IMPROVING REHABILITATION OUTCOMES AFTER TOTAL HIP ARTHROPLASTY

by

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ABSTRACT

Hip osteoarthritis (OA) is a complex condition requiring characterization of the effects on individuals’ function. The remediation of muscle strength and functional mobility deficits is not achieved through total hip arthroplasty (THA) alone, thus understanding the time course of recovery and the effects of rehabilitation will inform rehabilitation priorities. The overall purpose of this doctoral thesis is to characterize the strength and functional deficits present in end-stage OA and following THA, and to investigate the efficacy of a rehabilitation intervention.

The first study examined strength and functional performance in patients with end-stage hip OA compared with healthy adults of similar age. The results of this study indicate that individuals with hip OA had strength deficits and performed poorer on tests of stair climbing, sit-to-stand and walking. They were also less physically active than their healthy peers. These findings indicate that prior to THA, these individuals have diminished strength and functional performance, which should be considered during postoperative rehabilitation planning.

The second study examined the time course of strength and functional recovery following THA. The results of this study indicated that patients see a significant decline in muscle strength and functional performance one month following surgery. Twelve months after THA, patients exhibit significant deficits in knee extensor and flexor
strength compared with healthy adults. Furthermore, although not statistically significant, differences in functional performance compared to healthy adults remained.

The third study examined the efficacy of a comprehensive, multi-component (CMC) rehabilitation program. The results of this study indicated that individuals who participated in the rehabilitation intervention had greater improvements in stair climbing ability, walking ability, balance and stability compared with individuals who did not receive intervention (CON). Further, there tended to be greater improvement in muscle strength by the end of intervention. Importantly, participation in the CMC intervention did not compromise safety, as there were no incidences of hip dislocation, injury or falls in either group.

Overall, the results of these studies indicated strength and functional deficits present in end-stage hip OA may not be completely remediated by THA surgery alone. An 8-week multi-component rehabilitation program may enhance recovery after THA.

The form and content of this abstract are approved. I recommend its publication.

Approved: Jennifer Stevens-Lapsley
CONTENTS

CHAPTER

I. INTRODUCTION ............................................................................................................................. 1

Study One: Strength and Function in Individuals with End-Stage Hip Osteoarthritis ............................ 2

Study Two: Outcomes Following Total Hip Arthroplasty .................................................................. 4

Study Three: Multi-Component Rehabilitation Following Total Hip Arthroplasty ............................. 6

II. BACKGROUND ............................................................................................................................. 10

Hip Osteoarthritis .............................................................................................................................. 10

Total Hip Arthroplasty ..................................................................................................................... 12

Outcomes Following Total Hip Arthroplasty ..................................................................................... 13

Rehabilitation After Total Hip Arthroplasty ...................................................................................... 16

Summary ............................................................................................................................................ 19

III. STRENGTH AND FUNCTIONAL DEFICITS IN INDIVIDUALS WITH HIP OSTEOARTHRITIS COMPARED TO HEALTHY, OLDER ADULTS ................................................. 21

Abstract ............................................................................................................................................ 21

Introduction ....................................................................................................................................... 22

Materials and Methods .................................................................................................................. 23

Results .............................................................................................................................................. 28

Discussion ........................................................................................................................................ 30

Conclusions ....................................................................................................................................... 34

IV. MUSCLE STRENGTH AND FUNCTIONAL RECOVERY DURING THE FIRST YEAR AFTER THA ........................................................................................................................ 36

Abstract ............................................................................................................................................ 36

Introduction ....................................................................................................................................... 38

Patients and Methods .................................................................................................................... 39
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Results</td>
<td>45</td>
</tr>
<tr>
<td>Discussion</td>
<td>46</td>
</tr>
<tr>
<td>V. MULTI-COMPONENT REHABILITATION FOLLOWING TOTAL HIP ARTHROPLASTY: A RANDOMIZED CONTROLLED TRIAL</td>
<td>55</td>
</tr>
<tr>
<td>Abstract</td>
<td>55</td>
</tr>
<tr>
<td>Introduction</td>
<td>57</td>
</tr>
<tr>
<td>Methods</td>
<td>61</td>
</tr>
<tr>
<td>Results</td>
<td>72</td>
</tr>
<tr>
<td>Discussion</td>
<td>80</td>
</tr>
<tr>
<td>Limitations</td>
<td>92</td>
</tr>
<tr>
<td>VI. SUMMARY</td>
<td>94</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>98</td>
</tr>
<tr>
<td>APPENDIX</td>
<td></td>
</tr>
<tr>
<td>A. REHABILITATION PROTOCOL</td>
<td>110</td>
</tr>
<tr>
<td>B. RAW DATA: FUNCTIONAL OUTCOMES</td>
<td>111</td>
</tr>
<tr>
<td>C. RAW DATA: MUSCLE STRENGTH OUTCOMES</td>
<td>112</td>
</tr>
<tr>
<td>D. RAW DATA: PATIENT SELF-REPORTED OUTCOMES</td>
<td>113</td>
</tr>
</tbody>
</table>
TABLES

TABLE

3.1 Participant Demographics.................................................................28

4.1 Baseline Characteristics of THA and Healthy Adult Group..........................41

4.2 Mean Changes for Primary and Secondary Outcomes ..................................47

5.1 Baseline Group Demographic Description ................................................74

5.2 Baseline Functional Performance and Muscle Strength ................................75

5.3 Changes in Functional Performance and Self-Reported Outcomes ..............77

5.3 Changes in Muscle Strength Outcomes ..................................................80
FIGURES

FIGURE

3.1 Participant Enrollment Flowchart ................................................................. 24
3.2 Muscle Strength Testing Positions ................................................................. 26
3.3 Hip and Knee Muscle Strength Outcomes For OA and Healthy Adult Groups ....... 29
3.4 Functional Performance Measures For OA and Healthy Adult Groups ............. 30
4.1 Self-Reported Outcomes After THA ............................................................... 48
4.2 Muscle Strength Outcomes After THA ............................................................ 49
4.3 Functional Performance Outcomes After THA ............................................... 50
5.1 Study Design ................................................................................................. 62
5.2 Pelvic Tilt Analysis ....................................................................................... 69
5.3 Participant Enrollment Flowchart ................................................................. 73
5.4 Mean Percent Change in Functional Performance Outcomes ......................... 78
5.5 Mean Percent Change in Muscle Strength Outcomes ..................................... 82
CHAPTER I

INTRODUCTION

Total hip arthroplasty is considered a common orthopedic procedure.¹ Currently, over 230,000 total hip arthroplasties (THA) are performed each year in the United States to alleviate pain and disability associated with osteoarthritis (OA).² Over the next 20 years, it is projected that more than 500,000 total hip arthroplasty (THA) procedures will be performed per year.³ Most patients report an overall improvement in health-related quality of life following surgery.⁴⁻⁶ However, the full recovery of muscle strength and function in older individuals after joint replacement remains a major challenge in rehabilitation. Interestingly, self-reported quality of life improvements may be the greatest early after THA,⁷ and quality of life may begin to decline as early as 18 months following surgery.⁷ Furthermore, quality of life measured by the Short Form 36 Health Survey (SF-36) scores have indicated lower physical function scores several years after surgery compared to both general population scores and to a cohort of adults without hip pathology.⁵⁻⁶

The general decline in self-reported quality of life may indicate that postoperative THA management is not adequate. In addition to the declines in self-reported outcomes, researchers have noted that deficits in muscle strength and postural control persist for several months and up to one year postoperatively compared to their age-matched cohorts.⁸⁻⁹ For example, Trudelle-Jackson et al.⁸ reported significant differences in postural stability in patients’ surgical hips one year after surgery and found a correlation between self-reports of decreased function and decreased hip abductor strength. Other studies have shown that hip strength was as much as 20% less in the surgical hip compared to the non-surgical hip one year after
THA, and strength losses and decreased limb loading can still be seen as far out as two years postoperatively.\textsuperscript{10,11} Additionally, this patient population is at an increased risk for falls due to the lasting impairments after surgery.\textsuperscript{8} Despite these deficits, rehabilitation after THA is rarely prescribed.\textsuperscript{8,12} The current normal postoperative course involves a voluntary exercise program for lower extremity strengthening and mobility initiated by inpatient physical therapists after surgery. Because many patients do not regain adequate strength and postural control, current rehabilitation strategies may not be adequate\textsuperscript{8,12} Therefore, quantifying acute strength, postural control and functional deficits before and after surgery, and the time course of their recovery, will allow therapists to better design rehabilitation programs for patients following THA to maximize long term recovery. Further, exploring the feasibility and efficacy of an intervention targeting these deficits may help prioritize rehabilitation priorities. Therefore, the overall purposes of this dissertation work are 1) to characterize the limitations present in end-stage hip OA, 2) describe the time course of recovery following THA, and 3) evaluate a comprehensive rehabilitation program aimed at improving functional mobility and other outcomes following THA. Together, with my research mentor, Dr. Stevens-Lapsley, I have designed a series of research projects which will answer the questions posed above.

\textbf{Study One: Strength and Function in Individuals with End-Stage Hip Osteoarthritis}

Osteoarthritis (OA) is characterized by cartilage loss,\textsuperscript{13} stiffness and pain,\textsuperscript{14} and frequently leads to disability,\textsuperscript{15} leading to 21 million Americans reporting activity limitations directly related to their arthritic condition.\textsuperscript{16} The risk factors for developing OA are numerous, but are primarily related to age,\textsuperscript{17} which is a significant concern for our
aging population. Despite the developing knowledge of the characteristics and cellular contributions to OA and its progression, the impact OA has on physical function and mobility is of greatest concern in rehabilitation.

Quantifying the extent of disease, disability and impact of hip OA on individual physical function remains challenging. Researchers have attempted to describe the severity of the disease and its progression through radiographs, self-reported function and functional performance tests. Since physical function is not highly related to either radiographic OA severity or self-reported function, quantifying physical function with performance tests may provide the most direct measure of individual capabilities. Therefore, this work examined muscle strength, performance-based functional capacity and self-reported quality of life measures in a cohort of individuals with end-stage hip OA and compared these outcomes to a cohort of similarly aged individuals with no history of hip pain or OA.

**Study One: Specific Aims**

**Specific Aim 1**

Determine if patients with end-stage hip osteoarthritis have deficits in lower extremity muscle strength in their surgical leg compared to healthy age-matched counterparts.

- **Hypothesis 1.1** Isometric strength (hip extensors, abductors, adductors, flexors; knee extensors, flexors) in the surgical leg will be decreased compared with healthy aged-matched counterparts.
Specific Aim 2

Determine if patients after THA have deficits in functional performance and physical activity compared to age-matched counterparts.

- **Hypothesis 2.1** Functional performance (stair climbing, sit-to-stand, timed-up-and-go and 6-minute walk) will be decreased compared with age matched counterparts.

- **Hypothesis 2.2** Self-reported physical activity and function (UCLA activity score) will be less than reported by similarly aged healthy counterparts.

**Study Two: Outcomes Following Total Hip Arthroplasty**

When conservative medical treatment fails in the treatment of OA, patients often choose to undergo total hip arthroplasty (THA). Generally, patients are satisfied with their immediate postoperative outcomes when compared with their severe pain and functional limitations prior to THA.\(^4\) However, researchers have suggested that deficits in hip muscle strength, postural control and function do not recover to match their age-matched cohorts.\(^8,9\)

Historically, the success of THA has been based on surgical outcomes and prosthesis survival,\(^25\) or have relied on patient self-reports with questionnaires to evaluate functional outcomes after THA.\(^4,8,26\) While examining patient-reported quality of life after THA is important in understanding an individual’s recovery, other methods of assessing the success of surgery are needed. Since subjective reports of function do not correlate well to objective measures of physical function,\(^27\) a comprehensive examination of objective functional performance after THA, combined with patient-reported outcomes, is warranted. The combination of subjective and objective
measures will provide information on disability and specific patient expectations after surgery, not just the health of the joint undergoing surgery.

Although several studies comparing health-related quality of life in patients after THA have been completed, few have included objective measures of function with patient reported quality of life measures. Additionally, many of the previous investigations are cross-sectional studies which have only looked at self-reported outcomes at one time point after surgery and have not quantified acute strength losses after THA or the time course of functional recovery to compare to their self-reported outcomes. Having such information on impairments and functional limitations, in addition to the self-reported outcomes in this population, will help physical therapists design appropriate rehabilitation programs. Further, quantifying longitudinal changes in these measures will provide a better understanding of the time course of strength and functional recovery, providing guidance for the prescription of appropriate interventions. Therefore, the purpose of this next study was to determine whether adults who have undergone total hip arthroplasty (THA) for end-stage osteoarthritis have postoperative deficits in strength of the surgical lower extremity, postural control, functional performance, and quality of life compared to healthy, similarly aged counterparts.

**Study Two: Specific Aims**

**Specific Aim 1**

Determine if patients after THA have deficits in lower extremity postoperative strength in the surgical leg compared to healthy age-matched counterparts.
• **Hypothesis 1.1** Postoperative isometric strength (hip flexors, extensors, and abductors; knee extensors, flexors) in the surgical leg will be decreased compared with healthy, similarly aged counterparts. Deficits will be apparent one month after surgery and will persist over the one year follow-up period.

**Specific Aim 2**

Determine if patients after THA have deficits in functional performance and postural control compared to age-matched counterparts.

• **Hypothesis 2.1** Functional performance (timed-up-and-go, functional stair climbing, 6 minute walk, sit-to-stand) and self-reports of activity and function (SF-36, HOOS, UCLA activity score) will be decreased compared with age matched counterparts. Deficits will be apparent one month after surgery and will persist over the one year follow-up period.

• **Hypothesis 2.2** Postoperative postural control (timed single limb stance [SLS]) will be decreased compared with healthy, similarly aged counterparts. Deficits will be apparent one month after surgery and will persist over the one year follow-up period.

**Study Three: Multi-Component Rehabilitation Following Total Hip Arthroplasty**

Patients after THA present with long-standing functional mobility difficulties several years after surgery. In particular, gait speed is nearly 20% slower than healthy, older adults and movement asymmetries persist, contributing to altered
mechanics during walking\textsuperscript{34} and stair climbing.\textsuperscript{34,37} Altered mechanics and poor movement quality during daily, functional tasks may negatively impact the health of other joints in the body, including the spine, thus furthering these patients’ difficulty with functional mobility. The persistent, multi-faceted deficits after THA\textsuperscript{31,38-40} suggest that current postoperative management fails to restore full function, highlighting a need for improved postoperative management.

The potential benefits of rehabilitation following THA have not been studied extensively and neither evidence-based guidelines nor a standard of care treatment exist after THA. Therefore, the effectiveness of a treatment approach on patients undergoing THA for osteoarthritis was evaluated. Specifically, a randomized, controlled trial was conducted, consisting of 20 individuals, to study the initial efficacy and safety of a comprehensive, multi-component intervention (CMC) on recovery in the first 10 weeks after THA. Subjects were randomized to one of two groups (10/group): CMC intervention, and a control group which did not participate in the CMC intervention. The CMC intervention involves strength training, neuromuscular control and functional training to improve muscle coordination around the hip and pelvis to enhance functional performance. This intervention is uniquely designed to promote early initiation of core stabilization and neuromuscular control of the pelvis and spine to enhance rehabilitation and maximize functional recovery.

**Study Three: Specific Aims**

**Specific Aim 1**

Determine whether CMC rehabilitation enhances recovery of functional performance after THA compared to CON. Functional outcome measures included
the stair climbing test (SCT; primary outcome), timed-up-and-go (TUG), five-time-sit-to-stand (FTSTS), 6-minute walk (6MW), 4-meter walk test (4MW), Short Form 12 Heath Survey (SF-12), Hip dysfunction and Osteoarthritis Outcome Score (HOOS), and University of California, Los Angeles (UCLA) activity score.

- **Hypothesis 1.1** CMC intervention will result in greater improvements in SCT (primary outcome), TUG, FTSTS, 6MW distance and walking speed (4MW) compared to CON at the end of intervention (primary endpoint; 10 weeks after THA).

- **Hypothesis 1.2** CMC intervention will result in greater improvement in self-reported function and physical activity (SF-12, HOOS, UCLA) at the end of intervention (10 weeks after THA).

**Specific Aim 2**

Determine whether CMC rehabilitation enhances recovery of balance and pelvic stability compared to CON group.

- **Hypothesis 2.1**: CMC intervention will result in greater improvements in balance as assessed by the Fullerton Advanced Balance Scale (FAB) compared with CON.

- **Hypothesis 2.2**: CMC intervention will result in greater improvements in pelvic tilt angle during a single limb stance task (modified Trendelenburg test) compared with CON.
Specific Aim 3

Determine whether CMC rehabilitation enhances muscle strength compared to CON group.

- **Hypothesis 3.1**: CMC intervention will yield greater improvements in hip (flexors, extensors, abductors, and adductors) and knee (extensors and flexors) muscle strength compared to CON at the end of intervention (10 weeks after THA).

Specific Aim 4

Determine the safety of CMC rehabilitation following THA compared to CON.

