2009

THE ROLE OF THE HIP ABDUCTOR MUSCLE COMPLEX IN THE FUNCTION OF THE PATHOLOGICAL HIP JOINT

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ABSTRACT OF DISSERTATION

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THE ROLE OF THE HIP ABDUCTOR MUSCLE COMPLEX IN THE FUNCTION OF THE PATHOLOGICAL HIP JOINT

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A dissertation submitted in partial fulfillment of the
requirements for the degree of Doctor of Philosophy in the
College of Health Sciences
at the University of Kentucky

By

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THE ROLE OF THE HIP ABDUCTOR MUSCLE COMPLEX IN THE FUNCTION OF THE PATHOLOGICAL HIP JOINT

The number of patients electing to undergo total hip arthroplasty (THA) in the United States has been projected to double by the year 2030, with a growing number of these patients below the age of 65 years. This cohort of patients not only desires to return to pain free daily activity, but wishes to participate in recreation and sporting activities. However, many of these patients report pain, impairments, and functional limitations following THA. The number one deficit observed for patients who fail conventional post-operative rehabilitation is persistent weakness of the hip abductor muscles. In order to safely progress these patients back to their desired activity level, appropriate post-operative rehabilitation programs need to be developed.

The primary objective of this dissertation was to examine the effectiveness of a hip abductor strengthening program on subjective and objective outcomes following THA. The secondary aims of this study were to document hip muscle activation and lower extremity movement patterns during functional exercises; and to compare short-term subjective and objective clinical outcomes for subjects following THA compared to controls.

Several observations were made from our results. First, the lunge, single leg squat, and step-up and over exercises may be appropriate to include in post-operative rehabilitation programs to transition THA subjects from static strengthening exercises to dynamic activities. Second, subjects at 6- and 12-weeks following THA continue to exhibit strength and functional deficits, which contributes to decreases in activity level. Third, the addition of an exercise program targeting the hip abductor muscles following THA may help to improve subjective and objective outcomes compared to conventional post-operative rehabilitation. Finally, findings from our results are summarized and we propose a model to develop patient-specific rehabilitation programs.

KEYWORDS: total hip arthroplasty, hip abductors, rehabilitation, functional exercises, clinical outcomes

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__May 1, 2009______________________
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RULES FOR THE USE OF DISSERTATIONS

DISSERTATION

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ACKNOWLEDGEMENTS

The following dissertation represents a culmination of four years of adversity, insight, hard work, and growth, of which would not be possible without the support of a truly amazing group of mentors. First, I need to thank my mentor and friend, Carl Mattacola- there was never a day where he stopped challenging me to grow, as a scholar and a person. He took an excitable, emotional, scattered kid and molded me into a confident, focused woman. I can’t thank him enough. Next, I would like to thank the other members of my dissertation committee: Dr. Gilson Capilouto, Dr. Tim Uhl, Dr. Patrick Kitzman, Dr. Jody Clasey, and Dr. Cale Jacobs. I have been so blessed to be surrounded by so many wonderful teachers and scholars. I am truly humbled by all the time and effort they put forth in helping me achieve my goals.

This dissertation could not have been possible without the wonderful people at both Lexington Clinic and UK Good Samaritan Clinic. Words cannot begin to express my gratitude for taking time from your busy schedules to assist me. Lastly, I have to thank my wonderful family and friends. To my UK “family”- your day-to-day support kept me sane and gave me strength to keep going every day. To my best friend and ‘sister’ Julie- thank you for being everything and anything I needed whenever I needed it. To my family- Sean Michael, my grandparents, and especially my mom and dad, I can’t say thank you enough. You are my strength, my focus, my determination, and everything that I strive to be. “Whaddya know we made our dreams come true! And there are fancy cars and diamond rings, but you know that they don't mean a thing. Well they all add up to nothing compared to you. Just remember me in ribbons and curls...I still love you more than anything in the world…Love, Your Baby Girl”.

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Pre- and Post-Operative Impairments, Functional Deficits, and Activity Limitations for Patients Undergoing Total Hip Arthroplasty

Introduction

The number of patients electing to undergo total hip arthroplasty (THA) in the United States has steadily increased in the past decade, with numbers totaling 202,000 persons in 2003[1]. These numbers are expected to double by the year 2030[1]. A growing number of patients undergoing this procedure are below the age of 65 years[2,3]. This cohort of patients represents a new challenge to physicians and rehabilitation specialists as they not only wish to return to pain free daily activities, but express a desire to continue to participate in recreational and sporting activities following THA[4-9]. Conflicting evidence exists as to whether participation in higher demand activities is detrimental to the health and longevity of the prosthesis[7,10-12]. Long term evidence suggests a fourfold increase in the risk of prosthetic failure for patients who participate in sporting activities, with a greater number of revisions due to aseptic loosening in this population[12].

Physician recommendations of which activities are appropriate following THA have been published[13, 14]; however rehabilitation programs focused on returning patients to a higher level of activity have not been addressed. In addition, numerous studies report pain, impairments and functional limitations to persist up to 6 years following surgery[4,15-22]. The prolonged presence of these disabling factors may result in an inability of younger patients to safely return to their desired activity level. With a greater number of younger patients undergoing THA, there is a need for post-operative treatment programs which will allow the patient to return to a higher level of function without risking the health and longevity of the implant. Understanding the functional limitations present prior to and following surgery will allow for more appropriate rehabilitation programs to be developed. The purpose of this review is (1) to examine the clinical presentation of patients who are less than 65 years of age prior to surgery, (2) to compare the effectiveness of different surgical techniques in this population, and (3) to assess the outcomes following surgery and rehabilitation for these patients.

Pre-Operative Clinical Findings in Patients with End-Stage Osteoarthritis of the Hip Joint

As stated previously, the number of patients who are less than 65 years of age electing to undergo THA is growing[2,3]. Many of these patients have enjoyed an active lifestyle throughout their lives; however, the pain they experience as a result of the degeneration to their hip joint prevents them from functioning at the same level[23]. The length of time a patient has been experiencing painful symptoms prior to undergoing surgery varies but has been reported to be up to 5 years, with mean times ranging from 11m to 4.7y[16, 24]. It has been proposed that pain caused by the joint damage leads to a reduction in activity levels which results in disuse atrophy and weakness of lower extremity muscles[16, 22, 24]. This perpetuates a cycle of increasing disability over time. Understanding the specific impairments and functional deficits associated with this disability is imperative to designing appropriate treatment programs.

Subjective Pre-Operative Clinical Findings

Numerous subjective rating scales have been developed to assess pain, function, and quality of life for patients with degenerative hip disease. The Harris Hip Score (HHS) is a joint specific measure which contains questions regarding pain, function, deformity, and range of motion[25]. Scores range from 0-100 points, with higher scores indicating less pain and greater function. A modified version of the HHS has been developed specifically addressing only the domains of pain and function[26]. The total score obtained using the modified HHS is then multiplied by the constant 1.1 to achieve a best possible score of 100 points. The Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC) is a disease specific questionnaire consisting of 24 questions which address a patient's level of pain, stiffness, and physical functioning[27]. The function subscale of the WOMAC contains 17 questions and is scored from 0-68 points, with higher scores indicating worse function[28]. The pain subscale of the WOMAC contains 5 questions and is scored from 0-20 points, with higher scores indicating worse pain[28]. Total scores range from 0-100, with the best possible score equaling 0 points. The Short Form 36 (SF-36) is a general body scale consisting of eight domains which assess functional status, well being, and overall health[28]. Each domain is scored individually using a 0-100 point scale, with the best possible score equaling 100 points. The three aforementioned scales have all been shown to be reliable and valid for use in studying outcomes of patients undergoing THA[25,28-30].

Subjectively, younger patients who elect to undergo THA reported pain which impairs function. Total scores for the HHS for this population ranged from 41-54 points[23,31-35], with all scores indicating severe pain and poor function. Similar findings were observed for scores of the WOMAC and SF-36 scales. The score on the function subscale of the WOMAC for patients prior to undergoing THA was reported to be 29 out of 68 points, while the score for the pain subscale was 9 out of 20 points[36]. The pre-operative SF-36 score for pain was reported to be 45 out of 100 points and the score for function was 40 out of 100 points[36]. Additionally, the score for role limitations due to physical health was 50 out of 100 points, suggesting patients were limited in their activity level as a result of their physical condition prior to surgery[36]. The scores obtained using these subjective scales indicated that patients awaiting THA experience a high degree of pain which limits their ability to function; however, they do not specify which activities were most limited and to what degree.

Pain was the most common symptom reported by patients less than 65 years of age who are awaiting THA. Up to 93% of patients rated their pain moderate to severe[24,37,38], while 80% of patients reported the occurrence of severe episodic pain on most to all days[38]. In addition, 88% of patients described pain at night which interferes with sleep[38]. Patients also reported that their pain level more than doubles following activity when compared to levels experienced at rest[24]. As high as 95% of patients reported pain during walking[37], with 66% unable to walk more than 15 minutes before their pain became severe[38]. As a result of pain, patients reported moderate to severe mobility[15,22,31-34,37-39] and physical functioning[36-38,40] impairments.

Difficulties in performing certain activities of daily living (ADL) have been reported by patients who are awaiting THA. In a single study, patients were asked to list the top five activities affected by their hip pain. The most common activities reported by patients were independent walking (73%), putting on socks and shoes (54%), stair climbing (35%), standing for prolonged periods of time (27%), and sleeping (24%)[23]. Less than 20% of patients also reported problems with completing housework, riding in a car, getting into and out of a bathtub, home maintenance, sexual relations, and community socializing[23]. Based on the data reported in this study, the pain experienced by patients awaiting THA affected the majority of activities of their daily life.

Other studies have also investigated specific activities which were hindered for patients with end stage osteoarthritis. It has been reported that 67% of patients had extreme difficulty or were unable to wash and dry themselves, while 80% of patients in this study had difficulty putting on shoes and socks[38]. Eighty-one percent of patients described extreme difficulty or were unable to climb one flight of stairs[38]. Standing from a seated position and getting in and out of a vehicle was described as difficult or impossible for 83% of patients[38]. The majority of patients also demonstrated an observable limp during gait[38], with half requiring assistance to walk[37]. Assistance with household shopping was required by 43-78% of patients[37,38], while 42% required assistance with performing housework[37]. In addition to affecting ADLs, half of patients reported participation in moderate activity less than daily, while 24% of patients never participated in recreational activity[37]. Twenty-three percent of patients had difficulty or were unable to participate in low impact activities, such as golf, swimming, dancing, gardening and bowling[23]. As a result, patients living with others become more dependent, while those living alone become increasingly isolated from others. This lack of independence has negative consequences on the patient's overall quality of life as evidenced by reported declines in social functioning, emotional and mental health[36,40]. While subjective information is critical to understand the impact of osteoarthritis on a patient's life, assessment of objective measures is required to ascertain the specific factors contributing to or resulting from altered function.

Objective Pre-Operative Clinical Findings

Numerous studies have identified reductions in muscle strength for patients with hip OA[16, 22, 24, 41, 42]. Quadriceps and hamstring muscle peak torque measures were reduced for the involved limb in patients with hip OA when compared to the uninvolved limb[22, 24] and to a group of controls[24]. In addition, involved limb hip extension and flexion isometric strength values were reduced by 25-32% and 28-49%[16, 41], respectively, when compared to the uninvolved limb and by 16% and 18% [41], respectively, compared to healthy controls. In men with unilateral hip OA, isometric strength of the involved hip abductors and adductors was equal to measures of the uninvolved hip, but reduced by

30% when compared to those of healthy controls[41]. A positive Trendelenburg test, indicating weakness of the hip abductor muscles, was also observed in 80% of patients with hip OA[42]. A significant relationship between a positive Trendelenburg test and the absence of gluteus medius and gluteus maximus muscle electromyographic (EMG) activity has been shown during gait, suggesting inactivity of these muscles results in functional alterations[32]. The failure of these muscles to activate will most likely lead to disuse atrophy, likely contributing to the observed hip abductor and extensor weakness in this population.

Multiple studies have also reported the presence of alterations in the properties of muscles acting upon the hip joint in patients with OA of the hip joint[24, 41,43]. The cross-sectional area of all thigh muscles was reduced by 6-13% in the involved hip compared to the uninvolved hip in a group of patients with hip OA, suggesting a general atrophy of the involved limb[41]. Atrophy of both Type IIa and Type IIb quadriceps muscle fibers was also observed in the affected hip of patients compared to a group of controls[24]. In addition, reductions in both the number and cross sectional area of Type II muscle fibers of the gluteus medius muscle were reported for patients with hip OA compared to controls[43]. Muscles with a higher proportion of Type I fibers tend to be stiffer, which reduces their shock absorbing ability. It has been theorized that the reduction in the shock absorption ability of the muscles surrounding the hip joint is a contributing factor to the development and progression of OA. This is substantiated by the observation of reduced external joint moments during gait[15]. A reduced external adduction moment reflects a compromise of the hip abductor muscles, and a reduction in this moment was shown to significantly correlate with an increase in hip joint contact force. Therefore, alterations in the morphology and activation of the gluteus medius muscle appear to be important contributing factors to both the development of the disease and the associated functional alterations observed in patients with hip OA.

Alterations in function have been observed during gait[31, 32,44], stair climbing[44], and clinical functional tests[22, 24,36,44] in patients with end stage hip OA. Patients demonstrated a reduction in gait velocity[32,44] as well as a decrease in time spent in the single limb stance phase of gait on the involved limb[32] when compared to a group of controls. Patients also traveled less total distance during a 6-minute walk test[23,31] and required significantly more time to climb a flight of stairs[44] than healthy controls. In addition, patients needed an average of 2.5 to 7.3 seconds more to complete the Timed-Up and Go (TUG) test when compared to controls[22,24,36,44]. Overall, patients with end-stage hip OA demonstrate a consistent reduction in the speed at which they function. As walk speed has been shown to moderately correlate with hip abductor muscle weakness[45], it is likely that the reduction in hip abductor strength measures observed in many patients with OA contributed to their functional decline.

As a result of the numerous impairments and functional deficits present in patients with end-stage hip OA, numerous studies have examined the effectiveness of rehabilitation programs implemented prior to surgical intervention in improving subjective and objective measures of pain and function. Patients who participated in 8 weeks of an exercise program exhibited no change in self-reported pain and function scores; however, the scores for a group of patients who did not participate in exercises decreased, indicating worse pain and function during this time[17, 36]. A similar trend was observed for measures of hip muscle strength, with the group of patients who completed exercises exhibiting increases in overall hip muscle strength after an 8-week intervention compared to decreasing strength measures for the control group[17]. However, patients who completed 8 weeks of supervised rehabilitation did not significantly differ in measures of gait speed, cadence, and walking distance compared to patients who did not complete exercises[46]. For patients with end-stage OA, pre-surgical rehabilitation may be beneficial for maintaining or improving pre-surgery pain[17,36] and strength measures[17]; however, these improvements do not appear to equate to enhanced function[46].

The true benefit of pre-operative rehabilitation appears to be at improving immediate post-operative outcomes. Patients who participated in an exercise program prior to surgery were able to perform immediate post-operative activities sooner and were discharged earlier than those who did not[33,36]. Participation in a pre-operative exercise program also resulted in greater and quicker improvements in gait speed and total walking distance in the first 6 months post-surgery[46]. In addition, patients who received pre-operative education, training, and coping strategies performed better[34,47], were discharged earlier[47-49], and reported greater levels of satisfaction[47,48] immediately following surgery. While pre-rehabilitation may not prevent the need for surgical intervention for patients with end-stage hip OA, it does appear to benefit pain and function post-surgery. In fact, baseline pain and functional status has been shown to be the single best predictor of outcomes at 6 months[50] and 2 years post-surgery[51]. Specifically, patients who had lower baseline scores of pain and function, indicating worse pain and function, did not achieve similar improvements in these measures as patients with higher pre-operative scores, even at 2 years post-surgery[51]. Therefore, it may be beneficial for patients to participate in a rehabilitation program prior to surgery in order to augment post-surgical outcomes.

Review of Implant Fixation Methods and Surgical Approaches for Total Hip Arthroplasty

The introduction of the cemented low-friction arthroplasty by Charnley in 1960 helped establish a new level of success for long-term outcomes following THA[52]. The long-term survival for this type of implant has been unsurpassed by newer techniques for all patients regardless of age at the time of surgery[53]. The development of modern uncemented and hybrid fixation methods has shown promising short-term outcomes in younger patients[11,54-58]; however, long-term survival is not available due to the infancy of these methods. Each surgical technique presents with its own unique set of benefits and complications; therefore, it is important to review the available evidence regarding prosthetic longevity and outcomes for the different techniques in order to determine which technique is appropriate for each individual patient.

Fixation Methods for THA

Low-friction cemented arthroplasty employs the use of a socket component made of high-density polyethylene and a femoral stem made of metal with a 22mm diameter head[59]. The axis of the acetabular component is inclined at an angle of 45 degrees. The recommended amount of acetabular anteversion is no more than 5 degrees [59], while the femoral component is placed in neutral anteversion[59]. Both components are fixed in bone using self-curing acrylic cement. The process of cement fixation has evolved over time. First generation cementing techniques employed by Charnley involved finger packing the cement into an unplugged canal[60]. What is termed 2nd generation cementing entailed the use of a medullary plug and cement gun, which resulted in a more even distribution of the cement[60]. Current cementing techniques consist of pulsatile lavage, porosity reduction, pressurization, and precoating[60]. Improvements in cementing technique have resulted in less breakdown of the cement mantle supporting the prostheses, thus increasing component survival.

Overall survival rates of low friction cemented THA have been projected for up to 38 years for patients who are less than 50 years of age at the time of surgery[61,62]. Overall prosthetic survival was 98% at 5 years, 93% at 10 years, 87% at 15 years, and 75% at 20 years[61]. The projected 25 year survival rate for cemented prostheses was 69%[62], while the projected overall survival rate at 38 years was reduced to 30%[63]. The overall revision rate for cemented implants was reported to be 29% at 20 years following surgery[62]. Implant survival has been shown to significantly relate to diagnosis at the time of surgery[61]. Patients with rheumatoid arthritis (RA) demonstrated the highest survival at 20 years with a 96% survival rate, while patients with OA demonstrated the lowest survival at 20 years at only 51%. Therefore, it appears the type of underlying disease is an important factor when considering cemented implants for patients less than 50 years of age.

When examining individual component survival for cemented implants, survival of the femoral component was reported to be superior to survival of the acetabular component[61,62,64]. The survival rate for the femoral component was reported to be 94% at 25 years[62] and 73% at 38 years[63], while survival of the acetabular component was only 76% at 25 years[62] reducing to 54% at 38 years[63]. In addition, only 5% of the femoral components required revision as a result of aseptic loosening compared to 19% of the acetabular components at 25 years[62]. Age has been shown to significantly affect the rate of revision for the isolated prosthetic components. Revision rates for the femoral component were reported to be similar between a cohort of patients older than 50 years at the time of surgery and a cohort of patients 50 years and younger[64] at the time of surgery who were at least 10 years post-surgery. Conversely, the revision rate at 10 years post-surgery for the acetabular component of patients 50 years or younger at the time of surgery was twice the rate of patients older than 50 years at the time of surgery[64]. A review of all studies examining revision rates for younger patients who underwent the Charnley low-friction arthroplasty revealed revision rates for the femoral component ranging from 4-25% and for the acetabular component ranging from 17-51% with a 10-18 year follow-up[64]. These results suggest that, for younger patients, a fixation method other than cement may be more appropriate to increase the longevity of the acetabular component.

As a result of the increased risk of subsidence seen with cement fixation of acetabular implants, uncemented implant fixation has been developed. With uncemented THA, both the acetabular and femoral implants are fixed without cement. Fixating the femoral component without cement has been implemented as a consequence of early cement mantle breakdown seen with first generation cementing techniques[65]. For the uncemented implant, the acetabular component is often made of titanium and contains an inner polyethylene liner[66]. The outer shell is porous coated to improve bony fixation and contains 3-5 holes to accommodate supplemental fixation through the use of bone screws[11,66]. The acetabular component is inserted using the line-to-line technique[11,66], in which the diameter of the component equals the outer diameter of the reamer used to prepare the acetabulum.

Overall survival for uncemented implantation has been reported between 81% and 98% at 10 years post-surgery for patients who are less than 50 years of age at the time of surgery[54,55]. At 15 years post-surgery, survival reduced to 47%[55]. The majority of uncemented implant failure also appeared to be a result of acetabular component loosening. The 10-year survival for the femoral component was 99% compared to 85% for the acetabular component[55]. The 15-year survival rate for the femoral stem was 97% compared to only 53% for the acetabular cup[55]. Therefore, while uncemented implantation techniques were developed in an attempt to improve acetabular component longevity compared to cemented techniques, it appears that screw fixation methods do not result in prolonged survival. A recent meta-analysis comparing survival of cemented and uncemented THA report no clear advantage for either procedure over the other; however, they did observe a non-significant trend for improved survival with cemented THA when age was not restricted to less than 55 years at the time of surgery[53]. Therefore, cemented THA may be more beneficial for patients who are older than 55 years of age at the time of surgery. The authors identified activity level, type of post-operative rehabilitation, and race as potential predictors of successful outcome[53]; yet the role of these factors in the occurrence of early failure has not been fully examined due to limited evidence. Therefore, these factors need to be addressed in future studies to determine if patient characteristics can be identified to assist in selecting the appropriate implant fixation for THA.

An alternative to total uncemented THA, hybrid THA implantation combines an uncemented acetabular component with a cemented femoral stem. The rationale for the hybrid fixation is that the two components fail for different reasons. The acetabular component for biological reasons, mainly the result of macrophagic induced pelvic lysis[65], while the femoral component fails for mechanical reasons, specifically caused by breakdown of the cement mantle, seen predominantly with first generation cementing techniques[65]. The 9-year survival rate for hybrid implants was reported at 98%, with no failures due to aseptic loosening[67]. No revisions of the acetabular component were reported as a result of aseptic loosening[60,68]. However, other studies report short-term revision rates (less than 10 years) for the femoral component as a result of femoral lysis ranging from 2-18%[60,65,68],with an additional 8% of femoral components exhibiting evidence of loosening[68]. A significant relationship between gender and femoral component failure has been observed for men under the age of 50 years[68], with an increase in failures observed for this cohort of patients. As a result, hybrid implantation may not be appropriate for younger males.

Based on the available evidence regarding survival rates for the different fixation methods for THA, cemented fixation appears to be the most appropriate for the majority of patients, provided that excellent cementing is achieved. Patient factors that may affect the longevity of the implant are younger age, male gender, and higher activity level. For patients with increased risk of early failure, recent advances in uncemented fixation techniques may be more appropriate. Failure rates for modern uncemented acetabular implants are comparable to cemented implants at 15 years for patients less than 50 years of age[53]. In addition, it has been theorized that a benefit of uncemented implants includes preservation of bone stock[69], which is an important determinant of success if revision surgery is required. Based on the decrease in survival over time for any implant, the majority of younger patients electing to undergo THA will most likely require a revision regardless of implant method; therefore preserving bone stock is critical for these patients during surgery.

Surgical Approaches for THA

While implant fixation method is an important determinant for prosthetic longevity, the surgical approach employed plays an important role in outcomes following surgery. The three most common surgical approaches cited are the posterior (PA) approach (Figure 1.1), anterolateral (AL) approach (Figure 1.2), and direct lateral (DL) approach (Figure 1.3). A 1998 survey of the American Academy of Hip and Knee Surgeons reported that 65% of surgeons prefer using the PA approach, 19% the AL approach, and only 13% the DL approach[70].

During the PA approach, the patient is positioned on their side with the non-surgical limb in contact with the table. The rotator cuff muscles of the hip joint are divided, and the superior, inferior, and posterior portions of the hip capsule are removed. The joint is then dislocated posterior to gain access to the femoral head and acetabulum[71]. The benefit of using the PA approach is that the abductor muscle complex remains intact[72], which reduces the incidence of abductor muscle weakness[72] and gait abnormalities[72,73] following surgery[74]. The major complication associated with this approach is an increased incidence of post-surgical dislocation rates[72,74,75], which have been reported to be as high as 5.9 times greater than the rates associated with the AL and DL approaches[74,75]. A recent meta-analysis comparing the incidences of dislocation between the three approaches reported a dislocation rate of 4.46% for the PA approach when repair of the disrupted soft tissue structures was not completed[76]. However, the incidence rate with a soft tissue repair reduced significantly to 0.49%, which is similar to the rates reported for the AL (0.7%) and DL (0.43%) approaches[76].

While the rate of posterior dislocation is greatly reduced when using the AL and DL approaches, the major determinant with both is the disruption to the hip abductor muscles. Specifically, both techniques require splitting of gluteus medius and/or gluteus minimus muscles to allow access to the joint[71,73,77]. Disruption of the abductor muscles during surgery has been associated with an increased incidence of post-operative muscle weakness and functional deficits[71-73]. Surgical limb abductor muscle strength was significantly decreased in patients who were operated on using the AL approach when compared to both their uninvolved limb[71] and the surgical limb of patients who were operated on using the PA approach[72]. Abductor muscle weakness associated with a positive Trendelenburg gait has also been observed in patients who underwent THA using the DL approach[78]. In addition, at 6 months following surgery, patients who underwent THA using the AL approach exhibited significant gait abnormalities when compared to a cohort of healthy controls[72,73]. The greatest kinematic alteration observed with the AL approach was a significant increase in trunk inclination angle during gait, which is a compensatory mechanism that reduces the torque required by the abductor muscles to control pelvic obliquity[73]. In addition, patients operated on using the AL approach displayed significantly reduced frontal moments during normal gait, also indicative of weakness of the abductor muscles[72].

While the risk of post-surgical dislocation using the AL or DL approach is significantly reduced, it appears that patients who are operated on using these techniques are at risk for greater long-term functional deficits compared to the PA approach. Therefore, the evidence supports the use of the PA approach with the inclusion of a soft tissue repair for best results. In addition, post-operative precautions have been implemented by surgeons to reduce the risk of dislocation following surgery[70]. Hip flexion range of motion is restricted to no greater than 90 degrees for the first three months. To assist patients in performing ADL's without increasing hip flexion, patients are instructed to use a high chair, a high toilet seat, and a reacher to pick up items[70]. By following these guidelines, patients are less likely to suffer a dislocation following surgery.

