MEASUREMENT RELIABILITY
AND EFFECT OF HIP STRENGTHENING EXERCISES
IN KNEE OSTEOARTHRITIS

by

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Abstract

The progression of knee osteoarthritis (OA), the most common cause of physical disability in older adults, is influenced by muscular and biomechanical factors. Reliability of muscular and biomechanical measures, including knee muscle strength and limb alignment, is critical. Furthermore, conservative interventions that slow the course of OA disease progression and prevent disability are urgently needed. The objectives of this thesis were to: 1) investigate the reliability of measures of knee muscle strength and alignment in persons with knee OA, and 2) determine the influence of an exercise intervention targeting hip muscles on knee joint loading in those with medial knee OA.

In the first study reliability of knee muscle strength measures was evaluated within one testing session in 40 persons with knee OA. Isometric and isokinetic peak torque values for the quadriceps and hamstring muscles demonstrated high degrees of intra-session reliability.

Reliability of lower limb alignment measures was determined following a bone landmark-based approach with use of a computer program. Excellent reliability coefficients were found which compared favorably with reliability of manual measures from schematics of limb deformities drawn with AutoCAD® software. When the computer method was applied to 100 full-limb radiographs of persons with or at risk for knee OA, alignment measures demonstrated high inter- and intra-reader reliability.

Hip muscle weakness may influence loading of the medial knee compartment. Hip abductor strength was evaluated in 40 individuals with medial compartment knee OA in comparison to a control group of 40 healthy older adults. The effect of an 8-week home-
based hip abductor strengthening program on the knee adduction moment was also assessed in this group with knee OA, compared with the control group which received no intervention. Following the exercise program the OA group demonstrated improvements in hip abductor strength and functional performance on a sit-to-stand task. There were no changes in the knee adduction moment. Thus, hip muscle strengthening did not influence joint loading, but may improve function in persons with knee OA.

Results from this thesis provide increased understanding of knee OA, from muscular and biomechanical perspectives, in the areas of measurement reliability and exercise intervention.
Co-Authorship

Elizabeth Sled was the primary author of all chapters within this thesis. Chapter 3 represents a manuscript in preparation for journal submission. Co-authors of Chapter 3 are Sandra J. Olney, Alison C. Chalmers and Wilma M. Hopman. Elizabeth Sled co-designed the study procedures with the help of Dr. Sandra Olney and was responsible for all data collection and interpretation for Chapter 3. Wilma Hopman assisted with statistical analysis. The manuscript was completed by Elizabeth Sled, with editing provided by the co-authors.

The material in chapter 4 is also a manuscript in preparation for journal submission. Chapter 4 was co-authored by Lisa M. Sheehy, David T. Felson, Patrick A. Costigan, Miu Lam and T. Derek V. Cooke. All experimental work, including training of readers, data collection, analysis and interpretation, was completed by Elizabeth Sled. Assistance with statistical analysis for the second study in Chapter 4 was provided by Dr. Miu Lam. Elizabeth Sled completed the initial draft of the manuscript that comprises this chapter and participated in subsequent editing with the co-authors.

Chapter 5 was designed by Elizabeth Sled, with input from Dr. Sandra Olney and Dr. Elsie Culham. All data collection, analysis and interpretation for Chapter 5 were completed by Elizabeth Sled. The manuscript that comprises this chapter was written by Elizabeth Sled, with editing and feedback provided by Dr. Olney and Dr. Culham.
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<table>
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<th>Description</th>
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<tbody>
<tr>
<td>ANOVA</td>
<td>analysis of variance</td>
</tr>
<tr>
<td>BMI</td>
<td>body mass index</td>
</tr>
<tr>
<td>CH</td>
<td>Condylar-Hip angle</td>
</tr>
<tr>
<td>CP</td>
<td>Condylar-Plateau angle</td>
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<tr>
<td>EMG</td>
<td>electromyography</td>
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<tr>
<td>FM</td>
<td>femoral mechanical axis</td>
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<tr>
<td>FS</td>
<td>femoral shaft (anatomic) axis</td>
</tr>
<tr>
<td>FTSST</td>
<td>Five-Times-Sit-to-Stand Test</td>
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<tr>
<td>GRF</td>
<td>ground reaction force</td>
</tr>
<tr>
<td>HKA</td>
<td>hip-knee-ankle angle</td>
</tr>
<tr>
<td>ICC</td>
<td>intraclass correlation coefficient</td>
</tr>
<tr>
<td>IRED</td>
<td>infra-red emitting diode</td>
</tr>
<tr>
<td>K/L</td>
<td>Kellgren and Lawrence (grade of osteoarthritis disease severity)</td>
</tr>
<tr>
<td>LBA</td>
<td>load-bearing axis</td>
</tr>
<tr>
<td>MAK</td>
<td>Mechanical Factors in Arthritis of the Knee study</td>
</tr>
<tr>
<td>MOST</td>
<td>Multicenter Osteoarthritis Study</td>
</tr>
<tr>
<td>MRI</td>
<td>magnetic resonance imaging</td>
</tr>
<tr>
<td>N(\text{m})</td>
<td>newton-metres</td>
</tr>
<tr>
<td>OA</td>
<td>osteoarthritis</td>
</tr>
<tr>
<td>PA</td>
<td>Plateau-Ankle angle</td>
</tr>
<tr>
<td>PASE</td>
<td>Physical Activity Scale for the Elderly</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
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</tr>
<tr>
<td>ROM</td>
<td>range of motion</td>
</tr>
<tr>
<td>SD</td>
<td>standard deviation</td>
</tr>
<tr>
<td>SAS</td>
<td>Statistical Analysis System</td>
</tr>
<tr>
<td>SPSS</td>
<td>Statistical Package for Social Scientists</td>
</tr>
<tr>
<td>TM</td>
<td>tibial mechanical axis</td>
</tr>
<tr>
<td>TS</td>
<td>tibial shaft (anatomic) axis</td>
</tr>
<tr>
<td>VAS</td>
<td>visual analog scale</td>
</tr>
<tr>
<td>WOMAC</td>
<td>Western Ontario and McMaster Universities Osteoarthritis Index</td>
</tr>
<tr>
<td>3-D</td>
<td>three-dimensional</td>
</tr>
<tr>
<td>2-D</td>
<td>two-dimensional</td>
</tr>
<tr>
<td>%BW*Ht</td>
<td>percentage of the product of participant weight and height</td>
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Chapter 1

General Introduction

1.1 Demographics and Socio-economic Burden of Osteoarthritis

The Bone and Joint Decade was launched in January, 2000, in recognition of the significant impact of bone and joint disorders on the individual, the health care system and society. The aim is to advance the understanding and treatment of these disorders through research, prevention and education (1).

Osteoarthritis (OA) is the most common chronic joint condition and a major source of pain and limitation of activity in older adults (2). Approximately 3 million Canadians (1 in 10) have OA and it is estimated that 85% of Canadians will have been diagnosed with OA by the age of 70 years (3). The 1996 to 1997 National Population Health Survey by Statistics Canada revealed that the prevalence of OA is 2.5 times and 6 times greater than that of heart disease and cancer, respectively (4).

Recent Canadian data on direct and indirect health care costs of OA indicate that the economic burden associated with OA is immense (5;6). Added to these costs are the intangible or quality-of-life related costs, which emphasize the personal and social consequences of OA. Osteoarthritis has a significant impact on health-related quality of life factors, including ambulation, body care and movement, emotional behaviour, sleep, home management and work, all of which contribute to the “humanistic” burden of OA (7). Osteoarthritis is positioned among the top 10 causes of disability worldwide (8). As aging is an important systemic risk factor for OA (9), the rapid increase in the percentage
of the population greater than 55 years makes OA a growing public health problem (10;11).

1.2 Osteoarthritis of the Knee

The knee joint is the weight-bearing joint most commonly affected with OA (12). Epidemiological studies estimate a prevalence of 10-12% for symptomatic, radiologically diagnosed knee OA in adults greater than 55 years of age (13). Joint replacement surgeries for advanced knee OA have increased markedly over the past decade. In Canada the number of total knee replacements rose by 81% from 1994-1995 to 2004-2005 (14).

Traditionally, OA has been conceptualized as a disease of articular cartilage. More recently, the contributions of bone and soft tissue structures to the pathologic process of OA have been recognized and the current understanding is that the pathology of knee OA involves the entire joint (9;15).

Articular cartilage forms a thin layer lining the bony ends of all synovial (diarthrodial) joints. It consists of a solid matrix (predominantly composed of collagen and proteoglycan molecules), which is saturated with water (16-18). The primary functions of articular cartilage are to: (a) distribute forces generated during joint loading over a wide area, (b) stabilize and guide joint motions, (c) contribute to joint lubrication, and (d) allow relative movement of the opposing joint surfaces with minimal friction (17;18). In a healthy joint, articular cartilage may withstand the large forces associated with weight-bearing and joint motion with little or no signs of wear (17;18). With injury
or degeneration related to OA, the earliest pathological change in cartilage is the deterioration of the solid matrix (16;18). Damage to the solid matrix is associated with changes in cartilage mechanics, including a significant loss of tensile, compressive and shear stiffness and an increased propensity for swelling of the cartilage (17;18). Cartilage degeneration may involve fibrillation (splitting of the cartilage surface), the presence of cracks or fissures and partial or complete loss of the tissue (16-18).

Sophisticated radiography techniques and magnetic resonance imaging (MRI) have provided evidence that bone pathology is an early feature in the initiation of knee OA (19). Increased mass and stiffness of subchondral bone (sclerosis), bony proliferation at the bone margins (osteophytes) (15) and an increase in metabolism of bone (bone turnover) (19) are characteristic bony changes in OA. Other pathological processes include changes to the soft tissue structures in and around the knee joint, which may consist of capsular stretching, synovial inflammation and ligament laxity (20). The disease process results in joint pain, swelling and reduced joint range of motion, with concomitant weakness of surrounding muscles.

Diagnosis of knee OA is made by clinical and radiographic evaluation. According to the American College of Rheumatology (21;22), clinical criteria for knee OA include knee pain, morning stiffness of the knee for \( \leq 30 \) minutes and crepitus on joint motion. Radiographic criteria consist of presence of osteophytes, the loss of joint space, or both (21;22).

Knee pain is the predominant symptom of knee OA and the reason why individuals seek medical attention (23-25). Secondly, people with knee OA may report
significant limitations in physical function. For those over the age of 65 years, OA of the knee accounts for greater physical disability in lower extremity tasks, such as walking, stair climbing and rising from a chair, than any other condition, clearly reducing quality of life and independence (26;27). Furthermore, the presence of other co-existing chronic conditions, including heart disease, pulmonary disease and obesity, increases the likelihood of subsequent disability in persons with knee OA (28;29). Given the prevalence of knee OA in society and the burden of physical disability from OA, continued attention must be given to determining the most effective approaches to painful knee OA (25).

1.3 Intent and Structure of Thesis

This thesis aims to promote a better understanding of knee OA, from muscular and biomechanical perspectives, in the areas of measurement reliability and exercise intervention. The intent of this thesis is to investigate the reliability of measures of knee muscle strength and frontal plane lower limb alignment commonly used in knee OA studies and to evaluate the influence of an exercise intervention on knee joint loading, strength, function and pain in persons with knee OA.

Chapter 2 of this thesis provides a review of the current literature on local, biomechanical risk factors for knee OA, outcome measures in knee OA research and changes in gait parameters demonstrated by those with knee OA. Interventions for OA, including bracing, orthotics and exercise, are also discussed.
Chapters 3-5 present a series of studies of individuals with knee OA. Lower extremity muscle strength is commonly measured in knee OA research. A review of the literature indicated that numerous knee muscle strength testing protocols were utilized and that poor intra-session reliability at higher isokinetic strength testing velocities was characteristic of some studies (30-32). Thus, in Chapter 3 we evaluated a group of 40 individuals with mild to severe knee OA in order to determine the reliability of commonly used isometric and isokinetic measures of knee muscle strength within a single testing session.

In addition to muscle strength measures, evaluations of frontal plane lower limb alignment are frequently performed in knee OA studies. Technical advances in medical imaging have led to a shift from use of conventional film radiographs to digital radiographs, requiring computer software programs for measurement of alignment from digital images. To evaluate the reliability of alignment measures using a computer-based method, the second study (Chapter 4) consisted of two reliability analyses. The first part compared measurements of lower limb alignment obtained manually and by a computer software program using schematics of limb deformities drawn with AutoCAD® software. An established approach, which involves the selection of 10 bone landmarks on the femur and tibia, was used to derive the alignment measures. For the second part of the study we applied the computer-assisted method to full-limb digital radiographs and evaluated the reliability of alignment measures using the bone landmarks-based approach.

Excessive knee joint loading during gait has been shown to contribute to the progression of knee OA (33). It has been postulated that the hip abductor muscles may
influence knee joint loading through their control of the pelvis in the frontal plane (34;35). Weakness of the hip abductor muscles in persons with knee OA may lead to impaired frontal plane pelvic control and greater loads through the medial compartment of the knee. However, few studies have assessed the strength of the hip abductor muscles in those with knee OA in comparison to healthy older adults (36). In addition, no study was identified which evaluated the effect of a strengthening program targeted specifically to the hip abductor muscles on reduction of knee joint loading. The purpose of the final study (Chapter 5) was to examine the influence of an 8-week home-based exercise program of hip abductor strengthening on hip muscle strength and knee joint loading in 40 persons with medial compartment knee OA when compared with a control group of 40 asymptomatic individuals. Secondary objectives were to evaluate the effect of hip abductor strengthening on functional performance during a sit-to-stand task and knee symptoms. This sample of 40 participants with knee OA was a different cohort from the cohort studied in Chapter 3.

The final chapter (Chapter 6) summarizes the findings of the thesis and provides a general discussion of the studies, including recommendations and suggestions for future research.
1.4 References


Chapter 2
Literature Review

2.1 Introduction

This review will present an update on the current knowledge of risk factors for the incidence and progression of knee osteoarthritis (OA) and a summary of common measures utilized in clinical knee OA studies. The characteristics of gait in persons with knee OA will also be reviewed. Finally, potential interventions for slowing disease progression and reducing pain and functional limitations, including various exercise interventions, will be discussed.

2.2 Risk Factors for Development and Progression of Osteoarthritis

Osteoarthritis is considered to be the product of a complex interaction between systemic and local biomechanical factors (1;2) (Figure 2.1). How risk factors interrelate to affect the incidence and rate of progression of OA is not yet fully known (3). The initiation and progression of knee OA may involve different risk profiles, as some early joint lesions remain stable over long periods while others progress rapidly (4).

The results of cohort-based epidemiological studies have provided new insights into the risk factors for the development and progression of radiographic knee OA. This review will focus on the recent literature concerning local biomechanical risk factors.
2.3 Local Biomechanical Factors in Knee Osteoarthritis

2.3.1 Joint Injury and Physical Activity

Local biomechanical factors which are considered to contribute to the incidence of knee OA include previous joint injury and meniscectomy (4;6-8), occupational tasks, particularly those that involve frequent kneeling, squatting and heavy lifting (9-12), and high intensity sports participation (4;13-15). Performance of recreational sports activities does not appear to increase the risk of subsequent knee OA (13;16;17).

2.3.2 Obesity

Longitudinal studies have demonstrated that obesity is a powerful risk factor for the development of knee OA, particularly in women (18-21). Obesity has also been
shown to increase the risk for radiographic OA progression (4:22-24). The increased risk for progression of knee OA among overweight persons appears to be limited to those with varus, but not valgus, alignment (25) and those with moderately malaligned limbs, rather than severe malalignment (23).

### 2.3.3 Static Lower Limb Malalignment

Frontal plane lower limb malalignment has been shown to increase the risk of disease progression, yet it is still unclear whether malalignment plays a role in the initial development of the disease. In 1,501 participants randomly selected as part of the Rotterdam Study, a large, prospective cohort investigation, Brouwer et al. (26) reported that knees with varus anatomic axis alignment and no OA at baseline demonstrated a two-fold increase in the risk of developing knee OA after 6.6 ± 0.5 years, compared to knees with normal alignment. Knees with valgus alignment showed a borderline significantly increased risk of developing knee OA. Further analyses of the participants stratified according to body mass index (BMI) indicated that the risk for developing knee OA in those with varus alignment at baseline was only significant for overweight and obese individuals, but not for the healthy weight group (26).