- **Hypothesis 4.1**: CMC intervention safety will be equivalent to CON as indicated by comparable incidence of musculoskeletal injury (e.g., hip dislocation), pain levels, and falls at the end of intervention (10 weeks after THA).
CHAPTER II

BACKGROUND

Hip Osteoarthritis

Osteoarthritis (OA) is the most common joint disease, compromising the quality of life of and creating frequent health problems for millions of older adults.\textsuperscript{14,41} Osteoarthritis is not a modern affliction. Hip OA and joint disability have been identified in ancient skeletons.\textsuperscript{28,42} Interestingly, the prevalence of hip disease in these ancient skeletons was similar to the prevalence reported in modern day.\textsuperscript{28} According to the Centers for Disease Control and Prevention,\textsuperscript{16} all forms of arthritis currently affect almost 50 million Americans, while an estimated 67 million Americans will be diagnosed with a form of arthritis by 2030. Some risk estimates for developing arthritis are near that of developing cardiovascular disease,\textsuperscript{17} indicating that arthritis is a major health issue facing our aging population. Specifically, hip OA affects up to 28\% of adults over the age of 65\textsuperscript{43} and the lifetime risk of developing hip OA is 25\%, indicating that one in four adults will suffer from hip OA during their lifetime.\textsuperscript{44} OA is characterized by joint degeneration and pain\textsuperscript{14} frequently leading to disability,\textsuperscript{15} and poses a significant burden on the healthcare system because many individuals seek the care of physicians and allied health professionals to alleviate pain and improve quality of life for those living with the disease.\textsuperscript{45}

The physical consequences of hip OA are multi-factorial. Those living with arthritis have seen negative effects on their physical and mental health,\textsuperscript{19} muscle strength,\textsuperscript{46,47} hip range of motion,\textsuperscript{48} and daily function.\textsuperscript{49} In particular, the effect of hip OA on skeletal muscle is marked by loss of muscle strength and muscle mass in the lower
extremity, a likely consequence of disuse.\textsuperscript{50} Further, due to high pain levels and significant hip stiffness,\textsuperscript{48} many individuals are physically inactive,\textsuperscript{51} furthering their muscle atrophy and negatively affecting their functional mobility. As a result, adults with hip OA report difficulty walking,\textsuperscript{49} rising from a chair,\textsuperscript{49} and climbing stairs.\textsuperscript{22} This combination of activity difficulty can lead to mobility disability,\textsuperscript{52} and places a significant financial burden on our healthcare system\textsuperscript{45} and increases mortality risk.\textsuperscript{52}

Osteoarthritis is typically characterized by the loss of articular cartilage in the affected joint. In addition to the loss of articular cartilage, the subchondral bone suffers changes as well, including formation of cysts and osteophytes.\textsuperscript{13} It is thought that these changes to the joint surface are what lead to painful and stiff joints. Once arthritis is present, the progression of disease has been linked to a pro-inflammatory cellular proliferation which affects the structure and development of articular cartilage, encouraging further breakdown of the articular surface.\textsuperscript{17} The specific reasons for the onset of OA are unknown, particularly in primary OA which develops in normal appearing joints.\textsuperscript{13,17} However, it has been accepted that “wear and tear” on the joints is the driving factor in developing OA. Alternatively, secondary OA arises as a result of trauma to the joint, such as injury, and is more prevalent than primary OA.\textsuperscript{17} While the specific causes for developing hip OA may be unknown, it is thought that anatomical abnormalities leading to instability and impingement, examples of joint trauma, may be one cause of disease development.\textsuperscript{17} Additional risk factors for the development of hip OA include advancing age, BMI and genetics.\textsuperscript{53}

To date, there is no cure for OA. Patients often seek medical care to address the pain and stiffness associated with hip OA in order to improve quality of life. Options for medical management include medications and joint injections to control inflammation, and alleviate pain and stiffness. However, when conservative medical management does not alleviate symptoms and improve mobility, surgery is often the next step. In
younger or more active patients, surgeons may prefer a hip resurfacing procedure, which includes replacing the joint surfaces with synthetic material, rather than replacing the entire femoral component. More often, surgeons will perform total hip arthroplasty (THA) to alleviate the pain, stiffness and resultant disability associated with hip OA.

**Total Hip Arthroplasty**

Total Hip Arthroplasty (THA) has been named “the operation of the century” and is recognized as one of the most noteworthy surgeries ever developed. The predecessor to the modern THA prosthesis was developed in the late 1930’s, however efforts to treat hip osteoarthritis (OA) surgically was pioneered more than 100 years ago. The early efforts in the 1930’s were marred by poor material selection and design, and it wasn’t until the 1960’s that John Charnley introduced a new way to perform THA surgery. Charnley is credited as the first surgeon to introduce the idea of using polyethylene as a weight-bearing material to create a low friction arthroplasty and was the first to use acrylic cement in living bone. With a high failure rate of 9% early on, THA was only used in the elderly or sickly people, as it was not expected to affect functional mobility or quality of life. However, as techniques have improved, a viable reason for undergoing THA was to improve quality of life. Since these early efforts, THA has become one of the most common orthopedic surgeries performed, the demand of which is expected to increase by 174% by the year 2030 in both young and older adults.

Modern improvements in THA have targeted a reduction in complications while trying to accommodate increased demand and longevity as younger, more active individuals have required this surgery. Currently, several approaches to performing
THA exist. These include: direct anterior, anterolateral, direct lateral, and posterolateral approaches, all of which affect the musculature around the hip differently. The posterolateral approach is the most widely used approach, and uncemented prostheses are currently the standard way to place the prosthesis. In the posterolateral approach THA, an incision is made surrounding the greater trochanter. Following the skin incision, the tensor fascia latae and gluteal fascia are incised, the gluteus maximus is divided and the gluteus medius is retracted away from the underlying muscles. Finally, the piriformis, gemeli and obturator externus are removed from their attachments so that an incision through the posterior capsule can be performed to access the joint. Moving the joint into flexion and internal rotation, the joint is dislocated, allowing access to the articular surfaces. Although this technique is preferred due to indirect, rather than direct effect on the abductor muscles of the hip, a number of muscles are affected or damaged during surgery and the posterior capsule incision may increase dislocation risk. Thus, surgeons have incorporated techniques to decrease the risk of dislocation, including repair of the posterior capsule and use of larger diameter femoral head components. This has decreased the risk of postoperative hip dislocation to approximately 2%.

**Outcomes Following Total Hip Arthroplasty**

Most individuals are satisfied with pain relief following THA and report an overall improvement in health-related quality of life. However, evidence suggests that individuals demonstrate deficits in muscle strength, functional mobility and postural control compared to their age-matched cohorts which may persist for several months to several years following THA. Muscle strength and functional mobility are negatively impacted immediately following THA. One week after surgery,
individuals demonstrate muscle strength losses of 20-30% and poorer performance on tests of functional mobility, such as walking. The muscle strength losses are not only isolated to the surgical limb hip flexors, extensors and abductors, but are also seen in the quadriceps muscle where atrophy and weakness are present.

While some of these deficits may be remediated through early rehabilitation, the full recovery of muscle strength remains challenging. It has been demonstrated that hip muscle strength does not fully recover after THA, such that patients consistently lack at least 20% of the hip muscle strength of healthy adults. Other studies have shown that hip strength was as much as 20% less in the surgical hip at one year postoperatively, and strength losses and decreased limb loading can still be seen as much as two years postoperatively. Muscle weakness is associated with poor self-reported function, decreased single limb balance, and increased fall risk.

In addition to the challenge of muscle strength recovery, individuals also struggle with postural control, or balance, as well as decreased functional mobility such as slower gait speed and difficulty with activities such as stair climbing. For example, gait speed is nearly 20% slower than healthy, older adults even ten years after surgery. Further, Trudelle-Jackson et al. reported significant differences in postural stability in patients’ surgical hips one year after surgery and found correlation between self-reports of decreased function and decreased hip abductor strength.

While the deficits in muscle strength and functional mobility are obviously observed, a third dimension of functional performance, neuromuscular control, must also be addressed. Neuromuscular control is the ability to perform functional tasks with synergistic muscle activity, producing coordinated, stable movements. Good neuromuscular control optimizes functional performance and reduces the risk of low back pain and other musculoskeletal injuries by coordinating hip and pelvic muscle
activity. \(^6^3\) In particular, neuromuscular control around the hip joint is demonstrated by optimal femoropelvic alignment, in which the pelvis can be maintained horizontally during single limb stance. Femoropelvic alignment is influenced greatly by the performance of the lateral muscles of the hip, in particular the hip abductor mechanism composed of the gluteus medius, the tensor fascia lata and their associated fascia, such as the iliotibial band. \(^6^4\) During a posterolateral approach surgery, these muscles are incised and divided, consequently affecting their performance. Thus, the full recovery of these muscles will affect stability around the hip and pelvis while recovering from THA. Because the role of these muscles are to both move and stabilize the hip, assessment and rehabilitation must address both functions. \(^6^4\)

As described above, the lateral musculature surrounding the hip should facilitate stability through the pelvis, hips and spine, thus optimizing movement quality. Emerging evidence suggests that not only do individuals have difficulty with functional mobility, but movement asymmetries contributing to altered mechanics and poor movement quality during walking \(^3^4\) and stair climbing \(^3^5\) also persist, \(^3^4, 3^6, 3^7\) suggesting poor neuromuscular control and pelvic stability during these activities. Of particular importance is the ability of the lateral hip musculature to maintain a level pelvis during walking and stair climbing, both of which include time standing on one leg. Specifically, individuals may adopt a Trendelenburg compensated gait pattern in which a pelvic tilt and trunk lean to the affected side are observed. As THA commonly results in abductor weakness, the persistent poor walking mechanics \(^6^5\) after surgery, including a Trendelenburg compensated gait, may be due to the inability of the hip abductors to stabilize the pelvis. Other consequences of poor neuromuscular control around the hip are increased stress through the hip joint during walking \(^6^6\) and increased compensatory spinal movement during single limb
activities. As the presence of hip abductor weakness and poor neuromuscular control of the lower limbs and pelvis after THA negatively affect functional tasks such as walking and stair climbing, this phenomenon may help explain why 46% of patients followed for seven years after THA required an assistive device during walking compared with only 8% of healthy, older adults followed over the same time period.

The difficulty with muscle strength recovery, functional mobility and neuromuscular control in the several years following THA may explain why patients have lower physical functioning scores on the SF-36 and are less physically active one year after THA. Research suggests that quality of life improvements may be greatest early after surgery. In particular, self-reported quality of life after THA may begin to decline as early as 18 months following surgery and significant drops in SF-36 scores have been observed 5 and 7 years after surgery. More importantly, the combination of these deficits, which can be present years after THA, has substantial consequences. For example, mobility disability (e.g., the inability to independently walk and climb stairs) places a significant financial burden on our healthcare system and is a risk factor for decreased life expectancy in older adults. Further, mobility disability lead to loss of independence and increases fall risk, which may also increase hospitalization and health care utilization.

**Rehabilitation After Total Hip Arthroplasty**

The persistent muscle strength and functional mobility deficits, combined with the general decline in self-reported quality of life after THA suggest that postoperative management is not adequate. Although the limited recovery and residual deficits in muscle strength and functional mobility are well documented, no
evidence-based rehabilitation guidelines for THA exist. Further, there is no consensus on the course of postoperative care following surgery, including from those performing THA. Recent publications from the American Association of Hip and Knee Surgeons suggest a need for standard postoperative management following THA. In two different surveys, surgeons reported varied preferences for postoperative activity restrictions and recommendations for returning to regular activity; there was no agreement on the best course of care following THA. Further, local, current practice patterns following THA primarily involve only home physical therapy following hospital discharge. Recent communication with local surgeons suggests that most do not prefer their patients attend outpatient rehabilitation because evidence evaluating potential benefits of and guidelines for rehabilitation after THA are not available. Although not well documented in the literature, conversations with rehabilitation specialists and orthopedic surgeons indicate a common misperception that early, intensive intervention may increase musculoskeletal injury, specifically hip dislocation risk. These conversations further suggest that healthcare professionals desire evidence of safe and effective rehabilitation approaches for patients after THA. Therefore, well-controlled studies are essential to better evaluate the safety and efficacy of postoperative rehabilitation approaches for THA.

Although no consensus on managing patients after THA exists, emerging literature supports the utilization of rehabilitation after surgery. In a meta-analysis of previously published trials, Minns-Lowe et al. reported a benefit to rehabilitation after THA, but emphasized that improvements in study quality and intervention are needed. Additionally, in a systematic review of rehabilitation strategies following THA, DiMonaco and Castiglioni concluded that although rehabilitation can improve outcomes following THA, there is poor evidence from which to create effective
exercise protocols. Due to the variable approaches to types of exercise, timing of rehabilitation initiation and variable intensity of exercise prescription, there is no consensus on the optimal type of exercise following THA. However, other preliminary studies have provided evidence that progressive, high intensity strength training after THA may be safe and effective for improving strength and functional performance. Specifically, Husby, et al. investigated the effects of intensive hip abductor strength training within the first month after THA (n=24) and found increases in hip abductor strength compared to a group receiving conventional therapy. Moreover, Rossi et al. observed 50% and 27% increases in hip extensor and flexor strength following early, inpatient and outpatient rehabilitation (n=11). Finally, Wang et al. found improvements in gait speed and six-minute walk distance in a group which began resistance training 3 weeks after surgery (n=28). Importantly, none of these aggressive strengthening approaches resulted in any increase in adverse events.

In addition to the benefits of strength training following injury or surgery, researchers have suggested that neuromuscular retraining may improve physical function and may address the poor quality of movement observed. Specifically, neuromuscular training utilizes weight-bearing exercises to improve muscle coordination and joint stabilization. This type of training has been used successfully to improve hip abductor strength, joint stability, and prevent injury in patients after knee injury, and to reduce symptoms in those with low back pain. Specifically applied to the hip joint, neuromuscular retraining techniques should address the role of the lateral muscles of the hip to stabilize the pelvis. Using weight-bearing exercises to instruct patients how to use their musculature to maintain optimal femoropelvic alignment may augment current strength training programs and further improve functional performance after THA by improving movement quality. Taken
together, these preliminary studies suggest potential benefits of rehabilitation programs focusing on muscle strengthening and neuromuscular control without compromising safety. While improving both strength and neuromuscular control after THA may appear to improve function, no investigations have comprehensively combined these strategies to target both strength and neuromuscular control to maximize functional performance after THA.

Despite the multifaceted deficits reported after THA and evidence that combined strength and neuromuscular control training improve outcomes in THA and in other populations, no studies have combined strength, neuromuscular control, and functional performance training into one intervention following THA. The fact that evidence-based guidelines and a standard of care treatment after THA do not exist, indicates that further investigation on effective rehabilitation strategies is needed. Therefore, a comprehensive study investigating the effects of a multi-component rehabilitation program after THA on muscle strength, neuromuscular control and functional performance is warranted. Such an intervention has potential to mitigate the long term deficits documented in this patient population with the ultimate goal of establishing a new standard of care for THA rehabilitation.

Summary

Hip osteoarthritis is a complex, multi-factorial condition requiring characterization of the effects of this condition on individuals’ functional mobility. Further, the remediation of muscle strength and functional mobility deficits are not achieved through total hip arthroplasty alone, and understanding the time course of recovery after surgery will help inform rehabilitation priorities. Further, current rehabilitation strategies appear to fall
short of goals to fully regain muscle strength and functional mobility and fail to address the multi-faceted deficits seen after surgery. Thus, the overall purpose of this doctoral thesis is to characterize the strength and functional deficits present in end-stage OA and following THA to develop and investigate the efficacy of a rehabilitation intervention to improve strength, function and neuromuscular control after THA.
CHAPTER III

STRENGTH AND FUNCTIONAL DEFICITS IN INDIVIDUALS WITH HIP OSTEARTHritis COMPARED TO HEALTHY, OLDER ADULTS

Abstract

Purpose

Hip osteoarthritis compromises quality of life for many individuals. This study quantified deficits in functional capacity for use in rehabilitation goal setting by combining assessments of muscle strength, function and physical activity in patients with hip osteoarthritis and healthy adults.

Methods

Twenty-six patients with end-stage hip osteoarthritis and 18 healthy adults participated. Isometric muscle strength around the hip and knee was measured. Function was assessed using stair climbing, five-time-sit-to-stand, timed-up-and-go and six minute walk tests. The UCLA activity rating scale assessed physical activity. Analyses of covariance (ANCOVA) were used to assess differences between groups.

1 The following article has been reprinted with permission from: Judd DL, Thomas AC, Dayton MR, Stevens-Lapsley JE. Strength and Functional Deficits in Individuals with Hip Osteoarthritis Compared to Healthy, Older Adults. *Disabil Rehabil*. 2014;36(4):307-12.
Results

Patients had 30% less knee extensor (P<0.001), 38% less knee flexor (p<0.001), 10% less hip flexor (P=0.47), 23% less hip extensor (P=0.24), and 17% less hip abductor strength (P=0.23) than healthy adults. Hip adductor strength was equal between groups (P=0.93). Patients were 50% slower on the stair climbing test (P=0.001), 34% slower on the timed-up-and-go test (P=0.004), 34% slower on the five-time-sit-to-stand test (P=0.001), and walked 28% less during the six-minute walk test (P<0.001). Patients were less physically active (P=0.001).

Conclusions

Patients had deficits in muscle strength, function and physical activity compared to healthy adults. Quantifying these deficits provides benchmarks for improvement during rehabilitation.

Introduction

Osteoarthritis (OA) is the most common joint disease, creating frequent health problems and compromising the quality of life for almost 27 million Americans. Specifically, hip OA affects up to 28% of adults over the age of 65 and the lifetime risk of developing hip OA is 25%, indicating that one in four adults will suffer from hip OA during their lifetime. Additionally, 21 million Americans report activity limitations directly related to their arthritic condition, potentially posing a significant burden on the healthcare system.

Generally, OA is characterized by cartilage loss, stiffness and pain, and frequently leads to disability. In addition to the loss of articular cartilage, the
subchondral bone suffers changes as well including formation of cysts and osteophytes. The specific reasons for the onset of OA are unknown and the risk factors for developing OA are numerous. For the rehabilitation professional, the impact of hip OA on muscle strength, physical functioning and physical activity is of interest and should serve to guide intervention planning. However, setting therapy goals for patients based on their physical status can be challenging, as the degree of improvement desired or required is unknown. Therefore, it is imperative to quantify muscle strength and functional deficits in patient populations and in non-patient populations before therapy goals can be determined.

Studies establishing estimates of muscle strength and physical function for people with and without OA can aid rehabilitation professionals in their goal setting and intervention planning. To our knowledge, no studies are available that compare patients with end-stage hip OA to healthy adults on the combined outcomes of muscle strength, physical functioning and physical activity. Therefore, the purpose of this study was to quantify the deficits in muscle strength, functional performance and physical activity in patients with end-stage hip OA compared to healthy adults to provide benchmarks for rehabilitation goal setting.

**Materials and Methods**

**Participants**

Patients with end-stage hip osteoarthritis who were scheduled for total hip arthroplasty (THA) were recruited from four community hospitals between June 2010 and August 2011 (Figure 3.1). Patients were recruited by physician referral or advertisement at pre-operative educational sessions. Healthy adults with no history of hip or knee osteoarthritis or joint replacement were recruited from the community via
email advertisement between January 2011 and March 2011. All participants were
between the ages of 45-80 and were excluded if they had: uncontrolled hypertension,
uncontrolled diabetes, body mass index ≥40 kg/m², additional lower extremity
orthopaedic pathology (e.g. hip dysplasia) or neurologic disorders that impaired daily
function. All participants attended one testing session to assess muscle strength,
functional performance, and physical activity levels. Each testing session followed the
same test sequence. Each participant was provided written, informed consent and the
study was approved by the Colorado Multiple Institutional Review Board.

