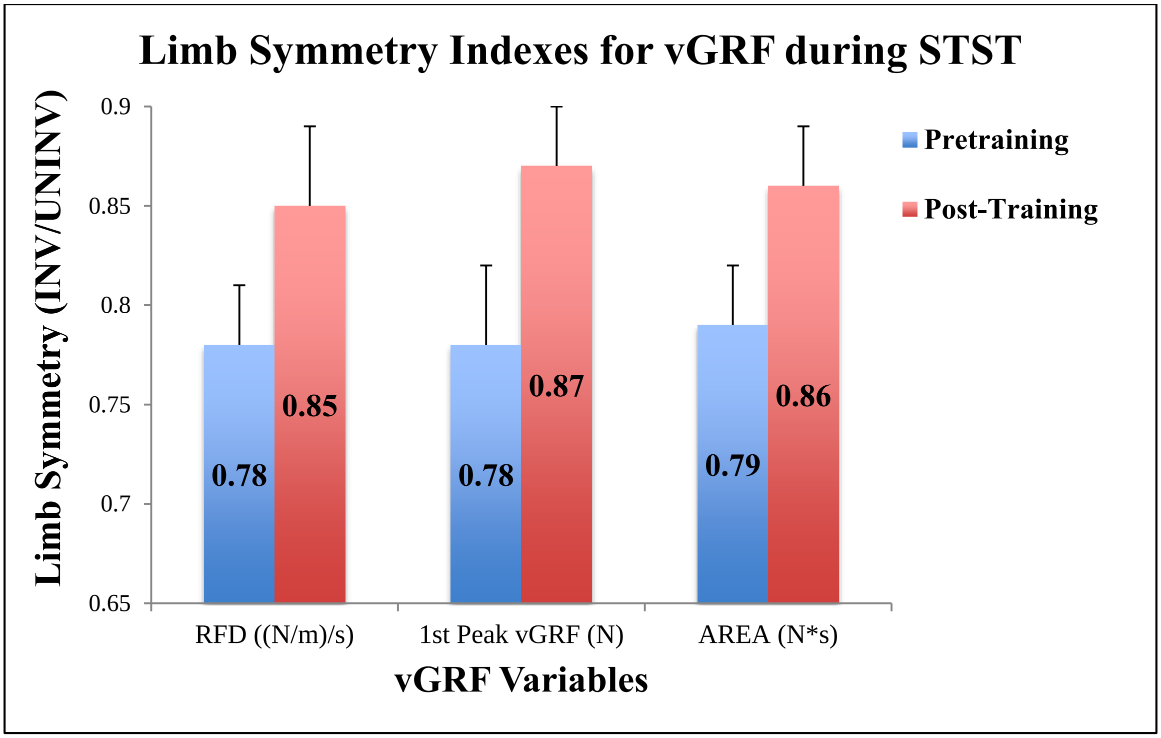

Figure 3.4. vGRF Asymmetry: Pre- vs. Post-Training. Average improvements in limb symmetry on functional weight-bearing STST trial. Note similar baseline for all vGRF variables, with injured limb index ~0.75 for each variable (i.e., 43% vs. 57% injured vs. uninjured % of total limb contribution). Post-training limb index ~0.85, indicates ~46% of total limb contribution comes from injured limb. Values of 1.0 indicate perfect symmetry (equal contribution bilateral) during STST.

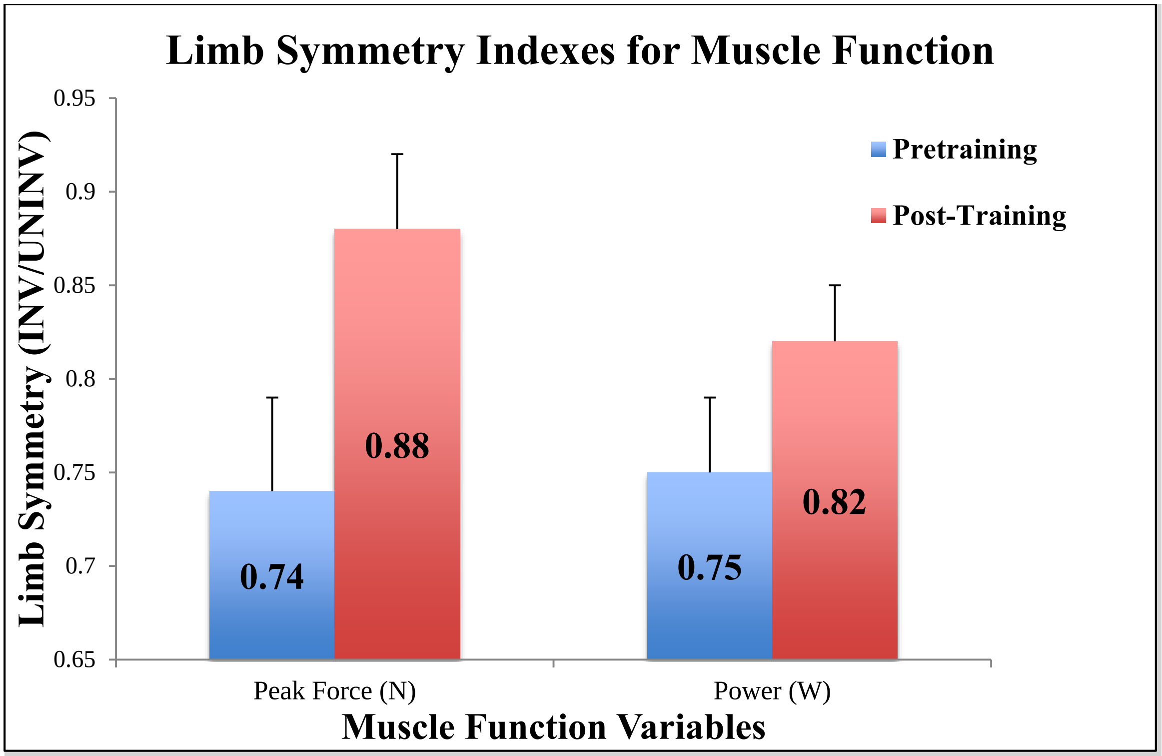

Figure 3.5. Muscle Function Asymmetry: Pre- vs. Post-Training. Average improvements in limb symmetry of muscle function: knee extension strength (peak Force (N)) and leg extension power (Power (W)). Baseline muscle function asymmetry appears similar to baseline vGRF asymmetry. Improvement in muscle strength asymmetry exceeds improvement in muscle power asymmetry with Hi-Toss training.