Hunter et al. (27) examined the influence of alignment on the development of knee OA in 110 incident knee OA cases and 356 random control knees from among participants in the Framingham Osteoarthritis study. In contrast to the findings by Brouwer et al. (26), baseline knee anatomic axis alignment was not associated with the development of knee OA on follow-up testing at a mean of 8.75 years from baseline. Neither varus nor valgus malalignment predicted incident knee OA after adjusting for
age, gender and BMI. The smaller case-control design of this study in comparison to the study by Brouwer et al. (26) and the demarcation points for alignment quartiles are factors that may have explained why a relationship between malalignment and incident OA was not detected (28).

Epidemiological studies have confirmed a strong relationship between lower limb alignment at baseline and progression of knee OA (26;29;30). In a prospective longitudinal cohort study of 237 community-dwelling persons with primary knee OA (30), varus mechanical axis alignment at baseline was associated with a 4-fold increase in the odds of medial compartment disease progression over an 18-month period after adjustments for age, gender and BMI. Baseline valgus alignment was associated with a nearly 5-fold increase in the risk of lateral OA progression. Cerejo et al. (29) further analyzed the results from this group of participants to examine the malalignment effect according to baseline stage of disease severity. The impact of varus or valgus malalignment on the odds of OA disease progression over 18 months was greater in knees with more advanced OA at baseline.

The above findings were substantiated in the Rotterdam Study (26), in which participants were followed over a mean of 6.6 years. The risk of OA progression was significantly greater in persons with varus alignment at baseline than those with normal alignment. Further evidence for the relationship between progressive joint deterioration and frontal plane malalignment has come from the study of bone marrow edema through magnetic resonance imaging (MRI). A longitudinal study by Felson et al. (31) demonstrated that bone marrow edema lesions were powerful predictors of structural
progression in persons with knee OA and that these lesions were strongly related to malalignment.

2.3.4 Dynamic Loading of the Knee Joint

Measures of lower limb alignment from radiographs reflect only a static observation of alignment. Three-dimensional (3-D) kinematic and kinetic analyses are required to offer a dynamic picture of the multiple forces imparted on the joint during ambulation (32-34). A major determinant of load on the knee joint is the external adduction moment, a gait parameter that has recently received considerable attention in the literature. The external knee adduction moment and its influence on the incidence and progression of knee OA will be discussed in Section 2.5.6 of this review.

2.3.5 Varus-Valgus Knee Joint Laxity

The results of cross-sectional studies suggest that increased varus-valgus knee joint laxity, producing abnormal displacement of the tibia relative to the femur in the varus-valgus direction, may be a factor contributing to the incidence and progression of knee OA (35;36). Varus-valgus laxity was greater in the uninvolved and involved knees of 164 individuals with OA than in the knees of a control group of 24 older adults without OA (35). Increased varus-valgus laxity was associated with greater joint space narrowing (35;36) and bony attrition (35) in those with knee OA.
2.3.6 Proprioceptive Deficits

Preliminary cross-sectional research has indicated that proprioceptive deficits may both precede the development of knee OA and influence structural disease progression. Among older adults, deficits in knee position sense and detection of movement at the knee were significantly greater in those with knee OA than those without OA (37-39). In addition, proprioceptive impairments were greater in both the arthritic and non-arthritic knees of individuals with OA than in healthy older adults without knee OA (39).

2.3.7 Muscle Weakness

Quadriceps muscle weakness may not only be a result of painful knee OA, but a risk factor for its development (40;41). In a prospective study of 280 community-dwelling older adults with no evidence of radiographic OA at baseline, reduced quadriceps strength relative to body weight appeared to be a risk factor for the initiation of knee OA in women, but not in men, on follow-up after a mean of 31.3 months (41).

The literature is conflicting as to whether lower extremity muscle strength protects against progression of structural changes in persons with knee OA or contributes to its advancement (42;43). Brandt et al. (42) measured baseline concentric isokinetic quadriceps strength in 79 individuals with knee OA and performed follow-up radiographic assessments at a mean of 31.5 months later. No significant differences in muscle strength were found between participants with radiographically stable OA and those whose joint damage progressed, suggesting that quadriceps weakness was not a risk factor for the progression of OA.
The influence of muscle strength on OA progression was also studied by Sharma et al. (43) in a prospective longitudinal cohort study of 237 persons with knee OA over an 18-month period. For the group of OA participants with more neutral knee alignment and low varus-valgus laxity the findings were consistent with those of Brandt and colleagues (42), in that quadriceps strength at baseline had no effect on disease progression. However, among those with increased varus-valgus malalignment and high varus-valgus laxity, greater baseline quadriceps strength was associated with a significant increase in the likelihood of OA progression. It was suggested that malaligned knees were less able to evenly distribute muscle forces, resulting in greater structural progression (43). Greater quadriceps strength may also increase compressive forces across the knee joint, an effect which may be heightened with malalignment (44).

Large-scale, longitudinal studies evaluating lower extremity muscle strength in cohorts of persons at risk for incident knee OA and progression of established OA will provide further understanding of the influence of muscle strength as a risk factor (45).

2.4 Measurement in Knee Osteoarthritis Research

2.4.1 Measurement of Osteoarthritis Disease Severity

Radiographic grading scales are used in clinical trials to determine the severity of knee OA and are commonly utilized as principal outcome measures to identify disease progression in longitudinal studies (46). These scales evaluate changes in cartilage and
subchondral bone and provide individual or overall (global) grading of radiographic features (47).

The first scheme for grading knee radiographs, which has been used extensively in clinical trials, was a global scale developed by Kellgren and Lawrence (K/L) (48;49). The joint is graded on a five-category scale (grades 0-4), according to the presence of osteophytes, joint space narrowing and subchondral sclerosis (48). Global radiographic grades are as follows: 0 = no radiographic findings of OA; 1 = questionable (doubtful narrowing of joint space and possible osteophyte lipping); 2 = mild (definite osteophytes and possible narrowing of joint space); 3 = moderate (multiple moderate osteophytes, definite narrowing of joint space, some bony sclerosis and possible deformity of bone ends); 4 = severe (large osteophytes, marked narrowing of joint space, severe bony sclerosis and definite deformity of bone ends) (46;48;50). Although the K/L grading scheme is still widely used, the scale is limited by its emphasis on the presence of osteophytes in the diagnosis of OA, inconsistencies in published descriptions of its radiographic features and its relative insensitivity to change over time (50;51).

Numerous other grading scales for assessing radiographic features of knee OA have been published. These systems include the Ahlback (52), Brandt (53), Scott (50) and Cooke (54) scales. The grading system described by Cooke et al. (54) was developed as a revision of Scott et al. (50) to provide a total joint scoring system that would be sensitive to change over time and to specific, biomechanical deformity in knee OA. This system is a unicompartment grading system, grading only the compartment that shows greater joint deterioration, since early knee changes are typically focused in one
compartment. Four categories of joint changes are graded as follows: joint space loss (0-3); femoral osteophytes (0-3); tibial erosion (0-4); and subluxation (0-3). Tibial erosion is graded according to the progression of features, from initial dicing, to marginal destruction, then fragmentation and finally gross bone damage. Subluxation is defined as a medial or lateral shift between the tibial spines and the femoral sulcus. The scores in each category are summed, producing a total score ranging from 0 (normal knee joint) to 13 (maximum radiographic disease severity) (54). Overall grading scores on the scale by Cooke et al. (54) demonstrated high inter-reader reliability and significant correlations with measures of lower limb alignment.

2.4.2 Measurement of Knee Alignment

Evaluations of knee alignment are important for investigating the influence of mechanical factors in OA, for guiding the conservative management of knee OA and for assisting the surgeon in surgical planning (26;27;30;55-57). Ideally, limb alignment measures are obtained from long-limb radiographs of the hip, knee and ankle joints using a standardized system for positioning the subjects (58). The gold standard measurement of lower limb alignment is the angle formed by the intersection of the femoral mechanical and tibial mechanical axes, often termed the hip-knee-ankle (HKA) angle (55;59;60) or the mechanical-axis angle (60-63) (Figure 2.2).

There is no general agreement concerning the mechanical axes of the knee (58). From anatomical studies the mechanical axis of the femur has been depicted as a line from the centre of the femoral head to the mid-condylar point of the distal femur (64), while the tibial mechanical axis is formed by a line from the centre of the tibial plateau
Figure 2.2  Common patterns of frontal plane lower limb alignment, modified from Cooke et al. (58).

A. Varus alignment: LBA passes medial to the knee and knee centre is displaced laterally (HKA is -ve).
B. Neutral alignment: knee center is located on the LBA (HKA = 0°); femoral and tibial mechanical axes are co-linear.
C. Valgus alignment: LBA is lateral to the knee and knee centre is displaced medially (HKA is +ve).

Legend:
LBA = Load-bearing axis  HKA = Hip-knee-ankle angle
FM = Femoral mechanical axis  TM = Tibial mechanical axis
(interspinous, intercruciate midpoint) to the centre of the tibial plafond distally (65). In a limb with neutral alignment the HKA angle approaches 180° and the femoral and tibial mechanical axes pass through the centre of the knee (55;59) (Figure 2.2B). The mechanical axes are co-incident with the load-bearing axis (LBA), the line representing the ground reaction forces (GRFs) passing from the centre of the ankle to the centre of the hip (55;59;63). In a limb with varus alignment the LBA passes medial to the knee and the knee centre is displaced laterally (Figure 2.2A), while in valgus alignment the LBA is lateral to the knee (Figure 2.2C) (59;63). The HKA angle is conventionally expressed as the angular deviation from 180°, such that the HKA angle = 0° in neutral alignment. Varus alignment is typically denoted as a negative value and valgus alignment as positive (55;58;59).

Other methods for measuring frontal plane mechanical-axis alignment are based on various single knee centre point approaches, in which a midpoint between the tibial spines and apex of the femoral intercondylar notch is located. This knee center point then becomes the distal point for constructing the femoral mechanical axis and the proximal point for the tibial mechanical axis (61;62;66). However, Cooke et al. (58) recommend the use of separate centre points at the femoral and tibial knee surfaces for detecting the presence of medial or lateral femoral subluxation and for determining the extent of the femoral and tibial contributions to overall alignment.

Several studies have investigated mechanical axis alignment in adult populations without OA, in attempts to establish normal values for frontal plane lower limb alignment. Mean values ranged from -1.0° to -1.3° of varus, with large standard
deviations around the mean (± 2.0° to 2.8°) (59;61;62;66;67). These findings indicate that malalignment is present in the general population, perhaps predisposing individuals to OA in later years. In those with established medial compartment knee OA, varus malalignment predominates. Mean values of varus angulation in medial OA study populations have been reported in the ranges of -3.34° (30), -6.67° (68), -7.1° (69) and -7.2° (67), with large standard deviations (± 3.8° to 4.8°).

While weight-bearing, full-limb radiographs allow for measurement of mechanical axis alignment, they expose the pelvis to ionizing radiation, require specialized equipment and expertise and are costly (70;71). Instead, measurement of anatomic axis alignment from knee radiographs is considered a valid alternative to alignment measures from full-limb radiography (60;70;71). Anatomic axis alignment is measured as the angle formed by the anatomic (shaft) axes of the distal femur and proximal tibia (the femur-tibial angle) on a radiograph of the knee (60). The femoral anatomical axis was shown to provide a reasonable estimate of the femoral mechanical axis, since these axes are offset from each other by approximately 4-5° (60;62;64;66;71). Offset-corrected anatomic axis measurement from knee radiographs is recommended as a cost-effective, practical approach to evaluating alignment in epidemiological studies and clinical trials (60;70;71).

2.4.3 Measurement of Lower Extremity Muscle Strength

Muscular strength may be defined as the maximum force a muscle or muscle group can generate. The product of the force and the force’s moment arm (the
perpendicular distance from the force’s line of action to the axis of rotation) is designated as torque, expressed in Newton-metres (N·m) (72). Static, or isometric, strength is the capacity to produce torque with a voluntary isometric contraction in which there is no visible change in the length of the muscle. Dynamic strength is measured as the torque produced during concentric actions (shortening of the muscle under load) or eccentric actions (lengthening of the muscle under load) (72;73). Advances in strength testing instrumentation have led to the development of isokinetic dynamometry as an accurate method for assessing dynamic muscle strength.

Both isometric and isokinetic measures of lower extremity muscle strength have been utilized in knee OA research and will be the focus of the next sections of this review. Advantages and disadvantages of the testing methods will also be highlighted.

2.4.3.1 Isometric Testing

Easily accessible instruments for testing isometric muscle strength boast the advantages of technical simplicity and low cost (72;74). For individuals with knee OA an additional advantage of isometric strength measures is that the loading rate on the knee joint can be controlled, thus minimizing the effects of pain inhibition during strength testing (75). A limitation of isometric testing is that the strength measures are recorded only at a specific point in the range of motion at which the isometric contraction occurs. Furthermore, static strength measures may not reflect the muscular actions required for daily functional activities which involve dynamic movements (74).

Peak torque or the average torque from several trials are commonly used as outcomes from isometric testing (72). Rate of isometric force development may also be
evaluated (76). The available literature indicates that isometric muscle actions should be held for at least 5 seconds and that 3 test repetitions should be performed to attain a maximal isometric contraction (74;76)

One device used for the assessment of isometric muscle strength is the hand-held dynamometer. A simple hand-held dynamometer consists of a handle, a resistance surface with an embedded force transducer and a digital display. The device is held by an examiner and applied to the tested segment of the body as the tested individual pushes against it (77). While hand-held dynamometers are portable and inexpensive (78), they require that the examiner have sufficient upper extremity strength to stabilize the device and maintain the isometric position in order to ensure that valid and reliable strength measures are obtained (77;79). This major limitation of hand-held dynamometers becomes particularly apparent when testing powerful muscle groups, such as the quadriceps. Martin et al. (79) tested a supine technique for measuring isometric quadriceps strength using a hand-held dynamometer in healthy older adults and found that isometric quadriceps strength scores were highly correlated with isokinetic strength scores. Both a hand-held dynamometer and a dynamometer attached to a portable steel frame were shown to produce reliable isometric strength measures of the hip, knee and ankle muscles in groups of older adults (78;80).

Other devices for measuring isometric muscle strength include force transducers (load cells) and strain gauges fitted to the framework of a chair and connected to computer software programs (76). This arrangement has been used in randomized controlled trials evaluating exercise interventions for knee OA to obtain measures of
isometric knee muscle strength as outcomes (81-83). Isometric measures of quadriceps and hamstring muscle strength acquired using a fixed load cell were shown to demonstrate discriminant validity and high test-retest reliability in persons with knee OA (75;81).

Isometric strength testing may also be performed using an isokinetic device by selecting an angular velocity of 0°/s. Isokinetic testing will be discussed in the next section.

2.4.3.2 Isokinetic Testing

An isokinetic dynamometer is a rotational device that consists of a lever arm attached to a dynamometer head. The participant applies a force on the lever arm and resultant muscle torque is recorded through rotation of the lever. Isokinetic dynamometers control angular velocity by providing a resistance proportional to the torque produced during muscle contraction throughout a joint’s range of motion. Angular velocity is pre-set by the examiner and kept constant by a feedback loop which continuously compares the actual angular velocity to the pre-selected velocity and adjusts the resistive moment applied by the braking mechanism of the dynamometer (84). Isokinetic strength represents the maximum torque that can be exerted when the joint is moving at a constant, pre-set angular velocity (76;84).

Isokinetic dynamometers provide assessments of dynamic and static muscle strength and are widely utilized in clinical and research settings. Concentric and/or eccentric isokinetic protocols may be selected during testing. Isokinetic dynamometry avoids joint or muscle overloading and is regarded as one of the safest forms of strength
testing (84). The use of isokinetic measures is limited in large-scale epidemiological studies, however, because of the disadvantages of cost and lack of portability of the equipment (79).