Patient Outcomes following THA

The goal of THA is to return the patient to pain-free function. Traditional post-operative treatment has focused on restoring mobility and may not adequately address pre-operative impairments in muscle strength and function. In order to progress younger patients back to participation in higher level activities, post-surgical impairments need to be addressed. Identification of persistent post-surgical impairments is imperative to the development of appropriate rehabilitation programs.

Subjective Post-Operative Clinical Findings

Subjectively, patients who have undergone THA reported marked improvements in pain, function, and quality of life measures following surgery. Patients reported overall function to be improved by 3 months post-surgery[30,79], with continued improvement up to 6 months[79]. Total scores on the HHS improved during the first 3 months to 80 points[23,31,33], with average scores at 1 year post-THA exceeding 90 points, indicating excellent outcome in these patients[15,23,31,33,39,80]. Post-surgical improvements observed with the HHS were maintained up to 7 years post-surgery, with 91% of patients still reporting good to excellent function[8,35,81] based on this scale. Improvements in total scores for the pain and function scales of the WOMAC and SF-36 were also reported at 2 months, with continued improvements at 8 months post-surgery[36]. The post-surgical scores for all subjective scales indicated good to excellent subjective clinical results following THA.

The majority of patients also reported significant improvements in their overall quality of life following surgery[82,83]. Within 3 months after surgery, mental health scores improved[30,79,84] and depression scores decreased[79] significantly compared to pre-operative levels. Patients also rated their emotional and social function as better[23,30]. A patient's social support, residential status, annual income, gender, and age have all been identified as independent factors affecting quality of life after THA[83,84]. Patients who are younger, male, have greater social support and earn a higher annual income experienced better mental, emotional and social health following THA. In addition, patients who live alone reported an even greater improvement in mental health because they were not as isolated as before surgery[84]. Overall, 78-96% of patients reported being satisfied with their outcome[38,85-87] and 87% reported that their expectations of the surgery were met[82]. However, despite being satisfied, many patients still experience some level of pain and functional limitations following THA.

Pain has been reported to decrease as early as the first post-operative day[79], with continued improvements noted up to 6 months[24,30,36,79,84,88,89]. The majority of patients experienced the greatest reductions in pain during the first three months post-surgery[30,88]. Pain levels were reduced an average of 71-93%[24,30] at rest and 96% following activity[24] within the first 3 months after THA compared to pre-operative levels. At 6 months post-surgery, 69% of patients had no incidence of sudden severe pain and 62% experienced no pain at night[38]. Seventy-nine percent of patients reported no pain during ambulation at 1-year post-surgery[37]. For the 21% of patients who did still experience pain during ambulation, only 3% described the pain as severe[37]. While pain levels were reduced following surgery, patients still reported significantly greater levels of pain during activity when compared to control subjects at 2 years post-surgery[20]. Overall, only 61% of patients reported complete relief of pain as far as 7 years post-surgery[8].

Improvements in the performance of daily activities have also been observed following THA. The majority of patients reported no difficulty in bathing independently or using the toilet[23,38,88] six months after surgery. Sixty-six percent of patients were able to put on their own shoes and socks without assistance[38,90]. Patients also reported reductions of symptoms during sitting[88], standing from a seated position[38], standing for prolonged periods of time[88], climbing stairs[8,22,38,90], and sleeping[23,88]. In addition, 77% of patients were able to get in and out of a car without pain and use public transportation without incident[38]. Fifty-seven to 73% of patients did not require any assistance with grocery shopping[37,38] and 76% were able to complete housework independently[23,37]. Patients also reported an improvement in sexual relations following surgery[88,90], with 50% of patients able to return to normal coitus[90]. While many patients reported improvements in function, continued functional disabilities may be the result of persistent impairments to the peri-articular muscles.

Objective Post-Operative Clinical Findings

Numerous studies have reported improvements in surgical limb muscle strength following THA[16,20,22,31,42,85,91]. Increases in peak isometric hip abduction[16,31,42,92], hip flexion[16], hip extension[16], knee flexion, and knee extension torque measures were noted up to one year post-surgery; however, values failed to equal those of the non-operative leg[16,42,92]. In addition, concentric and eccentric quadriceps muscle peak torque measures of the operative leg did not improve following surgery and remained less than the non-operative leg at 5 months post-surgery[22,24]. Equal isometric strength bilaterally was noted 2 years after THA for measures of hip abduction, hip adduction, and hip extension[91]; however, these measures failed to reach values obtained by healthy controls[20,21,85]. A possible explanation for persistent muscle weakness may be the lack of appropriate rehabilitation focusing on muscle strengthening following THA. Traditional theory suggests that pre-operative muscle weakness is the result of prolonged pathologic pain in the hip joint[20]. THA should result in the removal of pain and subsequent ability of the patient to increase daily activities, which would result in improved muscle function[16].

Based on the results provided here, this does not appear to occur. Persistent weakness of the muscles supporting the hip joint results in alterations in the forces applied to the joint structures, which may lead to instability[18]. This may place the implant at an increased risk for early wear, as muscle weakness has been associated with decreased protection of the implant[18]. These findings highlight the need for structured rehabilitation programs focusing on improving muscle strength, specifically of the hip abductor muscles.

Improvements in ambulation measures have been reported following THA. Overall, the distance patients were able to walk improved following THA[8,38,88], with up to 84% of patients able to walk an unlimited distance without pain[8,90]. In addition, improvements in gait velocity[31,80,85,90,93,94], cadence[80,85,90], step length[90,93], and time spent in single limb stance phase of the operative limb[32,93] were reported up to 2 years post-surgery; however gait velocity remained reduced by 20% compared to normal values[20,85,94]. At 10 years post-surgery, step velocity remained decreased and step length and stride length became reduced compared to normal[95]. More importantly, no differences in these parameters were observed between THA patients younger than 65 years when compared to older THA patients. As a significant positive correlation has been reported between gait speed and hip abduction strength[45], it may be that younger THA patients were unable to reach gait velocities equal to a healthy cohort due to the persistent weakness of the hip abductor muscles. In fact, it has been purported that the primary cause of gait problems following THA is disruption and weakness of the abductor muscles[72], again supporting the need for rehabilitation programs which strengthen this muscle group.

Balance deficits were also present following THA. Using the NeuroCom Balance Master, patients who were an average of 271 days following THA demonstrated greater movement during standing balance tests when compared to healthy controls[90], indicative of impaired balance. Specifically, patients had more difficulty when their visual input was challenged. In addition, patients following THA displayed slower reaction times to an external cue and a reduced ability to control movements during challenged balance tasks[90].

Despite these observed deficiencies, the majority of younger THA patients reported participation in recreational activities[5,6,8,9,37,39,81,82]. Between 80-91% of patients reported participation in moderate recreational activities on a consistent basis[6,8,37,39,81,82]. Approximately 50% of patients were able to participate in sport[5,8,9,82]; however, the number of sports one was able to participate in was reduced following THA[6]. Patients also heeded physician recommendations and limited participation to low impact sports[6,9,13,96]. The major risk associated with participation in sport following THA is accelerated wear of the prosthesis[7]; however, three years post-surgery, there was no evidence of implant loosening or early signs of wear for patients who participated in such low impact sports as bowling, golfing, gardening, swimming, and biking[39]. In addition, those patients who were active in sport had lower revision rates compared to inactive patients[9]. While it may be appropriate for patients to participate in sports following THA, it is important that patients complete rehabilitation focusing on increasing muscle strength prior to returning to activity. Resumption of physical activity while muscles are weak may expose the hip joint to increased forces, a precursor to early prosthetic failure[94].

Immediate post-operative rehabilitation for patients following THA generally focuses on regaining mobility and returning a patient to pain-free activities of daily life[97,98]. While rehabilitation is often successful in returning patients to daily function, persistent strength and functional deficits were noted up to 10 years post-surgery. The number one deficit associated with patients who failed conventional rehabilitation was weakness of the hip abductor muscle complex[99]. As many as 73% of patients with unsuccessful post-operative outcomes presented with dysfunction of the hip abductor muscles at 3-months post-surgery. Functionally, these patients exhibited an increase in hip adduction motion of the operated limb during stance combined with an increased trunk lean toward the involved side[99]. Both are compensatory mechanisms for weakness of the abductor muscles. Following a rehabilitation program focusing on balance and strengthening of these muscles, hip abductor muscle strength improved and 94% of patients reported good to excellent outcomes[99]. The findings of this study highlight the importance of strengthening the hip abductor muscles in order to achieve good clinical outcomes following THA.

Numerous studies have also reported outcomes following structured rehabilitation programs specifically targeting muscle weakness and functional deficits[17,18,21,45,97,100-102].

Patients who completed 8 weeks of strengthening exercises and hydrotherapy pre-operatively and 9-weeks of exercises initiated 3 weeks post-surgery demonstrated greater improvements in strength, range of motion, and self-reported pain and function compared to patients who did not exercise[17]. Mean values for muscle strength were not provided; therefore, it is unknown whether strength measures improved to values equal to a healthy cohort. Participation in 8-weeks of exercises focusing on functional movements, balance, and strength initiated 2 months following THA also resulted in significant improvements in gait, stair climbing ability, and self-reported measures of pain and function compared to subjects who did not complete training[100]. In addition, patients who participated in 8 weeks of weight-bearing strengthening exercises beginning an average of 7 months post-surgery demonstrated significant improvements in self-perceived function, postural sway, and strength measures compared to controls[18]. Interestingly, patients in the same study who completed only isometric strengthening and range of motion exercises exhibited no improvements in any measure following training[18]. This highlights the importance of incorporating resistive, functional exercises in rehabilitation programs in order to improve functional outcomes for patients following THA.

Additional studies have examined the effectiveness of exercise interventions employed at 1-2 years following THA[21,45,101]. Patients who participated in a daily, 12-week exercise program, including range of motion, strengthening, single-limb balance exercises, and 30-minute walks exhibited improvements in hip abduction strength, walking speed, and self-reported pain and function compared to subjects who did no exercise during that time[45]. Compliance was a big determinant in outcomes for these patients, as only those patients who completed >50% of the exercise sessions showed improvements. The same rehabilitation program was employed for two different cohorts of patients, one beginning at 1 year post-THA[101] and one beginning 2 years following THA[21]. Both studies reported significant improvements in hip abductor muscle strength of the involved limb, gait speed, and cadence following the 6-week program incorporating isometric strengthening and range of motion exercises compared to pre-intervention levels and to subjects who only participated in walking. Those patients who also completed eccentric weight-bearing abduction exercises exhibited increases in the uninvolved limb hip abductor muscle strength as well[21]. In addition, there was no difference in outcomes between patients who participated in supervised exercises and those who completed exercises at home[101].

The benefits observed from structured rehabilitation programs emphasize the importance of such programs for younger patients following THA who wish to participate in recreational activities. Patients who participated in such programs during the initial post-operative period exhibited greater improvements in muscle strength and functional measures following THA compared to patients who did not[17,18,100]. Most importantly, structured rehabilitation programs need to be implemented early post-operatively as it has been reported that patients who began rehabilitation later than 6 months following surgery had poorer clinical outcomes than patients who began rehabilitation at an average of four months post-surgery[99]. These included persistent pain, weakness, and presence of a limp following the intervention[99]. As weakness of the hip abductor muscles has been identified as a primary contributor to poor outcomes post-operatively, rehabilitation programs should include exercises which target these muscles. In addition, as shown above, exercises performed in a weight-bearing position appear to be more beneficial than non weight-bearing exercises. Therefore, identification of exercises which best activate the hip abductor muscle complex in a functional manner is required to create the most appropriate rehabilitation programs for patients following hip surgery.

Previous studies have examined EMG activation levels of the gluteus medius muscle during weight-bearing and non-weight-bearing rehabilitation exercises[103-107]. Overall, non-weight-bearing exercises, such as active hip abduction performed in a side lying or standing position, resulted in less gluteus medius muscle activation when compared to weight-bearing exercises[103,107]. In addition, gluteus medius muscle activation during exercises in which the base of support was reduced, such as during a unilateral squat[106,107] or side-bridging[107], was greater than during exercises performed with a greater base of support, such as bilateral squats[106]. As the function of the gluteus medius muscle is to prevent tilting of the pelvis in a weight-bearing position[108], it would make sense to perform rehabilitation of this muscle during weight-bearing strengthening exercises. Identification of appropriate weight-bearing exercises which target the gluteus medius muscle and do not violate early post-operative restrictions following THA is needed. In addition, as the number of younger patients electing to undergo THA continues to increase, there is a need to identify rehabilitation programs which will progress these patients effectively from static strengthening exercises to dynamic functional exercises in order to prepare them for return to recreational activities and sport.

Appropriate rehabilitation following THA is crucial to the improvement of lower extremity muscle strength and return to normal function. Defining the desired functional level for individual patients is fundamental to designing appropriate rehabilitation programs. Traditional post-operative treatment has centered on returning the patient back to activities of daily life[98]; however, many younger patients express a desire to return to recreation and sporting activities[4-7,9]. The few studies which have examined the effectiveness of structured rehabilitation programs on strength and function following THA have shown beneficial effects[17,18,21,45,97,100,102]; however none of these studies has included dynamic functional exercises. In addition, the main focus of the previous studies examining rehabilitation has been on subjective outcomes[45,99] and measures of strength[17,18,21,45,99,101]. The few that have incorporated objective functional measures have reported improvements in the overall task, such as timed gait and stair climbing[17,45,101]; however, understanding why patients improve is important. Are the current rehabilitation programs sufficiently addressing the biomechanical components of function or are they just allowing the patient to become more proficient at performing tasks using adaptive behaviors. The inclusion of objective measures of function which can isolate performance during different components of the task are important to determine the true benefit of post-operative rehabilitation.

Purpose

The primary purpose of this research project was to investigate the effectiveness of adding a strengthening program targeting the hip abductor muscles on subjective and objective outcomes for patients less than 65 years of age following THA. A secondary purpose was to identify muscle activation levels of the hip musculature during functional exercises to identify the appropriateness of including these exercises into post-operative rehabilitation programs. This study was designed to address the following aims:

1. To document lower extremity kinematics and hip muscle activation levels during three lower extremity functional exercises.

2. To compare short-term objective and subjective outcome measures following THA between surgical patients and a healthy cohort.
3. To determine the effectiveness of adding a hip rehabilitation program targeting the hip abductor muscle complex on hip abductor muscle strength, activity level, self-reported measures of pain and function, and objective measures of function during the step-up and over and sit-to-stand tests in a population of patients less than 65 years of age following THA.

Overview

The methods, results, discussion, and limitations from each of the three aims are presented in the following sequence. Chapter 2 summarizes hip muscle activation levels and associated kinematic movement patterns during three functional tasks. Chapter 3 presents short-term subjective and objective clinical outcomes for patients following THA when compared to healthy controls. Chapter 4 compares subjective and objective clinical outcomes between a group of patients who participated in a strengthening program targeting the hip abductor muscles and a group of patients who did not. Chapter 5 summarizes the relevant findings from all aspects of the study to address important clinical and patient-specific findings in the development of appropriate rehabilitation programs following THA.

Operational Definitions

For the purposes of this study, the following definitions were used:

Subject Inclusion Criteria

Subjects following THA were included in this study if they had (1) undergone unilateral total hip arthroplasty, (2) were less than 65 years of age, (3) had no history of vestibular disorders, (4) presented with no major co-morbidities, and (5) were otherwise medically stable. All THA subjects were recruited from one of two local physicians (MG, CC).

Control subjects participated in this study if they had (1) no history of pain or injury to either hip joint, (2) no history of any major lower extremity injury in the previous year, (3) no history of surgery to either hip joint, and (4) were able to perform the functional tasks being evaluated. Subjects who reported a history of minor sprains or strains or chronic conditions such as tendonitis were included in the study if these conditions were completely asymptomatic at the time of the study.

Subject Exclusion Criteria

Subjects who had undergone THA were excluded from the study if they (1) did not have surgery from one of the participating surgeons, (2) had symptoms of pain in the opposite hip joint from the side undergoing surgery, (3) or were deemed unable to participate by their physician for any reason.

Involved Limb

The involved limb was defined as the limb for which the surgical patients underwent THA. Conversely, the uninvolved limb was the limb which had not undergone THA.

Limb Dominance

Limb dominance was determined by asking each subject with which leg they would kick a ball. The dominant limb was used for testing for control subjects.

Subjective Clinical Measures

Subjective clinical measures included any examination of pain or function which was expressed solely by the subject. We assessed pain and function through the use of two scales, a modified version of the Harris Hip Score (HHS) and the International Physical Activity Questionnaire (IPAQ).

Strength

Strength was defined as the maximum isometric force that the subjects generated during manual muscle testing of the hip abductor muscles. Isometric strength represented the force recorded using a hand-held dynamometer, expressed as a percentage of the subject's body weight.

Objective Clinical Measures

Objective clinical measures included examinations which assess a subject during function and from which numeric feedback can be obtained. We assessed function during 4 exercises, the single leg squat, lunge, step-up and over, and sit-to-stand.

Single Leg Squat (SLSQ)

The SLSQ required the subjects to squat down as far as they were able standing only on their dominant limb and return to single-leg stance without losing their balance.

The SLSQ was divided into two phases for the purposes of EMG muscle analysis, eccentric phase (E) and concentric phase (C). E was defined as the time from onset of activity to maximum knee flexion of the squat leg, while C was defined as the time from maximum knee flexion of the squat leg to offset of activity.

Lunge (LU)

The LU required the subjects to step out to a predetermined distance using their dominant leg, lunge down as far as possible, return to full knee extension of the lunge leg, and return to their starting position. For the purposes of EMG analysis, the LU was divided into 2 phases, eccentric phase (E) and concentric phase (C). E was defined as the time from onset of activity to maximum knee flexion of the lunge leg in the descent phase of the lunge, and C was defined as maximum knee flexion of the lunge leg in the descent phase to offset of activity.

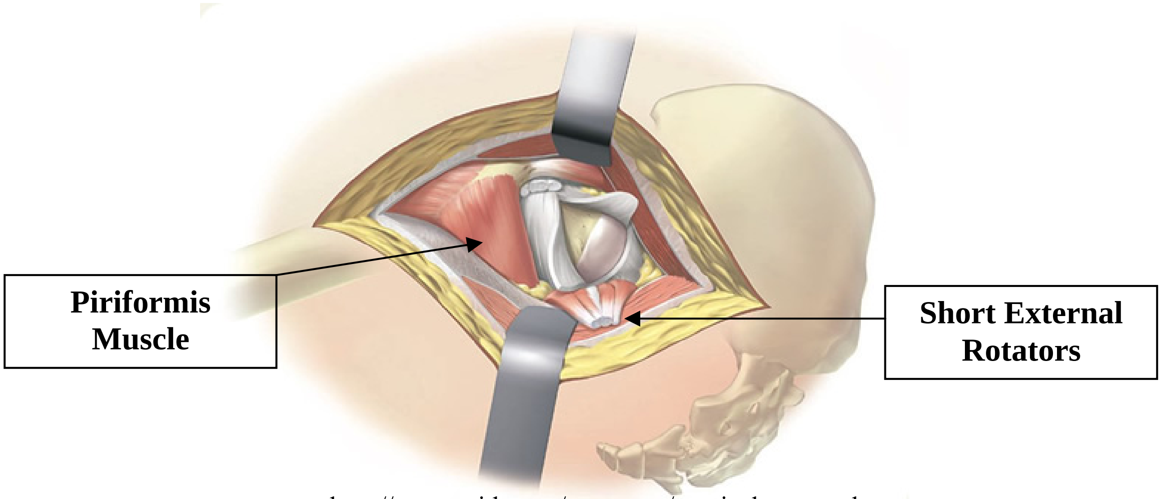
Step-Up and Over (SUO)

The SUO required the subjects to step up onto a 0.2m box using one leg, swing their other leg up and over the box, and then step off the box with the stepping leg and come to a stance on the platform. Subjects who needed to were allowed to place the swinging leg on the box prior to stepping off the box. The SUO was divided into two phases for only the EMG analysis, concentric (C) and eccentric (E). C was defined as the time from onset of activity to maximum knee extension of the step-up leg, while E was defined as maximum knee extension of the step-up leg to offset of activity.

Sit-to-Stand

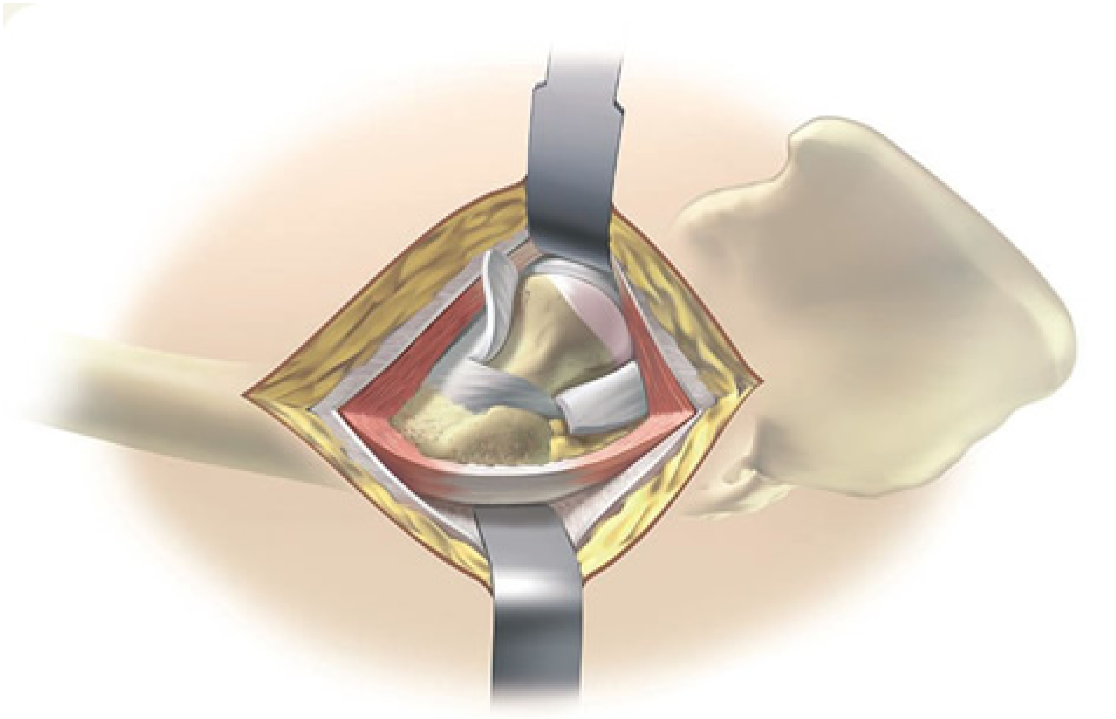
The STS required the subjects to rise from a seated position off a 0.91m high box as quickly as possible and come to a steady stance. They were told to then hold this stance as steady as possible for a period of approximately 5 seconds.

Figure 1.1: Posterior Surgical Approach for Total Hip Arthroplasty (THA)



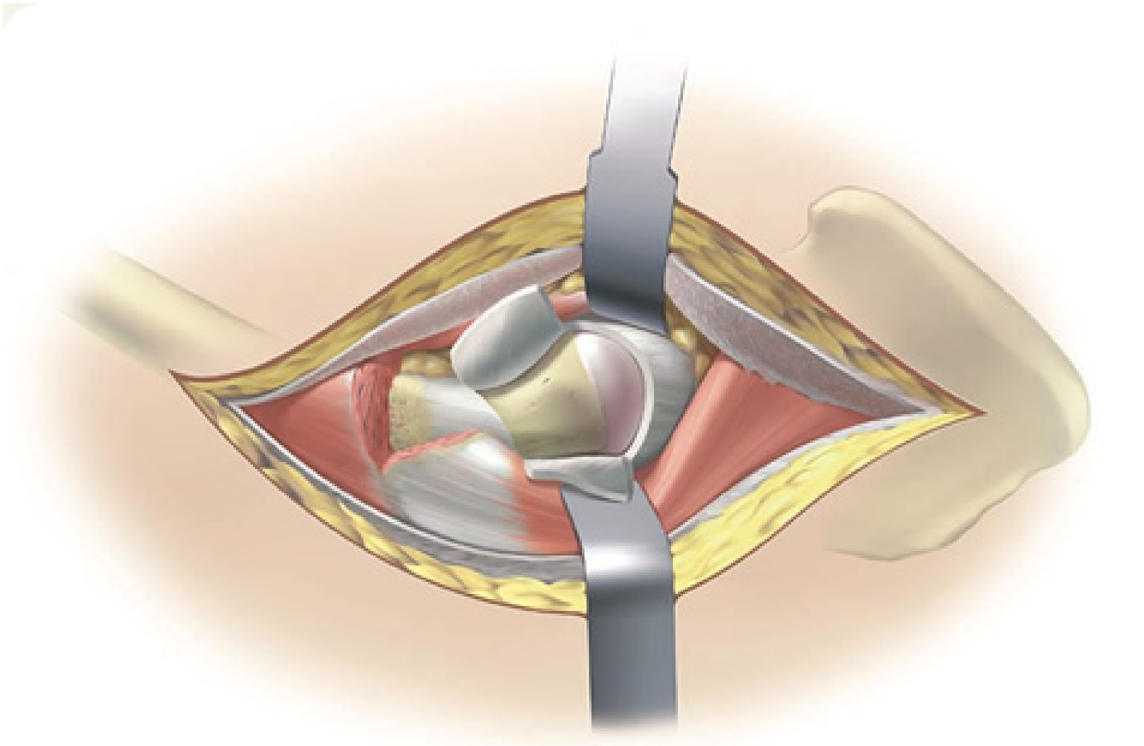
http://evertsmith.com/treatment/surgical-approaches

Figure 1.2: Anterolateral Surgical Approach for Total Hip Arthroplasty (THA)



http://evertsmith.com/treatment/surgical-approaches

Figure 1.3: Direct Lateral Surgical Approach for Total Hip Arthroplasty (THA)



http://evertsmith.com/treatment/surgical-approaches

Chapter 2

Identification of Lower Extremity Kinematics and Hip Muscle Activation during Three Functional Exercises

Introduction

Closed kinetic chain (CKC) exercises are integral for rehabilitation programs following lower extremity pathology. Much of the past research has focused on the activation levels of the quadriceps and hamstrings muscle groups in identifying rehabilitation exercises for injuries to the knee joint[109-116]. More recent investigations have highlighted the importance of the muscles acting upon the hip joint, specifically the hip abductor muscles, in preventing and treating distal lower extremity pathologies[117-121]. Particularly, altered activation levels of the gluteus medius muscle have been purported to result in increased frontal plane motion at the hip joint during weight-bearing, producing greater degrees of knee valgus angle[122]. This position has been cited as a possible causative factor for lower extremity pathology[123]. As a result, activation levels of the gluteus medius muscle during lower extremity rehabilitation exercises has received considerable attention in identifying appropriate treatment strategies[104,105,122,124-127]. While numerous studies have investigated the function of the gluteus medius muscle, limited information exists regarding the influence of the activation levels of other muscles acting upon the hip joint. In addition, little has been documented regarding the influence of muscle function on movement patterns of the hip joint itself during functional exercises. In order to better identify alterations in hip function following hip pathology or surgery and plan appropriate treatment strategies, description of movement patterns and muscle activation levels in healthy individuals is required.