Table 3.2.
Mean Pre-/Post-Training vGRF Variables During Sit-to-Stand Trials.

	Pre-Training	Post-Training	Significance	Mean Change [95% CI]	Effect Size
RFD (N/s)/kg					
Involved	17.0 (7.6)	22.2 (7.8)	p < .001	5.24 [2.97 – 7.51]**	0.69
Uninvolved	21.5 (8.5)	26.3 (8.8)	p < .001	4.81 [2.25 – 7.37]**	0.57
AREA (N*s)/kg					
Involved	3.3 (1.1)	2.8 (0.8)	P < .005	-0.53 [-0.88 - -0.18]**	0.49
Uninvolved	4.5 (2.1)	3.3 (1.2)	p < .001	-1.22 [-1.76 - -0.69]**	0.58
AREA (UN-INV)	1.3 (1.4)	0.7 (0.8)	p < .001	-0.65 [-0.99 - -0.31]**	0.47
1st Peak vGRF (N/kg)					
Involved	4.3 (0.8)	4.5 (0.6)	p < 0.05	0.28 [0.11 – 0.45]*	0.35
Uninvolved	5.4 (0.5)	5.4 (0.5)	p = 0.37	-0.08 [-0.25 – 0.10]	NS

Average Pretraining and Post-Training vGRF values among HF recipients 3-7 months post-HF. Mean change [95% CI] listed. * = change score significant at p < 0.05, ** = change score significant at p < 0.005. vGRF = vertical Ground Reaction Force. RFD = Rate of Force Development. AREA = calculated asymmetry measure depicting lower extremity asymmetry during rising phase of STST. NS = nonsignificant, N = Newton, s = seconds, kg = kilogram.

Table 3.3.
Mean Pre-/Post-Training Muscle Function Variables.

	Pre-Training	Post-Training	Significance	Mean Change [95% CI]	Effect Size
Strength (N/kg)					
Involved	3.1 (1.6)	3.7 (1.4)	p < .001	0.58 [0.30 – 0.86]**	0.36
Uninvolved	4.2 (1.6)	4.2 (1.4)	p = 0.95	-0.01 [-0.32 – 0.30]	NS
Power (W/kg)					
Involved	1.2 (0.6)	1.5 (0.6)	P < .001	0.29 [0.09 – 0.49]*	0.47
Uninvolved	1.6 (0.7)	1.8 (0.7)	p < 0.05	0.28 [0.06 – 0.50]*	0.41

Average Pretraining and Post-Training vGRF values among HF recipients 3-7 months post HF. Mean change [95% CI] for each variable, and effect size for changes with training listed. * = significant, p < 0.05, ** = significant, p < 0.005, NS = not significant.

N = Newton, W = Watt, kg = kilogram.

Table 3.4. Limb Symmetry Index Correlations: vGRFs and Muscle Function.

	RFD LSI	**Peak vGRF LSI**	**AREA LSI**
Peak Force LSI	**0.72** (p < 0.001)	**0.71** (p < 0.001)	**0.66** (p < 0.001)
Power LSI	**0.76** (p < 0.005)	**0.58** (p < 0.005)	**0.59** (p = 0.005)

Pearson Product Moment Correlations of Limb Symmetry Index Values. RFD = Rate of Force Development, vGRF = vertical Ground Reaction Force, LSI = Limb Symmetry Index. All values listed are significantly correlated at $p<0.05$

CHAPTER 4

DOES MUSCLE QUALITY IMPROVE WITH EXTENDED HIGH-INTENSITY RESISTANCE TRAINING AFTER HIP FRACTURE?

Introduction

Hip fracture is a devastating event for many older adults, with 25% not surviving the year following fracture,[1] and recovery of prefracture mobility is incomplete in more than 60% of survivors.[1,2] Approximately 1.6 million older adults worldwide sustain a hip fracture each year,[3] and this estimate is expected to approach 4.5 million by 2050.[4] Given the enormous costs and consequences, management of older adults following hip fracture has become a large-scale healthcare and societal issue.[5,6] Identifying novel strategies to improve the survival and physical function in this vulnerable population are necessary.

Older adults after hip fracture experience a "catabolic crisis," that most often prevents full recovery.[7] In comparison to the gradual muscle loss typical of aging (i.e., sarcopenia), acute changes in muscle after hip fracture have an immediate impact on physical function. Older women typically gain 1.7% of fat mass and lose 1% of lean mass per year with aging.[8] However, following hip fracture a 6% decline in lean muscle mass, and up to 11% increase in fat mass is evident in the first year.[9,10] Relative inactivity is high in the acute recovery period following hip fracture, exacerbating the impact on lean muscle mass in this population. Healthy older adults experience ~0.95 kg of lean leg mass loss following just 10 days of bed rest,[11] a rate of muscle mass loss 3-6 fold greater than younger adults experiencing a similar period of bed rest.[7] Regional changes in muscle mass occurring with hospitalization and relative inactivity indicate that the lower extremities are primarily impacted, with nearly 90% of the total body muscle mass loss coming from the legs, specifically the quadriceps.[12]