Accurate dynamic strength measurements with isokinetic dynamometry require that the effect of gravity be considered, an important factor when testing seated knee extension/flexion. The performance of knee extension requires the individual to lift the weight of the limb and the lever arm of the machine against gravity, while gravity assists the motion of the limb and the lever arm during the knee flexion motion. To compensate for gravity and avoid measurement errors, an automated gravity correction procedure is inherent in modern isokinetic dynamometers as part of the software system (74;76).

Other potential measurement errors with isokinetic dynamometry are velocity and torque overshoot, which produce impact artifact (74;85). Velocity overshoot occurs when the limb accelerates past the desired velocity and braking takes place to slow the limb to the pre-selected velocity, resulting in torque overshoot (an inflated torque spike). At the end of the repetition when the dynamometer begins to decelerate the lever arm in anticipation of changing directions, the lever arm impacts the mechanical end stop and may oscillate slightly, producing an inflated isometric spike. These large, rapid spikes in the torque curve should not be confused with actual muscle torque production and must be removed during data processing. “Windowing” of the isokinetic data is a term which refers to filtering out all data that are not obtained within the pre-set angular velocity in order to eliminate erroneous torque values (86;87).
Recommended guidelines for isokinetic testing include: proper positioning of the individual in the dynamometer, with the axis of rotation of the machine aligned with the joint being tested; stabilization of the individual with straps to restrict motion to the joint being tested and avoid extraneous movements; the performance of several practice trials to allow familiarization with the equipment; and at least 3-4 test repetitions (74;88).

Isokinetic tests in clinical trials for knee OA have focused predominantly on dynamic evaluation of the quadriceps and hamstring muscles, particularly in the concentric mode. The most common angular velocities selected for isokinetic testing of the knee muscles were 60°/s, 90°/s and 120°/s (40;42;89-95).

2.4.4 Gait Analysis

Quantitative gait analysis provides a valuable tool for assessing the pathology and progression of knee OA, for offering insights concerning potential disease-modifying strategies and interventions and for evaluating the effectiveness of treatment interventions (32;96;97).

Modern gait laboratories are typically equipped with a sophisticated motion analysis system and one or more force platforms to provide simultaneous force data. Current three-dimensional (3-D) motion analysis systems consist of multiple cameras, markers to track joint motion and direct computer interfacing (98). Motion analysis is aimed at evaluating quantitatively the spatial movements of body segments and the motions of joints connecting segments. This information can be used for providing an objective description of motion (kinematics) and for calculating joint forces and moments associated with the motion (kinetics) (99).
Markers placed on body landmarks either reflect light (passive systems) or emit light (active systems). Passive systems (e.g. Vicon, Oxford, UK) use wireless, reflective markers that reflect projected light back to the cameras. Active systems (e.g. Optotrac, Northern Digital Inc., Waterloo, ON) utilize infrared light-emitting diodes (IREDs), which generate their own light and are connected with wiring to a control unit attached to the participant. The active markers flash sequentially and the marker positions are detected by the cameras based on flash timing (99;100).

Various marker configurations are employed in gait laboratories. One typical configuration uses arrays of markers placed on rigid plates attached to the body. Clusters of markers mounted on rigid structures tend to reduce unwanted marker movement and error compared to independent markers placed directly on the skin. At least three markers are needed to define each segment (101).

To acquire 3-D motion data, two-dimensional (2-D) coordinate information is obtained initially from the cameras and the location of the markers. From these sets of 2-D coordinates, 3-D spatial coordinates are calculated using a common approach based on the direct linear transformation method (101;102). An advantage of modern motion analysis systems is that the coordinate position data can be rapidly calculated from multiple markers throughout an entire movement sequence (100). Thus, gait trials can be viewed within minutes of data collection, enabling examination of the data for potential errors while the participant is still present in the laboratory (103).
2.4.4.1 The Gait Cycle

A complete gait cycle is defined as the sequence of events which occurs from initial contact of one foot to the successive initial contact of the same foot (104). The gait cycle is typically normalized, such that each event is expressed as a percentage of the whole, with initial foot contact designated as 0% and the successive foot contact of the same limb selected as 100%. The gait cycle includes stance phase (when the foot is in contact with the ground), representing about 60% of the gait cycle in healthy adults at normal walking speed, and swing phase (when the foot is not in contact with the ground), which makes up about 40% of the gait cycle (98).

Although different terminology exists for further division of the gait phases, stance phase is traditionally subdivided into heel strike (including initial contact and foot flat events), midstance and push-off phases (with heel off and toe off events during this sub-phase). A commonly used terminology from Ranchos Los Amigos (105) divides stance phase into the sub-phases of loading response, midstance, terminal stance and pre-swing. Swing phase is typically subdivided into early swing, mid-swing and late swing phases. Throughout the gait cycle there are two periods of double limb support when both feet contact the ground and two periods of single limb support when the body is supported by one limb (98;106).
2.5 Gait Characteristics in Persons with Knee OA

2.5.1 Temporal Spatial Parameters

Common temporal variables measured in gait include gait speed, stance/swing time, stride/step time, single limb/double limb support time and cadence (number of steps per minute). Spatial or distance parameters include stride length (the distance from one foot strike to the next foot strike by the same lower extremity), step length (the distance from the foot strike of one extremity to the foot strike of the contralateral extremity) and step width (the width of the walking base, between the midpoint of the heel of one foot to the same point on the other foot) (98;104;106).

Altered temporal-spatial gait characteristics have been demonstrated in persons with varying severities of knee OA. Those with mild to severe knee OA walked at a significantly slower self-selected gait speed than healthy control participants (107-110). Others (111;112) reported no differences in self-selected normal walking speed between those with less severe or more severe knee OA and asymptomatic control subjects.

Related to decreased gait speed, individuals with knee OA demonstrate significantly decreased stride length, shorter step length, lower cadence, longer stride time and an increase in double limb support time compared to healthy control participants (107;109). These changes may be mechanisms to increase weight-bearing stability during ambulation.
2.5.2  Kinematic Analysis

Kinematics provides a description of human movement without regard to the forces, either internal or external, that cause the motion. Kinematic gait variables include linear and angular displacements, velocities and accelerations. Angular displacement describes the range of motion of a body segment related to an adjacent segment (113).

Dynamic sagittal plane range of motion (ROM) at the hip, knee and ankle joints was significantly reduced in 58 persons with severe knee OA who were compared to 25 healthy, age- and gender-matched subjects (107). In this study OA participants walked at significantly reduced self-selected speeds in comparison with the control group. When gait speed was controlled (all participants walking at speeds between 1.12 and 1.34 m/s), a group of 15 individuals with moderately severe knee OA demonstrated less knee flexion and extension ROM during gait than an asymptomatic control group matched for age, gender and weight (114).

Other studies reported that those with knee OA made initial contact with the ground with the knee more extended compared to age-, gender- and weight-matched healthy adults without knee OA (115;116). In addition, significantly lower mean knee angular velocities and maximum knee extension velocities were found in persons with moderately severe knee OA in comparison with asymptomatic control subjects matched by age, gender and weight when both groups ambulated at similar gait speeds (114).
2.5.3 Kinetic Analysis: Overview

Kinetics refers to the study of the forces and moments that cause motion and provides insight as to the basic mechanisms of movement (98;117). Kinetic analysis requires GRF data, which can be derived from force platform measurements during gait. The GRF represents the force of the ground on the foot, which is equal in magnitude and opposite in direction to the force that the body exerts on the ground through the foot. The sum of the vertical force component and anterior-posterior and medial-lateral horizontal shear forces constitutes the GRF vector (118;119).

Combined data from external forces (GRFs), kinematic analysis (velocities and accelerations of joint positions) and anthropometric measures (segment mass, centre of mass and moment of inertia) allow for the calculation of forces and moments. To obtain 3-D kinetics, force platform data must be synchronized with the kinematic data. Current motion analysis systems enable the simultaneous collection of kinematic and force platform data at compatible sampling rates (117;119). An inverse dynamics approach is applied to indirectly determine forces and moments from kinematics and anthropometrics. Inverse dynamics uses a link-segment model which moves from distal to proximal and treats limbs as rigid segments connected by joints or links, following Newtonian mechanics, in order to calculate kinetic parameters (117;119).

A critical factor in 3-D kinetic analysis is the location of joint centres. One technique involves the approximation of joint centres based on the location of anatomical landmarks in relation to the marker clusters attached to the body. The knee joint centre may be estimated as the midpoint of the distance between the lateral and medial
epicondyles and the ankle joint centre as the midpoint of the distance between the lateral and medial malleoli. One simple method for locating the hip joint centre is to estimate 25% of the distance between the right and left greater trochanter landmarks (117).

Quantification of joint moments during gait can assist in identifying the nature and cause of functional abnormalities (32). Moments may be classified as external or internal. External moments are the moments about the joint centre which are produced by external forces, including GRFs and inertial forces. The external moment is equal and opposite to the net internal moment generated by muscles, joint capsules and ligaments to counteract the external forces acting on the body (98;120). In this review, moments will be referred to according to the external moment convention unless stated otherwise. Moments are often normalized to participants’ body weight and height and expressed in the units of percentage body weight and height (%BW*Ht) to allow for comparison between subjects.

The following sections will describe the typical kinetic features (GRFs and moments) which characterize the gait of persons with knee OA.

2.5.4 Ground Reaction Forces

Evaluation of GRFs in those with knee OA may provide an indication of loading through the lower extremity joints. Several studies showed that the vertical loading rate, or the slope of the GRF, was significantly higher in those with knee OA compared to asymptomatic control participants (114;116;121). One study of small sample size and low statistical power found no difference in knee joint forces or vertical loading rates between OA and control groups (115).
Using principal component analysis and discriminant analysis, Astephen et al. (121) identified that the loading response phase of the gait cycle immediately following initial foot contact was a discriminatory phase distinguishing between the gait patterns of those with and without knee OA. Gait features during the loading response phase may be important in the development and progression of knee OA. Radin et al. (122) found that a group of people with a history of knee pain (who were free of pain at the time of testing) and negative knee radiographs (possibly ‘pre-osteoarthritic’) demonstrated increased rapidly-applied loading at initial contact compared to a healthy group with no history of knee pain or radiographic evidence of OA. Rapid joint loading may increase a joint’s susceptibility to articular cartilage damage (122;123).

### 2.5.5 Sagittal Plane Moments

Decreased external knee flexion moments in mid-stance phase of the gait cycle were reported in several studies comparing persons with knee OA and asymptomatic control participants (108;110;112;120;124). Principal component analysis and discriminant analysis revealed that smaller knee flexion moments during stance were important features distinguishing the gait of those with knee OA (108). The external knee flexion moment is counteracted by the internal knee extension moment. A gait pattern requiring decreased quadriceps contraction (‘quadriceps avoidance’ pattern) may have been adopted in an attempt to reduce compressive forces on the knee joint and alleviate pain (120;125).

Other studies examining sagittal plane moments in persons with knee OA have shown conflicting results. Increased knee moments throughout the stance phase of gait
were found in those with severe knee OA in comparison with healthy, age- and gender-matched control participants. These moments were maintained for longer periods, possibly to stabilize the knee joint for weight transfer in stance (107). No differences in sagittal plane moments between knee OA and control groups were reported by other authors (116;126).

2.5.6 Frontal Plane Moments: The External Knee Adduction Moment

A more recent focus on frontal plane biomechanics during gait, in addition to sagittal plane patterns, has provided greater understanding of dynamic knee joint loading in persons with knee OA. Direct measurement of joint loads is not feasible on a large scale in humans due to the invasive nature of the method. However, accumulating evidence indicates that the external knee adduction moment measured during quantitative gait analysis provides a valid, indirect estimate of dynamic load on the medial compartment of the knee (32;127-129).

The knee adduction moment is the moment tending to adduct the knee throughout most of the stance phase of gait and is larger than the moments tending to flex, extend, and internally or externally rotate the knee (130). Quantification of the knee adduction moment may be obtained by calculating the product of the frontal plane GRF vector and the perpendicular distance from the GRF vector to the knee joint centre (Figure 2.3). This distance is termed the frontal plane lever arm (131). Hunt et al. (131) reported that frontal plane lever arm magnitude was greater in knees affected with OA than in unaffected knees. Furthermore, the peak knee adduction moment magnitude was more highly correlated with the magnitude of the peak frontal plane lever arm than with the
Figure 2.3 The external knee adduction moment, calculated as the product of the frontal plane ground reaction force vector and the frontal plane lever arm (the perpendicular distance from the ground reaction force vector to the knee centre), modified from Specogna et al. (69).
peak frontal plane GRF vector. It was suggested that interventions focused on reducing the magnitude of the lever arm may be beneficial for those with medial knee OA.

Across the stance phase of gait the knee adduction moment has a typical biphasic pattern with two distinct peaks (132). In general, the first peak occurs in the first half of stance during the loading response phase shortly after initial contact. The second peak is associated with late stance when the whole foot is in contact with the ground prior to push off (Figure 2.4).

The knee adduction moment has been implicated as a major determinant of medial to lateral load distribution at the knee joint. Hurwitz et al. (127) tested the validity of the knee adduction moment as a measure of knee joint loading in a study of bone mineral content of the proximal tibia in healthy adults. The authors reported a significant positive correlation between the peak knee adduction moment and the ratio of medial to lateral tibial bone mineral content. Wada et al. (129) confirmed these findings of an increased medial to lateral ratio of bone mineral density in the proximal tibia with increasing magnitude of the peak knee adduction moment in 69 individuals with medial compartment OA. It was postulated that the higher bone mineral density was a consequence of greater loads through the medial compartment of the knee.

Recently, Zhao et al. (133) investigated the relationship between the knee adduction moment during gait and in vivo measurements of medial compartment load using an instrumented knee implant in a single subject. The knee adduction moment was shown to be highly correlated with internal medial compartment contact force and medial to total force ratio, further strengthening the hypothesis that the knee adduction moment
Figure 2.4  The external knee adduction moment across the stance phase of gait. Note the typical biphasic pattern with two distinct peaks.
can be used as a surrogate measure of medial compartment load during gait (133).

Higher knee adduction moments have been reported in those with medial knee OA compared to healthy participants of similar age, weight and height (111;116;124;132). The higher knee adduction moments during stance phase were identified as discriminatory features of persons with knee OA when gait patterns were evaluated with principal component analysis and discriminant analysis techniques (121;124).

Peak knee adduction moment values demonstrated excellent test-retest reliability (ICC of 0.86) in 31 persons with medial compartment knee OA awaiting high tibial osteotomy (134). Testing was conducted on two separate occasions and the mean time between sessions was 3.4 ± 2.0 days. The findings suggested that the knee adduction moment is a reliable outcome measure for distinguishing among patients over time, as in clinical trials investigating the effects of interventions on the reduction of medial knee joint loading.

2.5.6.1 Knee Adduction Moment and its Relationship with Disease Severity, Alignment and Pain

A report of significant correlations between the peak external knee adduction moment and radiographic disease severity (r = 0.68), as measured by the K/L grading system, was provided in a cross-sectional study by Sharma et al. (135) of 54 persons with medial knee OA. The magnitude of the peak knee adduction moment was higher in knees with K/L grades of 3 or 4 compared with grades of 0 to 2 (p < 0.001). These results persisted after controlling for age, gender and severity of pain. When only joint space
width was considered, significant correlations were found between the peak knee
adduction moment and medial joint space width ($r = -0.45$). Other studies have
confirmed these findings of an association between the knee adduction moment and
radiographic OA grades (111;116;136;137).

A positive relationship between the knee adduction moment and static lower limb
alignment, as measured by the mechanical axis angle, has been demonstrated in persons
with knee OA (69;129;132;137). Although the strengths of the associations varied in
these studies ($r$ values from 0.23 to 0.74), those with greater varus alignment had higher
knee adduction moments during gait.