Alterations in lower extremity muscle activation patterns have previously been documented for individuals with different lower extremity pathologies, specifically anterior knee pain (AKP)[117], chronic ankle instability (CAI)[121], severe ankle sprains[128], and patients with end-stage hip osteoarthritis (OA). Delays in muscle onset latency as well as shorter overall muscle durations have been documented for the gluteus medius muscle during stair climbing in patients with AKP[117] and during inversion ankle perturbations for patients with CAI[121]. Additionally, muscle onset delays and reductions in muscle duration for the gluteus maximus muscle were observed for patients following severe ankle sprain during hip extension movements[128]. However, none of these studies documented lower extremity kinematic movement patterns in accordance with the changes in muscle activity. Long et al (1993)[32] reported the absence of gluteus medius and maximus muscle activation for patients with hip osteoarthritis prior to undergoing total hip arthroplasty. The absence of activity for these muscles was associated with the presence of a Trendelenburg gait; however, the authors did not quantify kinematic changes associated with the Trendelenburg gait. Because of this, it cannot be determined whether the alterations in muscle activation patterns contribute to alterations in lower extremity movement patterns during the tasks.

Lower extremity kinematic movement patterns have been documented during jumping and landing, squatting, and cutting exercises in healthy populations[122,129-132]. Females have been shown to exhibit greater knee valgus[130,131] and knee extension[129] angles during landing when compared to males. Mean hip internal rotation and extension angles were greater for females during a side-step cutting task when compared to males[133]. Sex differences in frontal and transverse plane hip motion were also observed during a single-leg squat task. It was found that females demonstrated significantly greater hip adduction and external rotation angles when compared to males during this task[122]. While kinematic movement patterns have been examined during more sport-specific functional exercises in healthy people and differences between the sexes has been documented, movement patterns during other CKC lower extremity rehabilitation exercises are scarce. An understanding of movement patterns and activation levels of the surrounding musculature during rehabilitation exercises will allow clinicians to better prescribe these exercises based upon the muscular demands.

Due to the lack of normative information regarding lower extremity kinematics and activation levels of the hip musculature during CKC rehabilitation exercises, it is important to document the movement patterns of an uninjured population during these exercises in order to identify abnormalities in patients with lower extremity pathology in the future. Identification of movement patterns following injury or surgery is essential to the development of appropriate treatment programs. In addition, determining if and to what extent the hip muscles are active during functional exercises will facilitate the incorporation of these exercises at the appropriate phase of a rehabilitation program.

Because sex differences in these variables have been demonstrated during the performance of lower extremity functional tasks in previous studies, examining a sex comparison during CKC rehabilitation exercises is warranted. Therefore, our purpose was to determine if lower extremity three-dimensional kinematics and hip muscle electromyography (EMG) activation differ between males and females during three functional tasks. For the kinematic measures, we hypothesized that females would demonstrate greater peak hip adduction and knee valgus angles and reduced peak knee flexion angles during all tasks when compared to males. For the EMG measures, we hypothesized that females would demonstrate reduced mean muscle activation levels of the dominant limb gluteus medius muscle and increased mean muscle activation levels of the rectus femoris muscle when compared to males during all tasks.

Methods

Subjects

The sample size required to detect significant differences was determined using statistical software (N-Query Advisor, Statistical Solutions, Saugus, MA). Effect size was based on previous findings for mean difference (Δ) and common standard deviation (σ) between men and women in hip flexion during performance of a single leg squat (Δ= 9° and σ = 8.2)[122]. The results of an independent two-sample t-test with alpha set at 0.05 revealed a sample size of 36 (18 per group) to achieve 90% power. Based upon these results, we recruited 44 subjects (22 men and 22 women) aged 18 and older to participate in this study. We included subjects if they had no history of any major lower extremity injury or surgery on either leg and were able to perform the three functional tasks being evaluated. Subjects who reported a history of minor sprains or strains or chronic conditions such as tendonitis were included in the study if these conditions were completely asymptomatic at the time of the study. The dominant limb was used for all testing. Leg dominance was determined by asking each subject with which leg they would kick a soccer ball. All subjects read and signed a consent form that was approved by the University Institutional Review Board.

Instrumentation

3-Dimensional Kinematics

Three-dimensional joint kinematics of the hip and knee were collected using Ascension's Flock of Birds electromagnetic sensors and the Motion Monitor software (Innovative Sports Training Inc., Chicago, IL). Electromagnetic sensors were placed on the sacrum, the lateral thigh above the lateral femoral condyle, and the tibial tubercle of the dominant limb of each subject using double-sided tape and Cover-Roll (Beiersdorf-Jobst, Charlotte, NC). Cardan angles of the hip and knee were calculated using the definitions of joint coordinate systems recommended by the International Society of Biomechanics[134]. Hip joint center was estimated using a method described by Leardini et al[135]. Calculations were based on data collected while the subject moved their hip through a series of 10 static positions, which represented movements about all three axes. Kinematic data were collected at a sampling rate of 103 Hz.

Electromyography Data

A 16-lead electromyography (EMG) system (Run Technologies, Mission Viejo, CA) was used to record muscle activity. A Myopac transmitter belt unit (Run Technologies, Mission Viego, CA) was worn by each subject during data collection and was used to transmit raw EMG data via a fiber optic cable to its receiver unit. Unit specifications include an amplifier gain of 2000Hz, an input impedance of 1MOhm, and a CMRR of 90dB. Muscle activation of the dominant limb gluteus maximus (GMAX), adductor longus (AD), rectus femoris (RF) muscles and the dominant (D) and non-dominant (N) limb gluteus medius (GMDD, GMDN) muscles were collected for each subject using bi-polar Ag-AgCl surface electrodes (Therapeutics Unlimited, Inc., Iowa City, IA) measuring 5mm in diameter with a center-to-center distance of approximately 2.0cm. Electrodes were placed in parallel arrangement over the muscle belly for each muscle, as described by Cram et al[136]. Prior to electrode placement, the skin was prepared by dry shaving the area, abrading the area with sandpaper, and cleansing it with alcohol to reduce impedance. Electrodes were attached using Cover-Roll (Beiersdorf-Jobst, Charlotte, NC). To determine accurate electrode placement, the subject was instructed to contract each muscle being tested while EMG activity was observed using the oscilloscope. EMG data were sampled at 1339Hz and synchronized with the kinematic data using the Motion Monitor Ascension software. The unique frequencies employed in this study were used to reduce distortion of EMG signal caused by the 100Hz DC pulse generated by the electromagnetic transmitter.

Procedures

All data were collected at the Musculoskeletal Laboratory. Each subject reported to the lab for one testing session which lasted approximately one hour. Upon arrival to the lab, subjects completed a written consent form and a member of the research team demonstrated and instructed each subject on the proper technique and procedures for the single leg squat (SLSQ), step-up and over (SUO), and lunge (LU) tasks. Each subject was allowed to practice until they felt confident in performing all three tasks. Prior to testing, each subject performed a 5-minute warm-up on an exercise bike, followed by a lower extremity flexibility program targeting the hip flexors, hamstrings, quadriceps, and hip adductors. Surface electrodes were then applied to the five muscles as described above.

Following electrode placement, each subject performed three maximal voluntary isometric contractions (MVIC) for each muscle. Each trial lasted 3 seconds with a 30-second break in between trials and a 2-minute break in between muscles to prevent fatigue. For the RF, the subject was seated on the edge of a table with a strap around the distal one-third of their shank. The subject was instructed to push against the strap, attempting to extend their knee. For the GMDD, the subject was standing facing a stationary pole and a strap was placed around both feet. The subject was instructed to push out against the strap with the dominant leg for GMDD, keeping their toes pointed forward, while standing on the non-dominant leg. They were allowed to stabilize by holding onto the pole. This was repeated using the non-dominant leg as the pushing leg for GMDN. For the ADD, the subject was standing. They were instructed to push the foot of their dominant leg against their non-dominant leg. For the GMAX, the subject was standing, leaning against a box for support. A strap was placed around the distal one-third of their thigh. They were asked to their flex their knee to 90º and push their thigh posterior against the strap, attempting to extend their thigh.

Following collection of the MVIC's, the subject was instrumented with the Flock of Birds sensors as described previously and underwent digitization. Once sensors were digitized, a static file was taken to determine resting angles of the knee, hip, and ankle joints to use for comparison. The subject then performed three trials each of the LU, SLSQ, and SUO exercises, with a 30-second rest between each trial. Subjects were given a 2-minute break between exercises to prevent fatigue[137]. Exercise order was randomized between subjects using a random number sequence.

Single Leg Squat (SLSQ)

Subjects were instructed to stand on their dominant leg with their hands crossed over their chest. The non-dominant leg was held in approximately 45° of knee flexion, and subjects were instructed not to contact the non-dominant leg with the dominant stance leg at any time during performance of the activity. The subjects were instructed to squat down as far as they were able and return to single-leg stance without losing their balance. We did not control the distance through which each subject squatted as we felt it better represented what would be seen in a clinical setting, where normal inter-subject variability would exist. Similarly, we have begun using this method to study patients for whom it is difficult to insist on a specific range of motion during the performance of the exercise. If a subject touched their foot to the floor or made contact with the non-dominant leg, the data was discarded and the trial repeated. (Figure 2.1)

Lunge (LU)

The distance each subject traveled during the lunge was equal to their leg length, as determined by measuring from the anterior superior iliac spine (ASIS) to the medial malleolus of the tibia. Subjects were instructed to step out to this position using their dominant leg, lunge down as far as possible, return to full knee extension of the lunge leg, and return to their starting position. If the subject did not reach the full lunge distance, the data was discarded and the trial repeated. (Figure 2.2)

Step-Up and Over (SUO)

Subjects stood next to a 0.2m high box on the platform. They were instructed to step up onto the box with their dominant leg, swing their non-dominant leg up and over the box, and then step off the box with their dominant leg and come to a stance on the platform. If the subject did not step over the box in one motion, the data was discarded and the trial repeated. (Figure 2.3)

Data Processing and Analysis

Raw kinematic data were smoothed using a fourth order low-pass filter with a cutoff frequency of 5Hz in the Datapac software (Run Technologies, Mission Viejo, CA). Onset of each activity was determined when knee flexion angle raised 3 standard deviations (sd) above baseline and remained there for at least 50ms. Offset of each activity was determined when knee flexion angle dropped below 3sd above baseline and remained there for at least 50ms. Onset and offset of each activity was used to demarcate the phases for EMG data analysis.

For EMG data collected during MVIC testing, raw signals obtained during the 3-second trials were band passed filtered from 20-500ms and full wave rectified using Datapac software. Each trial was analyzed by dividing the data into 500ms windows, each overlapping by 100ms. The mean amplitude for each 500ms window of each trial was acquired and the highest mean amplitude for each trial was obtained. The peak mean amplitude of the three trials for each muscle was used for normalization.

For EMG data obtained during the three exercises, raw EMG signals were band passed filtered at 20 to 500Hz, stored on a personal computer, and analyzed using the Datapac software. In order to determine the appropriate data smoothing parameters, the fidelity of the muscle amplitude after signal smoothing was evaluated using time constants from 5ms-50ms at 5ms time increments. Based on the results of this analysis, filtered EMG signals were processed using root-mean squared smoothing with a 20ms time constant. Data were normalized to 100% of the maximal voluntary isometric contraction (MVIC) to allow for comparison between subjects.

For EMG data analysis, the three exercises were divided into two phases, Concentric (C) and Eccentric (E). Three trials of each task were recorded, analyzed, and averaged for later statistical analysis. For the LU, E was defined as the time from onset of activity to maximum knee flexion of the lunge leg in the descent phase of the lunge. C was defined as maximum knee flexion of the lunge leg in the descent phase to offset of activity. For the SLSQ, E was defined as the time from onset of activity to maximum knee flexion of the squat leg. C was defined as the time from maximum knee flexion of the squat leg to offset of activity. For the SUO, C was defined as the time from onset of activity to maximum knee extension of the step-up leg. E was defined as maximum knee extension of the step-up leg to offset of activity. We were not interested in comparing the phases of activity; therefore, we performed separate analyses for each phase of each muscle for the three exercises. The dependent variables were average root-mean squared (RMS) amplitude represented as percent of maximum during each phase of each exercise for the five muscles (RF-C, RF-E, AD-C, AD-E, GMDD-C, GMDD-E, GMX-C, GMX-E, GMDN-C, GMDN-E).

For the kinematic data analysis, peak knee and hip joint angles were determined throughout the entire exercise for each of the cardinal planes. The average of the peak joint angles obtained for each plane for the three trials for each exercise was used for statistical analysis. The dependent variables were peak knee flexion (KF), peak knee valgus (KV), peak hip flexion (HF), peak hip extension (HE), peak hip adduction (HAD), and peak hip external rotation (HER) angles for each exercise.

For each dependent variable, separate 2x3 repeated measures analyses of variance (ANOVA) were conducted. The independent variables were sex (Male, Female) and exercise (LU, SLSQ, SUO). Post hoc Bonferroni comparisons were performed for all significant findings. Alpha level was set *a priori* at $p \leq 0.05$.

Results

A total of 44 subjects (22 men, 22 women) participated in this study. Data for two subjects had to be discarded due to data collection errors; therefore, the final analysis was run using data from 42 subjects, 21 female (23±6yrs, 167.6±5.1cm, 63.7±5.9kg) and 21 male volunteers (23±4yrs, 181.4±7.4cm, 85.6±16.5kg). Average height and mass were significantly greater for the males compared to the females ($p < 0.05$).

3-Dimensional Kinematics

Means and standard deviations of peak angles for all kinematic variables for both men and women while performing the three exercises are shown in Table 2.1.

Knee Flexion

There was a significant main effect for sex ($p = 0.02$). Peak KF angles were significantly reduced in females (74.7 ± 13.9º) when compared to males (79.2 ± 12.9º) across all exercises.

Knee Valgus

There were no significant differences between sexes for peak KV angles during any of the exercises ($p = 0.92$).

Hip Flexion

There was a significant sex by exercise interaction. Post-hoc testing revealed that peak HF angles for females were significantly reduced during the SLSQ when compared to males ($p = 0.05$).

Hip Extension

There was a significant main effect for sex ($p = 0.001$). Peak HE angles were significantly greater in females ($10.1 \pm 7.2^{\circ}$) when compared to males ($5.02 \pm 5.6^{\circ}$) across all exercises.

Hip Adduction

There were no significant differences between sex for peak HAD angles during any of the exercises ($p = 0.065$).

Hip External Rotation

There were no significant differences between sexes for peak HER angles during any of the exercises ($p = 0.96$).

Mean EMG Amplitude (% MVIC)

Means and standard deviations for the average RMS amplitudes for the concentric (C) and eccentric (E) phases of the five muscles during the three exercises for men and women are shown in Tables 2.2 and 2.3, respectively.

Gluteus Maximus

There was a significant sex by exercise interaction during E for the GMX. Post-hoc testing revealed that although females demonstrated greater activation during all three tasks (LU: 27.6 ± 3% vs. 13.7 ± 2.9%, respectively; SLSQ: 29.7 ± 3.7% vs. 16.8 ± 3.6%, respectively; SUO: 17.6 ± 2.2% vs. 10.4 ± 2.2%, respectively), this was only significantly different during the LU ($P=0.002$) and SLSQ ($P=0.016$). In addition, females demonstrated significantly greater average RMS amplitudes during the LU when compared to the SUO (27.6 ± 2.9% vs. 17.6 ± 2.2%, respectively ($P < 0.001$)) and during the SLSQ when compared to the SUO (29.7 ± 3.6% vs. 17.6 ± 2.2%, respectively (P <

0.001)), while males demonstrated significantly greater RMS amplitudes during the SLSQ when compared to the SUO (16.8 ± 3.6% vs. 10.4 ± 2.2%, P = 0.004).

There was a significant main effect for sex during C (P = 0.02). Average RMS amplitudes for GMX were significantly greater for females (31 ± 16%) when compared to males (19.6 ± 15%) across all exercises.

Rectus Femoris

There was a significant main effect for sex during both E (P=.006) and C (P=.03). Average RMS amplitudes for RF were significantly greater for females when compared to males for E (23.3 ± 11.5% vs. 13.03 ± 11.3%, respectively) and C (16.3 ± 9.4% vs. 9.8 ± 9.6%, respectively) across all exercises.

Adductor Longus

There were no significant differences between sexes for either phase for the AD muscle during any of the exercises (P = 0.20).

Gluteus Medius-Dominant

There were no significant differences between sexes for either phase for the GMDD muscle during any of the exercises (P = 0.56).

Gluteus Medius Non-Dominant

There were no significant differences between sexes for either phase for the GMDN muscle during any of the exercises (P = 0.11).

Discussion

The purpose of our study was to determine if lower extremity three-dimensional kinematics and hip muscle EMG activation levels differed between males and females while performing CKC rehabilitation exercises. Knowledge of potential differences between sexes for uninjured participants provides a more accurate comparison when interpreting data following injury or surgery. Our results demonstrated that females moved into reduced degrees of knee flexion and greater degrees of hip extension angles when compared to males across all exercises. Females also moved into lesser degrees of hip flexion during the single leg squat when compared to males. Females demonstrated increased activation levels of the rectus femoris and gluteus maximus muscles compared to males across all exercises.

We believe the sex differences in peak knee and hip joint angles observed in our study may be the result of strength differences between the two groups. While we did not measure strength of the lower extremity muscles, males have been shown to exhibit greater peak isometric and isokinetic strength measures for the hip and knee[124,132,138,139] when compared to females. It may be that the males in our study exhibited greater overall lower extremity strength, which allowed them to descend into greater degrees of knee flexion during the SLSQ and LU when compared to the females.

Our results are opposite of those reported by Zeller et al (2003)[122]. They observed females to descend to greater degrees of knee and hip flexion when compared to males during the SLSQ. This difference may be the result of different subject populations. Zeller et al (2003) studied young intercollegiate athletes, while we studied a sample of the population that was more diverse in their level of activity. Therefore, the lower extremity muscle strength of the women in our study may have differed than the women in Zeller's study, possibly accounting for the inability to squat to similar degrees of knee flexion. Future studies are needed to confirm if these results are consistent across different populations.

We did not observe any significant differences between sexes for any of the transverse or frontal plane motions during any exercise. These results differ from those of Zeller et al (2003)[122]. They observed significantly greater hip and knee frontal and transverse plane motions between sexes during the single leg squat. Specifically, females moved into significantly greater degrees of knee valgus and hip adduction and external rotation motion[122]. It is worth noting that both our study and Zeller et al (2003) reported peak transverse hip motion to occur in external rotation rather than internal rotation. When the hip adducts, it normally causes the femur to internally rotate, placing the knee in a valgus position[140]. Both studies only reported the peak transverse plane motion which occurred about the hip joint throughout the exercise, which was into external rotation; however, neither study examined when during the exercise this angle occurred. It may be that the timing of peak hip external rotation angle did not coincide with the occurrence of peak hip adduction and peak knee valgus angle during the task. This is being addressed in future studies.

The lack of sex differences observed in peak frontal and transverse plane angles in our study compared to Zeller et al (2003) may again be the result of the different subject populations included. Our population was slightly older and more representative of the general active population; therefore, while both studies did not control the depth to which subjects were instructed to squat, our population may have been unable to squat to as great a distance as a population of trained athletes. Knee Flexion angles were greater in the Zeller et al (2003) study (90º for males and 95º for females)[122] than our study (67º for males and 60º for females) during the SLSQ. Zeller et al (2003) proposed that as females moved into greater degrees of knee flexion during the squat, their hip musculature was less able to control movement into the frontal and transverse plane motions when compared to males[122]. Both the male and female subjects in our study failed to squat to depths equal to the subjects in Zeller et al, and thus may not have required as great a demand on the supportive musculature to control the frontal and transverse plane motions during the squat.

In accordance with our results, Claiborne et al (2006) observed no significant differences between genders in peak knee frontal plane motions during a SLSQ[139]. Subjects in this study were instructed to squat to only a depth of approximately 60 degrees of knee flexion. Sixty degrees and 67 degrees were the average amount of knee flexion observed in our study for females and males, respectively, and this value was 35 degrees less than the average observed for females in the Zeller et al (2003) study. Based on these findings, it may be that as knee flexion angle increases for females during a SLSQ, they lack the control of the hip stabilizing muscles to maintain proper frontal and transverse plane motion at the knee and hip. This relationship has been quantified in a study by Willson et al (2006)[132], in which a significant negative relationship was observed between hip external rotation strength and the degree of frontal plane motion during a single leg squat. Based on these findings, it may be that the reductions in hip and knee muscle strength observed for females do not affect function until they reach a certain depth of a squat, at which point those muscles must work more to control and stabilize the leg during the motion. This suggests that it may be beneficial to control the depth of the single leg squat to 60 degrees of knee flexion for females initially during rehabilitation to try to control excess motions from occurring into the frontal and transverse planes at the knee and hip joint. Once it is observed that the squat can be performed in a controlled manner, the depth of the squat can be gradually increased. However, further study is required before firm clinical recommendations can be made.

Our findings are also contrary to what previous studies have reported during explosive tasks such as landing[129-131] and cutting[133], where significant increases in frontal plane knee motion for females were noted when compared to males. The differences between our studies may be the result of the difference in the tasks performed. The exercises performed in our study were more controlled and may not have been as challenging as exercises reported in other studies, which employed more explosive tasks. Based on these results, we recommend incorporating the three exercises examined in our study early into closed kinetic chain rehabilitation programs following lower extremity injury especially in females to allow for activation of the hip musculature during functional exercises while limiting excess frontal plane motion at the knee joint. Employing these exercises prior to initiating landing or cutting exercises may assist in strengthening the muscles which help to control these motions and allowing the transition to more explosive tasks to be done in a protected manner.

For mean EMG muscle activation of the five muscles examined, we detected significant gender differences in the rectus femoris and gluteus maximus muscles only during the LU, SLSQ, and SUO exercises. RMS amplitude of both muscles was significantly greater for females during both the eccentric and concentric phases of the exercises when compared to males. Zeller et al (2003) also observed significantly greater mean RMS EMG amplitude of the rectus femoris muscle for females when compared to males during a SLSQ[122]; however, they did not observe any differences for the gluteus maximus muscle when comparing by sex. Their lack of significant findings for this muscle group may be the result of large standard deviations observed for this muscle for both males and females. They reported standard deviations that were 1/3 of the mean for females and greater than half of the mean for males for the gluteus maximus (81.2%$\pm$28.9 vs. 62.7%$\pm$43.8, respectively)[122]. It may be that the inclusion of a greater number of subjects in our study allowed us to reach statistical significance compared to their study. However, it should be noted that, while gluteus maximus muscle activity between sexes was not statistically significant in their study, the mean difference of 18.5% may be clinically relevant. While both studies found sex differences in mean gluteus maximus and rectus femoris muscle activation levels during the SLSQ, it is difficult to directly compare the percentages obtained in their study to ours as they reported the mean maximum muscle activation level during the entire exercise, while we reported the mean RMS amplitude during the concentric and eccentric phases of each exercise separately. We felt that dividing the exercises into their eccentric and concentric phases would provide us with a better understanding of the muscle's contribution to the performance of the exercise. However, regardless of the magnitude of activation, it appears that females activate the rectus femoris and the gluteus maximus muscle more during the LU, SLSQ, and SUO when compared to men. We feel this is again the result of strength differences between sexes as stated previously. If overall muscle strength was reduced in females, it would require greater activation of the muscle to perform the task[141]. As both of these muscles would be activating to produce movements in the sagittal plane, the increased muscle activity observed for females may have contributed to the reduced peak knee flexion angles when compared to males. Our data suggests that it is important to consider sex differences when examining measures of muscle activation for these two muscles.

Interestingly, neither our study nor the study by Zeller et al (2003)[122] reported significant sex differences in the dominant limb gluteus medius muscle activation during any task. In our study, we also did not observe any differences between sexes for the adductor longus or non-dominant limb gluteus medius muscles. The dominant limb gluteus medius muscle exhibited activation levels equal to or below 30% of MVIC for both males and females during all three exercises. The non-dominant limb gluteus medius muscle exhibited activation levels that were below 20% for both males and females during all three exercises. The exercises we chose require movements which occur mostly in the sagittal plane; therefore, it would be expected that the gluteus medius muscles would not be working to produce active movements in the frontal plane during the tasks. Based upon the moderate level of activation observed for these muscles, they appear to function as joint stabilizers during these exercises and not active movers. This finding is in accordance with multiple studies which have reported the main function of the gluteus medius muscle as stabilization of the pelvis rather than active abduction of the thigh[108, 142, 143]. While differences were not observed in an uninjured population, alterations in the activation levels of these muscles may exist in patients following lower extremity pathology. Alterations have been reported for patients with anterior knee pain (AKP)[117] and chronic ankle instability (CAI)[121] for the gluteus medius muscle of the injured extremity. These studies observed prolonged onset times and shorter durations of this muscle; however they did not report mean activation level. For patients with end-stage hip osteoarthritis, there was an absence of activation of this muscle during gait[80]. This requires further study in individuals with lower extremity pathology and following surgery to determine the extent of alterations in gluteus medius muscle activation levels, the effect these alterations may have on function, and the effect surgical intervention may have on muscle activation levels.