The rapid mass loss accompanying hip fracture puts many at significant risk of long-term mobility and physical function deficits. As little as 5 days of bed rest contributes to a 4% decrease in leg lean muscle mass and a 16% reduction in knee extension muscle strength in otherwise healthy older adults.[13] Similar rates of decline are evident in older adults with reduced activity or 7-10 days of bed rest largely due to blunted muscle protein synthesis and reduced mTORC1 signaling.[11,14-16] Indeed, the majority of the body composition changes (fat mass, lean mass, and bone mineral density) evident at 1 year after fracture occur within the first 60 days.[9,17] Recent studies suggest that older adults exhibit poor muscle recovery following disuse-related muscle loss.[18,19] Lower lean mass and lower strength in the legs, particularly in the surgical limb, are linked to poor mobility and muscle function.[20-22] Unfortunately, muscular deficiencies in the surgical limb seem recalcitrant for years after the initial trauma and accompanying surgical intervention following hip fracture.[21,23] In combination, adverse effects on muscle composition are associated with increased disability, recurrent fracture, and mortality.[17] Studies identifying associations between quadriceps muscle density (a measure of lean tissue) and bone density, further accentuate the importance of preserving lean muscle mass as part of a multimodal strategy to improve physical function and mitigate future fracture risk.[24-26]

Bridging our understanding of muscle size and muscle strength, muscle quality, defined as muscle force per unit of muscle cross-sectional area,[27,28] is emerging as a salient contributor to health and physical function in older adults, particularly among frail, older women.[29] Misic et al. have implicated muscle quality as the strongest independent predictor of lower extremity physical function among older adults, explaining up to 42% of the identified variance in physical function.[30] Besides predicting physical performance and fatigue,[31] muscle quality is associated with gait variability,[32] mobility impairments, self-reported limitations in physical function, and disability.[33,34] In light of ample recent evidence, most researchers agree that lower extremity muscle quality is independently associated with physical function, despite individual differences in sex, age, or BMI.[27,29,30,35-38] Thus, in addition to efforts to mitigate losses in muscle mass and muscle strength, recovery of muscle quality may be a critical target for intervention strategies to prevent declines in physical function in older adults following hip fracture. Muscle quality rates of decline are cited as ~5-9% over 3 years among community-dwelling older men and women,[36] or 11%-13% over a 5-year span.[27] The rate at which muscle quality declines among older adults after hip fracture is undocumented. To our knowledge, there have been no efforts to document muscle quality deficits, nor describe muscle quality improvements occurring in response to rehabilitation after hip fracture.

The purpose of this study was to describe changes in muscle quality and its components (i.e., force and lean mass CSA) in response to an extended high-intensity task-oriented resistance training regime implemented between 3 and 6 months after hip fracture. Secondarily we describe the changes in clinical measures of physical function after extended training. We hypothesized significant improvements in muscle quality would occur following the intervention, which would accompany physical function gains.

Methods

Participants

A convenience sample of 17 community-dwelling older adults recovering from hip fracture, and recently discharged from approximately 8-12 weeks of usual-care physical therapy, participated in the study. Each of the participants had incurred a hip fracture in the past 2 to 6 months (mean = 3.6 ± 1.1 months), and was discharged from physical therapy in the preceding 1-12 weeks (mean = 2.4 ± 1.3 weeks).

Participants were recruited from University of Utah (UU) and Intermountain Healthcare (IHC) hospital systems over a 21-month period between July 2013 and March 2015. Individuals identified through the Enterprise Data Warehouse (EDW), and/or residing in various regional rehabilitation facilities as having undergone surgical repair for hip fracture in the preceding 2-6 months were provided a recruitment flyer and letter of invitation informing them of this study. Those desiring to participate in the study were screened and, if eligible, enrolled.

Inclusion criteria were a unilateral hip fracture in the past 6 months, functionally independent, community-dwelling, and completion of usual care physical therapy (acute, subacute, and home health interventions). Individuals were excluded based on significant osteoarthritis (taking regular medications for joint pain), obvious lower extremity range of motion impairments, and various known medical conditions, (e.g., neurological, cardiovascular, respiratory diseases, or cancer), likely to interfere with their ability to effectively participate in high-intensity resistance training. Participants underwent cognitive screening via the Montreal Cognitive Assessment (MoCA), a standardized cognitive screening test with high sensitivity (90%), and specificity (87%) for differentiating individuals with mild cognitive impairment from those with normal cognition.[39] Participating individuals were required to score greater than 23/30 on the MoCA to insure their cognitive capacity to provide informed consent.

Thigh Muscle Composition, Muscle Strength and Muscle Quality

Magnetic resonance imaging (MRI) was used for determination of the cross-sectional area (CSA) of lean muscle mass and intramuscular adipose tissue (IMAT) as previously described.[40] Bilateral magnetic resonance imaging (MRI) scans of the thighs were obtained and subjects were placed supine in a 3.0 Tesla whole body MR imager (Siemens Trio, Siemens Medical, Erlangen, Germany). The legs were scanned in a coronal plane and the midpoint of the thigh was determined and defined as half way between the superior margin of the femoral head and the inferior margin of the femoral condyles. Axial imaging (5mm thick slices at 1 cm intervals) of the legs was then performed over 1/2 the length of the femur, centered at the midpoint of the thigh. Separate fat and water images were created with custom software using the three-point Dixon method.[41] A tissue model was then used to calculate estimates of total fat and non-fat volume fractions on a per-pixel basis, which were displayed in image form. Five images from the middle 1/3 of each thigh were used to determine average cross-sectional area (cm^2) of IMAT and lean tissue. Manual tracing eliminated subcutaneous fat and bone and isolated the fascial border of the thigh to create a subfascial region of interest (ROI). Total IMAT and lean tissue were calculated by summing the value of percent fat fraction and percent lean tissue fraction over all pixels within the ROI using custom-written image analysis software (MATLAB; The MathWorks, Natick, Massachusetts). (**Figure 4.1**). This sum was multiplied by the area of each pixel to give total fat and lean tissue CSAs within the ROI and the respective IMAT and lean tissue cross sectional areas were calculated after excluding subcutaneous adipose tissue and bone.[41] The same investigator, blinded to time point of the scan and slice location, performed measurements of individual participants before and after training. Intrainvestigator reliability of this technique in our laboratory is excellent (mean ICC=0.99) and has been previously published.[42] To normalize lean mass and IMAT for thigh size, the percent of lean mass and IMAT was calculated for each subject. Percentages were calculated by dividing the area of lean mass or IMAT by the overall area of the thigh excluding subcutaneous adipose tissue and bone.