Studies have demonstrated that pain intensity among persons with knee OA is
related to the knee adduction moment (138-140). Hurwitz et al. (139) studied the inter-
relationship between pain and the knee adduction moment after individuals with knee OA
had discontinued their arthritis medication for a 2-week washout period. Following gait
analysis and clinical evaluation, participants with OA were then administered a non-
steroidal anti-inflammatory drug, acetaminophen, or placebo for 2 weeks and gait
evaluations were repeated. The change in the peak knee adduction moment between the
two evaluations was inversely correlated with the change in pain ($r = -0.48$). Those with
lower pain scores on the Western Ontario and McMaster Universities Osteoarthritis Index
(WOMAC) demonstrated a significant increase in the knee adduction moment between
initial and final testing. The authors postulated that an inhibition of the pain protective
reflex occurred in those with decreased pain, which resulted in increased joint loading
and higher knee adduction moments (139).
2.5.6.2 Knee Adduction Moment as a Risk Factor for Incidence and Progression of Knee Osteoarthritis

The effects of dynamic mechanical factors on the pathogenesis and rate of progression of knee OA is not yet fully known (141). Studies of small sample sizes have provided preliminary evidence that the magnitude of the knee adduction moment may influence subsequent initiation of knee OA (142;143). Amin et al. (142) reported that a higher knee adduction moment at baseline was associated with the development of chronic knee pain in a group of older adults evaluated 3-4 years later. Since knee radiographs were not performed at baseline or at follow-up, the study investigated chronic knee pain and not necessarily knee OA.

Stronger evidence exists for the role of the knee adduction moment as a risk factor for knee OA progression. Miyazaki et al. (137) tested the hypothesis that dynamic load at baseline could predict radiographic disease progression in persons with medial compartment knee OA at 6-year follow-up. Those who showed progressive medial joint space narrowing over the 6-year period had higher baseline knee adduction moments, compared to those without disease progression. The sensitivity, specificity and positive predictive value of the baseline knee adduction moment for radiographic disease progression were reported to be 88%, 83% and 80%, respectively (137).
2.5.7 Frontal Plane Hip Moments

Alterations in frontal plane hip biomechanics have been reported in those with knee OA, possibly as compensations to reduce knee joint loading during gait (108;116;144;145). Mundermann et al. (116) found that, immediately following initial contact, maximum external hip abduction moments were increased in persons with knee OA compared to matched control participants without knee OA. During mid-stance and terminal stance lower first and second peak external hip adduction moments were observed in persons with more severe OA, while those with less severe knee OA had hip adduction moments that were similar to matched control participants (116). Findings of reduced stance phase peak hip adduction moments were also reported in other studies of individuals with moderate and severe knee OA (108;144;145).

2.6 Strategies and Interventions to Lower the Knee Adduction Moment

2.6.1 Gait Strategies

Certain characteristics of gait are associated with a lower peak external knee adduction moment (97;111;132;146-148). Individuals with knee OA may adopt gait strategies unconsciously in attempt to reduce medial compartment load and decrease pain (149). It has been suggested that these adaptive strategies could be reinforced or learned as part of gait training in rehabilitation and could potentially produce a disease-modifying effect for those with medial compartment knee OA (34;97;111)
2.6.1.1 Decreased Walking Speed

One potential adaptive gait strategy is decreased walking speed. Mundermann et al. (111) studied 44 individuals with knee OA of varying disease severity who were matched by age, gender, height and weight to 44 asymptomatic control participants. When participants walked at their self-selected normal walking speed, the relationship between maximum knee adduction moment and walking speed was highly specific to the individual and depended on disease severity. The slopes of the walking speed/maximum knee adduction moment relationship were significantly greater in those with less severe knee OA than the asymptomatic control participants. Results of the study suggested that those with less severe knee OA may automatically reduce their walking speed as a strategy to decrease mechanical loading of the knee (111).

2.6.1.2 Toe-out Gait

Increased toe-out angle of the weight-bearing foot during stance phase of gait is a pattern often adopted by persons with knee OA (97;132;146;148). The toe-out gait strategy may be a mechanism to decrease the knee adduction moment and unload the medial compartment of the knee. Greater toe-out during gait would theoretically result in a more lateral displacement of the centre of pressure, thus shifting the GRF vector closer to the knee joint centre and reducing the frontal plane lever arm (97;132;146;148). In those with knee OA, ambulating with a greater amount of self-selected toe-out has been shown to correlate with a reduced second peak knee adduction moment during late stance (97;132;146;148). Jenkyn et al. (148) reported that the magnitude of the frontal plane
lever arm was shorter in the toe-out condition throughout the gait cycle in 180 individuals with medial compartment knee OA. Increasing the toe-out angle beyond a self-selected degree further reduced the second peak knee adduction moment in 10 persons with knee OA (146).

Previous studies found no relationship between increased toe-out angle and the first peak knee adduction moment during early stance phase of gait in those with knee OA (97;132;146). The lateral shift of the centre of pressure with toe-out gait may only occur in late stance. However, Jenkyn et al. (148) recently reported that toe-out gait produced small, but significant, reductions in the frontal plane lever arm and knee adduction moment in early stance phase, which were accompanied by significant increases in the sagittal plane lever arm and external knee flexion moment. The authors suggested that externally rotating the hip to increase the toe-out angle converts a portion of the knee adduction moment into a flexion moment in early stance, which may help to shift load from the medial knee and distribute loading more equally between compartments (148).

In an 18-month longitudinal study, Chang et al. (97) demonstrated that a greater toe-out angle during gait at baseline was associated with a decreased likelihood of OA disease progression. Similar results were obtained after adjusting for potential confounding factors, including age, gender, BMI, knee pain severity and baseline radiographic disease severity. The authors suggested that toe-out angle is potentially modifiable through gait training or use of foot orthotics. Clinical trials would be required
to evaluate the effectiveness of increasing toe-out angle as a rehabilitation strategy for slowing the progression of knee OA (97).

2.6.1.3 Lateral Trunk Lean

Lateral trunk lean, a gait pattern observed clinically in some individuals with knee OA, is another strategy which may be adopted to reduce knee joint loading. Leaning the trunk laterally over the stance limb would shift the centre of mass laterally, resulting in a lateral displacement of the GRF vector and a decrease in the magnitude of the lever arm about the knee (147).

A study to quantify the magnitude of lateral trunk lean during gait included small samples of individuals with unilateral and bilateral knee OA and a group of asymptomatic control participants (150). Results of the study demonstrated no significant difference in the lateral trunk lean angle between the three groups. Those with bilateral knee OA demonstrated a tendency to lean their trunk towards the swing side during ambulation, which, theoretically, would increase loading in the medial compartment, a characteristic gait that the authors suggested may contribute to the progression of knee OA.

Hunt et al. (147) measured lateral trunk lean during gait in 120 patients with medial compartment knee OA and reported that first and second peak knee adduction moments demonstrated significant negative correlations with lateral trunk lean (r = -0.39 and -0.33, respectively). Furthermore, trunk lean towards the stance limb explained a considerable portion of the variation in the first peak external knee adduction moment. The magnitude of lateral trunk lean had a higher correlation with the peak knee adduction
moment than other kinematic variables, including gait speed and toe-out angle. The findings indicated that future gait studies of lateral trunk lean in persons with knee OA are warranted, particularly in trials investigating risk factors and interventions for knee OA.

It may be that individuals with knee OA alter their gait pattern through a combination of mechanisms, including decreased gait speed, lateral trunk lean and toe-out walking (148). Further research is required to determine the long-term benefits of these compensatory gait patterns as potential therapeutic interventions for reducing knee pain and slowing disease progression.

2.6.2 Conservative Interventions: Bracing and Orthotics

Non-surgical interventions, including knee braces and foot orthotics, offer the potential for decreasing the knee adduction moment and alleviating pain in persons with knee OA.

2.6.2.1 Knee Braces

Valgus-producing unloader braces aim to reduce compressive load on the medial compartment through the application of an opposing external valgus (abduction) moment to the knee (151). Studies evaluating the effectiveness of valgus braces for reducing the knee adduction moment in persons with knee OA have produced mixed results. No differences in gait parameters, including the knee adduction moment, were found during testing with and without valgus bracing after 9 weeks and 1 year of brace wear in 19 individuals (13 persons at one-year follow-up) with knee OA (152). Other knee OA
studies of similar sample sizes have demonstrated a significant decrease in the knee adduction moment with bracing (153-155). Gaasbeek et al. (154) found that the greater the degree of varus malalignment, the greater the reduction in peak knee adduction moment achieved by the brace.

Pollo et al. (151) estimated medial compartment load using an analytical model which incorporated kinematic and kinetic gait analysis data and the measured brace moments. Net knee moments were calculated as the external adduction moment minus the brace valgus moment. Significant reductions in estimated medial compartment load were found for valgus bracing at each of the valgus angulations studied compared with the unbraced condition. In addition, the net knee moment was significantly reduced with valgus bracing compared with no brace (151). In contrast, Otis et al. (156), using similar estimations to calculate medial compartment load, reported no significant differences in medial compartment forces between sham bracing (no valgus correction) and valgus bracing.

While the effectiveness of valgus bracing for reducing medial compartment load in persons with knee OA is still uncertain, subjective findings of decreased pain and improved function from use of valgus braces have been reported (151-155).

2.6.2.2 Foot Orthotics

Valgus (laterally) wedged insoles have been recommended for the conservative management of knee OA as a means of directly altering knee joint biomechanics. The mechanism by which laterally wedged insoles may influence the knee adduction moment is not clear. It has been postulated that wedges shift the calcaneus into a valgus position
relative to the tibia, thus shifting the centre of pressure laterally during walking (157-159). These adjustments would theoretically shorten the frontal plane lever arm at the knee and decrease the joint moment.

Reductions in peak knee adduction moments and decreased knee pain have been reported with the immediate use of laterally wedged insoles in those with medial compartment OA in comparison to using no insoles and non-wedged control insoles (160-162). In contrast, results of a study by Maly et al. (158) demonstrated no immediate differences in the displacement of the centre of pressure or the peak knee adduction moment between the conditions of routine footwear, a valgus heel wedge and a modified valgus orthosis in persons with medial knee OA.

A two-year prospective randomized controlled trial by Pham et al. (163) failed to demonstrate improvements in knee symptoms or the prevention of long-term structural deterioration with the use of laterally wedged insoles compared to neutrally wedged insoles in persons with medial knee OA. This study did not include gait analysis and, thus, it was not possible to determine if use of the orthotics reduced the knee adduction moment. In addition, the insoles utilized in the study wedged the rearfoot only. Hinman et al. (164) found that full-length insoles which wedged the entire lateral border of the foot significantly reduced the first and second peak knee adduction moments compared with no insoles, but that rearfoot wedges had no significant effects. Full length insoles may be necessary for effectively altering lower limb biomechanics and influencing symptoms and disease progression.
Hinman et al. (160) reported that the use of laterally wedged insoles produced an immediate reduction in peak knee adduction moments in the first and second half of stance and at 50% of stance phase. After three months of treatment with insoles, there were improvements in pain and self-reported physical function. Those factors which predicted clinical outcome with wedged insoles were disease severity, baseline self-reported function score and magnitude of immediate change in walking pain and first peak knee adduction moment, although much of the variance in outcome was unexplained. Given the lack of consistent responses to lateral wedging in persons with medial knee OA, it has been suggested that laterally wedged insoles may be more effective in certain sub-groups of this population. Further studies are needed to identify characteristics which predict a favourable outcome (164).

2.7 Exercise Interventions

2.7.1 Strengthening Exercises: Influence on Pain and Function

Randomized controlled trials have demonstrated that both home-based and facility-based programs focusing exclusively on lower extremity muscle strengthening are effective for persons with mild to moderate knee OA (83;165-169). Benefits include reduced knee symptoms, increased muscle strength, improvements in self-reported physical functioning and performance of functional tasks, and enhanced health-related quality of life. These benefits were found as early as 6-8 weeks from baseline (166-168) and over the long-term (up to 2 years) (83). Decreased pain and improvements in self-
reported and objective measures of physical function occurred regardless of the mode of strengthening (isometric, isotonic or isokinetic), with no differences between the programs when the strength modes were compared (166;169). Both high- and low-intensity resistance programs were shown to produce significant improvements in pain, self-reported physical function and objective functional measures in persons with knee OA (167). Contrary to those findings, a 6-week high-intensity strengthening program had no effect on pain or function, but a small effect on quality of life, in those with moderate to severe knee OA (170).

Exercises, in combination with manual physical therapy techniques, have been shown to decrease pain and improve self-reported and objective measures of physical performance over the short-term in randomized controlled trials of persons with knee OA (81;171;172). Long-term benefits of manual therapy and exercise were found at one-year re-assessment (172), while another study reported no significant differences between treatment and control groups at 9 months’ follow-up (173). Hydrotherapy-based strengthening programs were also effective for improving pain and/or self-reported and objective measures of physical function in those with knee OA (174-177).

It has been suggested that generic, minimally supervised exercise programs may not be appropriate for all individuals with knee OA. In particular, generic strengthening exercises for persons with OA and malaligned or lax knees may produce negative effects of increased joint reaction forces and damage to articular cartilage (43). Specific exercise programs which consider the local mechanical environment of the joint may be more effective (43;45).
In summary, evidence from published systematic reviews of the literature indicate that strengthening exercises alone as well as physical therapy in the form of manual therapy and supervised exercise programs produce small to moderate beneficial effects on pain, physical function and health-related quality of life in persons with knee OA (178-182).

2.7.2 Influence of Exercise on Gait Parameters

Few studies have investigated the effects of exercise on gait mechanics in persons with knee OA. Temporal-spatial parameters were evaluated in a study by Peterson et al. (183), in which 102 individuals with knee OA were randomly assigned to an 8-week, hospital-based exercise intervention group (n = 47), consisting of fitness walking, light stretching and strengthening exercises 3 times/week, or a control group (n = 45), which received weekly telephone contact. Following the 8-week intervention period, participants in the exercise group demonstrated significantly increased stride lengths at natural and fast walking speeds compared to the control group.

Fransen et al. (81) randomly assigned participants with knee OA to three groups: individual physical therapy treatments at the discretion of the treating physical therapists (n = 43); small group sessions of stretching and strengthening exercises led by a physical therapist 2 times per week, supplemented by a home exercise program (n = 40); and a control group which received no treatment (n = 43). Following the 8-week interventions, both forms of physical therapy treatments resulted in significantly increased gait speed and stride length in comparison to the control group (81).
The influence of exercise on kinematic and kinetic parameters during gait has also been investigated. The Fitness and Arthritis in Seniors Trial (FAST), a 2-centre, single blind randomized controlled trial, was conducted to determine the long-term effects of aerobic walking and weight training interventions on gait mechanics over an 18-month period in older adults with knee OA (184). Both the aerobic exercise group (n = 33) and the resistance exercise group (n = 34) completed a 3-month facility-based program, followed by a 15-month home-based program consisting of aerobic walking and resistance exercises, respectively. The control group (n = 36) participated in a health education class. Following the 18-month period, the aerobic group and, to a lesser extent, the weight-training group demonstrated improved walking speed, cadence and stride length compared to the health education group. Greater mean ankle and knee angular velocities and vertical and anteroposterior propulsive forces were also apparent in both exercise groups, particularly the aerobic walking group. In both exercise groups the changes in gait were associated with a reduction in knee pain during ambulation, indicating that these individuals were able to exert greater loads through the lower extremity without any negative influences on symptoms (184).

Initial studies have also examined the effects of exercise on the knee adduction moment. In an 8-week uncontrolled pilot study of 13 persons with early knee OA, the knee adduction moment was measured during gait analysis and while participants performed a one-leg rise from a stool (185). Measurements were performed at baseline and following an exercise intervention targeted towards improving lower extremity strength and neuromuscular control. On post-intervention testing, there was a significant
reduction in the peak knee adduction moment during one-leg rise, but not during gait. The lack of change in the adduction moment during gait may have been due to the low power of the study and the mild disease severity of the participants (185).

The effect of quadriceps strengthening on the knee adduction moment was evaluated in 107 persons with medial knee OA in a 12-week randomized controlled trial (186). Participants were stratified according to alignment (more varus or more neutral alignment) and were randomly assigned to a supervised home-based quadriceps strengthening program or a control group which received no intervention. After 12 weeks of quadriceps strengthening there was no significant change in the knee adduction moment in either the group with varus malalignment or the more neutral group. Based on a power analysis, the authors reported that the non-significant finding was unlikely due to insufficient power. Results of the study did show that quadriceps strengthening produced a decrease in knee pain in persons with more neutral alignment, but not in those with greater varus malalignment (186).