Figure 3.1. Participant enrollment flowchart.
Outcome Measures

Muscle Strength

Strength of the hip flexors, extensors, abductors, and adductors and the knee extensors and flexors was assessed using an electromechanical dynamometer (HUMAC NORM, CSMI Solutions, Stoughton, MA) connected to a Biopac Data Acquisition System (Biodex Medical Systems, Inc., Shirley, NY) running AcqKnowledge software (v 3.8.2). Strength was measured in the affected limb for patients with hip OA and in the right limb of healthy adults. For hip flexor and extensor strength assessment, participants were positioned in supine with the hip flexed to 40° (Figure 3.2a). Hip abductor and adductor strength were measured while participants were positioned side-lying with 0° of hip flexion/extension and 0° of hip abduction/adduction (Figure 3.2b). Knee extensor and flexor strength were assessed while the participants were seated with 85° of hip and 60° of knee flexion as previously described (Figure 3.2c). Participants performed a series of maximal voluntary isometric contractions (MVICs) which were preceded by two sub-maximal warm-up contractions. All participants were given visual targets and strong verbal encouragement during each MVIC to aid in eliciting maximal effort. All MVICs were performed by allowing the patient to gradually increase force to his/her maximum ability; maximal effort was maintained for three to five seconds. Patients were allowed 30 second rest periods between repetitions. MVICs for all muscle groups were performed twice and the trial with the highest torque (Nm) was normalized to participant body mass (kg) and used for analysis.
Figure 3.2 (A-C). Muscle Strength Testing Positions. A) Study participant positioned on the dynamometer for hip flexor and hip extensor strength testing B) Study participant positioned on the dynamometer for hip abductor and hip adductor strength testing C) Study participant positioned on the dynamometer for knee extensor and knee flexor strength testing

Functional Performance

Measures of functional performance included the stair climbing test (SCT), five time sit-to-stand test (FTSTS), timed-up-and-go test (TUG) and six minute walk test (6MW). The SCT determines how long it takes a patient to ascend and descend 12 stairs. Participants were instructed to climb a flight of 12 stairs, turn around at the top and descend the same flight as quickly and safely as possible. They were permitted to use the handrail for balance but were instructed not to use the handrail to push or pull
themselves up or down the stairs. The FTSTS test measures the time it takes to stand up from and sit down in a chair five consecutive times. Each participant was seated in a standard chair (height 43.2 cm) and was instructed to transfer to a standing position and return to a sitting position as quickly as possible five times. Participants were instructed not to use their arms to push themselves up from the chair unless they were unable to complete the task without the use of their arms. The TUG measures the time to rise from a chair, walk 3 meters, turn around, and return to a sitting position in the same chair without physical assistance. The 6MW test assesses how far a person can walk in six minutes. Each participant performed this test in a 30.5m hallway and the total distance covered, in meters, was recorded.

Physical Activity

All participants reported their physical activity level using the UCLA Activity Scale. This scale consists of 10 activity levels ranging from “wholly inactive” (level 1) to “regular participation in impact sports” (level 10) and has been used effectively to monitor physical activity in individuals with OA.

Statistical Analysis

Since no preliminary data were available, sample size estimates were determined using data from the 6MW test from the first eight THA and eight healthy adults tested. Using the means and standard deviations from the 6MW test in each group, our effect size was 0.67. Using a type I error protection of 0.05 and a power of 0.95, we anticipated 18 patients were needed to detect a difference in 6MW distance (primary outcome). The sample size of THA patients was conservatively increased to 26 to account for the potential to follow-up after THA or possible data collection problems.
Study data were collected and managed using REDCap electronic data capture tools hosted at the University of Colorado Anschutz Medical Campus. REDCap (Research Electronic Data Capture) is a secure, web-based application designed to support data capture for research studies. Analyses of covariance (ANCOVA) were used to assess differences in each independent variable between hip OA patients and healthy adults, using sex as a covariate. An alpha level of 0.05 was designated for statistical significance. Statistical analyses were performed using IBM SPSS software (version 19, Armonk, NY). To further describe the differences between groups in each outcome measure, percentage differences between groups, using group means, were calculated.

**Results**

Twenty-six patients with end stage OA and 18 healthy adults participated in the study (Table 3.1). There were no differences in age or BMI between the hip OA group and the healthy group. Further, the ANCOVA results showed no effect of sex on any of the outcomes measured.

| Table 3.1. Participant Demographics. *Mean ± standard deviation, unless otherwise noted. BMI= body mass index. OA= osteoarthritis |
|---|---|---|---|
| **Sample Size** | Hip OA | Healthy Adults | p-value |
| | n=26 | n=18 | -- |
| **Sex** | 18 female; 8 male | 11 female; 7 male | -- |
| **Age (years)** | 61.4±8.1 | 58.7±7.3 | p=0.27 |
| **BMI (kg/m²)** | 27.9±5.1 | 29.9±14.3 | p=0.50 |
**Muscle Strength**

Patients with hip OA had 30% less knee extensor strength (P<0.001) and 38% less knee flexor strength (P<0.001) than healthy adults (Figure 3.3). Further, patients demonstrated 10% less hip flexor strength (P=0.47), 23% less hip extensor strength (P=0.24), and 17% less hip abductor strength (P=0.23) than healthy adults. Hip adductor strength was nearly equal between groups (P=0.93) (Figure 3.2).

![Figure 3.3. Hip and knee muscle strength in hip OA group and healthy adult group. Mean ± standard error. * differences between groups (P<0.05).](image)

**Functional Performance**

Compared with healthy adults, patients with end-stage hip OA had increased difficulty with all functional tasks (Figure 3.4). Specifically, patients were 50% slower on the SCT (P=0.001) and 34% slower on the TUG (P=0.004). Further, adults with hip OA performed the FTSTS 34% slower than healthy adults (P=0.001) and walked 28% less distance during the 6MW (P<0.001).
Figure 3.4. Functional performance measures for participants in hip OA group and healthy adult group. Mean ± standard error. SCT= stair climbing test; FTSTS=five time sit to stand; TUG=timed up and go; 6MW= six minute walk test. *difference between groups (P<0.05).

Physical Activity

Participants with end-stage hip OA were less physically active than healthy adults (P=0.001). The average UCLA activity score for patients with hip OA was 5.5±1.7, indicating they participate in moderate activity, but not on a regular basis. Comparatively, the average UCLA activity score for healthy adults was 7.6±1.9, indicating they regularly participate in active events.

Discussion

Due to the fact that not all individuals with end-stage hip OA are candidates for total hip arthroplasty, developing appropriate and effective rehabilitation interventions to improve physical functioning is imperative. This study evaluated the combined outcomes
of muscle strength, functional performance, and physical activity in a group of people with and without end-stage OA to quantify the differences in these outcomes. These data suggest that adults with end-stage hip OA have less knee extensor and flexor strength, poorer performance on physical function tests and are less physically active than their healthy peers indicating that rehabilitation professionals should consider a comprehensive approach at improving these aspects in this population.

While 10-25% deficits in hip muscle strength were observed, differences compared to healthy adults were not significant, which was unexpected. However, strength differences of 10% or greater have been considered clinically meaningful for other lower extremity muscle groups,44 therefore, the differences observed in the current study could be considered clinically meaningful. Nevertheless, our hip strength results are similar to the results reported by Rydevik et al.46 who found no differences in isokinetic hip flexor and extensor strength in individuals with hip OA compared with healthy adults. Additionally, Grimaldi et al.95 reported no differences in hip muscle cross sectional area compared with healthy adults. However, Arokoski et al.96 did report differences in hip muscle strength in patients with hip OA compared with healthy controls and Rasch et al.47 found differences in isometric hip muscle strength when comparing the diseased hip to the healthy hip in patients. The current study results, combined with the differing results previously reported,46,47,95,96 suggest considerable variability in muscle strength outcomes around the hip joint. Such variation might be explained by difficulties isolating specific muscles during testing or related to the choice of testing positions. Additionally, this study included participants in a wide range of ages, including those considered young for joint replacement surgery. The inclusion of this younger cohort could have contributed to lack of significant differences between our patient and healthy groups, as strength loss due to OA in younger individuals may not be as dramatic. Due to the varied outcomes in previous work, and in light of the fact that
clinically significant differences in hip muscle strength were observed, we recommend that rehabilitation specialists do evaluate the muscle strength surrounding the hip to guide clinical decision making.

In contrast with the strength findings in the hip musculature, our results do suggest that individuals with end-stage OA exhibit weakness in the knee extensor and flexor muscles compared to healthy adults. The presence of knee extensor weakness is a clinically important finding in this population due to the relation between knee extensor strength and functional mobility\textsuperscript{22} and may explain the reason adults with hip OA struggle with daily activity\textsuperscript{97} and performed poorly on the functional tasks evaluated in this study. However, whether quadriceps weakness is related to hip disease itself, or a secondary product of disuse and physical inactivity is less clear. In agreement with our findings, Rydevik \textit{et al.}\textsuperscript{46} indicated that adults with only mild to moderate hip OA displayed knee extensor weakness of up to 20\% compared with healthy adults. Similarly, Rasch \textit{et al.}\textsuperscript{47} also reported knee extensor weakness in the arthritic limb compared to the contralateral limb in patients with hip OA. Nonetheless, quadriceps strength plays an important role in daily function\textsuperscript{22} and quadriceps weakness is clearly present in this population, suggesting that individuals with hip OA may benefit from a rehabilitation program which includes a quadriceps strengthening component.

In combination with strength deficits, individuals with hip OA were slower on the SCT, FTSTS, TUG and walked less distance during the 6MW test than healthy adults. The deficits in functional performance all exceeded values considered to be clinically meaningful.\textsuperscript{98,99} These findings are consistent with others who have reported that patients with hip OA have difficulty with daily activity.\textsuperscript{20,49} Additionally, several studies\textsuperscript{20,21,46} have indicated that individuals with hip OA report lower scores on the Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC) physical functioning subsection. Overall, these previous studies support our findings that
individuals with hip OA have difficulty with daily activities such as walking, stair climbing and rising from a chair. However, the current study provides a more comprehensive examination of functional performance and muscle strength in patients with hip OA compared to healthy adults by combining several assessments of functional capacity. These data provide values for goal setting and intervention planning for patients living with end-stage hip OA and offer estimates of the amount of improvement which may be meaningful.

Finally, individuals with hip OA are less physically active than their healthy peers. This finding is consistent with previous studies. Specifically, Venhoff et al. and Pisters et al. not only observed lower levels of physical activities in individuals with hip OA, but also found that this was related to diminished functional ability and was a risk factor for future physical limitations. Further, Holsgaard-Larsen, et al. suggest that the increase in mortality risk experienced by those with OA may be ameliorated with increases in physical activity. Therefore, it is important to ensure that rehabilitation interventions not only consist of muscle strengthening and functional training, but that techniques to improve physical activity levels are included.

The results of this study provide a comprehensive description and quantification of the deficits in muscle strength, functional performance, and physical activity in patients with end-stage hip OA. Since many people with end-stage OA may not be candidates for THA, or may elect not to have surgery, rehabilitation professionals may play an integral role in improving function in this population. These data suggest that rehabilitation should focus on knee extensor and flexor strengthening, functional training and techniques to improve physical function, the combination of which may not be the standard of care presently. Further, rehabilitation professionals should implement a plan of care which aims to improve muscle strength by 30-40% and physical functioning by 40-50% to restore patients’ level of function to that of their healthy peers.
Study Limitations

We acknowledge limitations to this study. First, the relatively small sample size may affect the generalizability of the study. However, our findings were consistent with other studies investigating function and strength in patients with hip OA. Nonetheless, further depicting the existence of strength impairments in this population.

Conclusions

Adults with end-stage hip OA were 10-38% weaker in their arthritic lower extremity, performed 28-50% poorer on functional tests and were less physically active than healthy adults. These results establish estimates of the deficits in muscle strength, physical function and physical activity for people with and people without osteoarthritis. This information can aid rehabilitation professionals in their goal setting and intervention planning for individuals living with end-stage hip OA. Further, muscle strength, function and physical activity should be studied after THA to assess the time course of recovery following surgery and the success of postoperative management.

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Declaration of Interest

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CHAPTER IV

MUSCLE STRENGTH AND FUNCTIONAL RECOVERY DURING THE FIRST YEAR
AFTER THA

Abstract

Background

Patients undergoing total hip arthroplasty (THA) often are satisfied with the decrease in pain and improvement in function they achieve after surgery. Even so, strength and functional performance deficits do persist after recovery, but these remain poorly characterized; knowledge about any ongoing strength or functional deficits may allow therapists to design rehabilitation programs to optimize recovery after THA.

Questions/Purposes

The purposes of this study were to (1) evaluate postoperative muscle strength, function, and quality of life during the first year after THA; and (2) compare strength and function in patients 1 year after THA to a cohort of healthy peers.

Methods

Twenty-six patients undergoing THA were assessed 1, 3, 6, and 12 months postoperatively, and 19 adults with no hip pathology were tested as a control group.

2 The following article has been reprinted with permission from: Judd DL, Dennis DA, Thomas AC, Wolfe P, Dayton MR, Stevens-Lapsley JE. Muscle Strength and Functional Recovery During the First Year Following THA. Clin Orthop Relat Res. 2014 Feb;472(2):654-64.
Isometric muscle strength (hip flexors, extensors, abductors, knee extensors, and flexors), functional performance (stair climbing, five-time-sit-to-stand, timed-up-and-go, 6-minute walk, and single-limb stance tests), and self-reported function (Hip Disability and Osteoarthritis Score, SF-36, and UCLA activity score) were compared.

Results

One month after THA, patients had 15% less hip flexor and extensor torque, 26% less abductor torque, 14% less knee extensor and flexor torque, and worse performance on the stair climbing, timed-up-and-go, single-limb stance, and 6-minute walk. Compared with healthy adults, patients 12 months after THA had 17% less knee extensor and 23% less knee flexor torque; however, the functional testing (including stair climbing, five-time-sit-to-stand, and the 6-minute walk) showed no differences with the numbers available between patients undergoing THA and healthy control subjects. SF-36 Physical Component Scores, although significantly improved from preoperative levels, were significantly worse than healthy adults 1 year after THA (p < 0.01).

Conclusions

Patients experience early postoperative strength losses and decreased functional capacity after THA, yet strength deficits may persist after recovery. This may suggest that rehabilitation may be most effective in the first month after surgery.

Level of Evidence

Level II, therapeutic study. See the Guidelines for Authors for a complete description of levels of evidence.
Introduction

Individuals are often satisfied with their immediate postoperative pain relief compared with their severe limitations prior to THA, and most patients report an overall improvement in health-related quality of life during the first year after surgery. However, self-reported quality of life after THA may begin to decline as early as 18 months following THA and functional mobility deficits persist several years after surgery. Therefore, the full recovery functional mobility for individuals after THA may be a challenge in rehabilitation. The persistent functional deficits present after THA may have substantial consequences, including leading to increased fall risk. Further, mobility disability (e.g., the inability to independently walk and climb stairs) places a burden on our healthcare system due to increased utilization and is a risk factor for decreased life expectancy in older adults.

Although several studies regarding THA have been completed, few have included performance-based measures which represent common activities of daily living. Historically, the success of THA has been based on surgical outcomes and prosthesis survival or has relied on patient self-reports with questionnaires to evaluate functional outcomes after THA. Because self-report measures of function do not correlate well to performance measures of physical function and may overestimate patients’ true functional abilities, a more comprehensive evaluative strategy is needed. Moreover, while some recent investigations have examined periodic recovery after THA, other investigations have been cross-sectional or have examined only two time points after THA. Therefore, the ability to identify the time course of functional recovery for comparison to self-reported outcomes is limited. Furthermore, few have examined both self-reported and performance-based outcomes as early as one month after THA to characterize outcomes during early recovery. Information regarding early strength and
function decline following THA can guide decision-making not only for surgeons prescribing rehabilitation early after surgery, but also to therapists to design effective intervention. Finally, no previous study has compared the combination of self-reported and performance-based strength and mobility outcomes to an identically tested cohort of healthy peers.

Considering the limitations of previous investigations, there exists a need to objectively and comprehensively evaluate functional and strength deficits after THA to provide insights into modifiable targets for postoperative rehabilitation. We therefore sought to (1) compare measures of postoperative hip and knee strength, functional performance and quality of life measured over the first year after THA to preoperative levels and (2) compare the outcomes one year post-THA to adults with no hip pathology. We hypothesized that adults undergoing THA will have deficits in postoperative hip and knee strength and demonstrate poorer mobility such that performance on each measure of function would be worse 1 month after THA (primary endpoint) when compared to preoperative levels. Furthermore, we hypothesized that patients would report worse outcomes on self-reported measure of quality of life and be less physically active 1 month after THA. Additionally, we hypothesized that 1 year after THA, deficits in surgical knee and hip muscle strength, functional performance, and quality of life will persist when compared to healthy peers.

**Patients and Methods**

This investigation was a prospective, longitudinal study. We enrolled patients undergoing THA between June 2010 and August 2011 and evaluated all outcomes before and 1, 3, 6, and 12 months after THA. We also examined a cross-sectional cohort of healthy older adults for further comparison.
Twenty-six patients undergoing THA, performed through a posterior approach, were recruited from four community hospitals by physician referral or advertisement at preoperative educational sessions. Nineteen healthy adults from the community were recruited by email advertisement. All participants were considered eligible if they were between the ages of 45 and 80 years and had no history of uncontrolled hypertension or diabetes, body mass index > 40 kg/m², additional orthopaedic pathology, or neurologic disorders that impaired daily function. Healthy adults had no known history of knee/hip osteoarthritis or joint arthroplasty. Each participant provided written, informed consent and the study was approved by the Colorado multiple institutional review board.

Sample size estimates were based on previous work examining lower extremity muscle strength before and 5 weeks after THA. Estimates from the nonsurgical leg were used to represent healthy control subjects. For calculations, differences in hip abductor strength between surgical and nonsurgical legs 5 weeks after THA are (mean ± SD) 23 ± 9 kg (surgical) and 37 ± 13 kg (nonsurgical). This represented a large effect size (1.25 SD). Presently, there is no evidence to determine the minimum clinically meaningful difference. From these numbers, a sample size of 15 subjects per group would provide 90% power to detect differences between patients with THA and healthy control subjects 1 month after surgery. Therefore, we estimated that we should enroll 20 participants with THA to anticipate a 20% dropout rate through 1 year and at least 15 healthy control subjects. Although our focus and sample size estimates centered on the 1-month time point after THA, we chose to additionally follow the trajectory of recovery over one year to better characterize recovery.