An isokinetic dynamometer (KinCom, Chattanooga Inc, USA) was used to determine unilateral knee extension strength. Participants were positioned with their hip at 90 and knee at 60 degrees of flexion. A maximal voluntary isometric contraction (MVIC) of the knee extensors, as well as the average force over a 3-second duration was recorded. The average MVIC of three trials (with 30-second rest between trials) was used for analysis. This method has excellent reliability (0.81-0.98).[43]

Muscle quality was calculated by dividing peak isometric knee extension force (Newtons) by quadriceps lean mass (cm^2).

Physical Function

Physical function was assessed with a battery of commonly used performance tests used to document physical performance in older adults. The Modified Physical Performance Test (mPPT), a 9-item test that mimics many tasks that older adults perform regularly is a reliable, valid measure of comprehensive physical performance.[44] The mPPT has been used to categorize frailty, with a score of 17-24 indicating moderate frailty, 25-31 considered mildly frail, and 32-36 indicating no frailty.[45] The Six Minute Walk (6MW) test is a reliable performance-based measure of physical function in older adults that is related to overall locomotor ability, and endurance,[46,47] with the goal of ambulating as far as one can over a 6-minute duration. The Timed Up-and-Go (TUG) test is a commonly collected mobility assessment among older adults, with scores > 13.5 seconds shown to be predictive of significant fall risk.[48] The Stair Climb Test (SCT) and Stair Descent Test (SDT) are valid, simple, quick, clinically relevant measures for assessing risk of functional decline in community-dwelling older adults.[49] The five times sit-to-stand (5xSTS) is a reliable, valid measure and a surrogate for lower extremity strength and power.[43,50,51] Poor 5xSTS performance predicts falls and impaired mobility.[52] The Berg Balance Scale (BBS) is a 14-item objective scale that provides a reliable and valid measure of static balance, with scores less than 45 indicating significant fall risk among older adults.[53,54]

The Lower Extremity Measure (LEM) is a 29-item self-report questionnaire that is reliable, valid, and responsive to improvement, with scores of 75 indicating moderate frailty, and scores above 85 indicating normal mobility and physical function after hip fracture.[55] Activities of Balance Confidence (ABC) scale is a 16-item, validated, reliable, self-report scale used to determine balance confidence. ABC is highly related to indoor fall frequency,[56] physical disability,[57] and mobility and balance performance among older adults after hip fracture,[58] with scores below 85 indicating balance limitations.

Intervention

A 3-month high-intensity, task-oriented, resistance training program with an emphasis on improving surgical limb muscle function, and whole-body balance and confidence was incorporated in this study. Participants attended three 60-80-minute supervised exercise sessions per week for 12 weeks for a total of 36 sessions. The group sessions included a 5-minute warm-up on a recumbent ergometer (Nustep Inc., Ann Arbor, MI) or gait training on a treadmill or over ground, six lower extremity strength exercises (straight leg raise, prone knee flexion, standing hip abduction, standing hip extension, seated knee extension, and seated leg press) performed 3x8 @ 85% of the surgical limb 1-RM, balance/mobility exercises (group Tai-Chi, sit-to-stand repetitions, task-oriented balance and gait training) with emphasis on restoring confidence and movement pattern symmetry, and 1-2x/weekly 5- to 10-minute lower extremity eccentric ergometer resistance training (Eccentron, BTE Tech, Hanover, MD). Following each exercise session, the participant consumed a protein-rich drink (17g whey protein (4.6g Leucine); BCAA Pepform BCAA Peptide, Glanbia Nutritionals, Twin Falls, ID) with the purpose of maximizing muscle mass and strength gains by enhancing the adaptive physiological response to resistance training.[59,60] 1-RM values were measured and recorded after the initial 3 weeks of training, then retested every 3 weeks to maximize resistance training stimuli. Depending on the specific exercise, individuals improved an average of 40%-65% in 1-RM over the 12-week course of training, similar to lower extremity gains documented after a similar post-hip fracture resistance training trial.[61]

Whole-body movements were incorporated to improve lower limb strength and increase balance confidence. During eccentric ergometric training, participants were encouraged to put equal pressure through each limb, and a target bar was progressively increased as tolerated, while maintaining 16-17/20 perceived rate of exertion throughout this portion of training. Tai-Chi inspired exercise movements were performed with progressively increasing angle and decreasing speed of joint movement to maximize the eccentric phase of the exercise. Four of the six movements were included in each group session, with individuals cued for appropriate weight-bearing and movement patterns, particularly over the involved limb. Primary movements encouraged shift of body weight onto and away from the involved limb, lunging and reaching movements, and efforts to improve confidence in performing whole-body movements. Task-oriented balance exercises were individualized to address deficits that were self-identified on LEM questionnaire, or identified during assessment on a GaitRite (CIR Systems Inc., Sparta NJ) ambulation mat. Examples of task-oriented training included stepping over a curb, walking up/down stairs, bending over to pick up object(s) from the floor, and ambulating up/down a ramp.