2.8 Frontal Plane Hip Musculature

The frontal plane hip muscles may function to provide stability at the pelvis, hip and knee. Research relating to hip and thigh muscle activity in healthy adults, those with lower extremity injuries and persons with knee OA are summarized in three sections below.
2.8.1 Dynamic Control of Frontal Plane Knee Stability

The effect of thigh muscular activity on varus/valgus knee stability was evaluated in a study of 5 healthy young male adults (187). Muscle activity was monitored by electromyography (EMG). Varus/valgus knee stability was quantified using a device designed to objectively measure resistance to angulation in the frontal plane, with the participants positioned in supine. Under varus loading, contraction of the knee extensor muscles with synchronous activity from the tensor fascia lata produced a delay in opening of the lateral side of the knee joint, thus resisting varus angulation. The authors postulated that the lateral thigh muscles and the iliotibial band, which originates in the tensor fascia lata, may function as lateral stabilizers at the knee. Contraction of the knee flexor muscles with synchronous activity from one of the hip adductor muscles (gracilis) resisted against valgus angulation (187).

Zhang and Wang (188) later provided a more specific investigation of dynamic control of the knee in abduction-adduction under both passive (muscle relaxed) and active (muscle contracted) conditions. In this study the axis of the joint driving device was aligned with the knee abduction axis, while in the study by Olmstead et al. (187) the device produced linear motorized perturbation of the limb from the ankle. Nine healthy male adults with no previous lower extremity injuries were tested. Electrodes were placed on the lateral and medial thigh muscles and participants sat upright in the joint driving device with the knee in full extension. Results of the study showed that when the participants actively resisted the adduction perturbations, the lateral muscles (biceps femoris, vastus lateralis and lateral gastrocnemius) contracted considerably. Similarly,
medial muscles (semitendinosus, gracilis and medial gastrocnemius) contracted to actively resist the abduction perturbations.

These studies provide evidence in healthy adults without knee pathology that the frontal plane lower limb muscles contribute to varus/valgus knee stability.

2.8.2 Hip Muscle Strength and Lower Extremity Injuries

Recent studies have investigated the role of the hip muscles in lower extremity injuries and the potential benefits of hip strengthening as part of rehabilitation following injury (189-194). Three-dimensional motion analyses of single leg squatting, landing from a jump and side-step cutting maneuvers indicate that the hip abductor muscles are important for controlling frontal plane hip and knee movements (191;195;196). Gender differences have also been reported, with healthy female adults demonstrating lower hip muscle strength (normalized to body mass) and reduced frontal plane hip and knee control compared to males (191;195;196). Significant negative correlations ($r = -0.35$) between hip abductor muscle strength and knee joint valgus displacement on single leg landing from a jump were found for women, but not for men, suggesting that hip abductor strength may play a more important role in neuromuscular control of the knee in females (191). The above findings may partially explain the higher incidence of anterior cruciate ligament injuries among female athletes participating in cutting and jumping sports (197;198).

Weakness of the hip abductor muscles has been reported in persons with patellofemoral pain syndrome (190;199-201) in comparison to non-injured, matched control subjects. Researchers have theorized that weakness of the gluteus medius muscle
as a hip abductor and external rotator may cause excessive femoral internal rotation and adduction and increased valgus knee motion with weight-bearing. Increased internal rotation of the femur beneath the patella may alter patellofemoral tracking and lead to greater lateral patellar contact pressure (202;203). Tyler et al. (194) studied the effects of a 6-week program consisting of hip strengthening and flexibility exercises on knee symptoms in 35 individuals with patellofemoral pain syndrome. Results of the study showed that gains in hip abductor and adductor strength were no different between those with symptomatic improvement and those without improvement in symptoms.

Runners with iliotibial band syndrome also demonstrated significant weakness of the hip abductor muscles, compared to non-injured runners (189). Fredericson et al. (189) proposed a mechanism, similar to the hypothesis in the above studies on patellofemoral pain syndrome, by which hip muscle weakness could contribute to iliotibial band syndrome. The authors suggested that weakness of the gluteus medius muscle in its actions of hip abduction and external rotation would lead to increased hip adduction and internal rotation during walking and running and would produce an increased valgus vector at the knee. This pattern could place tension on the iliotibial band, making it more prone to impingement against the lateral epicondyle of the femur, especially during early stance phase when maximum deceleration occurs to absorb GRFs. Following a 6-week strengthening program targeting the hip abductor muscles, 22 of 24 runners with iliotibial band syndrome were painfree and had returned to running (189).
2.8.3 Hip Muscle Strength in Persons with Knee OA

The hip abductor and adductor muscles may assist in regulating medial-lateral load distribution across the knee joint. Frontal plane hip muscles are important for maintaining stability of the pelvis during gait (204). It has been hypothesized that weakness of the stance limb hip abductor muscles would lead to drop of the pelvis towards the contralateral (swing) limb during gait, which would shift the centre of mass towards the swing limb. This shift in the centre of mass would theoretically increase the magnitude of the frontal plane lever arm, leading to higher knee adduction moments and greater medial compartment knee joint forces in the stance limb (116;144) (Figure 2.5).

Few studies have assessed hip muscle strength in persons with knee OA. Yamada et al. (205) measured isometric strength of the hip abductor and adductor muscles in 32 women with medial compartment OA (49 knees) in comparison to a control group of 13 women with no history of knee problems. No significant differences were found in hip abductor or adductor muscle strength between the OA and control groups and between knees with varying severity of OA. However, the adductor to hamstring ratio was significantly greater in OA knees than control knees, and increased with increasing grade of OA disease severity. The authors suggested that the hip adductor muscles may have increased in strength over time to decrease varus angulation of the limb and reduce the knee adduction moment in those with knee OA (205).

Significant age-associated declines in isometric and isokinetic strength of the hip abductor and adductor muscles have been documented (206;207). Reduction in strength of these muscles with aging may potentially contribute to frontal plane postural instability.
Figure 2.5  Potential mechanism by which stance limb hip abductor muscle weakness could lead to an increase in the knee adduction moment during gait and cause greater loading through the ipsilateral medial compartment of the knee, modified from Chang et al. (144).

CM = centre of mass
and falls among older adults (207). Given that knee OA affects mostly older adults and
often leads to lower activity levels, hip muscle weakness may be present in those with
knee OA.

To our knowledge, the role of hip muscle strengthening in the treatment and
prevention of knee OA has not been investigated. Hip abductor strengthening may be
important for improving frontal plane pelvic stability and reducing compressive load at
the knee.

2.9 Concluding Remarks

Based on the literature presented in this chapter, the following chapters provide
further exploration of measures of muscle strength, lower limb alignment and gait in
persons with knee OA. This review has also highlighted the current emphasis in the
literature on the pursuit of effective, non-surgical interventions to reduce medial
compartment loading and slow disease progression in knee OA. Presented in this thesis
(Chapter 5) is the investigation of one potential exercise intervention for influencing knee
joint loading, pain and function.
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Chapter 3
Strength Testing in Persons with Knee Osteoarthritis:
Measures of Reliability and Influence of Pain

3.1 Abstract

Objectives: The aims of the study were to: 1) determine the reliability of isometric and isokinetic strength measures within one testing session in persons with knee osteoarthritis (OA), and 2) assess the influence of pain during strength testing on the consistency of the measures.

Methods: Forty participants with symptomatic knee OA were recruited. Peak isometric knee flexion and extension strength measures and concentric isokinetic strength measures at angular velocities of 60°/s, 90°/s and 120°/s were obtained using the Biodex Isokinetic Dynamometer. Intensity of knee pain was recorded on a visual analog scale (VAS) at baseline and immediately after each strength test.

Results: High reliability coefficients were found for the repetitions of isokinetic and isometric tests (ICCs from 0.95 to 0.98). When the repetitions were averaged, tests of reproducibility between the three angular velocities revealed ICCs of 0.98 for both isokinetic knee extension and flexion. There were weak associations between mean peak torque values and corresponding mean changes in VAS pain scores from baseline for all strength tests.
Conclusions: All isometric and isokinetic strength tests demonstrated a high degree of reliability within a single testing session. Knee pain during strength testing did not influence measurement consistency.

3.2 Introduction

Measurement of muscle strength is important in knee osteoarthritis (OA) research. Lower extremity weakness, particularly of the quadriceps muscles, is a common feature of persons with knee OA (1;2). Cross-sectional and longitudinal studies have indicated that quadriceps weakness may not only be a consequence of knee OA (3;4), but a risk factor for its development (2;5). Quadriceps muscle weakness is also implicated as a determinant of physical disability in knee OA (6-11). Measures of knee muscle strength are incorporated in OA clinical studies investigating the effects of lower extremity strength training on pain, function and OA progression (12-14). Despite the importance of strength measures in knee OA research, the literature has offered little comprehensive guidance to assure a researcher that a particular method provides consistent measures.

Isometric and isokinetic measures of muscle strength at various angular velocities have been employed in knee OA studies, with little justification for their use. When selecting a method for strength testing the researcher may be constrained by factors such as costs, testing time, availability and portability of strength testing instruments and suitability for the study group. Isokinetic dynamometers which can also be set at a velocity of zero are often utilized in knee OA research to provide both static and dynamic assessments of knee muscle function (2;8;9;13;15-17). Some knee OA studies have
incorporated isometric measures of quadriceps muscle strength using specially designed chairs fitted with strain gauge load cells (7;12;14;18;19).

Isokinetic strength tests have included angular velocities ranging from 30°/s to 180°/s in studies of persons with knee OA (2;8-10;13;15-17;20-22). The most common isokinetic testing velocities reported in these studies were 60°/s, 90°/s and 120°/s (2;8;9;13;15-17;20;21). Isokinetic concentric measures were predominant in the literature, while eccentric muscle strength was tested less frequently (2;15;16;23). Studies that have incorporated eccentric measures with isokinetic testing of the quadriceps and hamstring muscles reported greater variability in eccentric compared to concentric mode in participants with knee OA (2;15;16).

Regardless of the methods used to assess muscle strength in persons with knee OA, reliability of the strength measures is essential. A fundamental component of reliability is the consistency of the measures within one testing session. Arthritic joints are characterized as being stiff and painful. Thus, it would be expected that the velocity of testing might affect reliability. Several studies have evaluated the consistency of various strength measures and angular velocities within single testing sessions in persons with knee OA (2;8;15;16). Sharma et al. (8) assessed quadriceps and hamstring muscle strength isometrically and isokinetically (in concentric mode) at only one angular velocity (120°/s) in a sample of 164 participants with knee OA. High reliability coefficients for the test repetitions were obtained, exceeding 0.98 for all measures. Three other studies of persons with knee OA have reported greater variability within repetitions with isokinetic testing of the quadriceps and hamstring muscles at 120°/s compared to
60°/s (2;15;16). These authors did not include the isokinetic measures of knee muscle strength at 120°/s in their final results, due to the variability among values. Thus, it is important that strength measures be reliable within a single testing session so that useful data can be obtained.

Pain associated with knee OA is often experienced as momentary and unpredictable. It might be expected that knee pain during muscle strength testing would affect measurement reliability, yet the influence of pain experienced during strength tests has not been studied extensively in those with knee OA. In the only study identified, Lankhorst et al. (17) evaluated the pain produced with isometric knee extension (tested at 90° of knee flexion) and isokinetic knee flexion and extension at angular velocities of 30°/s, 60°/s, 120°/s and 180°/s in 39 patients with knee OA. The authors predicted that individuals with less pain would produce greater torques. However, very small negative correlations were obtained between torque production at any velocity and pain experienced during the specific strength tests. The authors concluded that the influence of momentary pain on torque production was minimal (17). The influence of knee pain on the consistency of the measures was not evaluated.

The 3 most commonly reported angular velocities for isokinetic strength testing in knee OA studies (60°/s, 90°/s and 120°/s) have not been evaluated with isometric knee flexion and extension tests to determine which measures provide the most reliable data within a single testing session in persons with knee OA. In addition, the influence of pain during isokinetic testing at these 3 common velocities has not been studied in comparison with isometric measures. As strength testing is performed routinely in knee OA studies,
often within a single testing session, it is essential to identify the most consistent methods for evaluating knee muscle strength. Thus, the purposes of our study were to: a) determine the reliability of commonly used isometric and isokinetic measures of muscle strength within one testing session in persons with knee OA, and b) assess the influence of intensity of knee pain experienced with these different strength tests on the consistency of the measures.

3.3 Sample and Methods

3.3.1 Participants

A convenience sample of 40 participants with physician-diagnosed tibiofemoral OA were recruited through newspaper advertisements and from a list of patients waiting for total knee joint replacement. Participants met all of the following criteria (24;25): age ≥ 40 years; self-reported pain in the knee(s) for most days of the month; and one of the following applied: a) radiographic evidence of knee OA as indicated by definite osteophytes in the medial and/or lateral tibiofemoral compartment in one or both knees (i.e. grade ≥ 2 of Kellgren and Lawrence (26) or grade > 2 of Cooke et al. (27)); b) documented evidence of cartilage loss in the knee by arthroscopy or magnetic resonance imaging (MRI).

Based on a consensus determined in association with the World Health Organization and the American Academy of Orthopaedic Surgeons (28), participants were excluded if they presented with any of the following: intra-articular corticosteroid or
visco-supplementation injection into either knee within the previous 3 months; other significant co-morbidities (including significant heart disease, stroke, and active treatment for cancer); OA from other types of arthritis, including rheumatoid arthritis and other systemic inflammatory arthropathies; history of avascular necrosis; prior periarticular fractures of the knee joint; Paget’s disease; villonodular synovitis; joint infection; neuropathic arthropathy; acromegaly; Wilson’s disease; hemochromatosis; gout or recurrent pseudogout; or osteopetrosis (28).

3.3.2 Data Collection

Testing was conducted in the Motor Performance Laboratory at Queen’s University, Kingston, Ontario. Participants attended one 90-minute testing session. The study was approved by the University Health Sciences Research Ethics Board and all subjects gave informed consent before participating (Appendix A).

Demographic Information

Background information regarding age, use of pain medication and use of walking aids was obtained. Body weight of the participants was measured in kilograms.

Muscle Strength Measures

All strength measures were performed by the same study clinician using the Biodex System 3 isokinetic dynamometer (Biodex Medical Systems, Shirley, NY, USA). The reliability and validity of angular position, isometric torque and concentric velocity measurements of the Biodex System 3 dynamometer have been established (29).
Isokinetic concentric measures of knee flexion and extension at various angular velocities using the Biodex dynamometer have also demonstrated good test-retest reliability and validity (30-32).

Participants completed a 5-minute warm-up on a stationary bicycle at a submaximal work level prior to testing. Strength measurements were conducted for the affected knee or, in the case of bilateral knee OA, the most symptomatic knee. Participants were positioned in sitting with the back supported and the hips at an 85° angle. The trunk and thigh were stabilized with straps and the lower leg was secured to the lever arm with a padded cuff positioned just proximal to the medial malleolus. The approximate axis of the knee (through the lateral epicondyle of the femur) was aligned with the centre of the dynamometer’s axis of rotation (Figure 3.1).

The order of isokinetic versus isometric strength testing was randomized for each participant. The order of isokinetic testing at the 3 angular velocities and of isometric knee flexion and extension was also randomized. Data were sampled at 100 Hz.

Isokinetic Testing

Concentric strength of the quadriceps and hamstring muscles was measured at 3 angular velocities: 60°/s, 90°/s and 120°/s. Testing was performed through each participant’s available range of knee motion. Participants completed a practice set of 3 sub-maximal concentric extension-flexion repetitions prior to each test to ensure familiarization with the test procedures. This was followed by 5 consecutive repetitions of maximal concentric knee extension and flexion for each test velocity, with verbal...
**Figure 3.1** Set-up for knee muscle strength testing using the Biodex System 3 Isokinetic Dynamometer.
encouragement provided to facilitate maximum effort. A 2-minute rest period was given between tests (33). Gravity-corrected peak torque values were obtained for each repetition.