There were no differences between the THA group and healthy adult group for age, sex, or body mass index (Table 4.1). During the 1-year follow up, we had eight subjects without complete testing. Two received contralateral THA before the 1-
year follow up, one had a dislocation after 6 months, one an intraoperative fracture, and four were unable to be reached at the 1-year time point.

All patients receiving THA had osteoarthritis. All operative procedures were performed using a posterior approach and cementless THA implants. After surgery, patients were directed by their surgeon to adhere to postsurgical movement precautions, including no hip flexion above 90°, hip internal rotation, or hip adduction. All patients received inpatient physical therapy, including education, activities of daily living, and mobility training during a 2- to 3-day postoperative hospital stay. All patients were then discharged to home and received anywhere from zero to eight home and outpatient physical therapy (PT) visits (mean±SD: 4.0±3.0 home PT; 2.0±3.0 outpatient PT visits). Anecdotally, communication with therapists, chart reviews, and patients’ reports indicated that treatment focused on mobility training, range of motion exercises, stretching and functional activity. The combination of the limited number of PT sessions, as well as the low volume and intensity of exercise suggests PT may not have substantially improved the trajectory of recovery.

| Table 4.1. Baseline characteristics of the THA and healthy adult groups |
|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
| Variable                   | Healthy (N Mean ± SD)       | THA (N Mean ± SD)           | P-value                    |
| Age (years)                | 19 59.63 ± 8.78             | 27 61.04 ± 8.18             | 0.59                       |
| Height (m)                 | 19 1.71 ± 0.09              | 27 1.69 ± 0.09              | 0.26                       |
| Mass (kg)                  | 19 79.53 ± 18.20            | 27 79.99 ± 17.49            | 0.93                       |
| BMI (m/kg²)                | 19 28.32 ± 7.04             | 27 27.98 ± 5.02             | 0.90                       |
| Men (%)                    | 8 (42)                      | 8 (30)                      | 0.38                       |
| Women (%)                  | 11 (58)                     | 19 (70)                     |                             |

THA= Total Hip Arthroplasty, BMI=body mass index. P-values are based on 2-sided, independent t-test for difference in group means or a chi-square test for independent proportions.
Outcome Measures

Functional Performance Measures

Measures of functional performance included the stair climb, five times sit-to-stand, timed-up-and-go, and 6-minute walk tests, and single limb stance time. The stair climb test determines the time to ascend and descend 12 stairs and assesses performance on a relatively demanding functional task. This test has excellent reliability (intraclass correlation coefficient [ICC]=0.90).99 Participants were instructed to climb a flight of stairs, turn and descend the same flight as quickly and safely as possible. They were allowed to use the handrail, but were encouraged to refrain from bearing weight through the handrail. The five times sit-to-stand test is a test of dynamic balance98 and measures the time it takes to stand from and sit in a chair five times.87 This test has high test-retest reliability (0.81)98 and has shown to be correlated with other tests of dynamic balance (r=0.64).107 Each participant was seated in a standard chair (height 46 cm) and instructed to transfer to a standing position and return to a sitting position as quickly as possible five times. Participants were instructed not to use the arms of the chair unless they were unable to stand without upper extremity support. The timed-up-and-go test, which assesses walking and dynamic balance, measures the time to rise from a chair, walk 3m, turn around, and return to sitting without physical assistance.88 This test is a reliable (ICC=0.75)99 and valid test, and provides assessment of fall risk. The 6-minute walk test89 assesses how far a person can walk in 6 minutes. This test has been used to measure endurance and has been validated as a measure of functional mobility following joint arthroplasty and has excellent reliability (ICC=0.94).108,99 Each participant performed this test in a 30.5-m hallway and the total distance covered, in meters, was recorded. In the single-limb stance test, a measure of static balance, participants were
asked to stand unsupported on their surgical limb. Time, up to 30 seconds, was recorded. The test has excellent reliability in older adults (ICC=0.86).\textsuperscript{109}

**Strength Testing Procedures**

Surgical limb hip flexor, extensor, and abductor strength, and knee extensor and flexor strength was measured at each testing session using an electromechanical dynamometer (HUMAC NORM, CSMI Solutions, Stoughton, MA). Positions chosen for testing were based on previous literature and considered patient safety for adherence to postoperative precautions after THA. Maximal voluntary isometric strength of the hip flexors and extensors were performed while participants were supine with the hip flexed to 40° using a strap around the waist to stabilize the pelvis.\textsuperscript{110} Strength testing of the hip abductors was performed while participants were sidelying positioned in 0° of abduction/adduction and flexion/extension with a strap to stabilize the pelvis.\textsuperscript{110,111} Maximal strength testing of the knee extensors and flexors were performed while patients were seated and stabilized, with a shoulder harness and waist strap, in 85° of hip flexion and 60° of knee flexion as previously described.\textsuperscript{84,85} Data were sampled using a Biopac Data Acquisition System at a sampling frequency of 2000Hz (MP 150 Biodex Medical Systems, Inc., Shirley, NY) and analyzed using AcqKnowledge software, Version 3.8.2 (Biodex Medical Systems). Strength measurements were expressed in units of torque (Nm). Each set of maximal isometric contractions was preceded by two sub-maximal warm-up contractions. All patients were given visual targets from the dynamometer’s output and strong verbal encouragement during each trial. Maximal voluntary isometric contractions for all muscle groups were performed twice; however, if maximal torque during the first two trials differed by more than 5%, a third trial was performed, as previously described.\textsuperscript{84,112-114} The trial with the highest torque was normalized to body mass (kg) and used for analysis.\textsuperscript{115}
Patient Perception of Quality of Life/Physical Activity

All participants completed the Medical Outcome Study SF-36 and patients completed the Hip Dysfunction and Osteoarthritis Outcome Score (HOOS) at each visit. The HOOS assesses pain, joint stiffness, physical, social, and emotional function of a person with hip osteoarthritis to determine the overall level of disability. The HOOS is a valid, reliable, and responsive self-administered instrument, with ICC values ranging from 0.78-0.91 depending on the subscale.116 The SF-36 is a reliable self-report survey (ICC=0.75-0.91)117 for assessing health-related quality of life 118-120. All participants reported their physical activity level using the UCLA Activity Scale 91. This scale consists of 10 activity levels ranging from wholly inactive (level 1) to regular participation in impact sports (level 10) and has been used to monitor physical activity after total joint arthroplasty 92.

Statistical Methods

Study data were collected and managed using REDCap (Research Electronic Data Capture) electronic data capture tools hosted at the University of Colorado, Anschutz Medical Campus 93. REDCap is a secure, web-based application designed to support data capture for research studies.

To address the first purpose of our investigation, comparing patient outcomes at various time points to preoperative values, we used a mixed-effects repeated measures model. We designated the 1-month time point as our primary endpoint for statistical analysis, but we were interested in the full 1-year time course of recovery. Therefore, the mixed-effects model utilized data from each measure at each time point to infer the differences in these outcomes over the 1-year follow-up period, including the 1-month time point. This mixed-effects model approach is similar to
performing a repeated-measures analysis of variance, with the benefit of retaining case data if there were missing values present at any time point. To address the second purpose of our investigation, comparing patient outcomes to measures in healthy controls, we used two-group, two-tailed t-tests to assess differences between healthy controls and patients at the 1-year time point. To additionally characterize this patient population, we calculated percent changes from the preoperative time point to the 1-month time point (primary endpoint) and provided estimates of the percentage differences between outcomes at 1 year and healthy adults.

Results

As was expected, 1 month after THA, patients had 15% less hip flexor torque \((P=0.03)\), 15% less hip extensor torque \((P=0.08)\), 26% less abductor torque \((P<0.01)\), and 14% less knee extensor \((P<0.001)\) and knee flexor torque \((P<0.01)\) compared with preoperative levels (Table 4.2). Additionally, patients with THA performed more poorly on the stair climb test \((P<0.001)\), timed up and go test \((P=0.02)\), single limb stance \((P=0.03)\), and 6-minute walk test \((P=0.03)\) than they did before THA (Table 4.2). However, performance on the five times sit-to-stand was similar preoperatively and 1 month after THA \((P=0.49, \text{Table 4.2})\). Despite poorer strength and functional performance 1 month after THA, patients had significantly improved HOOS scores in all domains \((p < 0.01)\) except sports and recreation \((p = 0.08; \text{Figure 4.1})\). Further, with patient data available, there was no difference in the Physical Component Score (PCS) of the SF-36 \((P=0.08)\) while HOOS scores continued to improve for one year \((P<0.01, \text{Figure 4.1A})\). Finally, UCLA scores indicated a drop in physical activity 1 month after
THA ($p < 0.01$) compared with before surgery and improvement in physical activity levels by the one year time point ($P=0.02$, Figure 4.1C).

Compared to the healthy adults, patients had 17% less knee extensor ($P=0.01$) and 23% less knee flexor torque ($P<0.01$; Table 4.2) after 1 year of recovery after THA. Further, patients were 15% slower on the stair climb test ($P=0.53$), 9% slower on the five time sit to stand test ($P=0.35$), 11% slower on the timed up and go test ($P=0.48$) and walked 8% less distance over six minutes ($P=0.24$) (Figures 4.2, 4.3). Further, SF-36 PCS scores improved from preoperative levels ($P<0.001$), but were worse than healthy adults one year after THA ($P<0.01$; Figure 4.1B). Physical activity levels were also lower than healthy adults one year after THA ($P=0.14$; Figure 4.1C).

**Discussion**

Patients’ quality of life after THA may decline as early as 18 months after THA $^7$ and strength and functional deficits persist several years after THA $^8$-$^{11}$. Although patients report reduction in pain after surgery, functional deficits that persist (and may worsen with age) suggest postoperative outcomes could be improved. The greatest change in strength and function may occur early after surgery; $^{106,121}$ however, data quantifying acute postoperative changes are lacking. Furthermore, few studies have measured these outcomes at regular intervals during recovery. $^{104-106}$ Because rehabilitation is most likely to be recommended in this timeframe, information on the deficits present early after surgery is required to make informed decisions regarding rehabilitative intervention. Using a comparison group of healthy older adults, this study identified the deficits in strength and outcomes scores that persist 1 year after THA suggesting a possible need for improvements in postoperative care.
Table 4.2. Mean changes and 95% confidence intervals for the primary and secondary outcome measures at 1 month (primary end point) and 3, 6, and 12 months for the THA group. *Negative values reflect a deficit from baseline, positive values reflect an improvement from baseline; p values are from the estimated between-group difference in change from baseline; †normalized to weight; CI = confidence interval.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Change from baseline to 1 month, mean (95% CI)</th>
<th>Change from baseline to 3 months, mean (95% CI)</th>
<th>Change from baseline to 6 months, mean (95% CI)</th>
<th>Change from baseline to 12 months, mean (95% CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normalized hip flexor strength† (Nm/kg)</td>
<td>-0.18 (-0.34 to -0.02)</td>
<td>0.03 (-0.19 to 0.14)</td>
<td>0.08 (-0.07 to 0.23)</td>
<td>-0.02 (-0.18 to 0.15)</td>
</tr>
<tr>
<td>Normalized hip extensor strength† (Nm/kg)</td>
<td>-0.16 (-0.35 to 0.02)</td>
<td>0.08 (-0.10 to 0.22)</td>
<td>0.04 (-0.17 to 0.26)</td>
<td>0.07 (-0.13 to 0.27)</td>
</tr>
<tr>
<td>Normalized hip abductor strength† (Nm/kg)</td>
<td>-0.20 (-0.33 to -0.06)</td>
<td>0.006 (-0.13 to 0.11)</td>
<td>0.13 (-0.04 to 0.29)</td>
<td>0.10 (-0.04 to 0.25)</td>
</tr>
<tr>
<td>Normalized quadriceps strength† (Nm/kg)</td>
<td>-0.20 (-0.30 to -0.10)</td>
<td>&lt;0.001 (-0.08 to 0.13)</td>
<td>0.13 (0.01 to 0.25)</td>
<td>0.19 (0.08 to 0.29)</td>
</tr>
<tr>
<td>Normalized hamstrings strength† (Nm/kg)</td>
<td>-0.11 (-0.19 to -0.03)</td>
<td>0.008 (-0.08 to 0.09)</td>
<td>0.06 (-0.01 to 0.14)</td>
<td>0.07 (-0.05 to 0.18)</td>
</tr>
<tr>
<td>Stair climbing test (seconds)</td>
<td>8.19 (3.76 to 12.62)</td>
<td>&lt;0.001 (-4.10 to -0.46)</td>
<td>-2.91 (-4.76 to -1.06)</td>
<td>-3.22 (-4.96 to -1.48)</td>
</tr>
<tr>
<td>Five-time sit-to-stand (seconds)</td>
<td>0.51 (-0.99 to 2.00)</td>
<td>0.49 (-3.35 to -0.98)</td>
<td>-2.44 (-3.63 to -1.24)</td>
<td>-2.56 (-3.83 to -1.29)</td>
</tr>
<tr>
<td>Timed Up and Go (seconds)</td>
<td>2.26 (0.45 to 4.07)</td>
<td>0.02 (-1.83 to 0.62)</td>
<td>-0.93 (-2.00 to 0.14)</td>
<td>-1.15 (-2.14 to -0.15)</td>
</tr>
<tr>
<td>Six-minute walk distance (meters)</td>
<td>-159.54 (-299.95 to -19.13)</td>
<td>0.03 161.31 (48.77 to 273.86)</td>
<td>206.04 (74.98 to 337.10)</td>
<td>274.46 (-757.65 to 1306.57)</td>
</tr>
<tr>
<td>Single limb stance (seconds)</td>
<td>-4.39 (-8.13 to -0.65)</td>
<td>0.03 0.60 (-1.76 to 2.97)</td>
<td>0.93 (-2.16 to 4.02)</td>
<td>1.62 (-1.33 to 4.57)</td>
</tr>
</tbody>
</table>
Figure 4.1 A-C. Self-reported outcomes after THA are shown. (A) HOOS subscales over one year are shown. * Indicates significant differences (p < 0.05) from preoperative levels. † Indicates significant differences (p < 0.05) from healthy adults. (B) Self-reported SF-36 Physical Component Score (PCS) over one year are shown. * Indicates significant differences (p < 0.05) from preoperative levels. † Indicates significant differences (p < 0.05) from healthy adults. The THA group is represented by solid black line; the healthy adult group is represented by dashed line. (C) UCLA Activity Scores over one year are shown. * Indicates significant differences (p < 0.05) from preoperative levels. † Indicates significant differences (p < 0.05) from healthy adults. The THA group is represented by solid black line; the healthy adult group is represented by dashed line.
Figure 4.2 A-E. Muscle strength outcomes for the (A) knee flexors, (B) knee extensors, (C) hip flexors, (D) hip extensors and (E) hip abductors over one year are shown. * Indicates significant differences (p < 0.05) from preoperative levels. † Indicates significant differences (p < 0.05) from healthy adults. The THA group is represented by solid black line and the healthy adult group is represented by dashed line.
Figure 4.3 A-E. Functional performance outcome measures preoperatively to one month after THA are shown including (A) the stair climbing test, (B) the five time sit-to-stand test, (C) the timed-up-and-go test, (D) the six minute walk test and (E) the single limb balance test. * Indicates significant differences (p < 0.05) from preoperative levels. † Indicates significant differences (p < 0.05) from healthy adults. The THA group is represented by solid black line and the healthy adult group is represented by dashed line.
We acknowledge the following limitations to our study. First, postoperative rehabilitation was not standardized. We intended to capture the general course of recovery after THA, including patterns of rehabilitation use after surgery from several practices. Although this may introduce variability in our results, we believe that makes our results more generalizable. Second, our sample size estimates may not be adequately powered to see differences in all outcomes at the 1-year time point as a result of the fact that these calculations were powered to infer differences in strength 1 month after surgery. As a result of variability in recovery, we may not be adequately powered to see differences 1 year after surgery. However, documenting the trajectory of recovery over the year provides important information. Finally, our inclusion criteria may underestimate deficits present in the general THA population. By limiting contralateral disease and comorbidities, we limited our population to include a higher functioning cohort than the broader THA population. However, by excluding confounding conditions, our results were not influenced by compromised function for other reasons.

We found that individuals experienced muscle strength loss, functional performance deficits, and decreases in physical activity 1 month after THA. Interestingly, strength loss in the surgical limb was not isolated to the hip musculature. Although the hip abductors experienced the greatest percent strength loss of all the musculature evaluated, acute strength loss was more global. Previously, Reardon et al. 59 indicated the presence of quadriceps weakness in this population 5 months after THA. The present study suggests that quadriceps weakness is not only present, but is worse 1 month after THA compared with preoperative values, indicating THA negatively impacts quadriceps strength. Furthermore, Bertocci et al 9 and Sicard-Rosenbaum et al. 33 demonstrated decreased torque in the hip flexors, extensors, and abductors several months to several years after surgery. Although these studies confirm the presence of prolonged hip muscle weakness after THA, our study provides direct evidence of muscle
strength losses early after surgery, at the time that rehabilitation could have the biggest impact to improve long-term outcomes. The presence of early strength loss supports the need for early rehabilitation intervention to remediate strength losses to optimize recovery beyond levels seen preoperatively. This may require increasing the frequency and intensity of current rehabilitation practices or require more consistent use of rehabilitation after surgery. Similarly, functional performance after THA was diminished 1 month after surgery. Previous investigations have indicated diminished functional capacity using patient self-report\textsuperscript{5,8} and performance tests\textsuperscript{33,47} several months to years after THA. However, no previous performance-based studies have evaluated these functional outcomes as early as 1 month after THA. The presence of long-standing deficits in functional performance in previous studies, combined with our findings of acute functional performance deficits, suggests the current approach to postoperative rehabilitation may not optimize recovery. Despite the strength and functional performance deficits 1 month after surgery, patients reported improvements in their self-reported function. This is likely the result of improvements in hip pain after surgery and further supports a growing body of literature indicating that self-reported measures may not correlate well with patients’ true ability after joint arthroplasty\textsuperscript{103,122,123}.