Data Analysis

Descriptive data were calculated for demographic and clinical variables and are presented as means ± SD. Means and 95% CIs of the primary outcome variables for comparison of differences between pre- and post-training were tested with paired-sample t-tests. Effect sizes were calculated for compositional and physical function changes observed with training. Statistical analysis was completed using SPSS version 22 with significance set at $p \leq 0.05$.

Results

Baseline Characteristics

Demographic and descriptive characteristics at baseline for the sample are presented in **Table 4.1**. The sample was representative of a typical community-dwelling, post-hip fracture population. Clinical measures, including usual gait speed of 0.9 m/s ± 0.3m/s, TUG of 12s ± 5.4s, and LEM of 74.7 ± 9.8 describe older adults who, though functionally independent, are presented with continued mobility impairments, and moderate fall risk after discharge from usual care.

Thigh Muscle Composition, Muscle Strength and Muscle Quality

The surgical limb lean quadriceps muscle mass was significantly smaller (36. 3cm^2 ± 11.1 cm^2 vs. 41.8 cm^2 ± 13.5 cm^2 $p < 0.001$), significantly weaker (251.9N ± 131.0N vs. 333.9N ± 131.0N $p < 0.001$) and had lower muscle quality (6.8 ± 2.4 vs. 7.7 ± 1.9 $p < 0.05$) than the nonsurgical limb at baseline. There was no significant difference between surgical limb and nonsurgical limb IMAT at baseline ($p = 0.57$).

Surgical limb quadriceps muscle mass increased significantly with training: mean change = 2.9cm^2, $p < 0.001$, with an average lean muscle mass gain of 9%. Muscle mass gain in the nonsurgical limb also increased with training: mean change = 2.7cm^2, $p = 0.001$, for an average lean mass gain of 7%. Knee extension strength increased significantly in the surgical limb with training: mean change = 43.1N, $p = 0.001$, for an average strength gain of 21%. Knee extension strength did not change significantly in the nonsurgical limb ($p=0.46$). Muscle quality improved significantly in the surgical limb with training: mean change = 0.5, $p < 0.05$, for an average gain of 14%. Muscle quality decreased in the nonsurgical limb: mean change = 0.6, $p < 0.05$. Quadriceps IMAT did not change significantly in either limb, while percent fat decreased significantly ($p < 0.05$) in both the surgical and nonsurgical limbs (**Table 4.2**).

Physical Function

All measures of physical function improved significantly with training ($p < 0.005$) and improvements exceeded clinically meaningful differences (CMDs) for all clinical measures in which CMD have been established (**Table 4.3**). Depending on the measure, observed clinical performance improved by an average of 10% - 30% yielding moderate to large effect sizes ranging from 0.50 to 0.98.

Discussion

Significant deficits in muscle mass and muscle quality are apparent 8-12 weeks after hip fracture in community-dwelling older adults after completing and being discharged from usual-care physical therapy. Similar to previous reports, surgical limb strength was significantly less in the surgical limb than the nonsurgical limb despite having undergone several weeks of usual-care rehabilitation.[61,62] Additionally, we identified sizable muscle mass and muscle quality deficits in the surgical limb (10-15%) compared to the nonsurgical limb after discharge from usual care. The novel findings from this study are that significant muscle mass and muscle quality improvements in the surgical limb are described for the first time, This finding indicates that acute declines in muscle mass and muscle quality in the surgical limb remain evident after usual-care, but can be significantly improved with extended high-intensity rehabilitation strategies. While muscle mass remains significantly lower in the surgical limb, even after extended rehabilitation, muscle quality improved such that there was no longer a significant between-limb difference in muscle quality following resistance training. Complementing these novel findings we describe anticipated physical function and strength gains.[63]

Consistent with previous studies incorporating high-intensity resistance training after hip fracture, significant improvements in physical function were clinically meaningful, and effect sizes for physical function outcomes were high.[63] Our results confirm previous reports suggesting that significant gains in strength, balance, mobility, gait, and self-reported function are expected after extended high-intensity resistance training.[61-63] The fact that these improvements were accompanied by improved muscle mass in the quadriceps region is encouraging in light of the fact that a significant amount of lean tissue is usually lost after hip fracture, especially in the lower extremities,[17] and muscle mass recovery after inactivity in older adults is often diminished.[19] Impairments in strength and power of the surgical limb may remain apparent for years after a hip fracture[21,23] despite traditional rehabilitation efforts; thus improvements in lean mass and utility of available muscle are important.

Muscle mass improvements were accompanied by significant improvements in isometric muscle strength and also muscle quality in the surgical limb. However, on the nonsurgical side, despite improved muscle mass, isometric strength did not change. This finding also explains why there was a decrease in nonsurgical thigh muscle quality considering that muscle quality is a simple calculation of force produced per unit of muscle mass. Likely, neural activation is at least partially responsible for the significant strength gains noted in the surgical limb and lack of strength improvement in the non-surgical limb. A recent study identified a 10% decrease in activation in the lower limb of older adults, but not younger adults, after 2 weeks of limb immobilization,[18] while resistance training has been shown to improve activation and muscle size among older adults after elective hip replacement surgery.[64] The surgical limb after hip fracture is relatively inactive in relationship to the nonsurgical limb, and thus improved neural activation combined with improvements in muscle mass likely contributed to increased isometric strength. However, the neural activation of the nonsurgical limb likely changed little as a result of the training, as the training specifically targeted surgical limb deficits. Thus, the improvements in muscle mass alone may not have been sufficient to induce significant improvements in nonsurgical limb isometric strength. Since we did not quantify neural activation we are unable to confirm the contribution of neural activation to isometric strength in this sample.