The exercises examined in our study did not result in activation levels of any of the five muscles above 30% of maximum (see Tables 2 and 3). The activation levels observed in our study are less than levels reported by studies in which muscle activation levels were examined during more explosive tasks. In comparison, average quadriceps muscle activation was shown to be up to 191% of maximum during side-step cutting maneuvers[144] and between 45%-85% of maximum during the performance of a soccer ball kick[145]. As a result, we would recommend incorporating the lunge, single leg squat, and step-up and over exercises into early closed kinetic chain rehabilitation to make the transition from isolated exercises targeting these muscles to more explosive, demanding exercises for the hip muscles.

Limitations

Our study design and methods had several limitations. We did not control for the speed at which the subjects performed the three tasks. We chose not to control for this factor so that the subjects would perform the tasks at their desired rate, which more closely mimics a true rehabilitation setting. Because of this, we were unable to determine the effect that speed had on muscle amplitudes; however, we feel that our results are more generalizable to a clinical setting. We also did not control the depth with which subjects performed the SLSQ or LU activities. We normalized lunge distance to leg length, but did not limit depth of the squat to provide for individual variation that would be present in the clinical setting. We chose to standardize the height of the box during the SUO and did not normalize step height to subject height. Males did exhibit significantly greater average height compared to females; however, it does not appear that the difference in average height effected movement patterns during the SUO as greater hip and knee flexion angles were not observed for females when compared to males during this task (KF: 82.5 $\pm$ 6.8 vs. 83.3 $\pm$ 6.70, respectively; HF: 49.7 $\pm$ 9.1 vs. 51.1 $\pm$ 10.6, respectively). While a main effect for sex was observed for KF, the interaction was not significant (P = 0.37).

Conclusions

We report that there were significant differences in lower extremity movement patterns and hip muscle activation levels between males and females during CKC rehabilitation tasks. Hip extension angle was greater and knee flexion angle was less for females when compared to males. Hip flexion angle was greater for females when compared to males during the single leg squat exercise. Muscle activation for the rectus femoris and gluteus maximus muscles was greater for females when compared to males. Due to the presence of sex differences observed in our study, it is important to compare the findings for injured subjects by sex to garner a better representation of altered kinematic angles and muscle activation levels due to pathology. The presence of sex differences may also highlight the need for the development of sex-specific rehabilitation protocols following injury or surgery. Clinically, it may be useful to incorporate the SLSQ, LU, and SUO exercises in the rehabilitation program as a transition from early phase controlled exercises to late phase functional strengthening exercise.

Table 2.1: Average Peak Range of Motion during Exercise (Mean ± SD)

Kinematic Angle	Exercise: Lunge (º)		Single Leg Squat (º)		Step-Up and Over (º)		Mean Across all Exercises (º)	
	Males	Females	Males	Females	Males	Females	Males	Females
KF	87.5 ± 11.2	82.3 ± 6.10	66.8 ± 9.70	60.0 ± 13.3	83.3 ± 6.70	82.5 ± 6.8	79.2 ± 12.9	74.7 ± 13.9†
KV	13.30 ± 7.3	12.9 ± 8.70	14.1 ± 8.80	12.4 ± 9.10	12.2 ± 7.80	12.9 ± 7.5	13.2 ± 7.9	13 ± 8.3
HF	74.2 ± 14.4	72.7 ± 10.6	61.7 ± 17.1*****	50.7 ± 17.4	51.1 ± 10.6	49.7 ± 9.1	62.3 ± 17	57.7 ± 16.6
HE	6.80 ± 5.20	9.20 ± 4.10	5.30 ± 3.30	11.2 ± 11.2	2.90 ± 7.20	9.9 ± 5.10	5.02 ± 5.6	10.1 ± 7.2†
HER	18.5 ± 7.80	19.3 ± 8.90	16.04 ± 6.4	14.9 ± 6.80	19.99 ± 7.2	20.7 ± 6.8	18.2 ± 7.2	18.3 ± 7.8
HAD	9.90 ± 6.20	13.3 ± 7.70	18.3 ± 10.7	22.4 ± 8.30	13.0 ± 5.00	17.4 ± 6.4	13.7 ± 8.4	17.7 ± 8.2

*Indicates a statistically significant gender by exercise interaction ($P<0.05$)

†Indicates statistically significant difference between genders ($P<0.05$)

KF= Peak knee flexion angle

KV= Peak knee valgus angle

HF= Peak hip flexion angle

HE= Peak hip extension angle

HER= Peak hip external rotation angle

HAD= Peak hip adduction angle

Table 2.2: Mean RMS EMG Activation Levels for the Eccentric Phase of Exercise (Mean ± SD)

	Exercise							
Muscle	Lunge (%)		Single Leg Squat (%)		Step-Up and Over (%)		Mean Across all Exercises (%)	
	Males	Females	Males	Females	Males	Females	Males	Females
GMND	14.8 ± 4.7	20.8 ± 15.9	10.6 ± 5.8	12.6 ± 9	13.3 ± 4.6	18.7 ± 14.3	12.9 ± 8.7	17.4 ± 8.9
GMD	15.5 ± 9	17.8 ± 8.8	25.3 ± 11.5	26.6 ± 6.8	14.4 ± 9.6	14.5 ± 4.6	18.4 ± 7.7	19.7 ± 7.8
ADD	12.5 ± 7.5	21 ± 17.9	17.5 ± 7.5	19.2 ± 12.1	16.2 ± 10.4	20 ± 18.6	15.4 ± 11.5	20 ± 11.5
GMX	13.7 ± 9.5	27.6 ± 16.9*	16.8 ± 14	29.7 ± 19.2*	10.4 ± 9	17.6 ± 11.3	13.6 ± 12.5	24.9 ± 12.7
RF	11.7 ± 6.9	23.9 ± 15.7	21 ± 12.1	30.8 ± 19.7	6.5 ± 3.4	15.1 ± 20.6	13.03 ± 11.3	23.3 ± 11.5†

*Indicates a statistically significant gender by exercise interaction

†Indicates statistically significant difference between genders ($p<0.05$)

RMS = Root mean square

EMG = Electromyography

GMND= Non-dominant gluteus medius muscle

GMD= Dominant gluteus medius muscle

ADD= Adductor longus muscle

GMX= Gluteus maximus muscle

RF= Rectus femoris muscle

Table 2.3: Mean RMS EMG Activation Levels for the Concentric Phase of Exercise (Mean ± SD)

	Exercise							
Muscle	Lunge (%)		Single Leg Squat (%)		Step-Up and Over (%)		Mean Across all Exercises (%)	
	Males	Females	Males	Females	Males	Females	Males	Females
GMND	17.2 ± 7.3	24.6 ± 18.1	11.6 ± 6.1	12.5 ± 9.3	14.8 ± 3.8	20.7 ± 14.6	14.5 ± 9.2	19.3 ± 9.4
GMD	11.6 ± 8.3	11.4 ± 4.8	31.2 ± 10.9	29.5 ± 7.5	15.5 ± 7.9	16.5 ± 5.7	19.4 ± 6.6	19.1 ± 6.8
ADD	8.1 ± 5.1	19.5 ± 28.5	16.3 ± 8.4	15.2 ± 8.2	15.3 ± 6.6	21.9 ± 14.9	13.2 ± 13.2	18.9 ± 13.2
GMX	10.7 ± 9.1	17.6 ± 13.7	33.9 ± 18.8	51.2 ± 32.1	14.1 ± 9	24.2 ± 16.3	19.6 ± 15.4	31 ± 15.7†
RF	6.2 ± 5.3	8.8 ± 12.4	16.4 ± 10.3	24.7 ± 16.4	6.8 ± 3.2	15.5 ± 19.3	9.8 ± 9.4	16.3 ± 9.6†

†Indicates statistically significant difference between genders ($p<0.05$)

RMS = Root mean squared

EMG = Electromyography

GMND= Non-dominant gluteus medius muscle

GMD= Dominant gluteus medius muscle

ADD= Adductor longus muscle

GMX= Gluteus maximus muscle

RF= Rectus femoris muscle

Figure 2.1: Single Leg Squat

Figure 2.2: Lunge

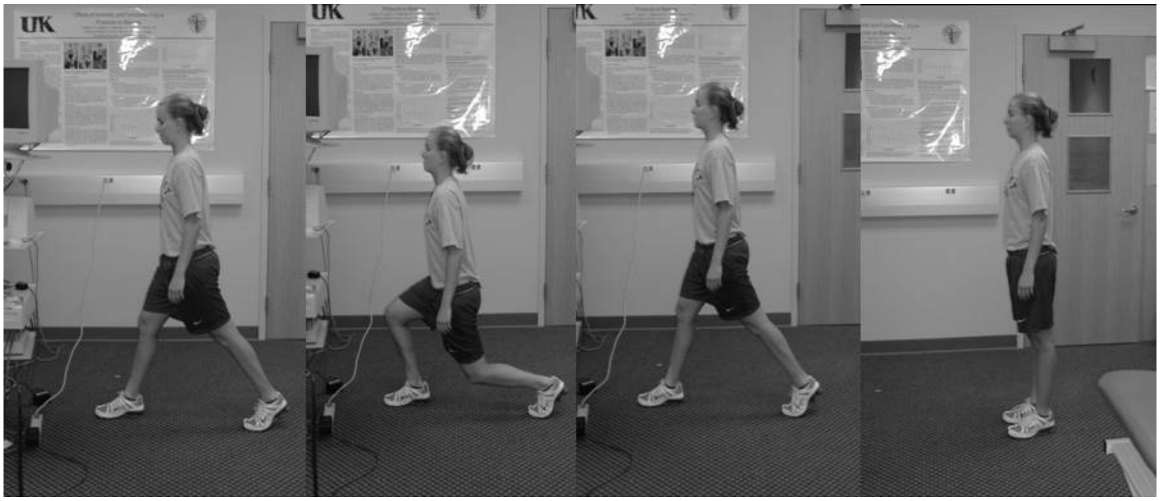
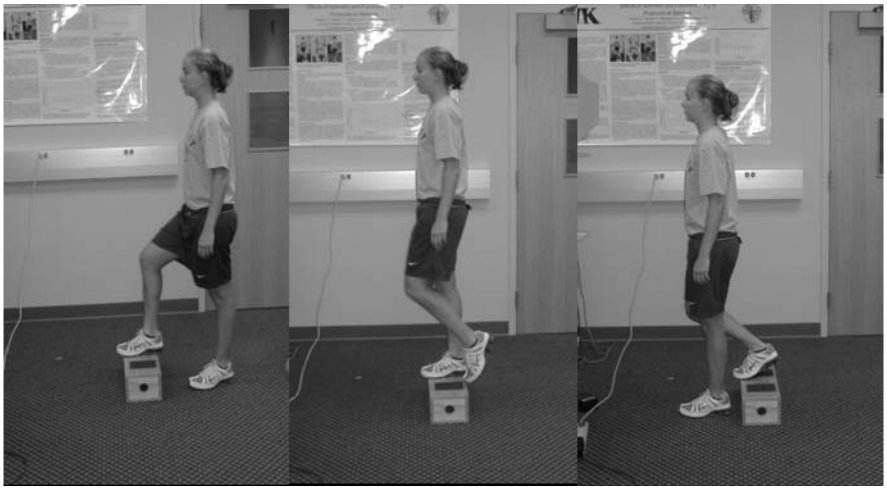


Figure 2.3: Step-Up and Over



Chapter 3

Short-Term Subjective and Objective Clinical Outcomes following Total Hip Arthroplasty in Patients Less than 65 Years of Age

Introduction

The number of patients electing to undergo total hip arthroplasty (THA) each year increased by 50% from 1990 to 2002, with numbers totaling 193,000 persons in 2002[2]. A growing number of patients undergoing this procedure are below the age of 65 years[2]. This cohort of patients represents a new challenge to physicians and rehabilitation specialists as they not only wish to return to pain free daily activities, but express a desire to continue to participate in recreational and sporting activities following THA[4-9]. Traditional post-operative treatment focuses on restoring mobility and may not adequately address pre-operative impairments in muscle strength and function. In order to progress younger patients back to participation in higher level activities, post-surgical impairments need to be recognized. Identification of persistent post-surgical impairments is essential to the development of appropriate rehabilitation programs.

Subjectively, patients who have undergone THA report marked improvements in pain[24,30,36,79,83,84,88], function[23,30,31,33,79], and quality of life[82,83] measures following surgery. However, many patients continue to describe limitations in social activities[19] and activities of daily life[19-23,37,38,90]. In addition, numerous studies report the continued presence of muscle weakness[4,16-18,20-22,24,42,91,92], and altered gait parameters[15,20,80,85,94,95] following THA. As a result, while many patients report overall improvements in function, continued problems with returning to their desired activity level may be the result of persistent impairments to the peri-articular muscles. While subjective information is critical to understand the impact of hip disease on a patient's life, assessment of objective measures is required to ascertain the specific factors contributing to or resulting from altered function after surgery.

Increases in peak isometric hip abduction[16,31,42,92], hip flexion[16], hip extension[16], knee flexion, and knee extension torque values are noted up to one year post-surgery; however, values fail to equal those of the non-operative leg[16,42,92]. Equal bilateral isometric strength has been noted 2 years after THA for measures of hip abduction, hip adduction, and hip extension[91]; yet, these measures fail to reach values obtained by healthy controls[20,21,85]. Similarly, while improvements in gait velocity[31,80,85,90,93,94], cadence[80,85,90], step length[90,93], and time spent in single limb stance phase of the operative limb[32,93] are observed up to 2 years post-surgery, gait velocity remains reduced by 20% compared to normal values[20,85,94]. More importantly, no differences in these parameters are observed between THA patients younger than 65 years when compared to older THA patients[95]. As a significant positive correlation has been reported between gait speed and hip abduction strength[45], it may be that younger THA patients are unable to reach gait velocities equal to a healthy cohort due to the persistent weakness of the hip abductor muscles. Consequently, the limitations in activity participation reported by patients following THA may be directly related to persistent hip abductor muscle weakness; however, few studies have objectively evaluated other daily functions of mobility and stair walking in younger patients following THA. In addition, it is important to examine the underlying biomechanical components of a functional task to determine if adaptations exist for patients who can complete the task as a whole. Therefore, the purpose of this study was to compare short-term subjective and objective clinical outcomes following THA in subjects less than 65 years of age to a cohort of age-matched control subjects. We hypothesized that subjects at 6- and 12-weeks following THA would exhibit reduced peak hip abduction strength, decreased activity levels, and functional alterations during the step-up and over (SUO) and sit-to-stand (STS) tests when compared to controls. In addition, we hypothesized that subjects at 12- weeks following THA would demonstrate significant improvements in peak hip abduction strength, activity level, and function as assessed during the SUO and STS tests compared to measures at 6-weeks post-surgery.

Methods

Subjects

The sample size required to detect significant differences was determined using statistical software (N-Query Advisor, Statistical Solutions, Saugus, MA). Effect size was based on pilot data for mean difference (Δ) and common standard deviation (σ) between post-surgical patients and healthy controls for isometric hip abduction muscle strength as a percentage of body weight ($\Delta = 20\%$ and $\sigma = 8$). The results of an independent two-sample t-test with alpha set at 0.05 revealed a sample size of 6 (3 per group) to achieve 90% power. As a result, 20 subjects were recruited to participate in this study. Ten subjects were recruited from the patient population of two surgeons (CPC and MG) (THA). Patients were included if they had undergone unilateral total hip arthroplasty, were less than 65 years of age, had no history of vestibular disorders, presented with no major co-morbidities, and were otherwise medically stable. Patients were tested at two separate time points, at 6 weeks following surgery (THA-6w) and at 12 weeks following surgery (THA-12w). The remaining 10 subjects were recruited from a cohort of healthy individuals (CON). Subjects in the CON group were included if they were between the ages of 35-65 years, had no history of pain or injury to either hip joint, and had no history of lower extremity injury in the previous year. Subjects in the CON group were matched by age and gender to patients in the THA group. Prior to participation in this study, all subjects read and signed a consent form that was approved by the University Institutional Review Board.

Instrumentation

Force platform Data

Ground reaction force data was collected using the static long force plate of the NeuroCom Smart Balance Master (NeuroCom International Inc, Clackamas, OR). The force plate consists of two 0.23m by 1.5m foot-plates connected in the center along the long axis by a pin joint. Each foot-plate rests on two force transducers mounted along the center line of the long axis, one located 0.74m anterior and one 0.74m posterior to the pin joint. Each transducer is also located 0.21m laterally from the pin joint. The collection rate of the long force plate is 100Hz. Raw force data from the plate was transmitted to a desktop computer via a cable and stored in the NeuroCom database. The Neurocom software was used to analyze the raw data and generate the dependent variables for each functional test. The SUO and STS tests were utilized for this study. The SUO and STS were chosen as they are functional tasks assessed using the Harris Hip Score, the subjective measure employed in our study. The dependent variables for the SUO test were lift-up index (LUI), movement time (MT), and impact index (IMP)[146]. LUI quantifies the average maximal concentric force exerted by the stepping leg, represented as a percentage of body weight (%BW). MT quantifies the average amount of time required to complete the task, represented in seconds (sec). IMP quantifies the average maximal vertical impact force of the lagging leg as it lands on the force plate, represented as a percentage of body weight (%BW). The dependent variables for the STS test were mean weight transfer (WT), mean rising index (RI), mean center of gravity sway velocity (SV), and mean Uninvolved/Involved Symmetry Index (UI)[146]. WT is the average time between the onset of the cue to move and the arrival of the center of gravity (COG) over the feet in time, expressed in seconds (sec). RI is the amount of force exerted by the legs during the rising phase, expressed as a percentage of body weight (%BW). SV is the average amount of COG sway during the rise to stand phase and the first five seconds of standing, expressed in degrees per second (º/sec). UI is the amount of weight borne by each leg during the rising to stand phase and the first five seconds of standing, expressed in percentage (%).

Isometric Hip Abduction Strength

Isometric hip abduction strength was measured using a handheld dynamometer (HHD) (J-Tech, Inc. Salt Lake City, UT) attached to a strap for stabilization during testing. The dynamometer has a maximum load cell capacity of 556.3 Newtons (N). The HHD was calibrated prior to the start of testing by placing known weights on the HHD and comparing this weight to the reported weight by the HHD. Calibration was repeated midway and at the completion of testing to verify accuracy. Acceptable inter-trial coefficient of variation was established prior to testing as less than or equal to 10%[147].

Self-Reported Measures

All subjects completed the Short Version of the International Physical Activity Questionnaire (IPAQ) (Appendix A). The IPAQ was created as an international tool to assess population levels of physical activity[148]. The short version of the IPAQ summarizes activity levels by recording the time spent walking, during moderate activities, and during vigorous activities[148]. The total minutes per week recorded for each category are then weighted by a metabolic equivalent (MET) energy expenditure estimate. The total minutes per week in vigorous activity (VIG) are multiplied by a factor of 8, by a factor of 4 for moderate activity (MOD), and by a factor of 3.3 for walking (WA). These values are then summed across domains to produce a weighted estimate of total physical activity per week (TOTAL). An analysis of the IPAQ using subjects from 12 different countries demonstrated good reliability and validity for documenting physical activity of the general population[148].

Subjects in the THA group completed a modified version of the Harris Hip Score (HHS) joint specific assessment questionnaire to determine patient pain and functional status following surgery (Appendix B). The modification of the original HHS assesses the domains of pain and function, with the domains of deformity and range of motion eliminated from the assessment[26]. The total score obtained is multiplied by 1.1 to give a total possible score of 100 points. The higher the score is indicative of greater function and less pain. The HHS has been shown to demonstrate high test-retest reliability and validity in patients following THA[149]. In addition post-surgical subjects were asked to record and report participation in any post-surgical rehabilitation.

Testing Procedures

Subjects in the CON group participated in one testing session. Subjects in the THA group participated in two testing sessions, at their 6-week and 12-week post-operative follow-up visits at the doctor's office. Upon arrival to the clinic, all subjects completed informed consent and provided demographic data and information regarding history of lower extremity injury. A study investigator assisted all subjects in completion of the IPAQ and subjects in the THA group in the completion of the HHS outcome forms. Each subject then performed isometric strength testing of the hip abductor muscle group and the functional testing protocol. Isometric strength testing was performed prior to functional testing in order to prevent fatigue from affecting strength measures. Subjects were given a 3-minute break between the strength and functional testing. Order of completion of the functional tests was randomized between subjects.

Strength Testing

The dominant limb of the CON group and the involved limb of the THA group were assessed for isometric strength testing. Leg dominance was determined by asking the CON subjects with which leg they would kick a ball. Subjects were instructed to lie on their side on a treatment table with the non-surgical or non-dominant leg in contact with the table. A pillow was placed between their legs to prevent the surgical leg from moving into adduction. The dynamometer was placed approximately 3cm proximal to the lateral knee joint line and was stabilized to the table by the use of a strap (Figure 3.1). Each subject completed three trials lasting 5 seconds with a 30-second rest in between the trials. Subjects were instructed to gradually generate maximum force over a 2-second period and then sustain maximum force over a 3-second period. The average of the three trials was used to determine maximum strength.

Functional Testing

Prior to completion of functional testing, subjects were instructed in the performance of both the SUO and STS tests. Subjects were allowed to practice each test until they felt confident in performing the test. Subjects were encouraged to complete the tests without the use of external support but were allowed to use it as needed to complete the tests. Each subject completed three trials each of the SUO and STS tests. Data was collected during each trial for 10 seconds. Subjects were given a 30-second rest in between trials and a 2-minute break between exercises to prevent fatigue.

Sit-to-Stand (STS)

Subjects were seated on a 0.91m high box on the platform. They were told they could use any method needed to stand up from the box. Once given the command, subjects were instructed to rise off the box as quickly as possible and come to a steady stance. They were told to then hold this stance as steady as possible for the remainder of the 10-second test. If a subject moved too early or did not complete a given trial, the data was discarded and the trial repeated. (Figure 3.2)

Step-Up and Over (SUO)

Subjects stood on the force platform behind a 0.2m high box. Extremity matching for the SUO was accomplished by matching the injured limb of the surgical patients to the same side limb of the control group. Once given the command, subjects were instructed to step up onto the box with their uninvolved limb and then bring their involved limb up and over the box onto the other side of the force plate (UN). They were instructed to complete the test as fast as possible. Once three trials were completed, subjects repeated the test, completing three trials by stepping up with the involved limb while the uninvolved limb was the lagging limb (IN). If subjects were unable to complete the test in one motion, they were allowed to bring the lagging limb to rest on the box prior to stepping down. (Figure 3.3)

Data Processing and Analysis

Maximal isometric hip abduction strength was expressed in Newtons (N). Subject weight was converted from kilograms (kg) by multiplying kg by the constant 9.81. The average force (N) from the three strength trials was then normalized to subject weight ([force (N) ÷ body weight (N)] x 100) to allow for comparison between subjects. Normalization resulted in average maximum hip abduction strength being expressed as percent body weight (%BW). This value was utilized for all statistical analyses.

Each of the dependent variables obtained during the Sit-to-Stand and Step-Up and Over tests were averaged across the three trials. The dependent variables for the Step-Up and Over were LUI (%BW), MT (sec), and IMP (%BW) for both the involved limb and uninvolved limb conditions. The dependent variables for the Sit-to-Stand were WT (sec), RI (%BW), SV (º/sec), and LR (%). The dependent variable for the HHS was the total score. For the IPAQ, the dependent variables were total amount of activity minutes per week (TOTAL) (MET·min/week), time spent in vigorous activities (VIG) (MET·min/week), time spent in moderate activities (MOD) (MET·min/week), and time spent walking (WA) (MET·min/week) per week. For HHS, a paired samples t-test was conducted. To assess differences between the CON and the THA group at both 6w and 12w, separate independent samples t-test were conducted for maximum hip abduction strength and each dependent variable of the IPAQ, STS, and SUO tests. To assess differences between THA subjects at 6w and 12w, separate paired t-tests were conducted for maximum hip abduction strength and each dependent variable of the IPAQ, STS, and SUO tests. A Bonferroni correction was applied to account for multiple comparisons; therefore, alpha level was set *a priori* at $p \leq 0.0167$. All calculations were performed using SPSS Version 15.0 (SPSS Inc, Chicago, Ill).

Results

A total of 20 subjects participated in this study. Subject demographics for each group are presented in Table 3.1. There were no significant differences between groups for subject age ($P = 0.96$), height ($P = 0.98$), or weight ($P = 0.15$). Six THA subjects at the 6wk test and one subject at the 12w test were unable to perform the SUO without external support. Performing the SUO with support alters the amount of force applied to the force plate and does not provide an accurate estimate of force production; therefore, we were unable to run statistics on data for the SUO for the post-operative subjects at 6-weeks post-surgery. Analysis of the SUO data for post-surgical patients at 12-weeks following surgery was compared to the control subjects.

Post-Operative Rehabilitation

All post-surgical subjects completed home health rehabilitation immediately following surgery. Total amount of home visits for each subject ranged from 3 to 12 sessions. Seventy percent of post-surgical subjects participated in additional out-patient rehabilitation during the study period. On average, subjects attended 2-3 sessions of supervised rehabilitation per week as well as completing daily home exercises. Home exercises included range of motion exercises, isometric muscle sets, and calf raises. Supervised exercise programs included balance and lower extremity strengthening exercises.

Harris Hip Score (HHS)

Means and standard deviations for the total score as well as the individual components of the HHS for each group are presented in Table 3.2. Total HHS scores for THA subjects were significantly lower at 6w (62.8 $\pm$ 20.9) when compared to 12w (78.4 $\pm$ 16.5; $P = 0.001$). (Table 3.2)

International Physical Activity Questionnaire (IPAQ)

Means and standard deviations for all IPAQ dependent variables are presented in Table 3.3. The IPAQ scores for the THA subjects at 6w were significantly reduced when compared to CON for TOTAL score ($P < 0.001$), WA score ($P < 0.001$), MOD score ($P = 0.016$), and VIG score ($P = 0.009$). The IPAQ scores for the THA subjects at 12w were significantly reduced when compared to CON for TOTAL score ($P = 0.012$) and VIG score ($P = 0.009$). There were no significant differences between THA at 12w and CON for MOD score ($P = 0.057$) and WA score ($P = 0.136$). IPAQ scores for THA subjects at 12w were significantly greater when compared to THA subjects at 6w for TOTAL score ($P = 0.001$) and WA score ($P = 0.001$). There were no significant differences between THA subjects at 12w and 6w for MOD score ($P = 0.179$).