We also found differences in lower extremity muscle strength and functional performance in patients 1 year after THA compared with their healthy counterparts. In contrast with our initial projections, strength deficits were seen primarily in the knee extensors and flexors of the surgical lower extremity, rather than in the hip musculature. A previous investigation by Reardon \textit{et al.}\textsuperscript{59} demonstrated quadriceps muscle weakness persists several months after surgery despite decreased hip pain, improvement in function, and participation in rehabilitation. Similarly, our study suggests that quadriceps weakness persists beyond the time point previously evaluated, to at least 1 year after
THA. This finding is significant because of the role of quadriceps strength in daily function. Quadriceps weakness negatively effects mobility,\textsuperscript{60,124,125} which may help explain why other researchers have found difficulties with functional performance after THA. Despite the fact that significant functional differences were not seen in our data, several studies have confirmed the presence of functional deficits and difficulty walking following THA. Specifically, Trudelle-Jackson \textit{et al.}\textsuperscript{8} demonstrated that patients had impaired self-reported function and postural control, while Vissers \textit{et al.}\textsuperscript{126} indicated that by 8 months after THA, patients functionally recover to only 80\% of that of healthy adults. Still, other investigators indicate that gait mechanics never fully recover after THA when compared with healthy adults\textsuperscript{36} and mechanics while climbing stairs are also impaired compared to healthy adults.\textsuperscript{35} Although our study has characterized strength and functional performance-based outcomes during the first year after THA, we were unable to capture the quality of movement, which may be crucial to understanding the difficulties present in these previous investigations. Taken together, there is evidence that, although patients do experience recovery and improvement in strength and functional performance after THA, mobility difficulties and functional deficits remain. The present study not only characterizes the time course of recovery during the first year following THA, but quantifies early postoperative deficits following THA. These measures are needed to plan effective rehabilitation programs. During the first few weeks after THA, patients experience hip and knee strength loss and decreased functional capacity, which improve initially, then plateau from 6 months to 1 year. However, some measures of strength remain less than the level of healthy adults, particularly quadriceps and hamstrings strength, suggesting rehabilitation strategies should be further optimized to include focused strengthening of the knee extensors and flexors in addition to those muscles around the hip.
Acknowledgments

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CHAPTER V

MULTI-COMPONENT REHABILITATION FOLLOWING TOTAL HIP ARTHROPLASTY: A RANDOMIZED CONTROLLED TRIAL

Abstract

Purpose/Hypothesis

Total hip arthroplasty (THA) is a common orthopedic surgery to address painful hip osteoarthritis. However, deficits in functional performance, balance and muscle strength persist after THA. One factor that may compromise poor function is altered movement patterns and lumbopelvic stability. The purpose of this investigation was to examine the efficacy of a multi-component (CMC) rehabilitation intervention, including movement reeducation on outcomes following THA compared to a control group (CON).

Subjects

Twenty patients ages 50 to 75 (10 women, 10 men, 61.9 ± 7.4 years) undergoing primary, posterior approach THA for hip osteoarthritis were randomized into 1 of 2 groups: CMC (n=10) or CON (n=10).

Materials/Methods

In addition to standard-of-care inpatient and home-based rehabilitation, the CMC group received an 8-week (2x/week) outpatient, multi-component rehabilitation program consisting of intensive strength training, mobility training and neuromuscular reeducation techniques. The CON group was supervised by a study therapist via home visit and phone calls and continued activity prescribed by an inpatient therapist, mirroring
standard of care. Functional performance was measured by the stair climbing (SCT), 4-meter walk (4MW), 6-minute walk (6MW), five times sit-to-stand (FTSTS), and timed-up-and-go (TUG) tests. Balance was assessed by the Fullerton Advanced Balance Scale (FAB) and movement pattern quality was assessed as amount of pelvic tilt during a single-limb balance task. Muscle strength and self-reported function (HOOS and SF12) were also assessed. All outcomes were collected before and 10 weeks after THA; differences from pre- to post-intervention were assessed for analysis.

Results

Six and ten weeks after THA, the CMC group had significantly greater improvements in SCT (P=0.04, P=0.030), 4MW (P= 0.04, P=0.001), 6MW (P=0.03, P=0.002), and FAB (P=0.02, P=0.002) compared with CON. There were no differences in improvement in FTSTS or TUG between groups. At 10 weeks, the CMC group tended to remain more stable at the pelvis (p=0.070) and there was a trend toward greater hip abductor strength improvement (P=0.090) and knee extensor strength improvement (P=0.060) in the CMC group, but no difference in muscle strength changes in other muscle groups. Further, the CMC group had significantly greater improvements in self-reported function in HOOS ADL (P=0.010), Pain (P=0.009) and QOL (P=0.040) subscales at 10 weeks, but no differences in improvements in HOOS Sports and Recreation (P=0.40) or Symptom (P=0.060) subscales compared to CON. There were no differences in improvements in SF12 scores between groups at either 6 or 10 weeks postoperative.

Conclusions

Participation in a multi-component rehabilitation intervention after THA resulted in greater improvements in functional performance and balance and movement patterns
despite the lack of significant difference in changes in strength. These findings indicated that functional performance, balance and movement patterns can be improved through emphasizing additional aspects of rehabilitation rather than solely relying on strength training techniques. Further, these findings suggest a shift in paradigm regarding exercise prescription after THA.

**Introduction**

Total hip arthroplasty (THA) has become one of the most common orthopedic surgeries performed. In the next 15 years, the demand for THA is expected to increase by 174%, to more than 500,000 per year, in both young and older adults. Generally, THA is considered a successful procedure as patients routinely report reduction in pain following surgery. However, full recovery of functional ability is challenging, as patients typically recover functional performance to 80% of the functional ability of healthy controls. Functional performance encompasses the patients’ ability to participate in typical activities of daily living such as rising from a chair, walking and climbing stairs. Functional performance may be compromised by the presence of postoperative muscle weakness, but may also be compromised by the presence of altered movement patterns. Specifically, after THA, individuals demonstrate asymmetrical limb loading during activities of daily living, decreased gait speed with abnormal gait mechanics, decreased postural control, and poor mechanics while climbing stairs. Some investigations suggest that walking mechanics never return to normal following THA.

Despite the increase in utilization of THA, and persistent challenges to recovery, no consensus exists for managing patients after THA. In a systematic review of
rehabilitation strategies following THA, DiMonaco and Castiglioni concluded that rehabilitation can improve outcomes following THA.\textsuperscript{55} However, variable approaches to types of exercise, timing of rehabilitation initiation and exercise intensity led to a lack of agreement on the optimal type of exercise following THA.\textsuperscript{55} A second review article by Minns-Lowe \textit{et al.}\textsuperscript{12} also demonstrated benefits of rehabilitation after THA, but emphasized that improvements in study quality and intervention are needed. Other preliminary studies have provided evidence that progressive, high intensity strength training after THA may be safe and effective for improving strength and functional performance.\textsuperscript{31,38,39,76,77}

While this previous research suggests that strength training exercise is efficacious for improving hip muscle strength and functional performance, strength training alone may not address the poor movement quality seen during activities such as walking after THA. Movement quality depends on the ability of the body to produce stable, coordinated movements during functional tasks, which is also referred to as neuromuscular control.\textsuperscript{61} Good neuromuscular control optimizes functional performance by coordinating hip and pelvic muscle activity,\textsuperscript{63} and with this coordinated muscle activity, provides stability to the hip and pelvis.\textsuperscript{63} Around the hip joint, optimal neuromuscular control is facilitated by the hip abductor muscles’ ability to provide stability to the pelvis during unilateral stance.\textsuperscript{64,67} The role of the lateral hip musculature, in coordination with lumbopelvic complex, is to continually and instantaneously adapt to movement in order to maintain a stable base for functional activity, such as walking.\textsuperscript{63} Without the lateral hip and abdominal musculature stabilizing the pelvis, compensatory movement may be seen, such as a Trendelenburg compensated gait pattern, negatively impacting functional performance.\textsuperscript{64} Pelvic stability is additionally facilitated though performance of the core musculature encompassing the abdominal and lumbar spine
A lack of strength in or a lack of recruitment of these muscles can lead to inefficient movement patterns due to lack of stability. This, in turn, results in compensated movement which may explain the altered movement patterns seen during activities of daily living and may lead to injury. Improving movement quality through improved pelvic stability requires additional types of exercise prescription beyond strength training as demonstrated in other populations. For example, concentrated training to improve muscle recruitment and core stability improves movement quality and minimizes injury risk in knee injury population. This technique, often referred to as neuromuscular reeducation, utilizes weight-bearing exercises to improve muscle coordination and joint stabilization. This type of training aims to improve sensorimotor control and stability by emphasizing muscle co-contraction, thus enhancing the postural role of weight-bearing muscles. Further, neuromuscular reeducation focuses on movement quality as the activities require strength, coordination and balance with the goal of producing movement without compensation. This type of training has also been used in rehabilitation after anterior cruciate ligament (ACL) reconstruction, ankle sprain, and in rehabilitation for patients with low back pain. Additionally, neuromuscular reeducation training has been utilized successfully in older adults with hip and knee OA. The addition of this type of training to a postoperative THA rehabilitation protocol has the potential to not only improve persistent poor movement quality following THA, but to change the approach by which patients after THA are rehabilitated.

Shifts in rehabilitation strategy have occurred in other patient populations. For example, following a lateral ankle sprain injury, once considered a relatively minor injury, individuals often suffer from chronic instability. Individuals would typically undergo treatment for acute pain and inflammation, followed by return to activities of daily living or sport. However, researchers discovered that persistent pain, functional mobility
limitations and feelings of instability posed a threat to full return to daily living and sports. After identifying that individuals suffered from chronic symptoms, known as chronic ankle instability, rehabilitation professionals began incorporating balance, neuromuscular reeducation and sensorimotor training techniques to improve outcomes for individuals after ankle sprain. Recent publications indicate that these training techniques have improved ankle strength and postural stability,¹³⁰,¹³¹ ankle kinematics during gait,¹³² and reduce the risk of reinjury.¹³³ Further, rehabilitation following anterior cruciate ligament (ACL) injury in the knee has a similar evolution. In addition to more aggressive mobilization and strength training following surgery, rehabilitation professionals sought the need to improve long standing gait and balance deficiencies. Neuromuscular reeducation techniques have been used successfully in this population to improve strength⁷⁸,¹²⁹ as well as improve movement strategies, and to reduce risk of ACL injury in at-risk populations.⁸⁰

Rehabilitation after THA requires a similar paradigm shift. Despite the strength, postural control and movement quality deficits reported after THA, no evidence-based recommendations exist to guide exercise prescription. The combination of evidence that 1) strength training improves outcomes after THA and 2) evidence that neuromuscular reeducation training is feasible and improves functional outcomes⁶¹,⁶³,⁷⁷,⁷⁸,¹³⁰-¹³³ indicates that the addition of neuromuscular reeducation exercise may further improve rehabilitation outcomes following THA. To date, no previous studies have combined strength training and neuromuscular reeducation training into one intervention following THA. Therefore, the purpose of this investigation was to examine the effects of a multi-component intervention including core stabilization exercise, neuromuscular reeducation, strength training and functional mobility training on outcomes following THA compared to a control group. It was hypothesized that the group participating in the rehabilitation intervention would demonstrate greater improvements in functional
performance, balance, pelvic stability, and muscle strength. Additionally, it was hypothesized that the multi-component rehabilitation intervention would be safe and would not lead to musculoskeletal injury, hip dislocation or falls.

Methods

Study Design

This study was a randomized, controlled trial designed to determine the effects of a multi-component intervention on outcomes following THA. Outcomes assessments occurred before THA and at 6 and 10 weeks after surgery, following the completion of the intervention period. Following THA surgery, standard inpatient and home rehabilitation programs were implemented for all patients to improve function and activities of daily living (Figure 5.1). Two weeks after surgery, patients were randomized in to one of two groups: CMC (experimental) group or CON (control) group, with stratification by sex using random block sizes of 2 within each stratum. Randomization occurred two weeks after THA to ensure there were no postoperative complications that would interfere with participation in rehabilitation. Each participant was provided written, informed consent and this study was approved by the Colorado Multiple Institutional Review Board.

Participants

Individuals between the ages of 50 and 75 who were planning a primary THA through posterior approach for the treatment of hip osteoarthritis were considered for participation. Patients were recruited from one of two hospitals, University of Colorado Hospital and Porter Adventist Hospital, by physician referral or advertisement at preoperative educational sessions between October 2012 and February 2014.
Individuals were enrolled if they also had no history uncontrolled diabetes, body mass index >40 kg/m², or additional orthopedic or neurologic pathology that impaired function.

Figure 5.1. Study Design.

**Rehabilitation Intervention**

Following THA surgery, study participants in both groups stayed in the hospital for 2-3 days during which rehabilitation was initiated as part of the standard postoperative course of care. All surgeons also recommended standard postoperative movement precautions including: 1) no hip flexion beyond 90°, 2) no hip adduction beyond midline, and 3) no hip internal rotation. Inpatient rehabilitation practices were similar at both hospitals and consisted of twice daily PT sessions and included mobility training, activities of daily living training and home exercise prescription. Home exercises consisted of isometric muscle training and range of motion exercises within postoperative surgical precautions. During the two weeks prior to randomization, all participants were seen by a study therapist once weekly to further advise on mobility and activities of daily living. Following randomization, the CMC group participated in outpatient rehabilitation 2x/week (approximately 45 minutes per session) for 8 weeks. The control group was supervised by the study physical therapist during the same time
frame, but did not attend outpatient rehabilitation. They continued activities prescribed by their inpatient physical therapist.

**Comprehensive Multi-Component Program**

The CMC program had four domains designed to address the common long-term impairments present after THA.\(^ {33,34,47} \) Each domain consisted of supervised exercise performed in the clinic and included similar exercises completed by the patient at home. The exercises in each domain progressed in intensity and complexity throughout the intervention to maximize movement quality, muscle strength and functional performance (Appendix A).

Each domain consisted of the following exercises:

1) **Core Stabilization**

This domain consisted of abdominal exercises based on the Pilates method to promote spinal and pelvic stability, promoting proper femoropelvic alignment and optimizing hip function.\(^ {64} \) Core stabilization exercises began with isometric, lower abdominal muscle training (e.g., supine pelvic tilts, lower abdominal bracing) in static and dynamic conditions and progressed to higher level lower abdominal training by increasing the complexity of the dynamic movements while using the abdominals to maintain a stable spine and pelvis (e.g., adding arm movements, leg lifts, etc.). These exercises further progressed to the addition of dynamic, upper abdominal exercises (e.g., curl ups) and exercises combining abdominal and hip musculature such as bridging.
2) Neuromuscular Re-education

The exercises in this domain focused on functional, weight-bearing exercises with the use of visual and verbal feedback to promote pelvic stability during movement. Patients began with supported weight shifts and bilateral stance activities focused on even weight distribution between limbs while maintaining a level pelvis and upright trunk posture. Following bilateral activities, patients progressed to supported single limb stance (SLS) balance activities and then to unsupported SLS activities focusing on pelvic and trunk stability using visual and verbal feedback such as mirrors and coaching from the treating therapist. Finally, patients progressed to dynamic SLS activities such as hip hiking, step downs and static and dynamic SLS activities on uneven surfaces such as foam and tilt boards.

3) Lower Extremity Strength Training

Therapeutic exercise in this domain consisted of progressive resistance exercises for the hip flexors, extensors, abductors and adductors as well as the quadriceps and hamstrings. Patients performed exercises for each muscle group based on an eight-repetition maximum, and resistance level was progressed when more than eight repetitions were possible. These exercises used a combination of free weights, resistance bands, and weight machines. Patients progressed from supine, sitting, and sidelying open kinetic chain strengthening activities to standing open and closed kinetic chain strengthening exercises.

4) Functional Training

The activities in this domain consisted of closed kinetic chain exercises that mimic daily activities. Patients began with gait training activities while
transitioning from an assistive device to independent ambulation. Following gait training, activities included sit-to-stand transitions, step-up exercises, wall squats and agility training.

Control Group Intervention

The control group (CON) did not participate in an outpatient physical therapy intervention, which mirrors common practice patterns seen after THA. Following discharge from the hospital, the control group was encouraged to continue mobility activities provided by their inpatient physical therapist. Control group participants were supervised by the study physical therapist by phone or through home visits once weekly during the 8 week intervention period. Thus, participants had attention from study staff during the intervention period and were monitored for complications. However, they were not provided with specific exercise prescription or instructions. As there is no standard of care for rehabilitation after THA, the control group participated in postoperative care similar to that of patients participating in previous observational studies in our laboratory, representing a typical course of postoperative management.

Outcomes

Functional Performance

To assess functional performance, patients performed a stair climb test (SCT; primary outcome), a five-time-sit-to-stand test (FTSTS), the Timed-Up-And-Go test (TUG), 4-meter walk test (4MW) and a 6-minute walk test (6MW). The SCT determines how long it takes a patient to ascend and descend 12 stairs. The SCT was chosen as the primary outcome for this study because it represents a high-level functional task requiring strength, stability and balance on one limb, thus isolating
function of the surgical and nonsurgical limbs. This valid, reliable\textsuperscript{89} measure was chosen as the primary outcome due to the difficulty patients have with stair climbing after THA,\textsuperscript{35} the high demand placed on the hip and knee musculature during this task,\textsuperscript{35} and its use in defining functional independence in older adults.\textsuperscript{52} Participants were instructed to complete the 12 stair ascent and descent without stopping and to do so as quickly as possible. The use of the handrail or assistive device was permitted if necessary. The FTSTS measures the time it takes to stand from and returning to sitting in a chair five consecutive times.\textsuperscript{87} Each participant was seated in a standard chair (height 46 cm) and instructed to completely stand and return to sitting as quickly as possible five times. Participants were instructed not to use the arms of the chair unless they were unable to stand without upper extremity support. The TUG measures the time to rise from a chair, walk 3 meters, turn around, and return to sitting.\textsuperscript{88} Participants were instructed to complete this task as quickly but as possible and were permitted to use an assistive device if necessary. The 4-meter walk test measures the time to walk 4 meters and has been used to generate gait speed values which have been associated with morbidity and mortality in older adults.\textsuperscript{134} Participants performed the 4MW twice, once with instructions to walk in their “normal, everyday pace” (4MW\textsubscript{usual}), and the second with instructions to complete the test as “quickly but as safely as possible” (4MW\textsubscript{fast}). The walking course set up for this test included a two meter distance from the start line to where timing was initiated and a two meter distance to the stop line from where timing was terminated. This allowed the capture of continual walking with acceleration and without deceleration at the timing start and stop lines. The 6-minute walk test\textsuperscript{89} (6MW) assesses how far a person can walk in 6 minutes. This test is widely used to measure endurance and has additionally been validated as a measure of functional
mobility following joint arthroplasty. The test was performed in a 30.5 meter hallway and the total distance covered, in meters, was recorded.