Inconclusive and limited evidence describing body composition changes occurring in response to rehabilitation after hip fracture currently exists.[61,65] Despite improved physical function in both studies, Binder et al. found no significant change in lean mass or bone mineral density (BMD) following 3 months of extended resistance training,[61] while Orwig et al., reported small, but nonsignificant improvements in hip region BMD with continued decline in lean mass (effect size = -0.3) after a year-long low-resistance home therapy training regime.[65]

The lean mass gains observed in the present study may have been amplified by the addition of the leucine-enriched protein supplementation since a recent meta-analysis reported that of the branch chain amino acids, leucine is a potent stimulator of muscle protein synthesis.[66] Thus, the ~5g leucine (within the 17g whey protein beverage) provided to participants following each exercise session might have served as an important rehabilitation countermeasure to maximize muscle gains in this vulnerable older adult population. Healthy older adults following a resistance training program that included protein supplementation had 0.69kg gain in lean mass and demonstrated 13.5kg greater capacity in 1-RM leg press, exceeding gains that resulted from resistance exercise without protein supplementation.[60]

Malnutrition is commonly found among older adults admitted to the hospital with hip fracture,[67] and the majority does not meet the recommended daily allowance (RDA) for protein (0.8 g/kg body weight/day).[68] High protein intake reduces risk of perioperative complications,[69] improves bone mineral density,[70] and enhances rehabilitation time[71] in this patient population. Women who are underweight (<20.5 BMI), have worse physical function and strength at 6 and 12 months after fracture than women of normal weight (20.5 – 33.0 BMI),[72] and typically lose a higher percentage of their body weight than those of normal weight (4.6% vs 1.3%) after hip fracture.[72] This accentuates the need for preserving mass and mitigating weight loss, particularly among the frail, since this subpopulation is most at risk for functional losses after hip fracture, yet least likely to receive robust resistance training. Though we do not know the direct effect that protein supplement had on gains in our sample, we have reason to suppose that the additional protein (and enriched leucine content) augmented muscle composition and strength gains in this population,[60] and should be considered in future strategies to mitigate postfracture muscle mass loss.

These results should be taken in light of some limitations. The participants were generally healthy, motivated, community-dwelling elderly participants recovering from hip fracture who were without significant cognitive impairment, and who volunteered for a physical therapy exercise program. Whether these results are generalizable to other older adults after hip fracture with additional impairments is unknown. We observed an average improvement of 14% in muscle quality in the surgical limb following training in participants used as their own controls. Therefore we are unable to fully attribute our findings to the intervention alone.

Conclusion

Despite having completed usual-care physical therapy, significant impairments in muscle quality and its components remain evident after hip fracture. Extended high-intensity resistance training following usual care after hip fracture improves muscle strength and physical function. Our results suggest that muscle mass and muscle quality deficits identified in the surgical limb can be reversed with training after hip fracture. Future studies should determine the impact that muscle quality has on long-term functional recovery and quality of life in this population.

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Table 4.1. Descriptive Characteristics of Study Sample.

Variable	Training Group (n=17)
Demographics	
Sex	5 Male, 12 Female
Age (yr)	77.0 +/- 12.0
Body Mass Index	26.0 +/- 6.2
Side of Injury	10 left, 7 right
Time since Fracture (mos)	3.6 +/- 1.1
Repair Type	9 ORIF, 8 hemi/THA
Performance-Based	
Cognitive Status (MoCA)	27.9 +/- 1.8
Usual Gait Speed (m/s)	0.9 +/- 0.3
Self-Report Function (LEM)	74.7 +/- 9.8
Timed Up-and-Go (s)	12.5 +/- 5.4
Peak Force$_{INV}$ (N)	251.9 +/- 131.0
Peak Force$_{UNINV}$ (N)	333.9 +/- 154.3

All measures refer to baseline measurement. Yr = year, mos = months, ORIF = open reduction internal fixation, hemi = hemiarthroplasty, THA = total hip arthroplasty, MoCA = Montreal Cognitive Assessment, m/s = meters/second, LEM = Lower Extremity Measure, s = seconds, N = Newtons

Table 4.2. Changes in Muscle Composition and Muscle Quality Components with Training.

	Pre-Training	Post-Training	Mean Change [95% CI]	Effect Size
Lean Quad Mass				
Involved	36.3 (11.1)	39.2 (11.4)	**2.9 [1.5 – 4.3]****	0.26
Uninvolved	41.8 (13.5)	44.5 (13.5)	**2.7 [1.4 - 4.0]****	0.20
IMAT Mass				
Involved	8.6 (3.2)	8.8 (3.3)	0.14 [-0.3 - 0.6]	NS
Uninvolved	8.4 (3.6)	7.9 (2.7)	-0.48 [-1.4 – 0.4]	NS
% Lean Quad				
Involved	80.7 (4.1)	81.8(4.4)	**1.1[0.2 – 1.9]***	0.27
Uninvolved	83.4 (3.9)	84.9 (2.5)	**1.6 [0.4 – 2.7]***	0.41
% IMAT Quad				
Involved	19.3 (4.4)	18.2 (4.1)	**-1.1 [-0.3 - -3.0]***	-0.27
Uninvolved	16.6 (3.9)	15.1 (2.5)	**-1.5 [-0.4 - -2.7]***	-0.41
Peak Force (N)				
Involved	251.9 (131.0)	294.9 (131.0)	**43.1 [20.1 – 66.0]****	0.33
Uninvolved	333.9 (154.3)	322.4 (128.4)	-11.5 [-43.6 – 20.6]	NS
Muscle Quality				
Involved	6.8 (2.3)	7.3 (1.9)	**0.5 [0.03 – 1.1]***	0.28
Uninvolved	7.7 (1.9)	7.1 (1.9)	**-0.6[-0.07 - -1.2]***	-0.33

Bold* = changes significant, p < 0.05, **Bold**** = changes significant, p < 0.005, NS = changes not significant, p > 0.05. Quad = quadriceps musculature

Table 3.4. Limb Symmetry Index Correlations: vGRFs and Muscle Function.