Isometric Hip Abduction Strength

Peak isometric hip abduction strength measures were significantly reduced for both THA subjects at 6w (9.1 $\pm$ 8.2%; $P < 0.001$) and at 12w (14.9 $\pm$ 10.1%; $P = 0.001$) when compared to CON (31.3 $\pm$ 7.9%). Hip abduction strength was significantly greater for THA subjects at 12w (9.1 $\pm$ 8.2%) when compared to 6w (14.9 $\pm$ 10.1%; $P = 0.001$).

Step-Up and Over

Involved Limb

Means and standard deviations for LUI, MT, and IMP for the SUO when subjects stepped with the involved limb are presented in Table 3.4. MT for the THA subjects at 12w was significantly greater when compared to CON (P = 0.003). There were no significant differences between THA subjects at 12w and CON for LUI (P = 0.18) and IMP (P = 0.79).

Uninvolved Limb

Means and standard deviations for LUI, MT, and IMP for the SUO when subjects stepped with the uninvolved limb are presented in Table 3.5. MT for the THA subjects at 12w was significantly greater when compared to CON (P = 0.001). There were no significant differences between THA at 12w and CON for LUI (P = 0.35) and IMP (P = 0.11).

Sit to Stand

Means and standard deviations for WT, RI, SV, and UI for STS for each group are presented in Table 3.6. RI for the THA subjects at 6w was significantly reduced (P < 0.001) and UI was significantly greater (P < 0.001) when compared to CON. There were no differences between THA subjects at 6w and CON for WT (P = 0.06) and SV (P = 0.35). RI for the THA subjects at 12w was significantly reduced (P = 0.001) and UI was significantly greater (P < 0.001) when compared to CON. There were no differences between THA subjects at 12w and CON for WT (P = 0.73) and SV (P = 0.87). RI for the THA subjects at 12w was significantly greater when compared to subjects at 6w (P = 0.013). There were no differences between THA subjects at 12w and 6w for WT (P = 0.04), SV (P = 0.38), and UI (P = 0.03).

Discussion

Our purpose was to compare short-term subjective and objective clinical outcomes for patients following THA under the age of 65to a cohort of age-matched controls. We observed significantly reduced hip abductor strength, reduced activity levels, and alterations during both the SUO and STS tests for subjects following THA when compared to healthy controls.

Our results demonstrated that subjective pain and function improved for our subjects from 6-weeks to 12-weeks following surgery. The average score on the HHS for our subjects at 6-weeks (63 points) and 12-weeks (78 points) post-surgery was less than the average score reported by a previous study[98]. Berger et al (2004) reported a mean HHS score of 94 points at 6-weeks following THA and 96 points at 12-weeks following THA[98]. Differences in HHS scores between our study and Berger et al (2004) may be due to different surgical approaches. All the subjects in our study underwent THA using a posterior approach, which requires disruption of the rotator cuff muscles and capsule of the hip joint[71,72], while the subjects in Berger et al (2004) underwent a minimally invasive approach where no muscle or tendon was cut during the procedure[98]. This may have resulted in decreased healing times for their subjects and a faster return to normal activities of daily life when compared to our subjects. Two studies reported mean scores of 82 points[31] and 84 points[23] at 12-weeks, which are closer to our findings at 12-weeks. Subjects in both studies underwent THA with a direct lateral surgical approach, which disturbs the anterior half of the gluteus medius and gluteus minimus muscles from their attachment on the femur[31], compared to the posterior approach in our study. It may be that disruption of any soft tissue during THA delays return to normal function.

To our knowledge, this is the first study to use the IPAQ to measure physical activity following THA. At 6-weeks following surgery, 80% of post-surgical subjects reported completing daily bouts of walking, 20% reported participation in moderate activity and no subject reported any participation in vigorous activity. By 12-weeks post-surgery, all 10 THA subjects reported completing daily bouts of walking, while 3 reported consistent participation in moderate activity. Moderate activities are those that require the subject to breathe slightly harder than normal and are moderately difficult. No post-surgical subjects reported participation in vigorous activities 3 months after surgery. In contrast, 9 out of 10 subjects in the control group reported participation in moderate activities, while 7 out of 10 reported participation in vigorous activities. The lack of participation in vigorous activities for post-surgical subjects, such as aerobics, running, fast bicycling, would be expected at this short time point following surgery due to post-surgical restrictions and guidelines[13]. Only 30% of our subjects reported consistent participation in these types of activities, including stair climbing, resisted strengthening exercises, and fast-paced walking. Of the other 7 subjects, 5 reported participation in some form of post-operative rehabilitation; however, they did not regularly complete exercises. In addition, the exercises performed by these subjects may not have been challenging enough. Hip abductor strength for the 3 subjects who did report consistent participation in moderate activities was 27% of body weight compared to only 9.8% of body weight for the remaining 7 subjects. The lack of participation in moderate intensity strengthening and functional training exercises for the majority of our subjects may have also contributed to the overall lower clinical function scores on the HHS compared to other studies. Mean HHS score for the 3 subjects who participated in moderate activities was 89 points compared to only 74 points for the 7 subjects who did not. These findings highlight the need for more intense, structured rehabilitation for younger subjects following THA.

The post-surgical subjects in our study demonstrated peak isometric abduction muscle strength values of only 29% of controls at 6-weeks and 52% of controls at 12-weeks after surgery. The reductions in peak isometric hip abduction strength observed for our subjects were consistent with previous studies reporting persistent muscle weakness to be present in younger patients following THA[4,16,20,22,24,31,42,71,85,91,92]. Maximum isometric abduction torque was reported to improve from 1-week to 6-weeks, from 6-weeks to 12-weeks, and from 12-weeks to 24-weeks post-surgery for one group of subjects following THA[31]. Strength values for their THA subjects were not compared to a control group, so we cannot determine if their values were reduced compared to controls; however, both our study and Vaz et al (1993) reported an improvement in strength from 6-weeks to 12-weeks following surgery, and their study reported continued improvement to persist up to 6 months post-surgery[31]. Our subjects demonstrated overall peak abduction strength deficits of 48% of the control group at 12-weeks after THA. At 1-year post-surgery, Shih et al (1994) reported peak hip abduction torque values to be 79-89% of control subjects[16]. Therefore, it appears subjects following THA continue to improve isometric hip abduction strength over the course of the first year after surgery. However, numerous studies have reported significant deficits to still exist in surgical limb hip abduction strength values when compared to both their uninvolved limb[20,71,91] as well as a group of controls[20,85,92] up to 4 years following surgery. Given this observation, one would expect subjects at 6-weeks and 12-weeks following surgery to continue to exhibit strength deficits as seen in our study, especially in light of the lack of consistent participation in post-operative rehabilitation.

Clinically, reductions in hip abduction strength during the early post-operative period following THA may be related to the use of external support during weight-bearing. Following THA, the use of a cane in the hand contralateral to the surgical hip has been recommended as an effective means of reducing forces on the hip joint[154]. In a study examining a single subject with an instrumented acetabular component, ambulation with a cane in the contralateral hand reduced peak acetabular contact pressure by 48% when compared to unaided walking[155]. Most of this reduction in contact force may be attributed to decreased hip abductor muscle force[155, 156]. Electromyography studies of ipsilateral limb gluteus medius muscle activation during ambulation with a cane in the contralateral hand demonstrated reductions in muscle activation levels of 31% when pushing with moderate force on the cane and 43% when pushing hard on the cane for a group of subjects after THA compared to walking without a cane[157]. In addition, the use of a cane during ambulation resulted in a 26% reduction in hip abduction joint moment when compared to ambulation without a cane for subjects at 4- and 8-months after THA[156]. Therefore, while the use of a cane is supported initially following surgery to reduce contact forces applied to the healing hip joint during gait, it may also contribute to persistent hip abductor muscle strength deficits as the activation of the abductor muscles is reduced during function. Seventy percent of our subjects relied on a cane for ambulation at 6-weeks following surgery. Thirty percent of subjects were still using the cane at 12-weeks post-surgery. Therefore, while abduction strength did improve compared to 6-week measures, it still remained reduced compared to controls at 12-weeks.

Weakness of the hip abductor muscles may also have contributed to the increased time taken by the THA subjects to complete the SUO test when compared to controls. The gluteus medius and gluteus maximus muscles of healthy individuals are active at amplitudes of 40-60% of their maximum through the loading and single limb stance phases of stair ascent to control lateral hip stability[160]. Following THA, subjects demonstrated reductions in peak hip adduction and external rotation moments of 25%

compared to controls during stair ascent[15], indicating deficits of the hip abductor muscles during this task. Increasing the speed of muscle contraction reduces the overall force a muscle can produce[161]; therefore, increasing the speed of contraction requires the muscle to contract to a greater extent to match the required load. In fact, Zimmerman et al (1994) demonstrated significant increases in mean EMG activation levels of both the quadriceps and gluteus maximus muscles as speed of stair climbing was increased[162]. Given the required activation levels of the hip abductor muscles during normal stair climbing[160] and the increased levels required to perform the task at a greater speed[162], the presence of dysfunction of these muscles following THA[15] may result in the need for post-surgical patients to slow the rate of movement during stair climbing to be able to successfully complete the task.

Interestingly, we did not find any differences between the THA group and control group for the lift-up or impact forces during the SUO. However, only the subjects who were able to complete the SUO without the use of external support were included in the analysis. At 6-weeks, only 4 subjects were able to complete the SUO without the use of external support. For these subjects, the average score on the stair climbing portion of the HHS at 6-weeks following surgery was 2 points, indicating that subjects could ascend stairs normally by holding onto the banister. The remaining 6 subjects averaged a score of 1.3 points, indicating they could climb stairs using any method available including external support. At 12-weeks, the 9 subjects who were able to complete the SUO averaged 2.9 points on the HHS for this task, indicating all were able to climb normally with or without using the banister. For the one subject unable to perform the test unaided, the score was a one, indicating the need to use any method to climb stairs. Therefore, the subjective data appears to match our findings of function during the SUO for this group of subjects.

As described previously, the gluteal muscles are active at 40-60% of their maximum during stair ascent[160]. Peak hip abduction strength for the cohort of THA subjects who were not able to complete the SUO independently was only 3.9% of body weight compared to 16.8% of body weight for the 4 subjects who could perform the SUO at 6-weeks. Therefore, a lack of hip abduction strength may have contributed to the inability of some subjects to ascend a stair unassisted at 6-weeks post-THA. This is further substantiated by the fact that the 5 subjects from the group who could not complete the test at 6-weeks improved isometric hip abduction strength by 131% at 12-weeks to 9% of body weight, at which time they were able to perform the SUO unassisted. Hip abduction strength for the one subject who was not able to ascend the stair unassisted at 12-weeks was only 3.5% of body weight.

For THA subjects able to complete the SUO at 12-weeks post-surgery, there were no significant differences between lift up and impact index force when stepping with either limb when compared to controls. However, when THA subjects stepped up onto the box using their surgical limb, they generated 13.6% BW more force than when they stepped up using their non-surgical limb at both 6- and 12-weeks post-surgery. The control group exhibited only a 3% side-to-side difference. A similar trend was noted for the impact forces for the THA group. While not significant, there was a 13% BW increase at 6-weeks and a 7% BW increase at 12-weeks when the THA subjects stepped down with their surgical limb compared to the non-surgical limb. For the control group, this difference was 1% of body weight. This is most likely a protective mechanism. When the subjects stepped down onto their non-surgical limb, they generated force equal to the control group at both 6-weeks and 12-weeks after surgery. However, when they stepped down onto their surgical limb, it was with 17% BW less force at 6-weeks and 10% BW less force at 12-weeks compared to the controls. Therefore, the THA subjects did not load their surgical limb to the same extent as either control subjects or similar to their contra-lateral limb.

An important factor to consider when deciphering the loading variables is the increased time it took the post-surgical subjects to complete the SUO. At 6-weeks post-surgery, THA subjects needed twice the time to complete the SUO when compared to controls (3.7sec vs. 1.6sec for involved limb SUO and 3.3sec vs. 1.6sec for uninvolved limb SUO, respectively). At 12-weeks, time was reduced by over a second for the THA subjects (2.5sec for involved limb SUO and 2.2sec for uninvolved limb SUO); however it was still approximately a second slower than the controls. Therefore, while the loading and impact forces were similar between the groups, the THA group took more time to generate these forces. As discussed previously, increasing the speed of stair climbing requires greater activation levels of the hip extensor and flexor muscles[162]. The control subjects were able to complete the SUO faster without applying a greater force to the force plate, which would indicate an increase of eccentric muscle control[163]. Two previous studies reported that, along with an increase in movement time, older subjects demonstrated earlier pre-activation of the quadriceps muscles during stair descent when compared to young people[163, 164]. The pre-activation of this muscle group serves to stiffen the knee joint to ready the leg for weight transfer[163] and prevent buckling upon impact[164]. By slowing the rate at which they performed the SUO, our post-surgical subjects may have been attempting to control impact and prevent buckling as a result of muscle weakness. Our data indicates that the THA subjects continue to demonstrate deficits in stair climbing ability at 3 months following surgery compared to controls.

During the STS, neither WT time nor SV differed between the control group and the THA group at 6-weeks or 12-weeks after surgery. Mean weight transfer time measures the time from the onset of the cue to move and the arrival of the center of gravity (COG) over the feet. Slower WT times decrease the ability of the subject to use momentum to move the body forward in preparation for standing. This may limit the ability of the subject to use this momentum to sufficiently lift their body off of the chair. The main contributor to forward movement of the COG has been shown to be the forward rotation of the upper body, which would require hip and trunk flexion[165]. According to our data, THA subjects at 6-weeks and 12-weeks after surgery do not appear to be limited in their ability to move into trunk and hip flexion to adequately shift their COG forward in preparation for standing. Similarly, the THA subjects do not demonstrate significantly impaired balance control, as evidenced by the similar SV scores compared to controls. This is contrary to a previous report in which subjects an average of 271 days following THA demonstrated significant alterations in postural control compared to healthy subjects[90]. However, the balance tests employed in their study assessed balance during increasingly challenging tasks and at the limits of stability. In our study, SV was measured during quiet standing on a hard surface. This task may not be sensitive enough to detect in postural control deficits in patients following THA.

While the WT and SV variables of the STS did not differ when compared to controls, the THA subjects did demonstrate significant deficits in RI. Rising index is a measure of the amount of force exerted by the legs onto the force plate during the rising phase of the STS. The rising phase is the time from when the COG reaches the toes until upright stance is achieved[165, 166]. Low scores as observed with our THA group indicate insufficient force and an inability to use the legs to achieve standing. This is most likely due to muscle weakness. During this phase, the gluteus maximus muscle is activated at only 20% of its maximal activity; however, the rectus femoris muscle is activated at 50% of maximum and the vastus medialis and vastus lateralis muscles are activated at 80% of their maximum[165]. Therefore, the rising phase of the STS is a quadriceps dominant activity. While we did not measure quadriceps muscle strength in our subjects, weakness and atrophy of this muscle group have been reported for patients following THA[24, 166]. Therefore, the reduction in RI observed for our THA subjects at both 6-weeks and 12-weeks is most likely the result of persistent quadriceps muscle weakness. As a result, the majority of subjects needed to use their hands to push off of the box during the test; accounting for the low force exerted by the legs onto the force plate. There was a trend for improved RI from 6-weeks to 12-weeks for the THA subjects. As peak hip abduction strength for these patients did improve during this time, it may be that overall leg strength improved to allow the patients to stand in a more normal manner.

Uninvolved to involved limb asymmetry index was also significantly different between the controls and THA subjects. At 6-weeks, the THA group loaded 22% BW more onto the non-surgical limb compared to surgical. This asymmetry was reduced to 10% BW more on the non-surgical limb at 12-weeks post-surgery. The control subjects only differed by 3% between limbs. Our results at 6-weeks are similar to previously reported values[166, 167]. Subjects at 1-year following THA loaded 20% greater force onto the non-surgical limb[167], while subjects at 19 months post-surgery loaded 22% greater weight onto the non-surgical limb[166]. Prior to rising, healthy subjects shift their COG between both feet allowing them to load each foot equally during standing[168]. In contrast, subjects after THA shift their COG toward the surgical limb, leaning their body toward the non-surgical limb[168]. This results in the overloading of the uninvolved limb during standing[168]. The asymmetry observed during standing for patients following THA is most likely the result of learned patterns prior to surgery. Individuals who elect to undergo THA have been experiencing painful symptoms in that hip joint for up to 5 years prior to surgery[24]; therefore, they may have become dependent on their contralateral limb.

Following surgery, they may avoid loading the newly implanted hip joint because of fear or because not loading it has become habitual[168]. With proper training, this asymmetry has been shown to decrease to only 6% more on the uninvolved limb, which approaches our control group[167]. The improvement to 10% for our subjects without training from 6-weeks to 12-weeks may be the result of improved muscle strength on the surgical limb which negated the need to shift their body toward the uninvolved limb to rise. It might also reflect the patient becoming more confident in functioning on the reconstructed limb. The patients in our study reported improved function and reduced pain at 12-weeks as evidenced by their increased HHS scores.

Limitations

Our study was not without limitations. Two different surgeons performed surgery for our THA subjects. Both surgeons performed the procedure using the same surgical approach, but the patients' overall experiences prior to, during, and following surgery may have differed. We chose not to control participation in post-operative rehabilitation for our THA subjects. Instead, we chose to examine activity level using the IPAQ. As demonstrated by our results, participation in structured rehabilitation programs may have affected our results; however, we feel that our data represents the true diversity of outcomes following THA which would be seen in a clinical setting. Unfortunately, we did not expect as many subjects in our THA group to not be able to complete the SUO independently at 6-weeks following surgery. While this limited our numbers for statistical comparison and lowered our power for the SUO variables, we feel our sample of subjects adequately represents the typical spectrum of functional ability following THA.

Conclusions

The results of our study demonstrate that strength and functional deficits exist in patients less than 65 years of age undergoing THA at 6- and 12-weeks following surgery. Maximum isometric hip abduction strength improves to only half of age matched controls s at 3 months post-operatively. The presence of persistent muscle weakness appears to affect daily function for this group of patients. Movement time during completion of the SUO was significantly longer for THA subjects when compared to controls. This is most likely a compensatory mechanism to control loading of the hip during impact, resulting in similar lift up and impact forces during stair ambulation when compared to control subjects. THA subjects were also not able to rise from a chair without using their arms to push them upward, indicating lower extremity weakness. In addition, during the rising phase of the STS, they loaded significantly greater weight onto their non-surgical leg at both 6- and 12-weeks following surgery when compared to controls. Based on the results of the IPAQ, the majority of our subjects did not participate in moderate intensity post-operative resistive strengthening programs, which is most likely the cause of the observed strength deficits. Those subjects who consistently participated in moderate activities exhibited greater values for hip abduction isometric strength as well as greater outcome scores on the HHS compared to subjects who did not. Therefore, our results highlight the need for structured, resistive post-operative rehabilitation programs to improve strength and resume normal function in younger patients following THA.

Table 3.1 Demographic Subject Data (Mean ± SD)

	Group	
	CON (n = 10)	THA (n = 10)
Gender (M,F)	5M, 5F	5M, 5F
Age (y)	50.5 ± 4.6	50.3 ± 10.5
Weight (kg)	76.1 ± 16.6	86.6 ± 14.7
Height (cm)	171.6 ± 15.9	171.5 ± 12.1
Time from surgery to first test (days)		43.9 ± 4.2
Time from surgery to second test (days)		80.8 ± 9.1

CON = Control group
THA = Total hip arthroplasty group
M = males
F = females
Y = years
Kg = kilograms
Cm = centimeters

Table 3.2: Scores for the Harris Hip Score by Questionnaire Component (Means ± SD)

Group	Component								
	Pain (44)	Limp (11)	Support (11)	Distance Walked (11)	Stairs (4)	Socks/ Shoes (4)	Sitting (5)	Public Transportation (1)	Total (100)
THA-6w	30.8 ± 9.3	6.4 ± 4.2	6.1 ± 4.1	5.3 ± 2.6	1.6 ± 0.5	1.8 ± 1.1	4.4 ± 0.97	0.7 ± 0.5	62.8 ± 20.9*
THA-12w	34.4 ± 8.8	8.3 ± 2.6	9.3 ± 2.8	8.3 ± 3.9	2.7 ± 1.6	1.8 ± 1.1	4.8 ± 0.6	0.9 ± 0.3	78.4 ± 16.5*

Total possible points are in parentheses
*Indicates a statistically significant difference between groups
THA-6w = Total hip arthroplasty subjects tested at 6-weeks post-surgery
THA-12w = Total hip arthroplasty subjects tested at 12-weeks post-surgery

Table 3.3: Scores for the International Physical Activity Questionnaire (Mean ± SD)

Group	TOTAL (MET·min/wk)	WA (MET·min/wk)	MOD (MET·min/wk)	VIG (MET·min/wk)
CON	9107 ± 2355	6999 ± 1742	1090 ± 1085	1028 ± 973
THA-6w	3307 ± 2016*	3235 ± 1959*	72 ± 151*	0 ± 0*
THA-12w	5652 ± 3091†‡	5352 ± 2846‡	300 ± 490	0 ± 0†

*Indicates a statistically significant difference between CON and THA-6w
†Indicates a statistically significant difference between CON and THA-12w
‡ Indicates a statistically significant difference between THA-6w and THA-12w
CON = Control Group
THA-6w = Total hip arthroplasty subjects examined 6-weeks post-surgery
THA-12w = Total hip arthroplasty subjects examined 12-weeks post-surgery
TOTAL = Total minutes of all activity per week on the IPAQ
WA = Total minutes of walking per week on the IPAQ
MOD = Total minutes of moderate activity per week on the IPAQ
VIG = Total minutes of vigorous activity per week on the IPAQ
MET˙min/wk = Metabolic minutes per week

Table 3.4: Involved Limb Step-Up and Over (Mean ± SD)

Group	LUI (%BW)	Variable MT (sec)	IMP (%BW)
CON	39.9 ± 7.8	1.6 ± 0.29	46.7 ± 19.7
THA-6w	45.8 ± 15.9	3.7 ± 0.95	44.2 ± 25.5
THA-12w	46.8 ± 13.5	2.5 ± 0.98*	44.5 ± 13.9

*Indicates a statistically significant difference between CON and THA-12w
CON = Control Group
THA-6w = Total hip arthroplasty patients subjects 6-weeks post-surgery n = 4
THA-12w = Total hip arthroplasty patients subjects 12-weeks post-surgery n = 9
LUI = Lift-Up Index
MT = Movement Time
IMP = Impact Index
BW = Body weight
Sec = seconds

Table 3.5: Uninvolved Limb Step-Up and Over (Mean ± SD)

Group	LUI (%BW)	Variable MT (sec)	IMP (%BW)
CON	36.7 ± 10.1	1.6 ± 0.31	47.7 ± 13.2
THA-6w	32.3 ± 9.6	3.3 ± 0.45	30.9 ± 8.7
THA-12w	33.1 ± 5.1	2.2 ± 0.38*	37.3 ± 13.3

*Indicates a statistically significant difference between CON and THA-12w
CON = Control Group
THA-6w = Total hip arthroplasty patients subjects 6-weeks post-surgery
THA-12w = Total hip arthroplasty patients subjects 12-weeks post-surgery
LUI = Lift-Up Index
MT = Movement Time
IMP = Impact Index
BW = Body weight
Sec = seconds

Table 3.6: Sit-to-Stand (Mean ± SD)

	Variable			
Group	WT (sec)	RI (%BW)	SV (º/sec)	UI (%BW)
CON	0.41 ± 0.13	21.6 ± 6.1	3.5 ± 0.6	2.6 ± 7.4
THA-6w	0.68 ± 0.4	8.1 ± 2.3*	3.1 ± 1.3	21.8 ± 16.6*
THA-12w	0.46 ± 0.46	12.8 ± 3.1†‡	3.4 ± 1.1	10.4 ± 12.9†

*Indicates a statistically significant difference between CON and THA-6w
†Indicates a statistically significant difference between CON and THA-12w
CON = Control Group
THA-6w = Total hip arthroplasty subjects examined 6-weeks post-surgery
THA-12w = Total hip arthroplasty subjects examined 12-weeks post-surgery
WT = Weight Transfer
RI = Rising Index
SV = Center of Gravity Sway Velocity
UI = Uninvolved/Involved Asymmetry Index
BW = Body weight
º/sec = degrees per second

Figure 3.1: Testing Position for Isometric Hip Abduction Strength

Figure 3.2: The Sit-to-Stand Test

Figure 3.3: The Step-Up and Over Test

Chapter 4

The Effectiveness of a Hip Exercise Program Targeting the Hip Abductor Muscle Group in a Population of Younger Patients following Total Hip Arthroplasty (THA)

Introduction

The number of patients electing to undergo total hip arthroplasty (THA) each year increased by 50% from 1990 to 2002, with numbers totaling 193,000 persons in 2002[2]. A growing number of patients undergoing this procedure are below the age of 65 years[2]. This cohort of patients represents a new challenge to physicians and rehabilitation specialists as they not only wish to return to pain free daily activities, but express a desire to continue to participate in recreational and sporting activities following THA[4-9]. Physician recommendations of which activities are appropriate following THA have been published[13,14]; however rehabilitation programs focused on returning patients to a higher level of activity have not been addressed. In addition, numerous studies report the presence of pain and functional limitations to persist in this cohort of patients up to 6 years following surgery[4,15-22]. The prolonged presence of these disabling factors may result in the patient being unable to return to their desired activity level. Therefore, it is important to determine appropriate post-surgical rehabilitation programs to help alleviate the continued deficits following THA in younger, more active patients.