**Patient Perception of Quality of Life/Physical Activity**

Patient perceptions of physical function and recovery were captured with the Medical Outcome Study SF-12 version 2, the Hip Dysfunction and Osteoarthritis Outcome Score (HOOS) and the UCLA activity scale at each visit. Results of the SF-12 are reported in two components, the physical component summary (PCS) and the mental component summary (MCS) and higher scores indicate better health status. The HOOS assesses pain, joint stiffness, physical, social, and emotional function of a person with hip osteoarthritis to determine the overall level of disability and is reported in five separate subscales. Higher HOOS scores on each subscale indicate less disability. The HOOS is a valid, reliable, and responsive self-administered instrument. The UCLA activity scale consists of 10 activity levels ranging from wholly inactive (level 1) to regular participation in impact sports (level 10). The UCLA Activity scale has been used to monitor physical activity after total joint arthroplasty.

**Balance and Neuromuscular Control**

To quantify both static and dynamic balance capabilities, patients performed two balance assessments. First, patients participated in the Fullerton Advanced Balance Scale (FAB), a valid and reliable metric for assessing static and dynamic postural control. The FAB consists of 10 individually scored items assessing both static and dynamic balance and has been validated for use in independent older adults. The FAB scale has been shown to be highly reliable, both in intra- and
inter-rater reliability (0.92–1.00 and 0.91–0.95, respectively). The FAB was chosen as it includes both low- and high-level balance activities, and it places a high demand on the hip musculature as patients attempt to maintain their balance during testing.

Second, patients completed a static single-limb balance test, based off of the Trendelenburg test proposed by Hardcastle and utilized measurement of pelvis angle in single-limb standing based on work by Youdas, et al. and Asayma et al. During this test, participants were asked to stand on one leg for as long as they could, up to 30 seconds. The test was performed on both the surgical and non-surgical leg and was videotaped for analysis. Anatomical landmarks were marked on each patient at the bilateral anterior acromion processes, sternum, bilateral anterior, superior iliac spines of the pelvis and bilateral patella. From each video, a still frame from the first 10 seconds of the task was created. The still frame was imported into NIH Image J (National Institutes of Health, Bethesda, Maryland) software for analysis. Using the Image J software, the anatomical landmarks were identified and marked using tools within the software (Figure 5.2). The coordinates of the landmarks were then exported and a measure of pelvic tilt was computed. The differences in pelvic tilt angles from preoperative to postoperative assessments reported during the single-limb task on the surgical leg was used for analysis. This test assesses neuromuscular control during a single limb stance as it provides an analysis of the ability of the hip abductor group to maintain pelvic control, by measuring whether the pelvis position can be maintained at horizontal during closed-chain, functional tasks.
Isometric Muscle Strength

Isometric strength of the hip abductor, adductor, flexor, and extensor and the knee extensor and flexor muscles was assessed at each testing session using an electromechanical dynamometer (HUMAC NORM, CSMI Solutions, Stoughton, MA). Positions chosen for testing were based on previous literature and considered patient safety for adherence to postoperative precautions after THA while trying to maximize stability. Maximal voluntary isometric contractions (MVIC) of the hip flexors and extensors were performed in supine with the hip flexed to 40° using a strap around the waist to stabilize the pelvis.\textsuperscript{110} Hip abductor MVICs were performed in a sidelying position with 0° of abduction/adduction and 0° of flexion/extension using a strap to stabilize the pelvis.\textsuperscript{110,111} Knee extensor and flexor MVICs were performed seated
with a shoulder harness and waist strap for stabilization. Participants were placed in 85° of hip flexion and 60° of knee flexion for testing as previously described.\textsuperscript{84,85} Data were sampled using a BiopacData Acquisition System (MP 150 Biodex Medical Systems, Inc., Shirley, NY) and analyzed using AcqKnowledge software, Version 3.8.2 (Biodex Medical Systems). All MVIC measurements were expressed in units of torque (Nm). Each MVIC was preceded by two sub-maximal warm-up contractions. Participants were given visual targets from the dynamometer’s output and strong verbal encouragement during each trial to maximize effort. MVICs for all muscle groups were performed twice; a third trial was performed if maximal torque during the first two trials differed by more than 5%, as previously described.\textsuperscript{84,112-114} For analysis, the trial with the highest torque was normalized to body mass (kg) and used.\textsuperscript{115}

**Safety Outcomes**

Patients reported fall and musculoskeletal injury history and pain levels at rest and with activity (numerical pain rating scale [NPRS; 0= no pain, 10= worst possible pain]) on a weekly basis during the intervention and at each postoperative testing session. Additionally, treating physical therapists monitored incidence of musculoskeletal injury, specifically hip dislocation, by completing a brief examination at each treatment session. Finally, all participants attended all postoperative clinic visits as proposed by their surgeon so any postoperative complications could be monitored.
Statistical Methods

Data Management. Study data were collected and managed using REDCap (Research Electronic Data Capture) electronic data capture tools hosted at the University of Colorado, Anschutz Medical Campus. REDCap is a secure, web-based application designed to support data capture for research studies.

Sample Size Estimates. Power and sample size estimates were computed from preliminary stair climbing test data from our laboratory in 23 patients before and after THA. We estimated that enrolling 17 patients would yield 80% power with an α-level of 0.05 to detect an approximately 5 second difference in SCT time between groups, a value which represents the threshold needed to interpret differences in this measure. This difference also represented a moderate effect size (0.5). Two recently completed clinical trials with similar outcome measures in patients following TKA in our laboratory have resulted in drop-out rates of 6.5% and 11.2% at 12 weeks post-op and 8.2% and 15.2% at 52 weeks. Thus, we conservatively estimated a 20% drop-out rate, such that we recruited 20 patients (10 per group) to participate.

Statistical Analysis. The primary aim for this investigation was to determine differences in change in functional performance between the CMC and CON groups. Specifically, the primary outcome for the investigation was change in stair climbing test (SCT) time from preoperative assessment to 10 weeks after THA (after 8 weeks of intervention). The difference in change in SCT time was estimated using a multiple regression model in which the 10 week change in SCT time was regressed on baseline SCT time and group. Regression analysis was chosen to estimate the change in outcomes in order to allow the effects of more than one independent variable to be considered. The difference in change in SCT time 6 weeks after THA was similarly analyzed, representing the mid-point of the intervention, for descriptive
purposes. The differences in all additional functional performance outcomes, balance and neuromuscular control, and muscle strength outcomes were analyzed similarly.

Preoperative characteristics of each group were compared using independent samples t-tests for continuous data or chi-square test for categorical data to evaluate equality between groups prior to intervention. For descriptive purposes, the percent change (post-pre/pre*100) was calculated for some outcome measures within each group. All analyses were intention-to-treat comparisons. SAS version 9.3 (SAS Institute, Inc; Cary, NC) was used for all data analyses. P-values less than 0.05 were chosen a priori to determine statistical significance.

**Results**

Two hundred twenty-seven patients were assessed for eligibility. One hundred twenty patients were not eligible to participate, 34 lived outside of our area and could not travel for therapy sessions, 26 declined to participate and 24 patients could not be contacted. Thus, twenty-three participants were assessed preoperatively. Prior to randomization, one participant had an intraoperative complication which made her ineligible to participate in exercise following surgery, thus 22 participants were enrolled. Two participants declined participation after randomization, one for transportation issues and one no longer wished to participate. Therefore, twenty participants completed the study, ten participants per group (Figure 5.3). There were no differences in age, height, weight, body mass index (BMI) or sex between groups (Table 5.1). Additionally, there were no differences in preoperative values for the SCT, FTSTS, TUG, FAB, 4MWusual, 4MWfast, 6MW, pelvic tilt angle, SF12, HOOS or UCLA Activity Score. There were also no preoperative differences in muscle strength (Table 5.2).
Figure 5.3. Participant enrollment flow chart.
Table 5.1. Baseline group demographic descriptions.

<table>
<thead>
<tr>
<th></th>
<th>CMC (Mean ± SD)</th>
<th>CON (Mean ± SD)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(n=10)</td>
<td>(n=10)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Age (years)</td>
<td>60.8 ± 7.6</td>
<td>63.0 ± 7.4</td>
<td>0.52</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>170.1 ± 10.4</td>
<td>173.1 ± 7.6</td>
<td>0.46</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>86.2 ± 25.0</td>
<td>89.4 ± 20.1</td>
<td>0.76</td>
</tr>
<tr>
<td>BMI (kg/m2)</td>
<td>29.4 ± 6.6</td>
<td>29.6 ± 5.2</td>
<td>0.93</td>
</tr>
<tr>
<td>Men (%)</td>
<td>5 (50)</td>
<td>5 (50)</td>
<td>1</td>
</tr>
<tr>
<td>Women (%)</td>
<td>5 (50)</td>
<td>5 (50)</td>
<td></td>
</tr>
</tbody>
</table>

Functional Performance

Six weeks after THA, representing the mid-point of the intervention period, the CMC group demonstrated significantly greater improvements in SCT time (P=0.04), 4MWfast time (P=0.04) and 6MW distance (P=0.03) compared to the changes in the CON group. Specifically, the CMC group shows improvements in these measures, while the CON groups shows declines (Figure 5.4). However, no differences in change in FTSTS time (P=0.13) or TUG time (P=0.24) from preoperative values to the 6-week time point was observed (Table 5.4).

At the primary end point of the study, 10 weeks after THA, representing the end of the intervention period, the CMC group demonstrated significantly greater improvements in SCT time (P=0.03), 4MWusual time (P=0.002), 4MWfast time (P=0.001) and 6MW distance (P=0.002) compared to the CON group. No differences in the change in FTSTS time (P=0.33) or TUG time (P=0.15) was observed 10 weeks after THA.
<table>
<thead>
<tr>
<th>Variable</th>
<th>CMC (Mean ±SD) (N=10)</th>
<th>CON (Mean ± SD) (N=10)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>FTSTS (s)</td>
<td>21.3 ± 10.0</td>
<td>16.4 ± 6.3</td>
<td>0.21</td>
</tr>
<tr>
<td>TUG (s)</td>
<td>11.2 ± 3.1</td>
<td>12.5 ± 7.9</td>
<td>0.64</td>
</tr>
<tr>
<td>FAB</td>
<td>23.2 ± 4.6</td>
<td>25.7 ± 4.3</td>
<td>0.24</td>
</tr>
<tr>
<td>SCT (s)</td>
<td>19.2 ± 10.9</td>
<td>20.4 ± 14.1</td>
<td>0.83</td>
</tr>
<tr>
<td>6MW (m)</td>
<td>366.1 ± 138.0</td>
<td>430.6 ± 170.4</td>
<td>0.37</td>
</tr>
<tr>
<td>4MWusual (s)</td>
<td>4.1 ± 1.3</td>
<td>3.7 ± 0.7</td>
<td>0.45</td>
</tr>
<tr>
<td>4MWfast (s)</td>
<td>3.0 ± 0.9</td>
<td>2.9 ± 0.6</td>
<td>0.83</td>
</tr>
<tr>
<td>UCLA activity score</td>
<td>4.8 ± 1.5</td>
<td>5.7 ± 2.1</td>
<td>0.32</td>
</tr>
<tr>
<td>Pelvic tilt angle (degrees)</td>
<td>0.18 ± 6.74</td>
<td>0.16 ± 5.01</td>
<td>0.99</td>
</tr>
<tr>
<td>Normalized surgical limb knee flexor strength (Nm/kg)</td>
<td>0.65 ± 0.22</td>
<td>0.64 ± 0.22</td>
<td>0.92</td>
</tr>
<tr>
<td>Normalized surgical limb knee extensor strength (Nm/kg)</td>
<td>1.35 ± 0.63</td>
<td>1.52 ± 0.41</td>
<td>0.48</td>
</tr>
<tr>
<td>Normalized surgical limb hip flexor strength (Nm/kg)</td>
<td>0.83 ± 0.46</td>
<td>0.99 ± 0.52</td>
<td>0.46</td>
</tr>
<tr>
<td>Normalized surgical limb hip extensor strength (Nm/kg)</td>
<td>0.50 ± 0.21</td>
<td>0.90 ± 0.68</td>
<td>0.10</td>
</tr>
<tr>
<td>Normalized surgical limb hip abductor strength (Nm/kg)</td>
<td>0.59 ± 0.32</td>
<td>0.65 ± 0.36</td>
<td>0.72</td>
</tr>
<tr>
<td>HOOS ADL</td>
<td>47.61 ± 16.51</td>
<td>57.35 ± 24.29</td>
<td>0.35</td>
</tr>
<tr>
<td>HOOS pain</td>
<td>40.31 ± 18.73</td>
<td>47.78 ± 22.17</td>
<td>0.46</td>
</tr>
<tr>
<td>HOOS QOL</td>
<td>22.66 ± 14.54</td>
<td>31.94 ± 18.87</td>
<td>0.27</td>
</tr>
<tr>
<td>HOOS SPR</td>
<td>27.34 ± 24.31</td>
<td>32.64 ± 19.96</td>
<td>0.63</td>
</tr>
<tr>
<td>HOOS Symptom</td>
<td>40.00 ± 23.90</td>
<td>57.22 ± 22.65</td>
<td>0.15</td>
</tr>
<tr>
<td>SF12 MCS</td>
<td>45.42 ± 13.58</td>
<td>51.75 ± 7.34</td>
<td>0.27</td>
</tr>
<tr>
<td>SF12 PCS</td>
<td>37.41 ± 8.76</td>
<td>37.52 ± 7.73</td>
<td>0.98</td>
</tr>
</tbody>
</table>
Patient Perception of Quality of Life/Physical Activity

Six weeks following THA, there were no differences in the change in four of the five HOOS subscales (ADL: $P=0.47$, Pain: $P=0.62$, QOL: $P=0.16$, Sport and Rec: $P=0.42$) between the CMC and CON groups compared with preoperative values (Table 5.3). However, the CMC group had greater improvement on the HOOS Symptom subscale ($P=0.04$) compared to the CON group. Additionally, there were no differences in the change in MCS ($P=0.68$) or PCS ($P=0.18$) subscales of the SF12 from preoperative values to the six week time point between groups. There was also no difference between the CMC and CON groups in the change in UCLA Activity score from preoperative values ($P=0.62$).

At the 10-week time point, the CMC group had significantly greater improvements in three of the five HOOS subscales (ADL: $P=0.01$, Pain: $P=0.009$, QOL: $P=0.04$) (Table 5.3). However, there were no differences in the change from the preoperative assessment to the 10 week assessment in HOOS Sports and Recreation subscale ($P=0.40$) or HOOS Symptom subscale ($P=0.06$). There were also no differences between groups in the change in the MCS ($P=0.68$) and MCS ($P=0.07$) subscales of the SF12 at the 10 week time point. Additionally, there were no differences between the CMC and CON groups in the change in UCLA activity score from preoperative values to 10 week values ($P=0.26$).

Balance and Neuromuscular Control

Balance

Results of the Fullerton Advanced Balance Scale (FAB) indicated the CMC group demonstrated significantly greater improvement in total score on the 10-item scale from
<table>
<thead>
<tr>
<th>Variable</th>
<th>6 week change</th>
<th>Control</th>
<th>CMC</th>
<th>Between Group Difference</th>
<th>p-value</th>
<th>10 week change</th>
<th>Control</th>
<th>CMC</th>
<th>Between Group Difference</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Five-time-sit-to-stand (FTSTS) (s)</td>
<td>-2.78 ± 1.85</td>
<td>-7.02 ± 1.85</td>
<td>-4.24 ± 2.67</td>
<td>0.13</td>
<td>-5.88 ± 1.00</td>
<td>-7.33 ± 1.00</td>
<td>-1.45 ± 1.45</td>
<td>0.33</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Timed-up-and-go (TUG) (s)</td>
<td>-0.30 ± 1.14</td>
<td>-2.29 ± 1.14</td>
<td>-1.99 ± 1.62</td>
<td>0.24</td>
<td>-2.47 ± 0.57</td>
<td>-3.68 ± 0.57</td>
<td>-1.21 ± 0.81</td>
<td>0.15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stair Climb test (SCT) (s)</td>
<td>3.42 ± 2.03</td>
<td>-2.78 ± 1.93</td>
<td>-6.20 ± 2.81</td>
<td>0.04</td>
<td>-1.59 ± 1.32</td>
<td>-5.90 ± 1.32</td>
<td>-4.31 ± 1.87</td>
<td>0.03</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 minute walk (6MW) (m)</td>
<td>-1.54 ± 14.05</td>
<td>46.10 ± 13.23</td>
<td>47.64 ± 19.59</td>
<td>0.03</td>
<td>36.48 ± 14.64</td>
<td>112.11 ± 14.64</td>
<td>75.63 ± 20.94</td>
<td>0.002</td>
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<tr>
<td>4-meter walk test-usual speed (s) (4MWusual)</td>
<td>0.56 ± 0.32</td>
<td>-0.18 ± 0.29</td>
<td>-0.74 ± 0.43</td>
<td>0.11</td>
<td>-0.03 ± 0.15</td>
<td>-0.76 ± 0.13</td>
<td>-0.73 ± 0.20</td>
<td>0.002</td>
<td></td>
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</tr>
<tr>
<td>4-meter walk test-fastest speed (s) (4MWfast)</td>
<td>0.81 ± 0.28</td>
<td>-0.07 ± 0.25</td>
<td>-0.88 ± 0.38</td>
<td>0.04</td>
<td>-0.01 ± 0.09</td>
<td>-0.52 ± 0.08</td>
<td>-0.51 ± 0.12</td>
<td>0.001</td>
<td></td>
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</tr>
<tr>
<td>Fullerton Advanced Balance Scale (FAB)</td>
<td>-2.60 ± 1.50</td>
<td>2.78 ± 1.32</td>
<td>5.39 ± 2.06</td>
<td>0.02</td>
<td>-0.45 ± 0.77</td>
<td>3.60 ± 0.73</td>
<td>4.05 ± 1.09</td>
<td>0.002</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pelvic Tilt Angle (degrees)</td>
<td>-2.39 ± 5.36</td>
<td>-0.81 ± 2.02</td>
<td>1.58 ± 0.42</td>
<td>0.42</td>
<td>-4.33 ± 5.77</td>
<td>-0.43 ± 5.12</td>
<td>3.9 ± 0.07</td>
<td>0.07</td>
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<tr>
<td>HOOS ADL</td>
<td>15.669 ± 5.602</td>
<td>21.685 ± 5.676</td>
<td>6.016 ± 8.036</td>
<td>0.47</td>
<td>19.945 ± 3.600</td>
<td>35.835 ± 3.825</td>
<td>15.890 ± 5.329</td>
<td>0.010</td>
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<tr>
<td>HOOS QOL</td>
<td>13.908 ± 6.615</td>
<td>28.311 ± 6.713</td>
<td>14.403 ± 9.549</td>
<td>0.16</td>
<td>25.120 ± 5.185</td>
<td>42.834 ± 5.513</td>
<td>17.714 ± 7.720</td>
<td>0.04</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HOOS Symptom</td>
<td>11.847 ± 4.642</td>
<td>27.128 ± 4.773</td>
<td>15.281 ± 6.817</td>
<td>0.04</td>
<td>19.366 ± 4.386</td>
<td>33.213 ± 4.672</td>
<td>13.847 ± 6.633</td>
<td>0.06</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SF12 MCS</td>
<td>3.231 ± 2.094</td>
<td>4.566 ± 2.227</td>
<td>1.335 ± 3.127</td>
<td>0.68</td>
<td>5.869 ± 2.193</td>
<td>4.501 ± 2.333</td>
<td>-1.369 ± 3.276</td>
<td>0.68</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SF12 PCS</td>
<td>0.070 ± 2.722</td>
<td>5.733 ± 2.887</td>
<td>5.663 ± 3.968</td>
<td>0.18</td>
<td>4.494 ± 2.220</td>
<td>10.914 ± 2.354</td>
<td>6.419 ± 3.236</td>
<td>0.07</td>
<td></td>
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</tr>
</tbody>
</table>
Figure 5.4. Mean percent change from preoperative to postoperative time points. Error bars are standard deviation.
preoperative values to the 6-week time point (P=0.02) compared with the change seen in the CON group. The CMC group showed an approximately 15% improvement on the balance scale (2.5 points), while the CON group showed an almost 15% decline in performance (2.5 points). Additionally, the CMC demonstrated significantly greater improvement in score from preoperative levels to the 10-week time point (P=0.002) (Table 5.3)