	RFD LSI	**Peak vGRF LSI**	**AREA LSI**
Peak Force LSI	**0.72** ($p < 0.001$)	**0.71** ($p < 0.001$)	**0.66** ($p < 0.001$)
Power LSI	**0.76** ($p < 0.005$)	**0.58** ($p < 0.005$)	**0.59** ($p = 0.005$)

Pearson Product Moment Correlations of Limb Symmetry Index Values. RFD = Rate of Force Development, vGRF = vertical Ground Reaction Force, LSI = Limb Symmetry Index. All values listed are significantly correlated at $p<0.05$

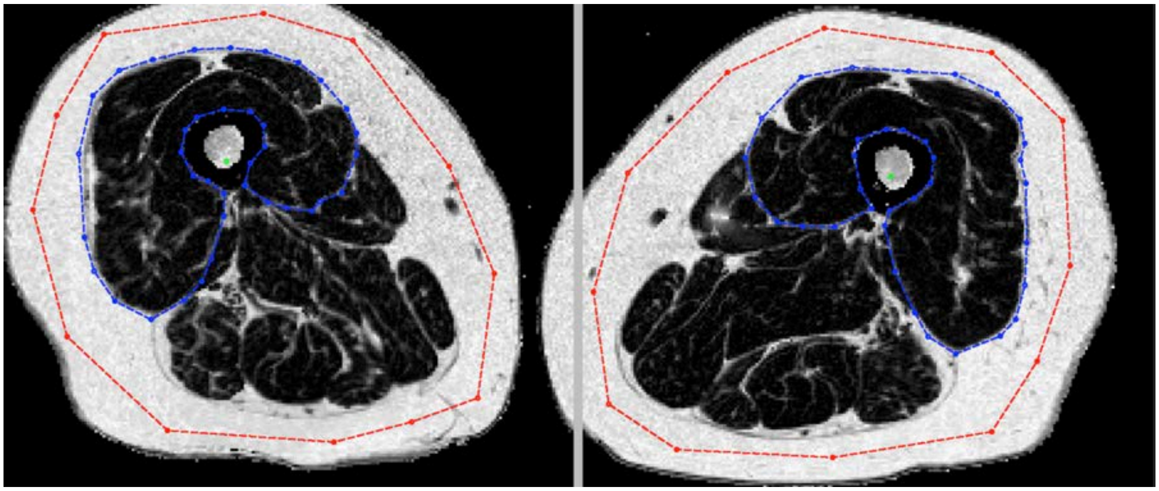

Figure 4.1. **Representative Baseline Images of Right and Left Thigh.** In this instance, right is the surgical limb, while left is the nonsurgical limb. The tracing of quadriceps musculature as described in methods section is depicted here. Note the improved appearance of the left thigh musculature (less fat infiltrate) compared to the right thigh. Baseline lean muscle mass is 31.1cm^2 in the surgical limb compared to 34.8cm^2 in the nonsurgical limb.

CHAPTER 5

CONCLUSIONS

Summary of Findings

Several specific research questions initiated this dissertation: In older adults who have experienced a hip fracture, does asymmetry predict physical function? In the same population, is a High-Intensity Task-Oriented resistance training strategy targeting Strength and Symmetry (HI-TOSS) able to reduce weight-bearing asymmetries during STST performance, and minimize asymmetries in muscle function when extended after discharge from usual-care among community-dwelling older adults who have experienced a hip fracture? Does HI-TOSS positively impact variables related to physical function (vGRF during STST, strength, power) in addition to potential symmetry improvements among these variables? Do high-intensity resistance strategies targeting asymmetries after fracture have a positive impact on muscle quality and its components (i.e., muscle strength and lean muscle mass) after hip fracture? Finally, to what extent is physical function improved with these strategies?

Our research identified weight-bearing asymmetry, calculated during rising phase of a STST (AREA), as a key predictor of physical function as measured by the stair climb test. This indicates that asymmetry during STST does independently predict performance in this high-level task, above and beyond other factors known to impact function. Our research did not identify AREA as a predictor of performance on a composite physical performance scale (mPPT) when other factors known to impact function were considered. We expected that asymmetry would provide an independent contribution to explain the variance in both measures of physical function. The inability of AREA to predict mPPT can be likely attributed to the relative ease of many of the tasks included in the mPPT, and the fact that several can be performed by compensating for surgical limb deficits without drastically affecting performance (e.g., static balance, level ground gait speed, and ability to don/doff jacket). This is in contrast to the fluid, dynamic contribution required from each limb during the stair climb task. Our findings indicate that asymmetry is a likely contributor to the relatively high prevalence of falls and low competency in stair climb performance among many older adults after hip fracture. Thus, challenging, high-level activity performance is more likely to be predicted by lower limb asymmetries after hip fracture compared to less-challenging ADLs. Clearly identifying and reducing weight-bearing asymmetries have the potential to reduce falls and improve function among those who are recovering from a hip fracture.

When we examined the ability of HI-TOSS to improve symmetry during a sit-to-stand task and aspects of lower extremity muscle function, we found that symmetry was improved for each of these variables. While muscle function and STST performance improved in the surgical limb for approximately 90% of participants in our study, muscle function and STST performance in the nonsurgical limb generally improved less consistently (approximately 70%), and to a lesser degree. On average, this tendency to improve more consistently and with greater magnitude in the surgical side improved the symmetry of these individuals. When examined more closely, there were some interesting findings in regard to symmetry gains in this sample. First, those with larger asymmetries improved more, on average, than those with lesser identifiable asymmetries. Second, small asymmetry did not always indicate good function, particularly among those who had symmetrical, but poor muscle function. Finally, a subgroup of high-functioning individuals seemed to have enduring asymmetries despite training and improved recovery in other areas. This indicates that perhaps there is a threshold which one must meet in order to demonstrate good competency in tasks of physical function, and once this threshold is met, further improvements in symmetry are less impactful. These findings support the utility of improving symmetry for many older adults, while indicating the need for further exploration in this area to identify subpopulations that benefit most from training and to establish when initiation of efforts to improve symmetry are most effective.