Numerous studies have reported impairments and functional deficits to persist in patients following THA[4,15-22]. The major long term disabling conditions identified post-surgery are muscle weakness[4,16-18,20-22,24,42,91,92], altered gait parameters[15,20,80,85,94,95], and limitations in social activities[19] and activities of daily living[19-23,37,38,90]. While hip muscle strength has been shown to improve to pre-surgery levels following THA, deficits up to 21% of the unaffected limb have been found to be present up to 1-year post-surgery[16,42,92]. Specifically, the number one deficit associated with patients who continued to experience pain and functional deficits following conventional rehabilitation was weakness of the hip abductor muscle complex[99]. Seventy-three percent of patients with unsuccessful post-operative outcomes presented with weakness of the hip abductor muscles at 3 months post-surgery[4]. As a result, the limitations in function and activity participation reported by patients following THA may be directly related to persistent hip abductor muscle weakness. Vaz et al (1993) reported a significant positive correlation to exist between hip abductor muscle strength and the total distance traveled during the 6-minute walk test in patients following THA[31]. Therefore, strengthening of the hip abductor muscle complex may help improve function in this patient population.

Immediate post-operative rehabilitation for patients following THA has generally focused on regaining mobility[97,98] and consists of isometric strengthening and range of motion exercises as well as a progressive return to walking and function[17]. While this type of unstructured rehabilitation is often successful at returning patients to daily function, persistent strength and functional deficits are noted up to 10 years post-surgery[17,18,21]. As a result, numerous studies have examined the effectiveness of structured rehabilitation programs specifically targeting muscle weakness and functional deficits after THA[17,18,21,45,100, 01]. Following rehabilitation, patients demonstrated significant improvements in pain[17,45], muscle strength[17,18,21,45], gait[21], function[17,45], and postural control[18] measures. Rehabilitation programs which included resistive functional exercises and eccentric hip abduction strengthening exercises result in greater outcomes than programs which do not[18,21,100,101]. While previous studies have examined specific post-operative rehabilitation programs for patients following THA, the majority did not initiate the program until at least 6 months following surgery, after patients presented with deficits[18,21,45,101]. Of the two programs initiated before 6 months post-operatively, one examined a rehabilitation program completed both before and after surgery[17] and the other did not include a control group for comparison[100].

The benefits from rehabilitation programs emphasize the importance of implementing structured rehabilitation to improve strength and function for all THA patients, and in particular younger patient who wish to participate in higher level of functions. As weakness of the hip abductor muscles has been identified as a primary contributor to poor outcomes post-operatively, rehabilitation programs should include exercises which target these muscles. Therefore, the purpose of this study was to determine the effectiveness of adding a hip abductor muscle strengthening program initiated 6-weeks following surgery on subjective and objective outcomes in a cohort of patients younger than 65 years of age following THA. We hypothesized that subjects who participated in an exercise program targeting the hip abductor muscles initiated at 6 weeks following total hip arthroplasty would demonstrate higher scores on the Harris Hip

Score and International Physical Activity Questionnaire, greater measures of hip abductor muscle strength, and better function during the Sit-to-Stand and step up and over tests when compared to subjects who did not.

Methods

Subjects

Potential subjects were included if they had undergone unilateral total hip arthroplasty, were less than 65 years of age, had no history of vestibular disorders, presented with no major co-morbidities, and were otherwise medically stable. Eligible subjects read and signed a consent form and were randomized to either an exercise group or a control group. Group allocation was determined through the use of a random number sequence. Group allocation was consecutively numbered in sealed envelopes. The subjects were unaware of group allocation at baseline testing. The research coordinator opened the envelopes following completion of all baseline testing.

Intervention

All subjects completed standard home health rehabilitation immediately following surgery. Total amount of home health visits for subjects ranged from 3 to 12 sessions. Subjects were allowed to return to activities of daily life and work as tolerated. At 6-weeks following surgery, subjects returned to the physician's office for their post-surgical follow-up appointment. Baseline testing took place during that office visit.

Control Group (CG)

Subjects who were assigned to the CG were encouraged to continue their daily activities and progress walking distance as tolerated. They were not prohibited from continuing exercise or from participating in physician-referred rehabilitation during the testing time. To document activity level, these subjects were provided with an exercise log and instructed to record the type and amount of exercise they participated in for the 6-week intervention period. They were asked to bring the log with them to the post-intervention testing session. Each subject was also contacted by a member of the research team each week to monitor progress and answer any questions.

Exercise Group (EG)

Subjects who were assigned to the EG completed a 6-week home-based exercise program. (Appendix C) The exercise program was divided into three phases, with each phase lasting 2 weeks (Tables 4.1, 4.2, 4.3). Each phase consisted of three exercises. Exercises in the program were chosen based on previous studies examining mean electromyographic activation of the gluteus medius muscle during specific non-weight-bearing and weight-bearing exercises[103, 127]. An adjustable 2.27kg cuff weight and Thera-band elastic resistance (Hygenic Corporation, Akron, Ohio) band providing medium resistance were given to each patient to use during the exercise program. Patients performed 4 sets of 10 repetitions for each exercise per session and completed three sessions per week. The amount of external resistance used during the performance of each exercise was increased progressively within and between each session. Patients in the EG were given a detailed progression sheet to follow during each phase as well as a general instruction sheet outlining the specifics of each exercise, including photos of the correct technique. Additionally, patients in the EG were provided with a CD of video examples of the proper performance of each exercise. Compliance with the home-based exercise program was monitored through the use of an exercise journal which the patient completed weekly and brought to the post-intervention testing session. A member of the research team contacted each patient by phone once per week to monitor progress and answer any questions regarding the exercises. If a subject had questions in between these calls, they were encouraged to contact the investigator.

Primary Outcomes

The primary outcome variables were the modified version of the Harris Hip Score (HHS) and International Physical Activity Questionnaire (IPAQ). The modified version of the Harris hip Score assessed the domains of pain and function, with the domains of deformity and range of motion eliminated from the assessment[26]. The total score obtained was multiplied by 1.1 to give a total possible score of 100. The higher score is indicative of greater function and less pain. The HHS has been shown to demonstrate high test-retest reliability and validity in patients following THA[149].

The short version of the IPAQ summarizes activity levels by recording the time spent walking, time spent during moderate activities, and time spent during vigorous activities per week[148]. The total minutes per week recorded for each category are then weighted by a metabolic equivalent (MET) energy expenditure estimate. The total minutes per week in vigorous activity (VIG) were multiplied by a factor of 8, by a factor of 4 for moderate activity (MOD), and by a factor of 3.3 for walking (WA). These values were then summed across domains to produce a weighted estimate of total physical activity per week (TOTAL). An analysis of the IPAQ using subjects from 12 different countries demonstrated good reliability and validity for documenting physical activity for the general population[148].

Secondary Outcomes

Isometric Hip Abduction Strength

Isometric hip abduction strength was measured using a handheld dynamometer (HHD) (J-Tech, Inc. Salt Lake City, UT) attached to a strap for stabilization during testing. The dynamometer has a maximum load cell capacity of 556.3 Newtons (N). The HHD was calibrated prior to the start of testing by placing known weights on the HHD and comparing this weight to the reported weight by the HHD. Calibration was repeated midway and at the completion of testing to verify accuracy. Acceptable inter-trial coefficient of variation was established prior to testing as less than or equal to 10%[147]. Each subject performed three trials of maximal strength testing of the involved limb with a 30-second break between trials.

Force Platform Data

Ground reaction force data was collected using the static long force plate of the NeuroCom Smart Balance Master (NeuroCom International nc, Clackamas, OR). The force plate consists of two 0.23m by 1.5m foot-plates connected in the center along the long axis by a pin joint. Each foot-plate rests on two force transducers mounted along the center line of the long axis, one located 0.74m anterior and one 0.74m posterior to the pin joint. Each transducer is also located 0.21m laterally from the pin joint. The collection rate of the long force plate was 100Hz. Raw force data from the plate was transmitted to a desktop computer via a cable and stored in the NeuroCom database. The NeuroCom software was used to analyze the raw data and generate the dependent variables for each functional test. The Step-Up and Over (SUO) and Sit-to-Stand (STS) tests were utilized for this study. The dependent variables for the SUO were lift-up index (LUI) expressed as a percentage of body weight (%BW), movement time (MT) expressed in seconds (sec), and impact index (IMP) expressed as %BW. The dependent variables for the STS were weight transfer (WT) expressed in sec, rising index (RI) expressed as %BW, sway velocity (SV) expressed in degrees per second (º/sec), and uninvolved-involved asymmetry index (UI) expressed as percentage (%). Subjects performed the SUO stepping with both the uninvolved limb and the involved limb. Three trials for each condition of the SUO as well as the STS were performed for each subject.

Blinding

Blinding of subjects to group assignment was not possible since they knew whether they were completing exercises or not. In addition, the investigator overseeing data collection was not blinded to group assignment. The primary outcome variables (HHS and IPAQ) were self-reported questionnaires. The secondary outcomes were calculated from standardized equipment, which was not altered by the investigator. Input from the investigator to each subject was also standardized.

Sample Size

The sample size required to detect significant differences was determined using statistical software (N-Query Advisor, Statistical Solutions, Saugus, MA). Effect size was based on previous data for mean difference (Δ) and common standard deviation (σ) between pre and post-intervention isometric hip abduction muscle strength as a percentage of body weight ($\Delta = 8\%$ and $\sigma = 8$). The results of an independent two-sample t-test with alpha set at 0.05 revealed a sample size of 34 (17 per group) to achieve 80% power. To protect against patients being lost to follow up, an additional 13 patients were recruited. Therefore, 47 subjects were recruited to participate in this study from the patient population of two surgeons (CPC and MG).

Data Analysis

For each dependent variable, separate 2x2 repeated measures analyses of variance (ANOVA) were conducted. The independent variables were group (EG, CG) and testing session (PRE, POST). Independent t-tests were used to compare subject demographic variables between groups. All calculations were performed using SPSS Version 15.0 (SPSS Inc, Chicago, Ill). Level of significance was set *a priori* at $p < 0.05$.

Results

A total of 47 subjects were recruited for this study. Details regarding subject randomization and retention are presented in Figure 4.1. Thirteen subjects were excluded prior to randomization. Twenty-one subjects were randomized into the EG and 13 subjects were randomized into the CG. Six subjects in the EG were lost to follow-up as a result of cancelled appointments. One subject in the EG was not included in the final analysis because they were unable to participate in post-intervention functional testing due to increased pain in the opposite hip joint. One additional subject in the EG was not included in the final analysis for the SUO and STS because of equipment failure; however, the scores for the HHS and IPAQ as well as the isometric hip abduction strength measures for this subject were included. Two subjects in the CG were lost to follow-up, one as a result of a cancelled appointment and one refused to complete testing at 12-weeks. Therefore, data analysis was conducted for 13 subjects in the EG and 11 subjects in the CG. Subject demographics are presented in Table 4.4. Results of separate independent samples t-test revealed no significant differences in subject weight ($P = 0.53$) or height ($P = 0.1$). Subjects in the EG were significantly older than subjects in the CG ($P = 0.04$).

Post-Operative Rehabilitation

For subjects in the Control Group, 73% reported participating in some form of out-patient rehabilitation program during the intervention period. On average, subjects attended 2-3 sessions of supervised rehabilitation as well as completing daily home exercises. Home exercises performed included range of motion exercises, isometric muscle sets, and calf raises. Supervised exercise programs included balance and lower extremity strengthening exercises.

For subjects in the Exercise Group, 92% of subjects reported completing the entire 6-week exercise program. The one subject who did not complete the program was unable to do so as a result of personal conflicts. No subject reported experiencing pain or injury during the completion of the exercises and no subject had to cease participation in the exercise program due to injury or pain. In addition, 85% of subjects were able to use the maximum amount of external resistance (2.27kg) during the performance of the exercises within the first week of the program.

Harris Hip Score (HHS)

Means and standard deviations for the total score as well as the individual components of the HHS for each group are presented in Table 4.5. There was a significant main effect for time ($P < 0.001$). Scores on the HHS at PRE (71.7 ± 19.2

points) were significantly less than scores at POST (86.7 ± 13.4 points) regardless of group. There was a trend toward a main effect for group (P = 0.06). Scores on the HHS for the EG (85.6 ± 21.3 points) were greater than scores for the CG (72.9 ± 23.2 points).

International Physical Activity Questionnaire (IPAQ)

Means and standard deviations for the IPAQ are presented in Table 4.6. There was a significant main effect for group (P = 0.049) for TOTAL. TOTAL scores for EG (6456.4 ± 3025.9) were significantly greater than TOTAL scores for CG (4555.8 ± 3289.6) regardless of time. There was a significant main effect for time (P < 0.001). TOTAL scores at PRE (4026.4 ± 2156.9) were significantly less than TOTAL scores at POST (6985.83 ± 2680.2) regardless of group.

Isometric Hip Abduction Strength

Means and standard deviations for peak isometric strength measures are presented in Table 4.7. There was a significant main effect for time (P < 0.001). Peak isometric hip abduction strength measures at PRE (9.7 ± 6.9%) were significantly less than at POST (15.1 ± 7.8%) regardless of group.

Step-Up and Over

Involved Limb

Means and standard deviations for Lift-Up Index, Movement Time, and Impact Index for SUO when subjects stepped with the involved limb are presented in Table 4.8. There was a significant main effect for time for LUI when subjects led with the involved limb (P = 0.037). LUI at PRE (43.2 ± 14.1%) was significantly greater than LUI at POST (39.8 ± 12.6%) regardless of group. There was a significant main effect for time for MT when the subjects led with the involved limb (P = 0.001). MT at PRE (3.0 ± 0.66sec) was significantly greater than MT at POST (2.2 ± 0.4sec) regardless of group. There was a significant main effect for group for MT when subjects led with the involved limb (P = 0.003). MT for EG (2.2 ± 0.48sec) was significantly less than MT for CG (3.0 ± 0.69sec). There was a significant main effect for time for IMP when the subjects led with the involved limb (P = 0.019). IMP at PRE (48.1 ± 17%) was significantly greater than IMP at POST (41.7 ± 3.6%) regardless of group.

Uninvolved Limb

Means and standard deviations for Lift-Up Index, Movement Time, and Impact Index for SUO when subjects stepped with the uninvolved limb are presented in Table 4.9. There was a main effect for time for MT when subjects led with the uninvolved limb ($P < 0.001$). MT at PRE (2.9 ± 0.5sec) was significantly greater than MT at POST (2.2 ± 0.52sec) regardless of group. There was a significant main effect for group for MT when subjects led with the uninvolved limb ($P = 0.02$). MT for EG (2.3 ± 0.4sec) was significantly less than MT for CG (2.8 ± 0.6sec) regardless of time. There were no significant differences for LUI when the subjects led with the uninvolved limb betweens groups ($P = 0.37$) or across time ($P = 0.38$). There were no significant differences between subjects for IMP when the subjects led with the uninvolved limb at either time ($P = 0.35$).

Sit to Stand

Means and standard deviations for Weight Transfer, Rising Index, Sway Velocity, and Uninvolved/Involved Index for STS are presented in Table 4.10. There was a significant main effect for time for WT ($P = 0.028$). WT at PRE (0.62 ± 0.39sec) was significantly greater than WT at POST (0.48 ± 0.4sec) regardless of group. There was a significant group x time interaction for RI ($P = 0.002$). At PRE, RI for EG (13.6 ± 5.4%) was significantly greater than RI for CG (8.8 ± 5.7%; $P = 0.007$). For CG, RI at PRE (8.8 ± 5.7%) was significantly less than RI for POST (13.6 ± 4.8; $P < 0.001$). There was a trend for a group by time interaction for UI ($P = 0.06$). At PRE, EG (4.7 ± 21.9%) exhibited less asymmetry during the STS when compared to CG (20 ± 21.9%; $P = 0.026$). For CG, UI at PRE (20 ± 21.9%) was greater than UI at POST (8.5 ± 16.5%; $P = 0.014$). There were no significant differences between groups for SV at either time ($P = 0.8$).

Discussion

Our purpose was to examine the effectiveness of a 6-week hip abductor strengthening program on short-term subjective and objective clinical outcomes for subjects following THA. Regardless of group, subjective clinical outcome assessed with the HHS improved from 6-weeks to 12-weeks. Subjects in the CG improved by 25%, while subjects in the EG improved by 20%. Twelve out of 13 subjects in the EG had scores above 80 points following intervention compared to 5 out of 11 subjects in the CG.

The one subject in the EG who did not score above 80 points only completed 2 weeks of the 6 week program, while the remaining 12 participants completed all 6 weeks of exercise. Previous studies reporting outcomes using the HHS report values of 94 points[98] at 6-weeks and 82[31], 84[23], and 96[98] points at 12-weeks. Both groups of our subjects demonstrated reduced scores on the HHS at 6-weeks when compared to Berger et al (2004)[98]. This may be the result of different surgical techniques employed in the studies. Our subjects underwent a posterior approach during surgery, which requires disruption of the rotator cuff muscles and capsule of the hip joint, whereas Berger et al (2004) utilized a minimally invasive surgical technique in which no muscle or tendon was cut[98]. The minimally invasive technique for THA may have reduced healing times from surgery, allowing patients to achieve excellent clinical outcomes faster.

The results at 3-months for our EG subjects are similar to those reported by Berger et al (2004) and higher than those reported by Vaz et al (1993) (82 points)[31] and Laupacis et al (1993) (84 points)[23]. Both of those studies utilized a direct lateral surgical approach which disrupts the anterior half of the gluteus medius and minimus muscles from their attachment on the greater trochanter[31], compared to our study in which the rotator cuff muscles and hip capsule were disrupted. Neither Vaz et al or Laupacis et al reported outcomes at 6-weeks post-surgery; however, the results of our CG subjects at 12-weeks (80 points) are similar to findings for both studies at 12-weeks. In addition, both studies reported improved scores of 95 points[31] and 92 points[23] at 6-months post-operative. Therefore, for subjects undergoing THA using a surgical approach in which any muscle is disrupted, achievement of near normal outcomes using the HHS can be expected by 6 months post-surgery.

In a previous study[45], the functional activity portion of the HHS, which includes the components of negotiating stairs, putting on socks and shoes, sitting, and using public transportation, was used as the dependent measure when examining outcomes following an exercise intervention post-THA. Jan et al (2004) examined the effects of a 12-week home exercise program for subjects 1.5 years following THA[45]. Subjects who completed greater than 50% of the exercise sessions improved scores on the functional activity portion of the HHS by 12% compared to no improvement for subjects who completed less than 50% of sessions and no improvement for subjects who completed no exercises.

The average score on the functional activity portion, out of a total possible 14 points, for their subjects regardless of group at pre-intervention (12.2 points)[45] was greater than the average functional scores observed for our subjects at pre-intervention (CG: 8.6 points and EG: 9.3 points) and for the CG at post-intervention (10.4 points), most likely due to the lengthened time from surgery for their subjects. However, scores on the functional activity components for our EG group at 3 months (12 points) was similar to baseline scores for their subjects at 1.5 years post-surgery. Subjects in our EG improved scores on the functional portion of the HHS by 29% compared to improvements of only 20% for the CG. In addition, 50% of subjects in the EG demonstrated a perfect function score (14 points) following intervention, while no subject in the EG had a perfect score pre-intervention and no subject in the CG had a perfect score at either testing session. Therefore, it appears that the addition of our exercise program was effective at improving self-reported function for subjects from 6-weeks to 12-weeks post-surgery.

To our knowledge, no study has utilized the IPAQ to document activity levels for subjects following THA. Total activity as reported using the IPAQ was significantly greater for the EG when compared to the CG, regardless of testing session; however, both groups increased activity level from 6-weeks to 12-weeks post-surgery. Subjects in the EG increased their total activity level by an average of 77% compared to 69% for the CG [(Post-intervention score – Pre-intervention score)/Pre-intervention score]. Five subjects in the EG reported participation in moderate activities at 3 months compared to 3 subjects in the CG. Moderate activities include those that require moderate effort to complete and cause the subject to breathe a little harder than normal; for example, stair climbing, light resistive strengthening exercises, and regular-paced biking. In addition, 2 of the 5 subjects in the EG reported consistent participation in vigorous activities at 3 months compared to no subjects in the CG. The vigorous activities reported by these subjects were step aerobics, heavy weightlifting, and elliptical training. Participation in moderate to vigorous activity may be related to the observed increases in peak hip abduction strength measures. The average peak hip abduction strength measures for those subjects who reported participating in moderate and vigorous activities, regardless of group, was 20.5% of body weight compared to only 12% for subjects who only participated in walking. It is interesting to note that hip abduction strength for subjects in the CG who only walked was 9.8% compared to 27% for subjects who participated in moderate activities consistently. In contrast, the five subjects in the EG who participated in moderate and vigorous activities in addition to the strengthening program demonstrated hip abduction strength values of 17.2% compared to 14.2% for subjects who only completed the exercise program. Therefore, it appears that the addition of the strengthening exercises may have contributed to increases in hip abduction strength measures for subjects whose only form of activity was walking when compared to subjects who did not complete the exercises.

Regardless of group, peak isometric hip abduction strength was shown to improve from 6-weeks to 12-weeks post-surgery. This finding is similar to a previous study which reported improvements in peak hip abduction torque to occur between 1- and 6-weeks, 6- and 12-weeks, and 12- and 24-weeks following THA[31]. The authors did not report mean strength values for the separate time points so we cannot compare the amount of improvement for our subjects to theirs; however, our subjects demonstrated an average improvement of 5.4% of body weight, which is a 92% increase in peak hip abduction strength from 6- to 12-weeks post-surgery.

We did not find any differences in peak hip isometric strength between the EG and CG at either testing session. Our results are in contrast to previous studies which reported that subjects who participated in structured strengthening programs demonstrated greater strength measures compared to subjects to who did not[17, 18, 21, 45]. The majority of those studies examined home and supervised rehabilitation programs initiated 8 months to 2 years post-surgery[18, 21, 45]. Improvements in hip abduction isometric strength have been observed up to one-year following surgery[16, 31], with no change in strength reported from 2 to 4 years following surgery[85]. Therefore, one would not expect subjects at greater than one-year post-surgery to improve over time. In fact, all of the studies reported no significant changes in strength measures for the control subjects during the intervention period[18, 21, 45]. Only one study reported strength outcomes following rehabilitation programs initiated during the first 6 months post-surgery[17]. Gilbey et al (2003)[17] reported that subjects who participated in an exercise intervention for the 8-weeks prior to and 9-weeks following surgery demonstrated significantly greater hip strength at 12-weeks post-surgery when compared to subjects who did not. In addition, only those subjects who completed the exercise program demonstrated significant improvements in hip strength at 12- and 24-weeks post-surgery compared to pre-surgical values. Hip strength in their study was a combined score of hip flexion, extension, and abduction strength[17]; therefore, we cannot compare our hip abduction strength values specifically to theirs. In addition, they only reported scores at 12-weeks post-surgery compared to pre-surgical values; therefore, it is unknown whether hip strength scores for their subjects changed from 6-weeks to 12-weeks. As our subjects only participated in 6-weeks of exercise following surgery, it may be that the extended exercise period for their subjects post-surgery (9 weeks) combined with 8-weeks of exercise pre-surgery resulted in greater strength improvements compared to a control group.

A possible reason why we observed improvements in hip abduction strength for our control group is that 73% reported participation in some form of post-operative rehabilitation and 27% reported consistent participation in moderate activities, including stair climbing, resisted strengthening exercises, and fast-paced walking. Subjects in the CG were asked to fill out a weekly log tracking the amount and type of activity they performed. In addition, all subjects were contacted each week by an investigator to monitor their status. As a result, it may be that the subjects in the CG were motivated to be physically active during the intervention period. In addition, as a result of the limited ability of these subjects to complete the functional testing independently at the 6-week session (only 5 subjects were able to perform the SUO without external assistance), several subjects stated that they did not realize how difficult it was for them to perform this task and would work to improve their performance. Gilbey et al (2003) did not report if and to what extent their control subjects were active during the intervention period[17]; therefore, it may be that the lack of improvement observed for their control subjects in hip strength from pre-surgery to 12-weeks post-surgery was a result of inactivity.

The most likely reason we did not observe significantly greater improvements in peak hip abduction strength for the EG is that the level of external resistance added during the performance of the exercises was not great enough to result in significant strength improvements. All subjects were provided with a 2.27kg adjustable cuff weight to use for the duration of the study. Eleven of our 13 subjects were able to perform the exercises using the maximum external load within the first week of training; therefore, strength most likely plateaued during the early phases of the the exercise program. It does not appear that introducing new exercises increased demand, as 11 subjects were able to start each new phase of exercises using 2.27kg without incident. When we designed this study, our primary goal and that of the surgeons was to do no harm with our exercise approach. As a result, we chose a very conservative program that could be completed at home with little supervision. One subject reported experiencing brief pain during or following the exercises, and no subject had to cease participation in the exercise program due to injury or pain from the exercises. Therefore, we believe the exercises themselves were not irritating and that it is safe to increase the amount of external resistance applied during the performance of our exercises based on the criteria that the subject is able to complete the task correctly but is challenged. Five pounds was equal to, on average, 25% of the maximal abduction muscle force for subjects in the EG at 6-weeks and only 14% of maximal abduction force at 12-weeks. Anderson and Kearney (1982) suggest that 40-60% of maximal effort of a muscle must be attained before adequate strength gains can be achieved[169]; therefore, our subjects were completing exercises well below the threshold for achieving strength gains. The lack of adequate external resistance during the exercises was most likely the reason we did not see significantly greater improvements in maximum hip abduction strength for our EG when compared to controls.

The overall improvement in hip abduction strength for all of our subjects may have contributed to improvements in performance of the SUO test. At the pre-intervention testing session, only 5/11 subjects in the CG and 11/13 subjects in the EG could perform the SUO without the use of external support. At the post-intervention testing session, all subjects in the EG and 10 of the 11 subjects in the CG were able to complete the SUO unassisted. Previous research has reported that the gluteus maximus and medius muscles of healthy individuals are active at 40-60% of their maximum during the loading and lift-up phases of stair ascent[160]. The average maximum hip abduction strength of the 8 subjects who were unable to perform the SUO independently at 6-weeks was 4.1% of body weight compared to 12.8% of body weight for the 16 subjects who were able to complete the test unassisted. At post-intervention testing, 7 of the 8 subjects who required assistance at 6-weeks were able to perform the SUO independently at 12-weeks. The average hip abduction strength measures for those subjects improved to 9.5% of body weight, while the one subject who was still unable to perform the SUO had maximum hip abduction strength of only 3.5% body weight. Therefore, it appears that as the subjects improved maximal strength of the hip abductors on the involved limb, they were able to complete the SUO independently.