**Neuromuscular Control**

Six weeks after THA, there were no differences in the change in pelvic tilt angle from preoperative assessment between groups (P=0.42), although the CON group demonstrated a 2.4 degree drop in pelvic tilt angle, while the CMC group showed less than one degree of change(Table 5.3 ). However, by the 10 week assessment, the CMC group tended to have less change in their pelvic tilt angle, indicating more stability, than the CON group (P=0.07).

**Isometric Muscle Strength**

Six weeks after THA, there were no differences between the CMC and CON groups in the change in hip flexor (P=0.57), hip extensor (P=0.27), hip abductor (P=0.58) strength from preoperative values. Additionally, there were no differences between groups in the change in knee flexor (P=0.06) or knee extensor (P=0.10) strength compared with preoperative values (Table 5.4).

At the end of rehabilitation, 10 weeks after THA, there were no differences between groups in the change in hip flexor (P=0.22), hip extensor (P=0.43), or knee flexor strength (P=0.82). There was a trend toward greater improvements in hip abductor (P=0.09) strength and knee extensor strength (P=0.06) in the CMC group compared with the CON group (Table 5.4).
Safety

Neither the CMC nor the CON group participants reported any hip dislocations throughout the duration of the study. Further, there were no reports of other musculoskeletal injuries or falls in either group. Finally, there was no difference in pre-assessment resting pain levels at each postoperative time point between groups.

Table 5.4. Changes in Muscle Strength Outcomes.

<table>
<thead>
<tr>
<th>Variable</th>
<th>6 week change</th>
<th>Between Group Difference</th>
<th>10 week change</th>
<th>Between Group Difference</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Control</td>
<td>CMC</td>
<td>p-value</td>
<td>Control</td>
<td>CMC</td>
</tr>
<tr>
<td>Normalized knee flexor strength (Nm/kg)</td>
<td>-0.056 ± 0.040</td>
<td>0.055 ± 0.038</td>
<td>0.112 ± 0.056</td>
<td>0.06</td>
<td>0.102 ± 0.060</td>
</tr>
<tr>
<td>Normalized knee extensor strength (Nm/kg)</td>
<td>-0.217 ± 0.088</td>
<td>-0.006 ± 0.082</td>
<td>0.211 ± 0.122</td>
<td>0.10</td>
<td>-0.035 ± 0.104</td>
</tr>
<tr>
<td>Normalized hip flexor strength (Nm/kg)</td>
<td>-0.161 ± 0.065</td>
<td>-0.109 ± 0.061</td>
<td>0.052 ± 0.090</td>
<td>0.57</td>
<td>-0.029 ± 0.062</td>
</tr>
<tr>
<td>Normalized hip extensor strength (Nm/kg)</td>
<td>-0.098 ± 0.130</td>
<td>0.112 ± 0.121</td>
<td>0.210 ± 0.185</td>
<td>0.27</td>
<td>0.045 ± 0.080</td>
</tr>
<tr>
<td>Normalized hip abductor strength (Nm/kg)</td>
<td>0.004 ± 0.041</td>
<td>-0.028 ± 0.039</td>
<td>-0.032 ± 0.056</td>
<td>0.58</td>
<td>-0.006 ± 0.068</td>
</tr>
</tbody>
</table>

Discussion

Participation in an 8-week, multi-component rehabilitation (CMC) program following total hip arthroplasty (THA) resulted in greater improvements in stair climbing and walking performance, as well as balance compared to a control group which did not
participate in rehabilitation after surgery. Further, there tended to be positive effect on pelvic stability during unilateral stance. This effect was seen at both the intermediate (6 week) assessment and at the conclusion (10 week) of treatment. Yet, the CMC intervention had mixed results regarding improvements in muscle strength around the hip or knee at either time point as there was a trend toward greater improvement in hip abductor and knee extensor strength at the end of intervention, but no differences in improvements in other muscle groups. However, since the study was not powered on muscle strength differences, the trends present may be important. Additionally, the CMC intervention resulted in greater improvements in some self-reported outcomes, but not in all self-reported outcomes. Importantly, the CMC intervention did not compromise the safety of the individuals receiving the intervention.

**Functional Performance**

The primary aim of this study was to investigate whether an 8-week, multi-component intervention (CMC) would result in greater improvements in functional performance, specifically stair climbing time, following THA compared to a control group (CON) who did not participate in an outpatient rehabilitation program. It was hypothesized that the CMC group would demonstrate greater improvements in stair climbing ability after intervention. The results of the study support this hypothesis, as greater improvements in stair climbing time were seen in the CMC group following intervention.

The significantly greater improvements in stair climbing ability in the CMC group after THA is evident in the different trajectories each group had in recovery.
Figure 5.5. Mean percent change from preoperative to postoperative time points. Error bars are standard deviation.
Specifically, the CMC group improved stair climb test time from preoperative levels at both the 6 and 10 week assessments, while the CON group demonstrated an initial decline in stair climbing performance, followed by improvement. Six weeks after surgery, the CMC group had improved their time by 3.5 seconds, greater than the clinically meaningful difference of 2.6 seconds,\textsuperscript{140} and representing a 5% improvement. Conversely, the CON group was approximately 6 seconds slower, representing a greater than 30% decline (Figure 5.3). By the 10 week time point, the CMC group showed further improvement to almost 6 seconds faster than preoperative levels, or 20% improvement, while the CON group, demonstrated a 4 second, or about 2%, improvement.

The fact that the CON group showed an initial decline before improving is not unusual, and is consistent with literature describing functional recovery after THA. Significant declines in functional performances have been documented as early as one week following THA.\textsuperscript{58} Further, this phenomenon is still present one month after THA, as individuals continue to demonstrate worse functional performance compared with preoperative levels. In previous work in this laboratory, an 8-second decline in stair climbing performance was still present 1 month after THA. Similar to the CON group, the cohort studied did not receive outpatient rehabilitation services.\textsuperscript{141} This suggests that having no rehabilitation, guided activity or exercise after surgery further perpetuates poor functional performance early after THA. However, the CMC group showed improvement in stair climbing performance as early as 6 weeks following THA, in contrast to previous literature.\textsuperscript{141} The evidence of early improvement in functional performance indicates that participation in a rehabilitation program with the addition of neuromuscular reeducation techniques to improve stability, hastens improvement in functional performance during the initial recovery period. Reasons for this recovery may be multi-factorial, but may lie in the mechanical link between the lumbopelvic complex and the lower extremity. Stair
climbing relies heavily on recruitment of the quadriceps muscle, however, greater improvements in stair climbing ability between groups was observed despite the fact that significant greater improvements in quadriceps strength was not. This finding could be related to the addition of neuromuscular reeducation to the protocol. The neuromuscular reeducation techniques used in the protocol focused on utilizing the lateral hip musculature and the abdominal musculature to stabilize the pelvis in a variety of situations, forcing the pelvis to become a stable base for movement, which is critical for producing efficient, coordinated movement. Furthermore, it is hypothesized that the gluteal muscles are responsible for stabilizing the femur against external joint moments caused by movement. Therefore, it is likely that improved alignment of the femur, through lumbopelvic stability, could lead to more efficient recruitment of the quadriceps, thus improving stair climbing ability.

In addition to greater improvements in stair climbing ability, the CMC group showed greater improvement in six minute walk distance and walking speed. The CMC group again showed improvements early (6 weeks) after THA. Walking relies on the coordination of several muscle groups and joint motions. To counter the dynamic nature of this functional task, lumbopelvic stability is required to produce efficient movement and likely plays a role in the differences in improvement between groups. The addition of this type of training has shown improvements in gait parameters in the lower extremity, and thus may hasten improvement walking capability and speed in this population.

Despite the greater improvements in stair climbing and walking, there were fewer differences in the lower functioning task of the timed-up-and-go (TUG) and in the five-time-sit-to-stand (FTSTS) test, a higher level bilateral task. The reason for the differences in change in functional performance could lie in the differences between the tasks from the higher level stair climbing and fast walking tests. For example, the TUG
has a bilateral component to the task, during the sit to stand transition, potentially allowing individuals to use the non-operative limb to aid in the most demanding part of the test thus aiding performance. Additionally, the distance walked is short (3 meters) and may not challenge individuals as there is often a ceiling effect observed in this test. The fact that the CON group showed a nearly half-second improvement in performance 6 weeks after THA indicates that this outcome measure may begin to improve early after surgery, with or without intervention, perhaps due to the lower functional demands of the task. Previously, declines in TUG performance were seen after THA earlier than 6 weeks after THA. However, in the current study, both groups improved TUG performance. One explanation for this observation could be the difference in testing time point, as these data were collected 6 weeks after surgery, rather than 1 week or 4 weeks after surgery as in previous literature. The difference of two additional weeks of recovery may reflect the natural recovery than earlier measurements.

The FTSTS test, unlike the TUG, is considered a higher functioning task. However, this test is a simultaneous bilateral task, meaning that both legs participate simultaneously in the activity and individuals never have to rely solely on the surgical leg to complete the task. Therefore, it is possible that individuals could over-utilize the non-operative limb to complete this task, and thus perform faster than expected. This phenomenon of asymmetrical loading is seen in other joint replacement populations, such as total knee arthroplasty, and has been reported after THA as well. The fact that there was not a precipitous drop in FTSTS performance in either group is consistent with previous data in the laboratory, as a similar trajectory of little change after surgery was observed. With the exception of the FTSTS, it seems the CMC group demonstrated greater improvements in tasks that would be considered higher demand tasks, such as stair climbing and fast walking, suggesting that neuromuscular training
techniques with the goal of improving lumbopelvic stability has a larger impact on more challenging and complex tasks. Specifically, the intervention required closed-kinetic chain exercises meant to promote stability through muscle co-contraction around the hip and spine during unilateral stance to enhance the stabilizing role of the muscles around the hip. Theoretically, promoting stability during unilateral stance contributes to improved performance on tasks which require strength and stability on one leg such as stair climbing and fast walking. Further, the effects of lumbopelvic stability, or lack thereof, may be more apparent during higher level tasks, which demand higher levels of stability.

Patient Perception of Quality of Life/Physical Activity

It was also hypothesized that patients in the CMC group would report greater improvements in self-reported function on the HOOS and SF12 as well as greater improvements in physical activity measured by the UCLA activity score (Table 5.4). The results of this study partially supported this hypothesis. Specifically, the CMC group reported greater improvements in 3 of the 5 HOOS subscales (ADL, Pain, QOL) 10 weeks after THA. However, there were no differences in improvements on the Sports and Recreation or Symptom subscales or differences in SF12 scores. Additionally, there were no differences in improvements in self-reported outcomes 6 weeks after THA. Following THA, both groups improved their self-reported function despite the fact that the CON group performed worse on performance-based functional assessments. This phenomenon has previously been observed after THA as well as after total knee arthroplasty and suggests that patients often overestimate their self-reported functional performance, likely due to decreases in pain early after surgery. Therefore, since both groups reported improvements in self-reported measures, differences between groups were not observed. Finally, there were no differences in changes in self-
reported physical activity levels at either time point between groups, despite the fact that
the CMC group had greater improvements in performance-based functional
assessments. It is likely that, despite improvement in function, further intervention aimed
at behavior modification and patient education may be needed to improve physical
activity levels.

Balance/Neuromuscular Control

A second aim of the study was to investigate the effects of the CMC intervention
on balance and neuromuscular control, or the ability to stabilize the pelvis during a
unilateral standing task. It was hypothesized that the CMC group would demonstrate
greater improvements in balance and stability following intervention than the CON group.
In accordance with this hypothesis, the CMC did show greater improvements in balance,
as measured by the Fullerton Advanced Balance Scale (FAB) and tended to have
greater pelvic control during unilateral stance (Table 5.4).

The FAB, consisting of 10 individually scored items, measures both dynamic and
static balance. Six weeks after THA, the CMC group demonstrated a greater than 15% improvement in score on the FAB compared with preoperative score, while the CON group scored more than 10% worse than the preoperative score. Ten weeks after THA, the CMC group showed further improvement over preoperative scores, with a nearly 25% percent improvement while the CON group was still almost 5% worse than
preoperative values. The importance of the FAB is its ability to predict fall risk in older
adults who are living independently. Specifically, a cut-off score of 25 out of a total
score of 40 is used to determine faller status. At the 6 week follow up, the mean
change in score in each group had different effects in this cut-off point. With the
improvement in score seen in the CMC group, the group mean was approximately 26,
while the decline in score in the CON group led to a mean score of approximately 23,
putting the CON group at risk for falling, as they now score less than 25. Further, with each 1-point decrease in score on the FAB, the probability of falling increases by 8%.\textsuperscript{146} In the case of the CON group, the observed decrease in score translates to a 20% increase in the risk of falling during the first six weeks after recovery, at a time when the hip is most vulnerable to injury such as dislocation.

Difficulty with balance after THA has been reported previously. For example, Trudelle-Jackson, \textit{et al.}\textsuperscript{8} reported that individuals demonstrate poorer postural stability in the surgical hip compared with the non-surgical hip 1 year after THA and Nallegowda, \textit{et al.}\textsuperscript{147} reported that individuals post-THA have differences in motor response and postural control compared with health, age-matched controls. Additionally, Nantel, \textit{et al.}\textsuperscript{148} described more difficulty with balance in THA patients compared with those undergoing hip resurfacing, despite the similarity in surgical procedure. Therefore, either the effects of surgical technique or effects of the prosthesis on joint performance may make balance more difficult.\textsuperscript{148} These deficits in balance remain, despite the reported improvement in balance compared with the balance deficits seen preoperatively\textsuperscript{47} indicating that, although improvements are seen, postoperative management has not fully addressed issues regarding restoring balance and stability. The current protocol specifically addressed balance and stability through neuromuscular reeducation techniques, and successfully improved balance in this population.

In addition to greater improvement in balance, the CMC group further demonstrated differences in stability during a single limb stance as measured by pelvic tilt angle during the task (Table 5.4). Specifically, the CON group demonstrated a drop in pelvic tilt angle during single limb standing at 6 weeks and a greater drop 10 weeks after THA, 2.4 degree and 4.3 degree changes, respectively. It has been reported that changes in pelvic angle over a sustained SLS task of 4 degrees are clinically meaningful.\textsuperscript{137} However, the methods for calculating this outcome measure differed,
making the clinically meaningfulness of these findings unknown. Conversely, the CMC group showed little change in this measure after THA, 0.81 degree and 0.41 degree changes, indicating the maintenance of a pelvic angle close to horizontal and less change from initial values. This drop in pelvic tilt angle indicates the CON group had more pelvic obliquity and consequential increase in standing side hip adduction angle. This posture has been shown to have a negative effect on patterns of hip joint loading during gait, which requires a period of single limb standing and indicates that lateral hip musculature and lumbopelvic complex is unable to stabilize the pelvis. Impaired loading of the joint can have negative consequences on the prosthesis as well as lead to altered movement patterns negatively affecting other joints. The improvement of pelvic stability may therefore normalize hip joint loading, mitigating the negative effects of poor pelvic movement and posture. The fact that the CMC group showed less change, or more stability, in this measure suggests that the focus on pelvic stability through weight-bearing neuromuscular reeducation techniques had a positive effect. Further, the lack of aberrant pelvic mechanics may also have led to better movement patterns during gait, leading to the observed improvements in functional performance.