When we examined a subpopulation of these individuals to determine the effect of HI-TOSS on muscle mass, muscle strength, and muscle quality, we determined that a significant improvement in muscle mass occurred in both the surgical and nonsurgical limbs, with a greater magnitude of improvement in the surgical than the nonsurgical limb. We found significant strength gains in the surgical side, which were not evident in the nonsurgical side. This resulted in significant gains in muscle quality, with no significant change in muscle quality in the nonsurgical side. We expected that participants who met entry criteria in this study would improve significantly in quadriceps lean muscle mass, strength, and muscle quality. We suppose that activation is at least partially responsible for the significant strength gains noted in the surgical limb and may provide some explanation for the loss of muscle strength improvements in the nonsurgical limb despite improvements in lean mass size. Immobility in older adults has a greater impact on neuronal motor function than in younger adults.[1] As the surgical limb was relatively inactive in relationship to the nonsurgical limb, strength gains are likely at least partially explained by an improved activation response in the surgical limb after exercise. Indeed, a recent study among noncopers after ACL repair indicated that lean mass atrophy and activation failure explained 60% of quadriceps weakness, while lean mass or lean volume did not sufficiently explain weakness.[2] Overall, muscle quality, muscle mass, and muscle strength are significantly improved in the surgical limb with HI-TOSS training.

Physical function improvements are significant after HI-TOSS training when extended after discharge from usual care in this population. Previous studies demonstrate changes in physical mobility and task performance that are similar to our findings when offered extended resistance training after usual care among those who have experienced a hip fracture.[3] These improvements in self-perceived function, as well as observed clinical performance, are likely to contribute to improved physical performance in the participants' homes and community.

Among community-dwelling older adults who have survived hip fracture, HI-TOSS training leads to many significant improvements that are not evident with usual-care rehabilitation. Since many of these changes are correlated with improved mobility, maintained independence, and reduced fall risk, we recommend continued study in HI-TOSS, and similar restorative rehabilitation approaches after hip fracture to further improve the physical capacity and general health of this vulnerable population.

Future Research

The HI-TOSS rehabilitation approach in this study was developed in an attempt to improve immediate and long-term outcome for survivors of hip fracture. Extended resistance training has long been noted as beneficial for improving physical function after hip fracture. Still, less than 10% generally receive resistance training in an out-patient setting after hip fracture, and training they receive at home rarely includes resistance training of adequate intensity to restore surgical limb muscle function or recover physical function losses.[4,5] Immediate evidence from our investigation in the effects of HI-TOSS on recovery after hip fracture is that symmetry as well as several other aspects of muscle and physical performance are improved.

Future research should identify long-term benefits from HI-TOSS training. Are identified aspects of recovery maintained over time? Individuals who have experienced a hip fracture are generally more sedentary than age-matched cohorts. Sedentary behavior and relative inactivity after resistance training may attenuate the improvements made with HI-TOSS. Additionally, though we were able to show that gains in symmetry are made with 12-week HI-TOSS training, we are uncertain if these improvements endure when the patient returns to their normal daily routine. It is suspected that many of these asymmetries are learned patterns of behavior in addition to surgical limb deficits, and despite improvements in muscle function, habitual movement patterns may endure. Though many of the variables that improved with HI-TOSS (e.g., vGRF values, strength, muscle quality, and physical performance measures) are significantly related to reductions in falls, long-term tracking of individuals and larger sample randomized controlled trials are indicated to determine whether gains made with HI-TOSS yield reductions in falls and other important outcomes for older adults, once returned back to their community dwelling.

Though sit-to-stand is one of the most common of challenging activities older adults perform each day, and maintained independence in this task is highly related to muscle function and physical performance in other ADLs,[6,7] there are other tasks in which weight-bearing asymmetries may provide insight into residual impairments after hip fracture. Weight-bearing acceptance onto the surgical limb, and purposeful stepping by the surgical limb is limited for several months after hip fracture.[8] Such limitations can lead to falls and may be one reason over 50% of individuals experience one or more falls in the 6 months after discharge from the hospital after incurring a hip fracture.[9]

Potential for improvement in implementation and understanding of HI-TOSS and similar resistance training strategies exists. It is readily apparent that the current management of hip fracture recovery is inadequate for recovery in muscle function or physical mobility. Older adults show high adherence to resistance training with good results in muscle function and minimal adverse events when such training is offered.[3,10-12] Indeed, recent studies indicate potential for initiating resistance training as early as 2 weeks after hip fracture, and show improved outcomes with good adherence and little pain/discomfort.[13] Since strength loss is approximately 50% in the initial 2 weeks after hip fracture,[14] and as much as 4% of lean mass may be lost in only 5 days of inactivity,[15] initiating rehab earlier may attenuate the rapid loss in muscle mass and function that is apparent in this population. A task-oriented, restorative rehabilitation approach, initiated early, might yield a better recovery in the surgical limb vs. current compensatory rehabilitation approaches that appear to encourage physical mobility through compensatory means resulting in enduring deficits, particularly in the surgical limb. Early awareness of potential surgical limb deficits combined with efforts to restore lower limb muscle function are likely to inspire improved strategies among both clinicians and patients, thus potentially reducing movement pattern asymmetries and inactivity before such movements become habitual and recalcitrant to change.

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