Isometric Testing

Isometric tests of knee flexion and extension were performed at angles of 45° and 60° of knee flexion, respectively, as measured by a goniometer. These testing angles were selected based on the findings of Murray et al. (34), which demonstrated during isometric contractions that mean maximum torque was greatest at 45° of knee flexion for the knee flexor muscles and at 60° for the knee extensor muscles in 72 healthy men. Three sub-maximal practice isometric contractions were completed for both knee flexion and extension prior to the respective tests. Participants then performed 3 maximal isometric contractions held for 5 seconds, with a 10-second rest between each contraction. Verbal encouragement was given to promote maximum effort. A 2-minute rest period was provided between the tests of isometric knee flexion and extension (33). Gravity-corrected peak torque values were obtained for each isometric contraction.

Assessment of Knee Pain

Intensity of knee pain during strength testing was recorded using standard 100 mm visual analog scales (VASs). The VAS has been shown to provide valid and reliable measures of chronic (35;36) and acute (37-39) pain intensity. In persons with knee OA, VAS scores have also demonstrated acceptable responsiveness to change (40). Pain was
assessed at baseline and immediately after each of the isometric and isokinetic tests. Participants made a vertical mark along the horizontal scale to denote any knee pain experienced with the specific test administered just previously. The left edge of the line represented “no pain” and the right edge represented “the worst possible pain”. Clean copies of VAS scales were completed by participants after each test and they were not permitted to view previous marks on the scales. Differences in VAS pain scores between baseline and immediately after each strength test were calculated for each participant.

Knee pain experienced over the previous week due to OA was assessed with the pain subscale of the Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC) (41), given in a Likert scale format. The WOMAC pain subscale evaluates the severity of knee pain during 5 activities (walking on a flat surface, going up and down stairs, at night while in bed, sitting or lying, standing upright). Participants ranked each item as 0-4, with 4 indicating extreme pain. A standard scoring system was used in which a total score was produced by summing the responses for each of the 5 items (total range from 0-20) (41). The reliability, validity and responsiveness of WOMAC pain measures have been determined in persons with knee OA (41;42).

3.3.3 Data Processing and Statistical Analysis

Torque data were filtered with a 6 Hz low-pass filter (Butterworth, 6th order). The Biodex output was also windowed to remove torque data that were not obtained at the preset isokinetic velocity ± 5% (31;43). Both filtering and windowing of the data were performed to reduce the possibility of selecting incorrect peak torque values for each repetition due to end range spike oscillations and artifact in the torque curve. An
example of filtered and windowed torque data is shown in Figure 3.2. Test-re-test reliability of windowed data for concentric knee flexion and extension at 60°/s and 180°/s on the Biodex dynamometer has been reported to range from 0.89 to 0.97 in healthy adults (31).

We examined the strength data visually and observed for each of the isokinetic measures that the windowed peak torque values for the first repetitions of concentric knee flexion and extension were lower than those for the last 4 repetitions in all subjects. Other authors have eliminated the first trials from their analysis of isokinetic measures for the knee muscles (44;45). Thus, the data from the first repetitions were omitted and the last 4 of the 5 windowed peak torque values from each test were used for subsequent data analysis. Reproducibility within participants was determined using intra-class correlation coefficients (ICCs [type 2,1]) for the 4 repetitions for isokinetic testing and the 3 repetitions for isometric knee flexion and extension. A description of types of ICCs can be found in Appendix B. In addition, the data were reorganized to facilitate a one-way analysis of variance (ANOVA) of the repeated isokinetic and isometric data as a second measure of variability.

Data for the 4 isokinetic repetitions were then averaged and ICCs (type 2,4) were used to compare the average of the peak torques at each velocity (e.g. average isokinetic knee extension at 60°/s, 90°/s and 120°/s and average isokinetic knee flexion at the 3 velocities) to assess reproducibility (Appendix B). Pearson product moment correlation coefficients were obtained to determine the relationships between isometric knee flexion and extension and isokinetic measures at the 3 different testing velocities. Pearson
Figure 3.2  Sample of knee torque data obtained with isokinetic concentric testing at an angular velocity of 120°/s after application of a 6 Hz low pass filter and windowing. Data were collected at 100 Hz. The thin black line represents the raw torque data and the thick black line shows the filtered and windowed data. Note 2 peaks for each of knee extension (positive torque values) and knee flexion (negative torque values).
correlations were also used to evaluate the relationships between strength scores and the WOMAC pain scores.

Since the distribution of the VAS pain scores was somewhat skewed, non-parametric statistics were used for analysis of the VAS pain data. The results were similar to the findings obtained with the equivalent parametric statistical analysis. Therefore, results from parametric analyses only are reported for consistency. A one-way ANOVA was used to compare the differences in the change scores for the VAS pain values between the 3 velocities of isokinetic testing and isometric knee flexion and extension, followed by Tukey’s test as post hoc analysis for further examination of group differences. Pearson correlations were performed to determine the relationships between the mean changes in VAS pain scores and the mean peak torque values for all isometric and isokinetic strength tests. The alpha level was set at 0.05 for all significance testing. Statistical analysis was performed using SPSS software (Version 14.0, SPSS Incorporated, Chicago, Illinois, 2005).

3.4 Results

Forty participants (19 male, 21 female) completed the study. The mean age was 65.6 ± 10.3 yr and the mean mass was 85.8 ± 20.0 kg. Descriptive characteristics of the participants are summarized in Table 3.1. Thirty-five of the 40 participants ambulated without the assistance of walking aids. There were no significant differences for any measures between those who reported taking pain medications and those who reported not using them.
Table 3.1  Descriptive characteristics of study participants (n = 40).

<table>
<thead>
<tr>
<th></th>
<th>Mean ± SD</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (yr)</td>
<td>65.6 ± 10.3</td>
<td>43 - 85</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>85.8 ± 20.0</td>
<td>56 - 140</td>
</tr>
<tr>
<td>WOMAC pain summary score (0-20)</td>
<td>6.5 ± 3.4</td>
<td>1-16</td>
</tr>
</tbody>
</table>

**Frequency**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
</table>
| Gender                         | Male: 19  
                              | Female: 21 |
| Affected / more affected knee  | Right: 19  
                              | Left: 21   |
| Walking Aids                   | None: 35  
                              | Cane: 2    
                              | Walker: 3  |
| Pain Medication                | No: 15  
                              | Yes: 25    |

SD = Standard deviation  
WOMAC = Western Ontario and McMaster Universities Osteoarthritis Index
The ICC values for the 4 repetitions of isokinetic testing and the 3 repetitions of isometric testing for knee flexion and extension were very high (ICCs from 0.95 to 0.98; p < 0.0001 for all) (Table 3.2). The results of the one-way ANOVA to further assess variability within repetitions for the isokinetic and isometric measures revealed no significant differences (p = 0.78 and p = 0.83 for isometric knee flexion and extension, respectively; p > 0.97 for all isokinetic measures). Thus, for all subsequent analyses, peak torque values were averaged for each of the isokinetic and isometric measures.

Table 3.3 shows the means and standard deviations for the peak torque values from isokinetic and isometric strength testing of the 40 participants. With all strength measures there were large standard deviations around the mean, indicating a sample representative of a wide range of strength capabilities.

When the isokinetic repetitions were averaged, tests of reproducibility between the angular velocities revealed high ICC values of 0.98 on isokinetic testing for knee extension (comparing 60°/s, 90°/s and 120°/s) and 0.98 for isokinetic knee flexion (comparing the three velocities). Mean peak torque values for the 3 velocities of isokinetic testing and isometric flexion and extension were highly correlated with each other (Table 3.4 and Table 3.5).

Table 3.6 presents the mean VAS scores for knee pain at baseline and immediately after each strength test and the mean changes in pain from baseline for the 40 participants. The low baseline VAS scores (3.0 ± 6.4 mm) and low WOMAC scores for pain over the past week (6.5 ± 3.4, out of a total possible score of 20) indicated that the group was not experiencing much knee pain. Mean VAS pain scores recorded after
Table 3.2 Intraclss correlation coefficients (ICCs) and confidence intervals for the 4 repetitions of isokinetic testing and the 3 repetitions of isometric testing for knee flexion and extension (p < 0.0001 for all measures).

<table>
<thead>
<tr>
<th>Strength Test</th>
<th>Intraclass Correlation Coefficient (95% Confidence Interval)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Extension</strong></td>
<td></td>
</tr>
<tr>
<td>Isometric</td>
<td>0.97 (0.95, 0.98)</td>
</tr>
<tr>
<td>Isokinetic 60°/s</td>
<td>0.97 (0.95, 0.98)</td>
</tr>
<tr>
<td>Isokinetic 90°/s</td>
<td>0.98 (0.97, 0.99)</td>
</tr>
<tr>
<td>Isokinetic 120°/s</td>
<td>0.95 (0.93, 0.97)</td>
</tr>
<tr>
<td><strong>Flexion</strong></td>
<td></td>
</tr>
<tr>
<td>Isometric</td>
<td>0.95 (0.92, 0.97)</td>
</tr>
<tr>
<td>Isokinetic 60°/s</td>
<td>0.97 (0.95, 0.98)</td>
</tr>
<tr>
<td>Isokinetic 90°/s</td>
<td>0.98 (0.97, 0.99)</td>
</tr>
<tr>
<td>Isokinetic 120°/s</td>
<td>0.98 (0.96, 0.99)</td>
</tr>
</tbody>
</table>
Table 3.3. Means and standard deviations of average peak torque values (n = 40).

<table>
<thead>
<tr>
<th>Strength Test</th>
<th>Mean (N·m)</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Extension</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Isometric</td>
<td>86.7</td>
<td>47.9</td>
</tr>
<tr>
<td>Isokinetic 60°/s</td>
<td>65.3</td>
<td>35.1</td>
</tr>
<tr>
<td>Isokinetic 90°/s</td>
<td>62.9</td>
<td>33.4</td>
</tr>
<tr>
<td>Isokinetic 120°/s</td>
<td>56.6</td>
<td>29.3</td>
</tr>
<tr>
<td><strong>Flexion</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Isometric</td>
<td>42.1</td>
<td>25.5</td>
</tr>
<tr>
<td>Isokinetic 60°/s</td>
<td>35.6</td>
<td>23.7</td>
</tr>
<tr>
<td>Isokinetic 90°/s</td>
<td>34.3</td>
<td>22.6</td>
</tr>
<tr>
<td>Isokinetic 120°/s</td>
<td>29.7</td>
<td>19.2</td>
</tr>
</tbody>
</table>

N·m = Newton-metres
**Table 3.4.** Pearson correlations between mean peak torque values for tests of knee extension (n = 40).

<table>
<thead>
<tr>
<th></th>
<th>Isokinetic 60°/s</th>
<th>Isokinetic 90°/s</th>
<th>Isokinetic 120°/s</th>
<th>Isometric</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isokinetic 60°/s</td>
<td>.964*</td>
<td>.940*</td>
<td>.855*</td>
<td></td>
</tr>
<tr>
<td>Isokinetic 90°/s</td>
<td></td>
<td>.965*</td>
<td>.895*</td>
<td></td>
</tr>
<tr>
<td>Isokinetic 120°/s</td>
<td></td>
<td></td>
<td>.908*</td>
<td></td>
</tr>
</tbody>
</table>

* * P < 0.001

**Table 3.5.** Pearson correlations between mean peak torque values for tests of knee flexion (n = 40).

<table>
<thead>
<tr>
<th></th>
<th>Isokinetic 60°/s</th>
<th>Isokinetic 90°/s</th>
<th>Isokinetic 120°/s</th>
<th>Isometric</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isokinetic 60°/s</td>
<td>.970*</td>
<td>.901*</td>
<td>.792*</td>
<td></td>
</tr>
<tr>
<td>Isokinetic 90°/s</td>
<td></td>
<td>.937*</td>
<td>.827*</td>
<td></td>
</tr>
<tr>
<td>Isokinetic 120°/s</td>
<td></td>
<td></td>
<td>.813*</td>
<td></td>
</tr>
</tbody>
</table>

* * P < 0.001
Table 3.6  Means and standard deviations (SD) of average visual analogue scale (VAS) pain scores after each strength test and of changes in pain from baseline (n = 40).

<table>
<thead>
<tr>
<th>VAS Pain Measure</th>
<th>Mean (mm)</th>
<th>SD</th>
<th>Mean change in pain from baseline (mm) (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>3.0</td>
<td>6.4</td>
<td></td>
</tr>
<tr>
<td>After isokinetic 60°/s (extension/flexion)</td>
<td>23.9</td>
<td>22.7</td>
<td>20.9 (21.6)</td>
</tr>
<tr>
<td>After isokinetic 90°/s (extension/flexion)</td>
<td>21.4</td>
<td>19.6</td>
<td>18.4 (18.6)</td>
</tr>
<tr>
<td>After isokinetic 120°/s (extension/flexion)</td>
<td>20.1</td>
<td>21.1</td>
<td>17.1 (19.9)</td>
</tr>
<tr>
<td>After isometric extension</td>
<td>20.1</td>
<td>18.8</td>
<td>17.1 (17.4)</td>
</tr>
<tr>
<td>After isometric flexion</td>
<td>11.5</td>
<td>16.6</td>
<td>8.5 (14.1)</td>
</tr>
</tbody>
</table>
each test showed large standard deviations, demonstrating that our sample of participants had a considerable range of reported pain severities with testing. One-way ANOVA revealed significant differences in the mean changes in VAS pain scores from baseline between the strength tests ($F = 2.564$, $p = 0.04$). Tukey’s post hoc comparisons showed the significant differences occurring between isokinetic testing at $60^\circ/s$ and isometric knee flexion, with greater pain produced at $60^\circ/s$ ($p = 0.025$). There were poor correlations between the mean changes in VAS pain scores and the corresponding mean peak torque values for the isometric and isokinetic strength tests (correlations ranging from 0.034 to 0.237). Mean scores on the WOMAC pain subscale also showed weak relationships with the mean peak torque values (correlations from 0.006 to 0.239).

### 3.5 Discussion

An important finding from our study was that all isometric and isokinetic strength measures demonstrated a high degree of reliability within a single testing session in our sample of 40 participants with knee OA.

The findings of reliable torque data among each of the strength measures may be attributable, in part, to the methods we employed in our study. Data were filtered at 6 Hz to remove spike oscillations that were not true peak torque measures. Windowing of the Biodex output was also performed to remove data that were not obtained at the preset angular velocity $\pm 5\%$. The method of windowing has been suggested to eliminate torque spike oscillations occurring as a result of acceleration and deceleration at the start and end of each test (31;43). A significant difference between windowed and non-windowed...
data during isokinetic testing for shoulder abduction and adduction was demonstrated in 50 healthy baseball pitchers (43). In addition, Gross et al. (31) found that test-retest reliability of isokinetic knee flexion and extension measures at 60°/s and 180°/s in 10 healthy young adults was significantly improved with windowing of the data compared to non-windowed data. Other studies investigating muscle strength in persons with knee OA using an isokinetic dynamometer have not typically reported filtering or windowing of the strength data, but our positive results suggest that this may be advisable.

An additional method we employed which likely contributed to the consistency of our measures was to omit the data from the first repetitions for all isokinetic tests, since these torque values were lower than the final 4 repetitions on observation of the data. A minimum of 3-4 test repetitions have been recommended for isokinetic measures (46;47). Other researchers testing isokinetic strength of the knee muscles in healthy adults and those with meniscal tears have reported that reliability of the measures was improved with elimination of the first trials from subsequent analyses (44;45). The isokinetic motions may have been novel for many of the participants in the current study, such that even with several submaximal practice trials at each angular velocity they may have proceeded more cautiously with the first repetitions of maximal extension/flexion testing.