**Muscle Strength**

A third aim of this investigation was to determine the efficacy of the CMC intervention on improvement in muscle strength following THA. It was hypothesized that the CMC group would demonstrate greater improvements in muscle strength in hip flexors, abductors and extensors as well as knee extensors and flexors. The results of the study showed mixed results in supporting this hypothesis. Six and 10 weeks after THA, following intervention, there was no statistical differences in improvement in strength in any muscle groups measured. However, at the 10 week time point, improvements in hip abductor strength and knee extensor strength tended to be greater
for the CMC group. Since this study was powered to detect differences in stair climbing rather than muscle strength changes, this finding is not surprising. Despite this, the trends toward statistical significance seen at 10 weeks are important to note, indicating that muscle strength differences are present. The findings that the CMC intervention did not lead to greater improvement in muscle strength could be related to dose of the strength training protocol. The protocol intended for participants to train each muscle group at a weight representing an 8-repetition maximum, as recommended for healthy, older adults.\textsuperscript{149} While later in the protocol this was feasible by all participants, it was more difficult early in the protocol. Within the first few weeks following THA, most patients demonstrated difficulty firing some hip muscles, particularly the hip abductors and hip extensors. Although no previous literature exists describing this phenomenon of difficulty activating these muscles, the fact that patients struggled with muscle firing made training at high levels difficult. Specifically, the overload required to induce muscle strength may not be possible in a muscle with an activation deficit\textsuperscript{150} since the muscle is not capable of firing to its maximal capacity. Therefore, strength training in the presence of a muscle activation deficit may not produce the muscle strength gains expected. This may explain why the greatest improvements in muscle strength came at the 10 week assessments and not the 6 week time point. Despite the fact that greater improvements in muscle strength were not seen in the CMC group, the trajectory of change in muscle strength was different than the CON group and in previous studies in our laboratory. Specifically, the CMC group showed improvements in muscle strength compared with preoperative values by 6 weeks after THA (Figure 5.5) whereas the CON group demonstrated declines in muscle strength at the 6 week time point. Furthermore, previous work in our laboratory indicated that muscle strength in these muscle groups declined during the first month after surgery and did not surpass preoperative levels until
6 months after THA.\textsuperscript{141} This suggests the CMC group saw an accelerated recovery of muscle strength after surgery.

It has been reported previously that strength training after THA can improve muscle strength as well as function.\textsuperscript{12,38,55,73} Additionally, it is commonly thought that improvements in strength lead to improvements in functional performance as well as balance. However, in the current study, significant improvements in functional performance were observed in the CMC group in the absence of statistically significant improvements in muscle strength. This finding could be due to the multi-component nature of the CMC intervention. The addition of neuromuscular reeducation exercises to strength training exercises, which seek to improve stability and coordination, may have an additive effect and contribute to improving function.

Often, adults decide to undergo THA to alleviate pain associated with hip osteoarthritis. However, one of the primary reasons which leads individuals to the final decision to have surgery is limitations in activities of daily living, work duties and recreational activities due to pain.\textsuperscript{151} Although the surgical procedure is successful in relieving pain, residual impairments in strength and functional performance may not restore individuals’ full functional capacity. Effective rehabilitation is one modality to restore functional capacity. As rehabilitation strategies in other injury populations with persistent functional deficits have evolved, rehabilitation after THA requires a similar change. The addition of neuromuscular reeducation techniques to a post-THA rehabilitation protocol for enhanced lumbopelvic stability, provides greater improvements in functional performance in the first few months following surgery and mitigated early functional declines previously reported.\textsuperscript{141} The acceleration of recovery also afforded improvements in balance and a reduction in fall risk during the early stages after surgery, lessening risk for falls and potential dislocations, a common concern in early recovery. The combination of improved functional performance, balance and stability
suggests patients may return to regular activities of daily living, work and recreation earlier after the completion of the rehabilitation protocol. The addition of neuromuscular reeducation training post-THA should be considered in future studies with longer follow ups and larger sample sizes to determine whether the shift in rehabilitation paradigm is warranted.

**Limitations**

There are limitations to the current study. First, this study consisted of a small sample size. Although the study was powered to evaluate differences in stair climb time between groups, the sample size was small. The conclusion drawn from 20 participants may not be robust enough to draw definitive conclusions regarding the efficacy of the intervention. Further, the study was powered to detect differences in stair climbing performance. Therefore, it may not have been adequately powered to see differences in our secondary outcome measures, such as muscle strength which may explain the lack of statistical significance in these outcomes. Subsequent studies should seek to examine the effects of this intervention on a larger sample to determine if the effects on strength are similar. Second, the fact that the intervention has multiple domains and different types of exercise limits interpretation of findings. The exercise protocol included more than one mode of exercise, so it cannot be determined which part of the intervention contributed the improvements in function observed. Additionally, each domain included activities or exercises that are closely related and therefore may have had an effect on more than one outcome. So, it may be that the combination of activities that improved function. Future studies should consider a design to answer this specific question, or consider collecting additional outcomes such as biomechanical outcomes to infer the mechanisms behind the observed improvements. Finally, the duration of follow up
assessment may also be a limitation of the study. Prior studies have indicated that recovery following THA may not be complete 10 weeks after surgery, as improvements are seen beyond the 10 week time frame.\textsuperscript{39,105} It is possible that further improvements may be seen longer term. Future investigations should include longer term follow up assessment to fully understand the effect of the CMC intervention on full recovery.
CHAPTER VI

SUMMARY

Osteoarthritis (OA) is the most common joint disease, compromising the quality of life of millions of older adults.\textsuperscript{14,41} Specifically, hip OA affects up to 28\% of adults over the age of 65.\textsuperscript{43} To date, there is no cure for OA. Patients often seek medical care to address the pain and stiffness associated with hip OA in order to improve quality of life. The primary intervention to alleviate pain and stiffness of hip OA is total hip arthroplasty. Total hip arthroplasty is considered a common orthopedic procedure\textsuperscript{1} and the demand for this surgery is growing yearly likely due to our aging population. Although THA is considered a successful surgery due to high patient satisfaction,\textsuperscript{152,153} full recovery of muscle strength and functional performance remain challenging suggesting that current rehabilitation strategies may not be adequate\textsuperscript{8,12}

Although the limited recovery and residual deficits in muscle strength and functional mobility are well documented, no evidence-based rehabilitation guidelines exist for patients after THA.\textsuperscript{73} Further, there is no consensus on the course of postoperative care following surgery, including from those performing THA.\textsuperscript{74,75} Due to the multi-factorial contributions to declines in functional performance following THA, a shift in rehabilitation strategy is necessary. However, rehabilitation priorities are difficult to set without the understanding of the deficits present before and after THA, and without the understanding of the efficacy of postoperative rehabilitation efforts. Therefore, the overall purposes of this dissertation work were to 1) to characterize the limitations present in end-stage hip OA, 2) describe the time course of recovery following THA, and 3) propose a comprehensive rehabilitation program aimed at improving functional mobility and other outcomes following THA.
In chapter III, the differences in muscle strength and functional performance were examined in a cohort of individuals with end-stage hip OA compared to a cohort of similarly aged healthy adults. The results of this study indicate that individuals with hip OA had strength deficits, particularly in knee extensor and flexor strength. Additionally, individuals with hip OA performed poorer on tests of stair climbing, sit to stand and walking. They were also less physically active than their healthy peers. These findings indicate that prior to THA, these individuals have diminished strength and functional performance, which should be considered during postoperative rehabilitation planning. Often, postoperative rehabilitation aims to improve acute impairments related to surgery, but it must also be acknowledged that deficits exist before undergoing surgery.

In chapter IV, the time course of recovery after THA and the comparison of 12 months of recovery to healthy adults were examined. The results of this study indicated that patients see a significant decline in muscle strength and functional performance one month following surgery. From that point, improvement is seen in all outcomes and patients regain their preoperative level of function by 3 months after THA. Twelve months after THA, patients exhibit significant deficits in knee extensor and flexor strength compared with healthy adults. Further, although not statistically significant, differences in functional performance remained.

In chapter V, the efficacy of a comprehensive, multi-component (CMC) rehabilitation program was investigated. The intervention was initiated 2 weeks after THA and lasted for 8 weeks. The results of this study indicated that individuals who participated in the rehabilitation intervention had greater improvements in stair climbing ability, walking ability, balance and stability compared with individuals who did not receive intervention (CON). However, improvements in muscle strength in the lower extremity were not different between the two groups. Importantly, participation in the
CMC intervention did not compromise safety, as there were no incidences of hip dislocation, injury or falls in either group.

Based on the findings of these three studies, a more robust understanding of the effects of hip OA and its resolution secondary to total hip arthroplasty and rehabilitation emerges. Further, the effects of a multi-component rehabilitation intervention, including neuromuscular reeducation techniques, on improving outcomes are also understood.

Prior to surgery, individuals with hip OA demonstrate deficits in strength and functional performance which is further hastened after THA. Therefore, rehabilitation strategies should address not only the acute impairments and limitations after THA, but strategies targeting long-standing strength and functional performance deficits should be considered. This may be accomplished with a multi-component program which addresses both muscle strength and neuromuscular reeducation techniques aimed to improve stability in the surgical hip. The addition of these techniques to a postoperative protocol has the potential to improve functional performance outcomes after THA through enhanced stability. Additionally, this protocol resulted in accelerated recovery time after surgery, since common postoperative declines in strength and function were mitigated. The importance of accelerated recovery lies in the fact that the CMC intervention has the potential to reduce fall risk, thus reducing dislocation risk and healthcare burden. Further, a quicker resumption of functional activities will lead to improved patient satisfaction and quality of life. These results suggest not only that the protocol was effective at improving rehabilitation outcomes after surgery, but suggests that a shift in postoperative rehabilitation utilization and exercise prescription is warranted.

In conclusion, hip osteoarthritis is a complex, multi-factorial condition requiring characterization of the effects of this condition on individuals' functional mobility. Further, the remediation of muscle strength and functional mobility deficits is not achieved
through total hip arthroplasty alone. Participation in an 8-week, comprehensive, multi-component rehabilitation program can enhance recovery after THA. Future work in rehabilitation strategies after THA should examine the effects of this program on a larger cohort of patients to examine the generalizability and feasibility of the intervention on a large scale. Furthermore, an examination of biomechanical outcomes, including a better understanding of pelvic stability before and after THA and its effects on physical function, will provide a more mechanistic understanding of recovery after THA. This examination will also afford an improved understanding of neuromuscular reeducation techniques on stability and function, thus leading to a shift of postoperative rehabilitation strategy.
REFERENCES


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## REHABILITATION PROTOCOL

Comprehensive, Multi-Component (CMC) rehabilitation protocol is detailed in the table below. Patients attended outpatient rehabilitation for 8 weeks, 2x/week, beginning 2 weeks after THA.

<table>
<thead>
<tr>
<th>Domain</th>
<th>Phase I (weeks 1 and 2)</th>
<th>Phase II (weeks 3 and 4)</th>
<th>Phase III (weeks 5 and 6)</th>
<th>Phase IV (weeks 7 and 8)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Warm Up</td>
<td>Slow treadmill walking (&lt; 2.0mph)</td>
<td>Treadmill walking (2.0-2.5mph)</td>
<td>Supine double knee folds Resisted BKFO Bridging Upper abdominal curl</td>
<td>Upper abdominal curl with double knee fold Supine leg circles Bridging w/ adductor squeeze</td>
</tr>
<tr>
<td>Core stabilization</td>
<td>Isometric lower abdominal training Kegel training Supine knee folds Bent knee fall out (BKFO)</td>
<td>Supine knee folds (single and double) Resisted BKFO Bridging</td>
<td>Supine double knee folds Resisted BKFO Bridging Upper abdominal curl</td>
<td></td>
</tr>
<tr>
<td>Neuromuscular Reeducation *with mirror</td>
<td>Standing weight shifts* Supported single limb stance (SLS)*</td>
<td>Weight shifts on foam* Unsupported SLS* Standing pelvic drop/lift w/ support*</td>
<td>SLS on foam* Unsupported standing pelvic drop/lift* Balance board*</td>
<td>SLS on foam or BOSU if able* Standing pelvic drop/lift on foam or BOSU if able* Balance Board*</td>
</tr>
<tr>
<td>Progressive Resistance Exercise (PREs) **ankle weights † Cybex</td>
<td>Supine hip abduction Clamshells (if able) Seated knee extension** Standing hamstring curl** Standing hip extension**</td>
<td>Sidelying clamshells Seated knee extension** Standing hamstring curl** Standing hip extension**</td>
<td>Resisted clamshells (theraband) Seated knee extension† Standing hamstring curl† Standing hip extension† Standing hip abduction†</td>
<td>Resisted clamshells (theraband) Seated knee extension† Standing hamstring curl†</td>
</tr>
<tr>
<td>Functional Training *with mirror</td>
<td>Gait training Review postoperative precautions</td>
<td>Gait training Sit-to-Stand (hips&gt;90)* Step ups (3-4”)*</td>
<td>STS Step ups (5-6”) forward and lateral* Gait/Agility training* Forward and backward</td>
<td>Wall squats* Step ups (8-12”) forward and lateral*</td>
</tr>
</tbody>
</table>

---

*with mirror

**ankle weights † Cybex

† Cybex
APPENDIX B

RAW DATA: FUNCTIONAL OUTCOMES

Raw data, means ± standard deviation, is presented for all functional outcomes in the table below.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Preoperatively</th>
<th>6 weeks postoperatively</th>
<th>10 weeks postoperatively</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CMC</td>
<td>CON</td>
<td>CMC</td>
</tr>
<tr>
<td>Five-time-sit-to-stand (FTSTS) (s)</td>
<td>21.31 ± 9.96</td>
<td>16.44 ± 6.28</td>
<td>12.35 ± 2.72</td>
</tr>
<tr>
<td>Timed-up-and-go (TUG) (s)</td>
<td>11.23 ± 3.09</td>
<td>12.51 ± 7.93</td>
<td>9.41 ± 1.19</td>
</tr>
<tr>
<td>Fullerton Advanced Balance Scale (FAB)</td>
<td>23.20 ± 4.57</td>
<td>25.67 ± 4.30</td>
<td>26.50 ± 4.20</td>
</tr>
<tr>
<td>Stair Climb test (SCT) (s)</td>
<td>19.19 ± 10.94</td>
<td>20.42 ± 14.06</td>
<td>16.78 ± 5.33</td>
</tr>
<tr>
<td>6 minute walk (6MW) (m)</td>
<td>366.07 ± 137.97</td>
<td>430.57 ± 170.43</td>
<td>430.50 ± 56.05</td>
</tr>
<tr>
<td>4-meter walk test-usual speed (4MWusual) (s)</td>
<td>4.08 ± 1.26</td>
<td>3.72 ± 0.70</td>
<td>3.79 ± 0.63</td>
</tr>
<tr>
<td>4-meter walk test-fastest speed (4MWfast) (s)</td>
<td>3.00 ± 0.90</td>
<td>2.92 ± 0.65</td>
<td>2.92 ± 0.43</td>
</tr>
<tr>
<td>UCLA Activity Score</td>
<td>4.80 ± 1.55</td>
<td>5.67 ± 2.06</td>
<td>5.00 ± 0.94</td>
</tr>
<tr>
<td>Pelvic Tilt Angle (degrees)</td>
<td>0.18 ± 6.74</td>
<td>0.16 ± 5.01</td>
<td>0.02 ± 5.00</td>
</tr>
</tbody>
</table>
APPENDIX C

RAW DATA: MUSCLE STRENGTH OUTCOMES

Raw data, means ± standard deviation, is presented for all muscle strength outcomes in the table below.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Preoperatively</th>
<th>6 weeks postoperatively</th>
<th>10 weeks postoperatively</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CMC</td>
<td>CON</td>
<td>CMC</td>
</tr>
<tr>
<td>Normalized knee flexor strength</td>
<td>0.65 ± 0.22</td>
<td>0.70 ± 0.23</td>
<td>0.59 ± 0.17</td>
</tr>
<tr>
<td>(Nm/kg)</td>
<td>0.64 ± 0.22</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Normalized knee extensor strength</td>
<td>1.35 ± 0.63</td>
<td>1.37 ± 0.42</td>
<td>1.31 ± 0.47</td>
</tr>
<tr>
<td>(Nm/kg)</td>
<td>1.52 ± 0.41</td>
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<tr>
<td>Normalized hip flexor strength</td>
<td>0.83 ± 0.46</td>
<td>0.77 ± 0.27</td>
<td>0.79 ± 0.26</td>
</tr>
<tr>
<td>(Nm/kg)</td>
<td>0.99 ± 0.52</td>
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<tr>
<td>Normalized hip extensor strength</td>
<td>0.50 ± 0.21</td>
<td>0.69 ± 0.44</td>
<td>0.75 ± 0.50</td>
</tr>
<tr>
<td>(Nm/kg)</td>
<td>0.90 ± 0.68</td>
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<td></td>
</tr>
<tr>
<td>Normalized hip abductor strength</td>
<td>0.59 ± 0.32</td>
<td>0.65 ± 0.36</td>
<td>0.65 ± 0.22</td>
</tr>
<tr>
<td>(Nm/kg)</td>
<td>0.65 ± 0.36</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
APPENDIX D

RAW DATA: PATIENT SELF-REPORTED OUTCOMES

Raw data, means ± standard deviation, is presented for all patient self-reported outcomes in the table below.

Abbreviations: HOOS = Hip disability and Osteoarthritis Outcome Score; ADL = Activities of daily living; QOL = quality of life; SF12 = Medical Outcome Study Short Form 12; MCS = mental component score; PCS = physical component score.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Preoperatively</th>
<th>6 weeks postoperatively</th>
<th>10 weeks postoperatively</th>
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<tbody>
<tr>
<td></td>
<td>CMC</td>
<td>CON</td>
<td>CMC</td>
</tr>
<tr>
<td>HOOS ADL</td>
<td>47.61 ± 16.51</td>
<td>57.35 ± 24.29</td>
<td>75.59 ± 16.10</td>
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<tr>
<td>HOOS pain</td>
<td>40.31 ± 18.73</td>
<td>47.78 ± 22.17</td>
<td>75.00 ± 19.15</td>
</tr>
<tr>
<td>HOOS QOL</td>
<td>22.66 ± 14.54</td>
<td>31.94 ± 18.87</td>
<td>53.13 ± 17.24</td>
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<tr>
<td>HOOS Sports and Recreation</td>
<td>27.34 ± 24.31</td>
<td>32.64 ± 19.96</td>
<td>41.25 ± 33.10</td>
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<tr>
<td>HOOS Symptom</td>
<td>40.00 ± 23.90</td>
<td>57.22 ± 22.65</td>
<td>73.50 ± 13.34</td>
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<tr>
<td>SF12 MCS</td>
<td>45.42 ± 13.58</td>
<td>51.75 ± 7.34</td>
<td>53.41 ± 7.57</td>
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<tr>
<td>SF12 PCS</td>
<td>37.41 ± 8.76</td>
<td>37.52 ± 7.73</td>
<td>42.19 ± 5.57</td>
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