While we did not observe any statistically significant differences between groups for the lift-up and impact indexes, we could only include those subjects who were able to perform the tests independently, as use of external support alters the amount of force generated by the subject during step up and step down. As a result, the number of subjects included in the pre-and post-intervention analysis for the CG was 5 compared to 10 subjects in the EG. No study has reported forces during stair climbing following an exercise program for subjects after THA; therefore, we cannot compare our findings to the findings of other authors. Values for the lift-up index during the SUO were similar between our groups regardless of testing session or with which limb they stepped with. Both groups demonstrated changes for lift-up index of less than 5% body weight from pre- to post-intervention. This difference was significant when subjects led with the involved limb, suggesting that subjects applied more of their body weight to the involved limb during stair ascent at 6-weeks when compared to 12-weeks regardless of group. Loading more weight onto the limb during stair ascent may reflect weakness of the muscles on the stepping limb. The improvement in hip abduction strength observed for our subjects from 6-weeks to 12-weeks may have allowed them to complete the task by applying more normal lift-up forces during the SUO.

Similar improvements over time were observed for impact index when stepping down onto the uninvolved limb. Both groups of subjects transmitted less force through the uninvolved limb at 12-weeks compared to 6-weeks, an average of 7.5% reduction for the EG and 5.2% reduction for the CG. The impact index is described as an indirect measure of eccentric muscle control of the support limb during the lowering of the opposite limb[163]. Therefore, at 12-weeks subjects were better able to control lowering of the uninvolved limb with the muscles of the involved limb. Both groups of subjects demonstrated significant improvements in maximum hip abductor muscle strength from 6-weeks to 12-weeks; therefore, the improvement in strength for our subjects may have contributed to the improved eccentric control during stair descent.

While there were no significant differences between groups for impact index when stepping onto the involved limb, subjects in the CG transmitted 10% BW less force at 6-weeks and 7% BW less force at 12-weeks during the stair descent phase when compared to the EG. In addition, the CG transmitted 10% BW less force at 6-weeks and 5% BW less force when they stepped down onto their involved limb at 12-weeks compared to when they stepped down onto their uninvolved limb. This may serve as a protective mechanism for subjects in the CG. They may avoid loading the newly implanted hip joint because of fear[166]. In contrast, subjects in the EG do not appear to avoid loading their surgical limb during the SUO.

Subjects in both groups significantly reduced the movement time required to perform the SUO from 6-weeks to 12-weeks post-surgery. In addition, subjects in the CG completed the SUO significantly slower than subjects in the EG regardless of testing session. During pre-intervention testing, the CG required on average a second longer to complete the SUO compared to the EG for stepping with both the involved (3.6sec vs. 2.5sec) and uninvolved limbs (3.2sec vs. 2.5sec). While the difference between groups was reduced at 12-weeks, subjects in the CG still required approximately a half-second longer than subjects in the EG to complete the test when leading with involved (2.5sec vs. 1.99sec) and uninvolved limbs (2.4sec vs. 2.0sec). Our results are similar to those reported in previous studies that suggest decreases in stair climbing time and increases in gait speed following an exercise intervention for subjects after THA[21, 45, 46, 100, 101]. Galea et al (2008) reported significant increases in time taken to climb 4 stairs following 8-weeks of either a home or supervised exercise program initiated 8-weeks post-THA[100]. Subjects in both groups also demonstrated improvements in walk speed following intervention[100]. There were no significant differences in outcomes between groups, suggesting that performance of the exercises with or without supervision was effective. We could not compare the time taken by our subjects to complete the SUO to the time required by their subjects to complete the stair climb test as their subjects' climbed four steps, while ours only had to climb one. Wang et al (2002) reported significant decreases in step velocity during gait for subjects at 12- and 24-weeks post-surgery when compared to pre-surgical values; however those subjects who completed exercises during 8-weeks prior to and 9-weeks following THA exhibited significantly greater step velocity post-surgery than subjects who did not complete exercises at both follow-up times[46]. Therefore, it appears that increases in the speed at which subjects can function improves within the first six months following THA regardless of participation in exercise programs. However, the results of our study and Wang et al (2002)[46] suggest that greater improvements in functional speed may occur with an exercise program initiated in the early post-operative phase. Additional studies have also reported significant improvements in gait speed following exercise intervention for subjects who were greater than 1-year post-THA[21, 45, 101]. However, unlike what was observed with our study and Wang et al[46], only the subjects who participated in exercise programs exhibited significant improvements in gait speed during the intervention period. Therefore, similar to the trend observed with increasing strength measures, it appears improvements in velocity of movement stabilize within the first year following surgery.

Similarly, subjects in our study exhibited significant reductions in weight transfer time during the STS following the intervention time regardless of group. Weight transfer time is a measure of the time from the onset of the cue to move until the arrival of the center of gravity (COG) over the feet. Increased WT time decreases the ability of the subject to use momentum to move the body forward in preparation for standing[146]. Therefore, our subjects at 12-weeks demonstrated an improved ability to use forward momentum to assist in lifting their body off of the chair. While WT is not the total time required to rise from a chair, improving WT may decrease the overall time an individual requires to raise from a chair by improving the transfer of momentum. While no previous study has reported a similar value to WT for subjects following THA, Galea et al (2008) did describe improvements in time to complete the Timed-Up-and-Go (TUG) test in subjects following an exercise program. The TUG requires the subject to rise from a chair, walk forward a distance of three meters, turn around, walk back to the chair and sit back down. Therefore, improving the time to rise from a chair may contribute to decreased time to complete this test.

Sway velocity scores during the rising phase and the first 5-seconds of quiet stance did not change between testing sessions and were not different between groups. No study has reported the effects of an exercise intervention on balance scores for patients following THA; however, one study did report significantly impaired postural control for subjects following THA when compared to controls[98]. The balance tests examined in their study assessed postural control during increasingly challenging tasks and at the limits of stability. In our study, postural control was assessed during eyes open quiet standing on a hard surface, which may not be sensitive enough to detect deficiency in this population.

The subjects in the CG exhibited significant improvements in rising index from 6-weeks to 12-weeks post-surgery. In addition, the CG demonstrated significantly reduced RI when compared to subjects in the EG at 6-weeks; however, this difference was negated at 12-weeks. Rising index is a measure of the amount of force exerted by the legs onto the force plate during the rising phase of the STS. The rising phase of the STS is the time from when the COG reaches the toes until upright stance is achieved[165]. Lower scores indicate insufficient force and an inability to use the legs to achieve standing as a result of muscle weakness. As a result, the subject must push themselves off of the chair using their arms. Since maximum hip abduction strength did not differ between our groups at either time point, it may be that subjects in the CG had reduced strength of other lower extremity muscles, specifically the quadriceps muscles, when compared to the EG at 6-weeks. The quadriceps muscles are active at 50-80% of their maximum during the rising phase of the STS[165]. While we did not measure quadriceps muscle strength for our subjects, previous studies have reported the presence of quadriceps muscle weakness in the surgical limb following THA when compared to both contralateral limb strength[166] and strength of a control group[24]. Subjects in the EG reported participation in greater levels of activity compared to the CG at the pre-intervention test, which may have resulted in reduced muscle atrophy and improved quadriceps muscle strength for the EG. The increased level of activity for subjects in the CG during the intervention phase may have improved overall lower extremity muscle strength, allowing them to complete the STS more effectively at 12-weeks.

Subjects in the EG demonstrated less asymmetry during rising and standing when compared to subjects in the CG. At 6-weeks, subjects in the CG loaded more of their body weight (20%) onto the uninvolved limb, while subjects in the EG loaded only 5% more of their body weight onto the uninvolved limb. Following the intervention, asymmetry was unchanged for subjects in the EG, while the subjects in the CG reduced the asymmetry to 9% BW. Subjects in the CG may load the uninvolved limb to a greater extent because of persistent muscle weakness of the involved limb. In addition, loading the surgical limb during rising may be avoided because of fear[166]. Our results for increased asymmetry during the STS for the CG are similar to those reported by Drabsch et al (1998) for subjects at 1-year post-THA. Subjects in their study loaded 20% more of their body weight onto the uninvolved limb during the STS[167]. Following a 6-week individualized training program tailored to improve the components of the STS, subjects in their study reduced the asymmetry by 14% to 6% greater weight on the uninvolved limb[167]. These values are similar to the values observed for our subjects in the EG at both 6-weeks and 12-weeks following surgery. The subjects included in the study by Drabsch et al (1998) reported persistent problems with movement prior to participation in the training program. As demonstrated with most of our dependent measures, the subjects in the CG exhibited poorer overall function at 6-weeks when compared to subjects in the EG; therefore, for subjects in the EG who were functioning more independently, the STS test may not be sensitive enough to detect deficits in movement ability.

Limitations

We chose not to control participation in exercise or activity for subjects during the 6-week intervention time. We did not feel it was clinically acceptable to prohibit post-operative patients from completing necessary rehabilitation. Likewise, we could not control the rehabilitation of the subjects to one clinic or therapist. Instead, we asked subjects to record the type, duration, and level of activities they completed during the intervention period in order to use this information when interpreting our findings. In addition, we assessed activity level of all subjects using the IPAQ. We relied on all subjects to record frequency of exercise and activity level during the intervention; therefore, it is possible that self-report bias affected our results.

We were not able to blind our study. The investigator who conducted the testing was aware of group assignment during both sessions; however, the subjects answered all the questions for the HHS and IPAQ without input from the investigator. In addition, measures for strength and the SUO and STS were calculated from standardized equipment, which was not altered by the investigator. Input from the investigator to each subject was also standardized; therefore, while investigator bias may have affected our results, we feel our standardization methods limited this effect. Our study employed blind randomization of subjects into either the control or experimental group. As a result, there was a discrepancy between groups at baseline testing. Future studies of this nature should stratify randomization based on functional ability of subjects during the SUO and STS in order neutralize differences at baseline testing.

We also did not expect as many subjects to be unable to perform the SUO independently at 6-weeks post-surgery. While this limited our numbers for statistical comparison and likely reduced our power to detect significant differences for the SUO, we feel our sample of subjects adequately represents the typical spectrum of functional ability following surgery.

Conclusion

The results of our study suggest that maximum hip abduction strength along with subjective and objective measures of function improve from 6-weeks to 12-weeks for all subjects following THA. However, those subjects who participated in a 6-week strengthening program targeting the hip abductor muscles participated more in moderate and vigorous activities. In addition, for subjects whose only form of exercise was walking, the addition of the exercises may have improved maximum hip abduction strength measures. The progressive strengthening program employed in our study appears to be safe for subjects to initiate at 6-weeks following surgery. In addition, as demonstrated with our results, subjects could benefit from completing the exercises using greater external resistance in order to generate significant improvements. We recommend subjects begin with external resistance at 5-10% of their maximum hip abduction strength measures and increase external resistance based on individual ability.

Table 4.1: Exercises Included in Phase I of the Intervention

Exercise	Description
Weight-bearing (WB) Hip Abduction	Subjects stand with both lower extremities 10cm apart. The external load will be applied to the uninvolved leg. They will abduct the uninvolved leg 25 degrees and return to the starting position, while maintaining their full weight on their involved leg. During the entire exercise, the subject will maintain their pelvis in a level position and minimize the amount of trunk lean.
Pelvic Hike	Subjects will stand with both lower extremities 10cm apart. While keeping both knees in a fully extended position, they will raise the involved side pelvis toward the ceiling. The patient will then return the pelvis to a level position. The external load will be applied to the involved leg for this exercise.
Mini-Squat	Subjects will stand approximately 6 inches in front of a standard height chair. They will place three (3) pillows on the chair. They will stand with their feet shoulder width apart. The external load will be held in both hands out in front of them for this exercise. They will be instructed to squat so that they bend their knees through an arc of 0 to 30 degrees of flexion, until their rear makes contact with the top pillow. They will be instructed not to squat past 30 degrees of knee flexion. They will be told to sit back so as to prevent their knees from going past their toes.

Table 4.2: Exercises included in Phase II of the Intervention

Exercise	Description
Non-weight-bearing (NWB) Standing Hip Abduction	Subjects stand with both lower extremities 10cm apart. The external load will be applied to the involved leg. They will abduct the involved leg 25 degrees and return to the starting position, while maintaining their full weight on their uninvolved leg. During the entire exercise, the subject will maintain their pelvis in a level position and minimize the amount of trunk lean.
Resisted Side Step	Subjects will stand will both feet approximately a distance of shoulder width apart. Thera-band® elastic resistance (Hygenic Corporation, Akron, OH) will be tied around both legs proximal to the patient's ankles. The patient will be instructed to flex their hip and knees to approximately 20 degrees of flexion. They will step out to the side a comfortable distance and bring the other foot to the stepping foot in a controlled manner. They will continue this for a total of 10 steps and then they will then step back, leading with the opposite foot. Down and back count as one trial. They will complete 3 trials of this exercise.
Medium-Squat	Subjects will stand approximately 6 inches in front of a standard height chair. They will place two (2) pillows on the chair. They will stand with their feet shoulder width apart. The external load will be held in both hands out in front of them for this exercise. They will be instructed to squat so that they bend their knees through an arc of 0 to 60 degrees of flexion, until their rear makes contact with the top pillow. They will be instructed not to squat past 60 degrees of knee flexion. They will be told to sit back so as to prevent their knees from going past their toes.

Table 4.3: Exercises included in Phase III of the Intervention

Exercise	Description
Non-weight-bearing (NWB) Sidelying Hip Abduction	Subjects will lie on their uninvolved side with the involved leg parallel to the uninvolved leg. They will place a pillow between their legs to prevent the involved leg from moving into adduction. The external load will be applied to the involved limb for this exercise. They will abduct the involved leg 25 degrees and return to the starting position.
Resisted Band Walks	Subjects will stand will both feet approximately a distance of shoulder width apart. Thera-band® elastic resistance (Hygenic Corporation, Akron, OH) will be tied around both legs proximal to the patient's ankles. The patient will be instructed to flex their hip and knees to approximately 20 degrees of flexion. They will step forward to a comfortable distance and bring the other foot to the stepping foot in a controlled manner. They will continue this for a total of 10 steps and then they will turn around and walk back. Down and back count as one trial. They will complete 3 trials of this exercise.
Full-Squat	Subjects will stand approximately 6 inches in front of a standard height chair. They will place one (1) pillows on the chair. They will stand with their feet shoulder width apart. The external load will be held in both hands out in front of them for this exercise. They will be instructed to squat so that they bend their knees through an arc of 0 to 90 degrees of flexion, until their rear makes contact with the top pillow. They will be instructed not to squat past 90 degrees of knee flexion. They will be told to sit back so as to prevent their knees from going past their toes.

Table 4.4: Subject Demographics (Mean ± SD)

	Group	
	CG (n = 11)	EG (n = 13)
Gender (M,F)	3M, 8F	11M, 2F
Age (y)	51.6 ± 10.9	58.3 ± 4.9*
Weight (kg)	84.3 ± 15.9	88.6 ± 17.9
Height (cm)	169.5 ± 13.2	177.6 ± 11.5
Time from surgery to first test (days)	44 ± 4	41.2 ± 3.8
Time from surgery to second test (days)	77.6 ± 13.8	89.7 ± 12.8

CG = Control group
EG = Exercise group
M = males
F = females
Y = years
Kg = kilograms
Cm = centimeters

Table 4.5: Scores for the Harris Hip Score by Questionnaire Component (Means ± SD)

	Testing Session			
Total possible score in ( )	PRE		POST	
Component	CG	EG	CG	EG
Pain (44)	32 ± 9.7	36.3 ± 9.1	35.5 ± 8.8	42.2 ± 4.1
Limp (11)	6.5 ± 4	8.8 ± 2.3	8.5 ± 2.6	9.3 ± 2
Support (11)	6.5 ± 4.1	8.3 ± 3.2	9.5 ± 2.7	10.2 ± 2
Distance Walked (11)	5.8 ± 3	8 ± 3.1	8.5 ± 3.8	10.5 ± 1.2
Stairs (4)	1.6 ± 0.5	1.9 ± 0.8	2.7 ± 1.2	3.3 ± 0.98
Socks/ Shoes (4)	1.8 ± 1.1	1.8 ± 1.0	2 ± 1.3	3.2 ± 1.0
Sitting (5)	4.5 ± 0.9	4.8 ± 0.6	4.8 ± 0.6	4.5 ± 0.9
Public Transportation (1)	0.7 ± 0.5	0.75 ± 0.5	0.9 ± 0.3	1 ± 0
Total (100)	65.5 + 21.8	77.9 + 16.5	80.2 + 16.7	93.2 + 9.6

Total possible points are in parentheses

PRE = Pre-intervention testing session

POST = Post-intervention testing session

CG = Control Group

EG = Exercise Group

Table 4.6: Scores for the International Physical Activity Questionnaire (Mean ± SD)

	Testing Session			
	PRE		POST	
Group	CG	EG	CG	EG
TOTAL (MET·min/wk)	3384 ± 1930	4667 ± 2316	5726 ± 2943	8244 ± 2420
WA (MET·min/wk)	3319 ± 1880	4655 ± 2313	5454 ± 2721	7534 ± 2109
MOD (MET·min/wk)	65 ± 145	12 ± 30	272 ± 474	538 ± 1069
VIG (MET·min/wk)	0 ± 0	0 ± 0	0 ± 0	186 ± 456

PRE = Pre-intervention testing session
POST = Post-intervention testing session
CG = Control Group
EG = Exercise Group
TOTAL = Total minutes of all activity per week on the IPAQ
WA = Total minutes of walking activity per week on the IPAQ
MOD = Total minutes of moderate activity per week on the IPAQ
VIG = Total minutes of vigorous activity per week on the IPAQ
MET·min/wk = Metabolic minutes per week

Table 4.7: Peak Isometric Hip Abduction Strength (%BW) (Mean $\pm$ SD)

	Group	
Testing Session	CG	EG
6-week	9.4 $\pm$ 7.8	14.6 $\pm$ 9.6
12-week	10.05 $\pm$ 6	15.1 $\pm$ 7.6

CG = Control group
EG = Exercise group

Table 4.8: Involved Limb Step-Up and Over (Mean ± SD)

	Testing Session			
	PRE		POST	
	CG	EG	CG	EG
LUI (%BW)	42.7 ± 15.4	43.6 ± 12.3	40.2 ± 17.4	39.4 ± 8.5
MT (sec)	3.6 ± 0.9	2.5 ± 0.4	2.5 ± 0.15	1.99 ± 0.4
IMP (%BW)	48.1 ± 23.8	48.1 ± 11	42.9 ± 18.6	40.6 ± 10.2

PRE = Pre-intervention testing session
POST = Post-intervention testing session
CG = Control Group
EG = Exercise Group
LUI = Lift-Up index
MT = Movement Time
IMP = Impact Index
%BW = Percent of body weight
Sec = seconds

Table 4.9: Uninvolved Limb Step-Up and Over (Mean ± SD)

	Testing Session			
	PRE		POST	
	CG	EG	CG	EG
LUI (%BW)	32.6 ± 8.3	36 ± 8.2	34.1 ± 6.5	37.7 ± 7.4
MT (sec)	3.2 ± 0.5	2.6 ± 0.5	2.4 ± 0.2	2.0 ± 0.6
IMP (%BW)	37.7 ± 17	47.6 ± 19	37.6 ± 15.9	44.3 ± 12.9

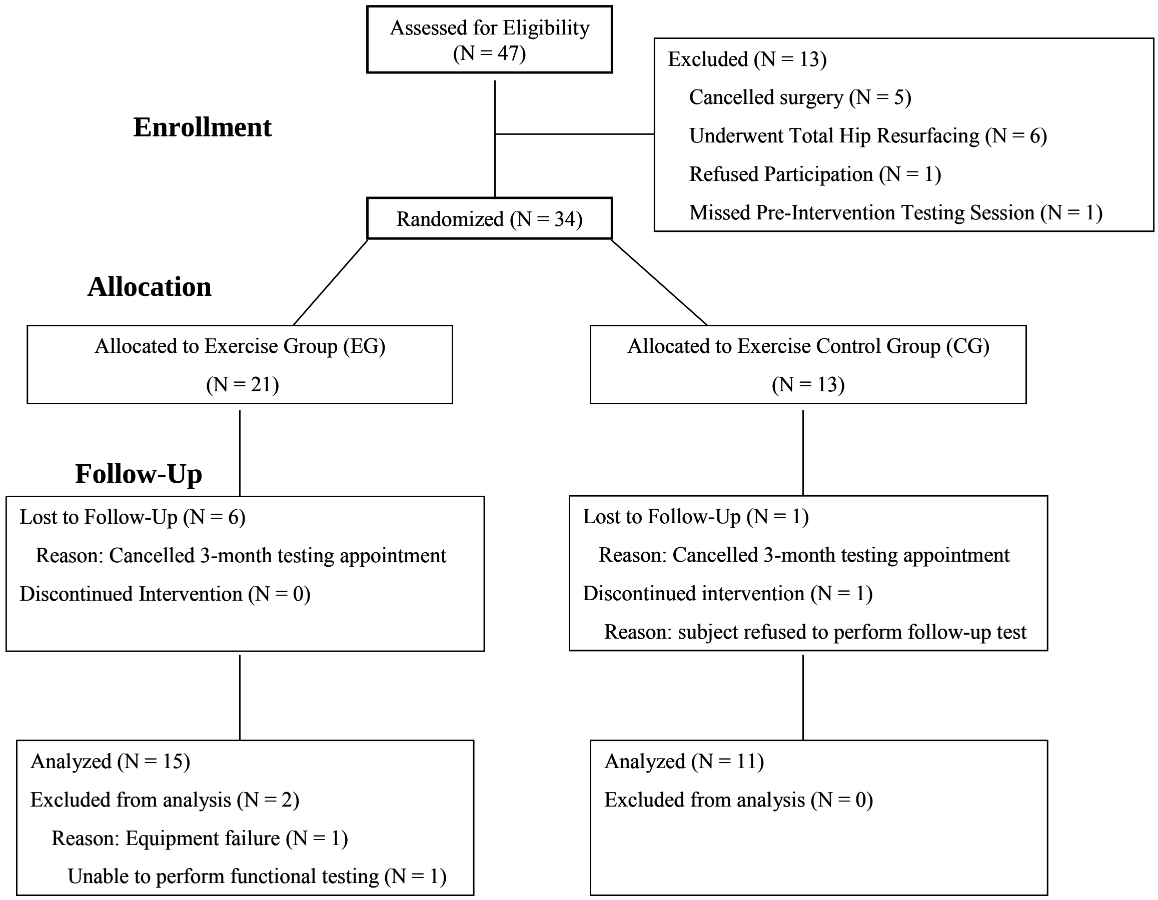
PRE = Pre-intervention testing session
POST = Post-intervention testing session
CG = Control Group
EG = Exercise Group
LUI = Lift-Up index
MT = Movement Time
IMP = Impact Index
%BW = Percent of body weight
Sec = seconds

Table 4.10: Sit-to-Stand (Mean ± SD)

	Testing Session			
	PRE		POST	
	CG	EG	CG	EG
WT (sec)	0.65 ± 0.4	0.6 ± 0.36	0.46 ± 0.44	0.49 ± 0.32
RI (%BW)	8.8 ± 3.3	13.6 ± 4.2	13.2 ± 3.2	13.4 ± 3.6
SV (º/sec)	3.2 ± 1.3	3.3 ± 1.2	3.5 ± 1.1	3.6 ± 1.49
UI (%BW)	20 ± 16.9	4.7 ± 12.4	8.5 ± 13.7	5.1 ± 7.7

PRE = Pre-intervention testing session
POST = Post-intervention testing session
CG = Control Group
EG = Exercise Group
WT = Weight Transfer
RI = Rising Index
SV = Sway Velocity
UI = Uninvolved/Involved Asymmetry
%BW = Percent of body weight
Sec = second

Figure 4.1: Flow Chart of Subject Participation



Chapter 5

Addressing Subjective and Objective Functional Deficits in Designing Activity-Specific Rehabilitation Programs following THA for Younger Patients

Summary

The primary purpose of this dissertation was to examine the effectiveness of a hip abductor strengthening program on subjective and objective clinical outcomes for patients less than 65 years of age following THA. In summary, we will examine the aims and major findings from Chapters 2 through 4 and discuss the implications of our results for treating younger patients following THA. In doing so, we will present a patient-specific activity spectrum which can be utilized to design more appropriate rehabilitation programs in the future. In conclusion, we will present the clinical implications of our study and recommendations for future research aimed at progressing post-operative clinical care for younger patients following THA.

Aims and Major Findings

Specific Aim 1: To document activation levels of the hip musculature and lower extremity kinematics during three functional exercises. In light of previous studies which reported significant differences to exist between males and females during the performance of functional tasks, we chose to examine kinematics and hip muscle activation levels during the lunge, step-up and over, and single leg squat between sexes. Peak hip flexion angle was greater and peak knee flexion angle was less for males compared to females. In addition, females demonstrated significantly greater muscle activation levels for the rectus femoris and gluteus maximus muscles during all tasks when compared to males. These findings are most likely the result of reduced lower extremity strength for the female subjects when compared to males. There were no differences in gluteus medius or adductor muscle activation levels between sexes. Muscle activation levels for all the muscles examined in our study were less than or equal to 30% of maximum; therefore, the performance of these exercises may not result in muscle activation levels which are adequate to increase strength. However, these exercises may be beneficial to incorporate into rehabilitation programs as a safe way to transition patients from early phase controlled exercises to late phase functional strengthening exercises.