Our findings related to the consistency of the strength measures may be compared to other studies of intra-session reliability in persons with knee OA. In 164 participants with knee OA enrolled in the Mechanical Factors in Arthritis of the Knee (MAK) longitudinal study, Sharma et al. (8) reported high reliability coefficients exceeding 0.980 for isometric measurements of the quadriceps and hamstring muscles and isokinetic
measures of the same muscle groups at 120º/s. A later study by Sharma et al. (9) of a larger cohort of 257 participants with knee OA from the MAK project also assessed intra-session reliability during isokinetic quadriceps and hamstring testing at 120º/s. Again, all ICCs for repetitions of the isokinetic tests for each muscle group and each leg exceeded 0.98.

In contrast, other authors found that isokinetic testing at 120º/s compared to testing at 60º/s produced greater variability in persons with knee OA (2;15;16). The reasons for the discrepancy in findings between studies are not clear. Age range of the OA participants, test set-up and protocols for testing appear similar in the studies which showed both consistent and inconsistent results with isokinetic testing at 120º/s. However, there may have been differences between the study populations in characteristics such as OA disease severity which could not be determined from the information provided. Different isokinetic dynamometer machines were also used between studies. Inconsistent results at higher speeds may have also been affected by deficiencies in filtering and/or windowing of the data.

Isometric and isokinetic measures, including isokinetic torque values at different velocities, were strongly correlated with each other in the current study. These findings are consistent with other studies in the literature which have found moderate to high correlations between isometric and isokinetic measures of the quadriceps and hamstring muscles in persons with knee OA (17;23).

An additional conclusion from this study was that knee pain occurring with strength testing did not detract from the consistency of the strength measures, based on
the findings that all isometric and isokinetic strength measures were highly reliable for a single testing session. Knee pain produced with strength testing may be brief and may have minimal influence on the consistency of the torque measures. Our study also revealed poor correlations between mean peak torque values and the corresponding mean changes in VAS pain scores for each strength test. Similarly, Lankhorst et al. (17) reported weak relationships between peak torque at any velocity and pain experienced during the isokinetic tests. The large standard deviations of pain scores with each test in the current study may have limited the possibility of detecting a relationship.

There were no significant differences in the change scores for VAS pain values between the 3 speeds of isokinetic knee flexion/extension testing or when comparing change scores for pain with isokinetic testing to isometric knee extension measures. The only differences in the change scores for pain were found between isokinetic testing at 60°/s and isometric knee flexion. Evaluation of quadriceps muscle strength is a primary focus of knee OA studies. The results of our study showed that both isokinetic and isometric modes of quadriceps muscle strength testing could be performed without one method producing greater pain.

Isokinetic testing was limited to the concentric mode in our study, due to greater variability with eccentric tests reported in the literature (2;15;16) and the predominant use of concentric strength measures in knee OA studies. One study of a group of 18 women with bilateral knee OA did report moderate to good correlations between isokinetic quadriceps and hamstring torques for both concentric and eccentric contractions at angular velocities of 60°/s, 120°/s and 180°/s (23). There may be incidences in which
eccentric knee muscle strength measures would be useful. In these cases, further research would be required to determine the most consistent strength measures since few studies have provided eccentric strength data in persons with knee OA (23).

Limitations of our study included the modest sample size of 40 participants and the large standard deviations around the means for participants’ strength and pain scores. This variability among our participants with knee OA increased the likelihood that our sample was representative of the population, but limited the possibility of obtaining findings of statistical significance with the sample size used. Future studies to investigate the reliability of strength measures could use several groups of participants with more homogeneous characteristics.

In summary, isokinetic knee muscle strength testing at 60°/s, 90°/s and 120°/s and isometric tests of the quadriceps and hamstring muscles were highly reliable for a single testing session in our sample of persons with knee OA using the methods described. All strength tests at all speeds used in this study could be performed consistently by individuals with knee OA. Knee pain during testing did not limit the ability of the participants to perform the tests consistently.

**Acknowledgements**

Dr. Kathleen Norman and Mr. Martin Héroux are gratefully acknowledged for their assistance with data processing.
3.6 References


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Chapter 4

Reliability of Lower Limb Alignment Measures using an Established Landmark-Based Method with a Customized Computer Software Program

4.1 Abstract

Until recently, mechanical alignment has been assessed using manual measurements that are potentially susceptible to person to person variability. **Objectives:** To evaluate the reliability of frontal plane lower limb alignment measures using a bone landmark-based method by: 1) comparing the reliability between measurements of alignment obtained manually with those obtained using a computer program, and 2) determining the inter- and intra-reader reliability of computer-assisted alignment measures from full-limb radiographs. **Methods:** An established method for measuring frontal plane limb alignment was used, involving selection of 10 bone landmarks of the femur and tibia. 1) To compare manual and computer methods, we used digital images and matching paper copies of 5 different alignment patterns simulating healthy and malaligned limbs which were drawn using AutoCAD® software. Seven readers were trained in each system. Paper copies were measured manually and repeat measurements were performed daily for 3 days, followed by a similar routine with the digital images measured using a computer program. Patterns were measured in a random order each day. 2) To examine the reliability of computer-assisted measures from full-limb radiographs, 100 images (representing 200 limbs) were selected as a random sample from
over 1500 full-limb digital radiographs which were part of the Multicenter Osteoarthritis (MOST) Study. Three trained readers used the software program to measure alignment twice from the same batch of 100 images, with 2 or more weeks between batch handling.

**Results:** Manual and computer measures of alignment showed excellent agreement (ICCs from 0.977 to 0.999 for computer analysis; 0.820 to 0.995 for manual measures). The computer program applied to full-limb radiographs produced alignment measurements with high inter- and intra-reader reliability (ICCs from 0.839 to 0.998).

**Conclusions:** Alignment measures using bone landmarks and computer assistance were highly reliable between multiple readers. They compared as well as or better than measures made by hand and were obtained much more quickly. The outcome supports the use of computer programs for analysis of alignment from digital images following an established bone landmark-based approach.

### 4.2 Introduction

Frontal plane lower limb malalignment is closely linked with the progression of knee osteoarthritis (OA) (1;2). Therefore, measures of alignment are important for understanding the course of OA progression and for guiding the conservative and surgical management of knee OA (3-5).

Frontal plane lower limb alignment is generally measured from full-length radiographs of the whole limb in stance. Alignment may be defined as the angle between the mechanical axes of the femur and tibia. This angle has been termed the hip-knee-ankle (HKA) angle (3;6-8) or the mechanical axis angle (4-6;9). Traditionally, measures
have been made by hand, which require the clinician to draw lines on the radiographs representing the femoral and tibial mechanical or anatomic axes and to manually define the resulting angles. With the advent of digital imaging, radiographic film is being rapidly replaced by digital images. As the digital images cannot be evaluated manually, software programs with electronic tools have been developed to aid in the measurements of alignment from digital radiographs (10-16).

Comparisons between manual measures and computer-assisted analysis of alignment have indicated good reliability for both methods, with a tendency towards higher reliability using computer-assisted analysis (11-18). Several of these studies investigated primarily the reliability of mechanical axis or anatomic axis angle measures (11;15-17). Other studies have evaluated specific approaches to measuring alignment and assessed the reliability of additional angular measures as well as leg lengths by hand and by computer (13;14;18). However, to our knowledge, a systematic reliability evaluation of manual versus computer measures applying an overall alignment measurement system, including femoral and tibial bone geometry and leg length measures, has not been performed. In addition, analyses of these measures have not been employed using multiple readers.

In this two-part study, we evaluated a well-established method for measuring frontal plane limb alignment that uses bone landmarks to define a diverse set of alignment and linear parameters (3;7;8;10;18). A custom software program (Horizon Surveyor, version 1.5, OAISYS Inc.) was developed for the computer-assisted analysis. The first study evaluated the method using schematics of limb deformities drawn with the
aid of AutoCAD® 2006 software (Autodesk Inc., San Rafael, CA, USA). The purpose of this study was to compare the reliability of manual and computer measures of alignment obtained using multiple readers. We postulated that semi-automated computer analysis of lower limb alignment would generate measurements with similar or greater reliability compared to those made only by hand.

In the second study our purpose was to determine the reliability of the same set of alignment and leg length measures using the landmark-based approach when computer-assisted analysis was applied to a large sample of full-limb radiographs. We hypothesized that these measures would demonstrate high inter- and intra-reader reliability.

### 4.3 Materials and Methods

#### 4.3.1 Methods Common to Both Studies

**Landmark-based Approach to Measuring Alignment**

The approach selected for measuring frontal plane limb alignment uses 10 bone landmarks of the femur and tibia to derive the frontal plane limb geometry (3;7;8;10;18). The HKA angle was measured as the angle formed by the intersection of the femoral mechanical (FM) and tibial mechanical (TM) axes (Figure 4.1). The FM axis was formed by a line from the centre of the femoral head to the mid-condylar point of the distal femur (19), while the TM axis was produced by a line from the centre of the tibial plateau (interspinous, intercruciate midpoint) to the centre of the tibial plafond distally (20). The HKA angle was expressed as degrees of deviation from 180°, such that the HKA angle
Figure 4.1. Diagram of frontal plane axes and angles in a limb with varus alignment, modified from Cooke et al.(7).

Legend:
LBA = Load-bearing axis
CH = Condylar-Hip angle: the angle of the femoral condylar tangent with respect to the femoral mechanical axis; varus negative, valgus positive
PA = Plateau-Ankle angle: the angle between the tibial margin tangent and the tibial mechanical axis; varus negative, valgus positive
CP = Condylar-Plateau angle: the angle between the femoral and tibial joint surface tangents; narrowing medially negative and laterally positive
HKA = Hip-knee-ankle angle: the angle between the femoral and tibial mechanical axes; varus negative, valgus positive
FM = Femoral mechanical axis
TM = Tibial mechanical axis
FS = Femoral shaft axis
TS = Tibial shaft axis (Note: TM and TS are typically co-incident when measurements are made from the full length of the tibia)
FM-FS = angle between the femoral mechanical axis and the femoral shaft axis
= 0° in neutral alignment. Varus angles were denoted as negative values and valgus angles as positive (3;8).

Also measured were the angular contributions of the femur and tibia to overall alignment and the angle formed by the femoral and tibial joint surface tangents. These angles included: Condylar-Hip (CH), the angle of the femoral condylar tangent with respect to the FM axis; Plateau-Ankle (PA), the angle between the tibial margin tangent and the TM axis; and Condylar-Plateau (CP), the angle between the femoral and tibial joint surface tangents, which represents the joint’s orientation (Figure 4.1). These angles are related to the HKA angle, such that \( HKA = CH + PA + CP \) (3;8). The CH and PA angles were notated as degrees of deviation from 90° (negative for varus and positive for valgus). The CP angle was designated varus (-) if it narrowed medially and valgus (+) if it narrowed laterally (3;8).

In addition to the HKA angle, we defined the anatomic (shaft) axes of the femur (FS) and the tibia (TS) (Figure 4.1). We derived the angular relationship between these anatomic axes (FS-TS) and the angular relationships with their mechanical counterparts (FM-FS, FM-TS, FS-TM). Finally, femoral length, tibial length and apparent leg length were measured.

**Semi-automated Computer Program**

The Horizon Surveyor (version 1.5, OAISYS Inc.) custom software program provided a selection of electronic tools, including straight line, ruler, circle and midline tools, which were used to define the 10 femoral and tibial bone landmarks on digital
images (Figure 4.2). Images for evaluation were imported as *.tiff, *.bmp or *.jpeg files.
The program included the means by which to calibrate the imaged material, allow
magnification and enhance the brightness and contrast of the image. The reader was
prompted to identify each landmark in a defined sequence and the data for the landmark’s
X-Y coordinates were collected. Angular and linear dimensions were automatically
derived by the software program.

Reader Training

Readers with backgrounds in health sciences were recruited and trained in the
method employed for the study. Training sessions involved identification of the specific
bone landmarks, the derived angular geometry, use of the computer program for
processing the images and application of the software tools used to define the landmarks.

4.3.2 Study 1: Comparison of manual and computer-assisted measures

Five patterns of frontal plane lower limb alignment, simulating full-length
radiographs of healthy and malaligned limbs, were drawn using AutoCAD® software.
The schematics of limb malalignment included variations in varus and valgus alignment,
joint space slope, femoral and tibial deformity and apparent leg lengths. The five patterns
are shown in Figure 4.3 (A-E). Paper copies of these images (8½ x 14 inch paper size)
were used for manual measurements. The patterns were exported from AutoCAD® as
digital images for computer-assisted measurements of alignment.
Figure 4.2. Examples of electronic tools (circle, ruler and midline tools) provided by the custom software program, Horizon Surveyor (version 1.5, OAISYS Inc.). Electronic tools were used to locate the 10 bone landmarks on the femur and tibia.
Figure 4.3 (A-E). Five patterns of frontal plane lower limb alignment, simulating full-length radiographs of healthy and malaligned limbs, drawn using AutoCAD® software.

A. Neutral limb with joint obliquity
B. Valgus limb
C. Knee varus, tibia valga
D. Knee valgus, tibia vara
E. Neutral limb
Seven trained readers performed manual measurements on all of the five alignment patterns daily for 3 days. Patterns were measured in a random order each day. Readers used a pencil and ruler (with 1 mm increments) to identify and mark the 10 bone landmarks on the paper copies of the patterns. No magnification was used. Lines were drawn between these landmarks to define the femoral and tibial mechanical and anatomic (shaft) axes and the joint surface tangents. A protractor was then used to measure the angles formed from these axes and tangents. Bone lengths and apparent leg lengths were also measured. Fresh paper copies were used for each day, without reference to the results from prior days. The collected data were entered by hand into a Microsoft Excel® (Microsoft Office 2003, Microsoft Corporation, USA) spreadsheet for analysis.

The process was then repeated using the Horizon Surveyor computer software program. All five alignment patterns were measured daily for 3 days and patterns were measured in a random order each day. Each reader identified the same bone landmarks on the digital images of the patterns. Magnification of the image within the software program was possible and used as required. The program automatically derived the same angular parameters and leg lengths. Digital length measures were converted to the paper equivalent using a linear calibration factor and the computer measurements were exported to a Microsoft Excel® spreadsheet.
4.3.3 Study 2: Reliability analyses of alignment measures from full-limb radiographs

A batch of 100 images (representing 200 limbs) was selected as a random sample from 30 similar batches from over 1500 full-limb digital radiographs (3000 limbs) obtained as part of the Multicenter Osteoarthritis (MOST) Study. This prospective epidemiological study of community-dwelling adults aged 50 to 79 years was initiated to identify risk factors for incident, symptomatic knee OA and progressive knee OA. The MOST study targeted persons with, or at risk for developing, knee OA. High risk individuals included those who were overweight, experienced knee symptoms and/or had a history of knee injury or surgery. Average age of the 100 participants (64 women, 36 men) whose radiographs were analyzed as part of the random sample of images for the current study was 63.3 ± 7.7 years (range: 50 to 79 years). Mean body mass was 88.7 ± 18.2 kg.

Weight-bearing, anteroposterior full-limb radiographs were obtained according to the method of Sharma et al. (2). A 130 X 36-cm graduated grid cassette was used and the x-ray beam was centred at the level of the knee joint at a distance of 2.4 metres. Depending on limb size and tissue characteristics, settings of 100 - 300 mA/s and 80 - 90 kV were employed. Participants stood without footwear and were positioned with the tibial tubercles facing forwards. All radiographs showed both limbs, including the entire hip, knee and ankle joints.
Three trained readers each measured the same batch of 100 images (200 limbs) twice, with a 2 or more week interval between batch handling. The software program was used to obtain angular and linear dimensions which were exported for analysis.

### 4.3.4 Data Analysis

**Study 1: Manual and computer-assisted measures from AutoCAD® patterns.** The data from all readers and all trials were reported using descriptive statistics (means and standard deviations for each measure). Different repeated measures analysis of variance (ANOVA) models treating patterns and readers as random effects were performed to: (a) compare all patterns assessed manually (3 sets of 5 patterns from each of the 7 readers) to all patterns evaluated using the computer program; (b) determine the reliability of manual and computer methods by calculating the intraclass correlations (ICCs [type 3,1]; in this case, treating the condition [manual or computer-assisted measures] as a fixed effect); and (c) assess the agreement (using ICCs [type 2,1]) for each reader on all variables under the 2 measuring methods (manual and computer) (Appendix B).