Specific Aim 2: To compare short-term subjective and objective clinical outcomes following THA in subjects less than 65 years of age to a cohort of age-matched controls. Persistent strength and functional deficits were observed for subjects at 6- and 12-weeks following THA. Maximum hip abductor strength recovered to only 29% of controls at 6-weeks and 52% of controls at 3 months. Additionally, subjects at both 6-weeks and 12-weeks post-surgery exhibited functional alterations during the step-up and over (SUO) and sit-to-stand (STS) tests compared to controls. Time required to complete the SUO was significantly longer for the THA subjects. During both the SUO and STS tests, the post-operative subjects loaded significantly less weight onto their involved limb when compared to the uninvolved limb and to control subjects. Hip strength deficits following THA have been associated with decrease gait velocity. This study confirms hip abduction weakness is present following THA and adds that other daily functional tasks of getting up from a sitting position and stepping up and over an obstacle are impaired to a significant degree following standard THA rehabilitation. These results would suggest greater emphasis needs to be placed on rehabilitation of functional tasks during the first 3 months following surgery to improve function and help increase physical activity of patients following THA. Overall lower extremity strength also appears to be reduced for the THA subjects, as they were not able to rise from a chair using only their legs to propel them upward. Only 30% of the THA subjects reported participating in consistent moderate level activities at 3-months following THA. Those subjects who did report a moderate activity level may have exhibited greater hip abduction muscle strength and higher outcome scores on the HHS compared to subjects who did not.

Specific Aim 3: To assess the effectiveness of a 6-week hip abductor strengthening program on short-term subjective and objective clinical outcomes following THA for subjects less than 65 years of age. Regardless of participation in the exercise program, subjects improved maximum hip abductor strength, activity level, and function during the SUO and STS tests from 6-weeks to 12-weeks post-THA. However, subjects who did participate in the exercise program demonstrated better self-report outcomes, were able to participate in higher level activities, and exhibited faster movement times during the SUO compared to subjects who did not. Maximum hip abduction strength did not differ between the groups; however, for subjects whose only form of activity was walking, those who completed the exercises had maximum strength values of 14.2% of body weight compared to only 9.8% of body weight for those subjects who did not. Only one subject reported brief pain during completion of the exercises and no subject was unable to complete the program due to pain or difficulty; therefore, it appears that our program was safe for subjects to initiate at 6-weeks following THA. However, in order to achieve greater improvements in strength, subjects needed to progressively increase the level of external resistance applied during the performance of all the exercises.

Proposed Activity-Specific Model for the Development of Post-Operative Rehabilitation Programs for THA

Our results are consistent with previous studies which reported persistent muscle weakness and functional deficits to exist in younger patients following THA[15-22, 24, 42, 91, 92, 99]. The most common reported deficit was reduced hip abductor muscle strength[16, 42, 92, 99]. Weakness of this muscle group contributes to altered kinematics during gait[15, 160] as well as reduced speed of movement[45]. Therefore, rehabilitation programs following THA should target this muscle group to assist patients in returning to normal function. Numerous studies have reported the benefits of a structured exercise program in improving strength and function in these patients[17, 18, 21, 45, 46, 100, 101]; however, the majority of those programs were initiated later than 6 months post-surgery after patients presented with deficits[18, 21, 45, 100, 101]. Post-operative rehabilitation programs that are initiated during the early post-operative period may reduce the occurrence of persistent deficits and allow patients to safely return to their desired level of activity. As such, identifying the type of activities a patient wishes to be able to perform following surgery is essential to creating appropriate rehabilitation programs. Considering this, we propose a patient-specific activity spectrum which lists common activities along a continuum from the most basic level to most advanced level of function (Figure 5.1). We also provide a scoring rubric for clinicians to use as a way to assess performance of patients during the listed activities. This spectrum will assist the rehabilitation specialist in selecting appropriate strengthening and functional exercises to progress patients back to the desired activity.

For those patients who wish to return only to activities of daily life on the low end of the spectrum, such as changing positions, walking, and stair climbing, the exercises included in our 6-week exercise program appear to be appropriate to improve performance of those activities and increase speed of movement. The exercises included in our 6-week strengthening program were based on previous studies which examined gluteus medius muscle activation levels during common hip abductor strengthening exercises[103, 127]. Weight-bearing exercises resulted in greater EMG activation levels of the gluteus medius muscle when compared to non-weight bearing exercises[103, 127]; therefore, we created a three phase progression of exercises which would challenge the hip abductor muscles during isolated movements, transitioning to early functional movements. We felt the combination of exercises would assist in improving muscle strength in a functional manner, allowing patients to return to activities of daily life safely and independently. This type of program appears to be appropriate to return patients back to activities on the low end of the spectrum.

Patients who wish to return to activities in the middle of the physical activity spectrum, such as squatting, carrying external loads, and picking up objects, should complete a rehabilitation program which progresses from the exercises included in our 6-week program to more demanding functional exercises. We feel the lunge, step-up and over, and single leg squat exercises may be appropriate to include in such a rehabilitation program as the final phase of exercises. While we did not observe these exercises to result in muscle activation levels higher than 30%, it is recommended that subjects perform these exercises with an external load. Therefore, we feel the addition of progressive external resistance during these exercises will prepare subjects for safe return to medium demand activities.

Patients who wish to return to activities at the higher end of the spectrum, such as rotation, landing, and lateral movements, should complete the same four phases of exercises as outlined above; however, they should then complete additional phases of exercises which focus on lateral movements, rotational movements, vertical movements, and jogging. Identification of evidence-based exercise progressions for return to these types of exercises for this population has yet to be examined. However, we feel the criteria provided to progress a patient through each activity included in the patient specific activity spectrum, which is included in Table 5, can be used as a guideline to create an exercise progression.

Conclusions and Future Directions

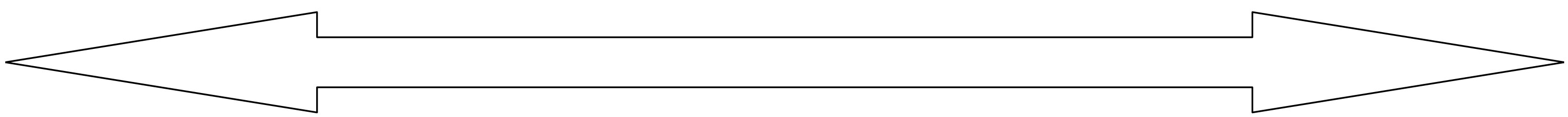
Our study is one of the first to examine the effectiveness of a progressive hip abductor strengthening program on outcomes for younger patients following THA in the early post-operative period. A few observations can be made from our results. We did not provide our post-operative subjects with enough external resistance to continue to challenge them throughout the exercise period. However, despite this, our program demonstrated positive effects on self-reported and objective measures of function. In addition, subjects who completed the exercises were able to participate in higher demand activities. Our program was safe for subjects to begin at 6-weeks following THA, as no subject had to cease completion of the exercises as a result of pain. Finally, as younger post-operative patients express a desire to return to higher demand recreational and sporting activities, appropriate rehabilitation programs need to be developed to address these needs. Our study provides initial evidence that such programs are feasible and have a positive effect on subjective and objective clinical outcomes for these patients. Most importantly, the exercise program incorporated in this study was a home program; therefore, the costs of additional post-operative rehabilitation using our program are small.

Future studies are being established to address some of the limitations within our study. We are using subjective data to identify criteria which patients need to meet before participating in our program of exercise, as our exercises are performed in a weight-bearing unsupported position. We are also modifying our original DAPRE program to progress patients based on percentages of their maximum strength. In addition, we are identifying higher demand exercises to incorporate into future studies examining hip musculature activation levels. It is our goal to develop a transitional evidence-based post-operative hip rehabilitation program to assist younger patients in returning to their desired activity level following THA.

Figure 5.1: Patient Specific Activity Spectrum

Place a mark on the arrow in the area that corresponds to the type of activity you want to be able to perform following surgery

Activity														
Changing Positions	Transfers	Walking	Stair Climbing	Stooping	Carrying External Loads	Squatting	Picking up Objects	Incline	Rotation	Jogging	Lateral Movements	Running	Jumping/ Landing	Cutting



Appendix A

INTERNATIONAL PHYSICAL ACTIVITY QUESTIONNAIRE (August 2002)
SHORT LAST 7 DAYS SELF-ADMINISTERED FORMAT
FOR USE WITH YOUNG AND MIDDLE-AGED ADULTS (15-69 years)

The International Physical Activity Questionnaires (IPAQ) comprises a set of 4 questionnaires. Long (5 activity domains asked independently) and short (4 generic items) versions for use by either telephone or self-administered methods are available. The purpose of the questionnaires is to provide common instruments that can be used to obtain internationally comparable data on health–related physical activity.

Background on IPAQ

The development of an international measure for physical activity commenced in Geneva in 1998 and was followed by extensive reliability and validity testing undertaken across 12 countries (14 sites) during 2000. The final results suggest that these measures have acceptable measurement properties for use in many settings and in different languages, and are suitable for national population-based prevalence studies of participation in physical activity.

Using IPAQ

Use of the IPAQ instruments for monitoring and research purposes is encouraged. It is recommended that no changes be made to the order or wording of the questions as this will affect the psychometric properties of the instruments.

Translation from English and Cultural Adaptation

Translation from English is supported to facilitate worldwide use of IPAQ. Information on the availability of IPAQ in different languages can be obtained at www.ipaq.ki.se. If a new translation is undertaken we highly recommend using the prescribed back translation methods available on the IPAQ website. If possible please consider making your translated version of IPAQ available to others by contributing it to the IPAQ website. Further details on translation and cultural adaptation can be downloaded from the website.

Further Developments of IPAQ

International collaboration on IPAQ is on-going and an ***International Physical Activity Prevalence Study*** is in progress. For further information see the IPAQ website.

More Information

More detailed information on the IPAQ process and the research methods used in the development of IPAQ instruments is available at www.ipaq.ki.se and Booth, M.L. (2000).

Assessment of Physical Activity: An International Perspective. Research Quarterly for Exercise and Sport, 71 (2): s114-20. Other scientific publications and presentations on the use of IPAQ are summarized on the website.

SHORT LAST 7 DAYS SELF-ADMINISTERED version of the IPAQ. Revised August 2002.

INTERNATIONAL PHYSICAL ACTIVITY QUESTIONNAIRE

We are interested in finding out about the kinds of physical activities that people do as part of their everyday lives. The questions will ask you about the time you spent being physically active in the **last 7 days**. Please answer each question even if you do not consider yourself to be an active person. Please think about the activities you do at work, as part of your house and yard work, to get from place to place, and in your spare time for recreation, exercise or sport.

Think about all the **vigorous** activities that you did in the **last 7 days**. **Vigorous** physical activities refer to activities that take hard physical effort and make you breathe much harder than normal. Think *only* about those physical activities that you did for at least 10 minutes at a time.

1. During the **last 7 days**, on how many days did you do **vigorous** physical activities like heavy lifting, digging, aerobics, or fast bicycling?

_____ days per week

No vigorous physical activities ***Skip to question 3***

2. How much time did you usually spend doing **vigorous** physical activities on one of those days?

_____ hours per day
_____ minutes per day
Don’t know/Not sure

Think about all the **moderate** activities that you did in the **last 7 days**. **Moderate** activities refer to activities that take moderate physical effort and make you breathe somewhat harder than normal. Think only about those physical activities that you did for at least 10 minutes at a time.

3. During the **last 7 days**, on how many days did you do **moderate** physical activities like carrying light loads, bicycling at a regular pace, or doubles tennis? Do not include walking.

_____ days per week

No moderate physical activities ***Skip to question 5***

4. How much time did you usually spend doing **moderate** physical activities on one of those days?

_____ hours per day
_____ minutes per day
Don’t know/Not sure

Think about the time you spent **walking** in the **last 7 days**. This includes at work and at home, walking to travel from place to place, and any other walking that you might do solely for recreation, sport, exercise, or leisure.
5. During the **last 7 days**, on how many days did you **walk** for at least 10 minutes at a time?
_____ days per week

No walking ***Skip to question 7***

6. How much time did you usually spend **walking** on one of those days?
_____ hours per day
_____ minutes per day
Don’t know/Not sure

The last question is about the time you spent **sitting** on weekdays during the **last 7 days**. Include time spent at work, at home, while doing course work and during leisure time. This may include time spent sitting at a desk, visiting friends, reading, or sitting or lying down to watch television.
7. During the **last 7 days**, how much time did you spend **sitting** on a **week day**?
_____ hours per day
_____ minutes per day
Don’t know/Not sure

This is the end of the questionnaire, thank you for participating.

Appendix B

Harris Hip Score

Pain	
44	None/Ignores
40	Slight, occasional, no compromise in activity
30	Mild, no effect on ordinary activity, pain after usual activity, uses aspirin
20	Moderate, tolerable, makes concessions, occasional codeine
10	Marked, serious limitations
0	Totally disabled
Function: Gait	
Limp	
11	None
8	Slight
5	Moderate
0	Severe
0	Unable to walk
Support	
11	None
7	Cane, long walks
5	Cane, full-time
4	Crutch
2	2 Canes
0	2 Crutches
0	Unable to walk
Distance Walked	
11	Unlimited
8	6 Blocks

5	2-3 Blocks
2	Indoors only
0	Bed and chair
Functional Activities	
Stairs	
4	Normally
2	Normally with banister
1	Any method
0	Not able
Socks/Shoes	
4	With ease
2	With difficulty
0	Unable
Sitting	
5	Any chair, 1 hour
3	High chair, ½ hour
0	Unable to sit, ½ hour, any chair
Public Transportation	
1	Able to enter public transportation
0	Unable to use public transportation
Total Points	________
	X1.1
	=======
Total Score	_________

Appendix C

Rehabilitation Program

1. Phase I (2 weeks):
    a. Goal of Phase I: The subject will work to progress from an external load during exercise that is equal to 0lbs to a load that is equal to and no greater than 5lbs. For each trial, the external load will be increased at a percentage of the previous trial. Each repetition will be completed using a three-count, with the patient raising the extremity at count one, holding for one count, and lowering the extremity for count three. If at any time the patient experiences painful symptoms in their hip, they will be instructed to cease exercise and contact the principal investigator immediately.
    b. Weight bearing (WB) hip abduction:
        i. The patient will stand with both lower extremities 10cm apart. The external load will be applied to the uninvolved leg for this exercise. They will abduct the uninvolved leg 25 degrees and return to the starting position, while maintaining their full weight on their involved leg. During the entire exercise, the patient will be instructed to maintain their pelvis in a level position and minimize the amount of trunk lean.
    c. Pelvic hike:
        i. The patient will be instructed to keep both knees in a fully extended position and raise the uninvolved side pelvis toward the ceiling, creating abduction of the involved hip. The patient will then return the pelvis to a level position. The external load will be applied to the uninvolved leg for this exercise.
    d. Mini-squat:
        i. The patient will place a chair approximately 6 inches behind them and place three (3) pillows on the chair. They will stand with their feet shoulder width apart. The external load will be dispersed evenly between both hands for this exercise. They will be instructed to squat so that they bend their knees through an arc of 0 to 30 degrees of flexion, until their rear makes contact with the top pillow. They will be instructed not to squat past 30 degrees of knee flexion. They will be told to sit back so as to prevent their knees from going past their toes.
2. Phase II (2 weeks):
    a. Goal of Phase II: The subject will work to progress from an external load during exercise that is equal to 0% of their body weight to a load that is equal to no greater than 5% of their body weight. The patient will follow the inter-trial progression provided for them based on their body weight. For each trial, the external load will be increased at a percentage of the previous trial. Each repetition will be completed using a three-count, with the patient raising the extremity at count one, holding for one count, and lowering the extremity at count three. If at any time the patient

experiences painful symptoms in their hip, they will be instructed to cease exercise and contact the principal investigator immediately.

b. Non-weight bearing (NWB) standing hip abduction:

    i. The patient will stand with both lower extremities 10cm apart. The external load will be applied to the involved leg for this exercise. They will then abduct the involved leg 25 degrees and return to the starting position, while maintaining their full weight on their uninvolved leg. During the entire exercise, the patient will be instructed to maintain their pelvis in a level position and minimize the amount of trunk lean.

c. Resisted side step:

    i. The patient will stand will both feet approximately a distance of shoulder width apart. Thera-band® elastic resistance (Hygenic Corporation, Akron, OH) will be applied proximal to the patient's ankles with neoprene straps. The resistance level (color of elastic band) will be determined as the color necessary to create similar peak external torque as dictated by the DAPRE progression. The patient will be instructed to flex their hip and knees to approximately 20 degrees of flexion. They will step out a comfortable distance and bring the other foot to the stepping foot in a controlled manner. They will continue this for a total of 10 steps and then they will then step back, leading with the opposite foot. Down and back count as one trial. They will complete 3 trials of this exercise.

d. Medium-squat:

    i. The patient will place a standard, non-rolling chair approximately 6 inches behind them and place two (2) pillows on the chair. They will stand with their feet shoulder width apart. The external load will be dispersed evenly between both hands for this exercise. They will be instructed to squat so that they bend their knees through an arc of 0 to 60 degrees of flexion, until their rear makes contact with the top pillow. They will be instructed not to squat past 60 degrees of knee flexion. They will be told to sit back so as to prevent their knees from going past their toes.

3. Phase III (2 weeks):

    a. Goal of Phase III: The subject will work to progress from an external load during exercise that is equal to 0% of their body weight to a load that is equal to no greater than 5% of their body weight. The patient will follow the inter-trial progression provided for them based on their body weight. For each trial, the external load will be increased at a percentage of the previous trial. If at any time the patient experiences painful symptoms in their hip, they will be instructed to cease exercise and contact the principal investigator immediately.

    b. NWB sidelying hip abduction:

        i. The patient will lie on their uninvolved side with the involved leg parallel to the uninvolved leg. The external load will be applied to the involved limb for this exercise. They will abduct the involved leg 25 degrees and return to the starting position.

c. Resisted Band walks
    i. The patient will stand with both feet approximately shoulder width apart. Thera-band® elastic resistance (Hygenic Corporation, Akron, OH) will be applied proximal to the patient's ankles with neoprene straps. The resistance level (color of elastic band) will be determined as the color necessary to create similar peak external torque as dictated by the DAPRE progression. The patient will be instructed to flex their hip and knees to approximately 20 degrees of flexion and walk 10 steps forward, keeping their feet shoulder width apart. They will then turn around and walk the 10 steps back. Down and back count as one trial. They will complete 3 trials of this exercise.

d. Full-squat:
    i. The patient will place a standard, non-rolling chair approximately 6 inches behind them and place one (1) pillow on the chair. They will stand with their feet shoulder width apart. The external load will be dispersed evenly between both hands for this exercise. They will be instructed to squat so that they bend their knees through an arc of 0 to 90 degrees of flexion, until their rear makes contact with the top pillow. They will be instructed not to squat past 90 degrees of knee flexion. They will be told to sit back so as to prevent their knees from going past their toes.

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Vita

Maureen K. Dwyer ATC

General Information

Birth place and date: Worcester, MA, 07/21/1978

Certificate or Specialty Board Licensure:
National Athletic Trainers Association Board of Certification #05002041

I. Education:

2005 – Present The University of Kentucky, College of Health Sciences, Doctor of Philosophy, Rehabilitation Sciences
Expected Completion: May 2009
Dissertation: The Role of the Hip Abductor Muscle Complex in the Function of the Pathological Hip Joint

2000 – 2002 The University of Kentucky, College of Education, Master's of Science in Kinesiology and Health Promotion, concentration in Athletic Training

1996 – 2000 Duquesne University, Rangos School of Health Sciences, Bachelor of Sciences in Athletic Training
NATA Approved Athletic Training Curriculum

II. Professional Experiences:

August 2005 – Present Research Assistant
Advisor: Carl G Mattacola PhD, ATC
Division of Athletic Training
Department of Rehabilitation Sciences
University of Kentucky, Lexington, KY

August 2002 – May 2005 Assistant Athletic Trainer
University of Richmond
Richmond, VA

August 2000 – May 2002 Graduate Assistant Athletic Trainer
Transylvania University
Lexington, KY

III. Teaching Activity

University of Kentucky

Spring 2009	AT700 Muscle Mechanics- Introduction to Kinesiological Electromyography: Guest Lecturer
2006-2009	AT680 Special Topics in Athletic Training: Peripheral Anatomical Dissection: Teaching Assistant
2006-2009	AT695 Orthopaedic Evaluation and Rehabilitation: Lower Extremity- Anatomy, Pathology and Rehabilitation of the Hip joint: Guest Lecturer

Transylvania University

Spring 2008	PE3034 Athletic Injuries and Rehabilitation: Guest Lecturer

Eastern Kentucky University

Fall 2008	ATR401 Rehabilitation Programs for the Hip Joint: Guest Lecturer

IV. Advising Activity

2008-Present	2 Master's students in Division of Athletic Training, University of Kentucky
2006-2008	3 Master's students in Division of Athletic Training, University of Kentucky

V. Honors

2009	Robinson Award for Research Creativity
2007 – 2008	Daniel R. Reedy Quality Achievement Fellowship
2006 – 2007	Daniel R. Reedy Quality Achievement Fellowship
2005 – 2006	Academic Excellence Scholarship
2005 – 2006	Daniel R. Reedy Quality Achievement Fellowship

VI. Professional Activity and Public Service

2009	Athletic Training & Sports Health Care Reviewer
2008	Journal of Athletic Training Reviewer
August 2006-Present	Journal of Sport Rehabilitation Reviewer
August 2006–June 2008	Journal of Sport Rehabilitation Editorial Assistant

Professional Organizations and Societies

2005-Present	Southeastern Athletic Trainer's Association
2000-Present	National Athletic Trainer's Association

VII. Speaking Engagements/Presentations

Invited

May 2009	University of Kentucky Sports Medicine Symposium, Lexington, KY *Rehabilitating Acetabular Labral Injuries in the Hip Joint*
July 2008	Duquesne University Alumni CEU Weekend, Pittsburgh, PA *Evidence-Based Assessment of the Pathological Hip Joint*
March 2008	Southeastern Athletic Trainer's Annual Clinical Symposium and Member's Meeting, Franklin, TN General Session II: Bone and Joint Series: *Evidenced-Based Hip Evaluation.*
January 2008	Kentucky Athletic Trainer's Association Annual Meeting and Clinical Symposium, Highland Heights, KY Athletic Training Student Symposium: *Functional Assessment of the Pathological Hip Joint.*
August 2007	University of Kentucky Rehabilitation Sciences Doctoral Program Fall Colloquium, Lexington, KY *Introduction to Bibliographic Software EndNote and Accessing Distance Learning Resources.*

Peer Reviewed

May 2009	56th Annual Meeting of the American College of Sports Medicine, Seattle, WA Poster Presentation: Prolonged Alterations in Hindlimb EMG Following ACL Transection in An Experimental Model Of Osteoarthritis. <u>Dwyer MK</u>,
June 2008	59th Annual Meeting and Clinical Symposia of National Athletic Trainers' Association, St. Louis, MN Poster- *Comparison of Lower Extremity Kinematics during Rehabilitation Tasks between Genders.* <u>Dwyer MK</u>, Boudreau SN, Mattacola CG, Lattermann CL, Uhl TL
March 2008	Southeastern Athletic Trainer's Annual Clinical Symposium and Member's Meeting, Franklin, TN Poster- *Comparison of Lower Extremity Kinematics during Rehabilitation Tasks between Genders.* <u>Dwyer MK</u>, Boudreau SN, Mattacola CG, Lattermann CL, Uhl TL
March 2008	Southeastern Athletic Trainer's Annual Clinical Symposium and Member's Meeting, Franklin, TN

	Oral- *Hip Musculature Activation during Functional Exercises: the Lunge, Single-Leg Squat, and Step-Up and Over*. Boudreau SN, Dwyer MK, Mattacola CG, Lattermann, C, Uhl TL
March 2008	Southeastern Athletic Trainer's Association Annual Meeting, Franklin, TN Poster- *Reliability and Validity of a 2-D Video Digitizing System Compared to a 3-D Digitizing System during Two Dynamic Tasks.* Amponsah GP, Dwyer MK, Mattacola CG, Uhl TL
February 2007	American Physical Therapy Association Combined Sections Meeting, Boston, MA Thematic Poster- *Gabapentin suppresses spinal cord injury induced spasticity in the rat.* Kitzman PH, Uhl TL, Dwyer MK
June 2006	12th Annual Kentucky Spinal Cord and Brain Injury Research Symposium, Lexington, KY Poster- *Suppression of the glutamatergic system for the management of spasticity in the rat: A preliminary study.* Kitzman PH, Uhl TL, Dwyer MK
May 2000	University of Kentucky Sports Medicine Symposium, Lexington, KY Oral- *A traumatic pneumothorax as a result of a rib fracture in a college baseball player*. Dwyer MK, Uhl TL

VIII. Research Creative Productivity

Publications: Peer Reviewed Journals

Dwyer, MK, Boudreau, SN, Mattacola, CG, Lattermann, CL, Uhl TL. *Comparison of Lower Extremity Kinematics and Hip Musculature Activation during Rehabilitation Tasks between Genders.* Journal of Athletic Training. In Press

Dwyer, MK, . *Prolonged Alterations in Hindlimb EMG Following ACL Transection in An Experimental Model Of Osteoarthritis*. Medicine and Science in Sports and Exercise. 2009; 41(5) Supplement.

Boudreau, SN, Dwyer, MK, Mattacola, CG, Lattermann, CL, Uhl, TL. *Hip Musculature Activation during Function Exercises: the Lunge, Single-Leg Squat, and Step-Up and Over.* Journal of Sport Rehabilitation. 2009; 18: 91-103.

Kitzman PH, Uhl TL, Dwyer MK. *Gabapentin Suppresses Spasticity in the Spinal Cord Injured Rat.* Neuroscience. 2007; 149(4): 813-21.

Mattacola CG, Dwyer MK, Miller AK, Uhl TL, McCrory JL, Malone TR. *Effect of Orthotics on Postural Stability During a Six-Week Acclimation Period.* Archives of Physical Medicine and Rehabilitation. 2007; 88(5): 653-60.

Mattacola CG, Dwyer MK. *Rehabilitation of the Ankle After Acute Sprain or Chronic Instability*. Journal of Athletic Training. 2002; 37(4): 413-429.

Dwyer MK, Uhl TL. *A Traumatic Pneumothorax as a Result of a Rib Fracture in a College Baseball Player*. Orthopedics. 2003; 26(7): 726-727.

IX. Grant Activity

2009 **University of Kentucky Department of Orthopaedics Grant**
Project: Examination of gluteus medius muscle activation before and following Total Hip Arthroplasty or Birmingham Hip Resurfacing in patients with unilateral hip osteoarthritis less than 65 years of age
Investigators: Giordani M, Dwyer M, Stafford K, Mattacola C
Status: Funded
Amount: $20,000