**Study 2: Full-limb radiographs.** Random effects 2-way ANOVA models were applied to calculate the ICCs (type 2,1) which evaluated inter- and intra-reader reliability for each of the angles and bone lengths. Statistical analysis was performed using the SAS statistical package (Version 9, SAS Institute Inc., Cary, NC, USA) and the alpha level was set at 0.05.
4.4 Results

4.4.1 Study 1: Comparison of manual and computer-assisted measures

Analysis of the data derived from the AutoCAD® patterns revealed no significant differences between manual and computer-assisted methods for all angular measures and bone lengths ($p > 0.05$). Reliability statistics for manual and computer measures of angles and bone lengths are displayed in Table 4.1. Excellent agreement was found for all variables with both methods (ICC$s$ from 0.977 to 0.999 for computer analysis; 0.820 to 0.995 for manual measures). For each measurement, the computer-assisted measure showed reliability that was slightly higher than the manual measurement. When each reader was evaluated individually, all measures demonstrated good to excellent intra-reader reliability using both applications (ICC$s$ from 0.730 to 0.998).

The difference in time required to complete the measures manually compared to the computer method was considerable. Computer-assisted measures were acquired in approximately half the time taken to perform the manual measurements and additional time was also needed for data entry and verification of the manual measures.
Table 4.1. Intraclass correlation coefficients (ICCs) and confidence intervals for manual versus computer-assisted measures of angles and bone lengths from patterns drawn using AutoCAD® software. A total of 105 manual measures (3 sets of 5 patterns from each of the 7 readers) and 105 computer-generated measures for each of the angles and bone lengths were evaluated in the reliability analysis.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Manual Measurement</th>
<th>Computer Measures</th>
</tr>
</thead>
<tbody>
<tr>
<td>HKA</td>
<td>0.993 (0.987, 0.996)</td>
<td>0.999 (0.999, 1.000)</td>
</tr>
<tr>
<td>CH</td>
<td>0.990 (0.983, 0.995)</td>
<td>0.992 (0.986, 0.996)</td>
</tr>
<tr>
<td>PA</td>
<td>0.906 (0.843, 0.948)</td>
<td>0.980 (0.964, 0.989)</td>
</tr>
<tr>
<td>CP</td>
<td>0.991 (0.985, 0.995)</td>
<td>0.995 (0.990, 0.997)</td>
</tr>
<tr>
<td>FM–FS</td>
<td>0.820 (0.710, 0.897)</td>
<td>0.977 (0.959, 0.988)</td>
</tr>
<tr>
<td>FM–TS</td>
<td>0.995 (0.991, 0.997)</td>
<td>0.999 (0.997, 0.999)</td>
</tr>
<tr>
<td>FS-TM</td>
<td>0.984 (0.972, 0.991)</td>
<td>0.999 (0.999, 1.000)</td>
</tr>
<tr>
<td>FS–TS</td>
<td>0.982 (0.969, 0.990)</td>
<td>0.998 (0.996, 0.999)</td>
</tr>
<tr>
<td>Femoral length</td>
<td>0.952 (0.918, 0.974)</td>
<td>0.997 (0.995, 0.998)</td>
</tr>
<tr>
<td>Tibial length</td>
<td>0.865 (0.779, 0.924)</td>
<td>0.982 (0.968, 0.990)</td>
</tr>
<tr>
<td>Apparent leg length</td>
<td>0.969 (0.946, 0.983)</td>
<td>0.999 (0.998, 0.999)</td>
</tr>
</tbody>
</table>

Legend:
HKA: hip-knee-ankle angle
CH: Condylar-Hip angle
PA: Plateau-Ankle angle
CP: Condylar-Plateau angle
FM-FS: Femoral mechanical axis–femoral shaft axis angle
FM-TS: Femoral mechanical axis–tibial shaft axis angle
FS-TM: Femoral shaft axis–tibial mechanical axis angle
FS-TS: Femoral shaft axis–tibial shaft axis angle
4.4.2 Study 2: Reliability analyses of alignment measures from full-limb radiographs

Mean HKA angle measurements from the 100 radiographs (200 limbs) in the sample were -2.1° ± 4.0° (range from -17.6° varus angulation to 12.8° valgus angulation).

The computer software program applied to full-limb radiographs produced measures that were highly reliable. As shown in Table 4.2, ICCs for inter-reader reliability were 0.947 or greater for all measures, except the angles CP (ICC of 0.884) and FM-FS (ICC of 0.839). All measures demonstrated high intra-reader reliability, with ICCs ranging from 0.908 to 0.998 (Table 4.2). Figure 4.4 shows the inter-reader agreement between two readers measuring the HKA angle on right knees. Figure 4.5 illustrates the intra-reader agreement for HKA angle measurements for one reader.

4.5 Discussion

The widespread use of digital imaging systems has necessitated the development of electronic methods, including software tools, for measurement of lower limb alignment (10-16). In this report we wished to evaluate the reliability of an established landmark-based approach for a full range of alignment measures and limb lengths obtained using a customized computer software program (3;7;8;10;18).

As a first step in our reliability evaluations we compared the use of computer-assisted analysis against traditional manual measurements on images simulating different limb alignments that were drawn in AutoCAD®. There were no significant differences
Table 4.2. Intraclass correlation coefficients (ICCs) and confidence intervals for computer-assisted measures of angles and bone lengths on 100 full-limb radiographs (200 limbs).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Inter-reader reliability</th>
<th>Intra-reader reliability</th>
</tr>
</thead>
<tbody>
<tr>
<td>HKA</td>
<td>0.995 (0.994, 1)</td>
<td>0.998 (0.998, 1)</td>
</tr>
<tr>
<td>CH</td>
<td>0.960 (0.953, 1)</td>
<td>0.966 (0.961, 1)</td>
</tr>
<tr>
<td>PA</td>
<td>0.947 (0.937, 1)</td>
<td>0.964 (0.959, 1)</td>
</tr>
<tr>
<td>CP</td>
<td>0.884 (0.864, 1)</td>
<td>0.908 (0.896, 1)</td>
</tr>
<tr>
<td>FM–FS</td>
<td>0.839 (0.720, 1)</td>
<td>0.934 (0.925, 1)</td>
</tr>
<tr>
<td>FS–TM</td>
<td>0.993 (0.989, 1)</td>
<td>0.998 (0.997, 1)</td>
</tr>
<tr>
<td>FS–TS</td>
<td>0.990 (0.988, 1)</td>
<td>0.996 (0.995, 1)</td>
</tr>
<tr>
<td>Femoral length</td>
<td>0.993 (0.992, 1)</td>
<td>0.994 (0.993, 1)</td>
</tr>
<tr>
<td>Tibial length</td>
<td>0.993 (0.989, 1)</td>
<td>0.995 (0.994, 1)</td>
</tr>
<tr>
<td>Apparent leg length</td>
<td>0.995 (0.993, 1)</td>
<td>0.995 (0.994, 1)</td>
</tr>
</tbody>
</table>

Legend:
HKA: hip-knee-ankle angle  
CH: Condylar-Hip angle  
PA: Plateau-Ankle angle  
CP: Condylar-Plateau angle  
FM–FS: Femoral mechanical axis–femoral shaft axis angle  
FM–TS: Femoral mechanical axis–tibial shaft axis angle  
FS–TM: Femoral shaft axis–tibial mechanical axis angle  
FS–TS: Femoral shaft axis–tibial shaft axis angle
Figure 4.4. Hip-knee-ankle (HKA) angle measures from full-limb radiographs: inter-reader agreement for 2 readers measuring on right knees.

Figure 4.5. Hip-knee-ankle (HKA) angle measures from full-limb radiographs: intra-reader agreement for 1 reader.
between manual and computer-assisted methods for all alignment and bone length measures. Both methods were reliable, although for each of the specific measurements computer-assisted analysis showed slightly higher reliability in comparison to the manual method. All 7 readers produced angular and linear measures that showed good to excellent intra-reader reliability. These findings indicate that a variety of readers can readily trained in use of the landmark-based method and the custom computer program developed to derive reliable measurements.

Of relevance, all measurements were obtained much more quickly by use of the computer program. The specific electronic tools provided by the computer software, including image magnification and enhancement, aided in the selection of bone landmarks and the speed of data acquisition. The custom software also optimized data collation and transfer of data for statistical analysis.

Our results using AutoCAD® patterns are similar to findings from previous studies which evaluated alignment measures obtained by computer analysis and manual methods. Anatomic axis angle measurements from radiographs of the knee (11;16) and mechanical axis angle measures from full-limb radiographs (13-15;17) demonstrated good reliability when manual and computer methods were compared, with less variability using the computer. Other studies measuring various joint orientation angles at the femur and tibia (13;14), following the system of Paley et al. (21), reported that computer-assisted analysis significantly reduced the variability of these lower limb geometry measures. Also supporting our findings, manual and computer-assisted measures of femoral and tibial length (14) and apparent leg length (13) from full-limb radiographs
showed good agreement. Finally, measurement times were reported to be significantly shorter using computer analysis compared to manual measurements (44% and 78% reduction in measuring time, respectively) in other papers (13;17) and in the current study.

In our second study we evaluated reader reliability when applying the landmark-based method using the computer program to a large sample of full-limb digital radiographs. The images evaluated were from an ongoing multi-centre OA project (MOST). Measurements of the HKA angle, other angular parameters and bone lengths all demonstrated high inter- and intra-reader reliability using the computer-assisted method. In particular, we obtained an ICC of 0.995 for inter-reader reliability of HKA angle measurements. These results are similar to other reported values of 0.91 (17) and 0.98 (15) for inter-reader reliability of the mechanical axis angle using computer-assisted analysis.

In the current study two angular measures demonstrated slightly lower reliability with computer-assisted analysis applied to full-limb radiographs. Intraclass correlation coefficients for inter-reader reliability (0.884) and intra-reader reliability (0.908) of the Condylar-Plateau (CP) angle were lower in comparison to the corresponding inter- and intra-reader reliability measures for the other angles and leg lengths using computer analysis. The CP angle represents the orientation of the knee joint’s articulating surfaces. One possible reason for lower reliability is that the bone landmarks used to derive this angle are located close together at the knee, which would increase the potential for
greater variance in the angular measurement compared to angles for which the bone landmarks are located far apart.

Femoral mechanical-femoral shaft axis (FM-FS) angle measurements demonstrated somewhat lower inter-reader reliability (ICC of 0.839), but higher intra-reader reliability (ICC of 0.934). A possible explanation for the inter-reader differences is that the femoral intertrochanteric bone landmark required to construct the femoral shaft axis is a less precisely defined point than the femoral head centre and, therefore, open to more inter-reader variation in its acquisition.

Our study has compared the semi-automated landmark-based computer program to traditional manual methods and demonstrated that measures were highly reliable when applied to standardized but varied alignment images with a number of trained readers. It has confirmed the general findings of previous studies from the literature investigating computer-aided measures of mechanical axis alignment and leg lengths. We have demonstrated the reliability of this approach to define other angular contributions of the femur, the tibia and the knee joint surfaces to overall alignment. We have also confirmed that alignment measures obtained with the computer method demonstrated excellent inter- and intra-reader reliability when evaluated with a large number of long limb images.

In summary, the landmark-based approach employed for measurements of long limb alignment, geometry and limb lengths was readily learned by multiple readers and produced high reliability coefficients when applied using computer-assisted analysis. While training is required for these measures, our data indicate that the skills needed are
learned rapidly. The consistency evident between multiple readers using the electronic method, the speed of data acquisition and the growing use of digital images lend support for the application of digital measurement systems employing a landmark-based approach.

Acknowledgements

The second study, using full-limb radiographs, was supported by the National Institutes of Health grants AR47785 and AG18820 and MOST Ancillary Study grant AP07-04. The authors wish to acknowledge the contribution of Mr. Christopher Wale, BSc (I-M Innovations, Inc.), in the design of the computer software tools and analysis program. The support of OAISYS Inc. in provision of the Horizon Surveyor software program used in these studies is appreciated.
4.6 References


Chapter 5
Home Program of Hip Abductor Exercises: Effect on Gait, Strength, Function and Pain in Persons with Knee Osteoarthritis

5.1 Abstract

Hip muscle weakness may result in impaired frontal plane pelvic control during gait, leading to greater medial compartment loading in persons with knee osteoarthritis (OA).

Objectives: This study investigated the influence of an 8-week home-based strengthening program for the hip abductor muscles on knee joint loading (measured by the external knee adduction moment during gait), strength, function and pain in individuals with medial compartment knee OA. Methods: Forty participants with knee OA were age- and gender-matched with an asymptomatic control group. Three-dimensional gait analysis was performed to obtain peak knee adduction moments in the first 50% of stance phase. Isometric and isokinetic concentric strength of the hip abductor muscles was measured using a Biodex Isokinetic Dynamometer. The Five-Times-Sit-to-Stand test evaluated functional performance. Knee pain was assessed with the Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC). Following initial testing, participants with knee OA were instructed in a home hip abductor strengthening program. All participants were re-evaluated after 8 weeks.

Results: The OA group demonstrated a significant improvement in isokinetic hip abductor strength following the intervention (p = 0.036). There was no change in the knee adduction moment over time (p > 0.05). Functional performance on the sit-to-stand
test improved in the OA group (p = 0.021) compared to the control group. The OA group showed a trend towards decreased knee pain (p = 0.05). **Conclusions:** Hip abductor strengthening did not reduce knee joint loading, but improved function, in a group of participants with medial knee OA.

5.2 **Introduction**

Excessive knee joint loading has been shown to contribute to the progression of knee osteoarthritis (OA) (1). During normal gait the load on the medial compartment of the knee is approximately 2.5 times greater than load on the lateral compartment (2). This asymmetry in the distribution of forces across the knee may help to account for the higher prevalence of medial compartment knee OA (3-5).

Knee joint loading during walking may be estimated quantitatively by the external knee adduction moment; the moment tending to adduct the knee during most of the stance phase of gait (6-8). Studies have indicated that the adduction moment provides a valid, indirect measure of the magnitude of dynamic load on the medial compartment of the knee (2;7;9-11). Higher knee adduction moments have been reported in persons with medial knee OA compared to asymptomatic control participants of similar age, gender, height and weight (12-15). Those with more severe knee OA also demonstrated higher knee adduction moments during gait than individuals with mild OA (8;10;15). The knee adduction moment has been shown to relate to radiographic disease severity (8;10;14-16), varus alignment (1;10;12;17) and knee pain (1;12;18-20).
The knee adduction moment is primarily the product of two variables; the frontal plane ground reaction force (GRF) vector and the frontal plane lever arm at the knee (the perpendicular distance from the GRF vector to the knee joint centre of rotation) (21). It has been suggested that gait strategies and interventions focused on decreasing the magnitude of the lever arm during gait may be effective for reducing load through the medial compartment. Increased toe-out angle during ambulation (12;22-24) and trunk lean towards the stance limb in gait (25) are two strategies adopted by individuals with knee OA which have been shown to decrease the magnitude of the frontal plane lever arm and reduce the knee adduction moment. Interventions which follow the same principles to reduce knee joint loading include stiff-hinged braces which apply an opposing external valgus moment at the knee (26-29), valgus (laterally) wedged insoles (30-32) and surgical realignment of the knee by high tibial osteotomy (33;34).

The hip abductor muscles may also influence knee joint loading through their control of the pelvis in the frontal plane (15;35). During the single-limb stance phase of gait, weakness of the stance limb hip abductor muscles may lead to drop of the pelvis towards the contralateral swing limb, shifting the body’s centre of mass away from the stance limb towards the swing side. These adjustments could theoretically increase the frontal plane lever arm magnitude, leading to higher knee adduction moments and greater forces across the stance limb medial compartment. This pattern at the hip has been proposed as a mechanism by which hip abductor weakness could potentially lead to greater knee joint loading in OA (15;35). Only one study was identified which evaluated
isometric hip abductor muscle strength in females with and without knee OA, and no differences in strength were found between the two groups (36).

Hip abductor weakness leading to drop of the pelvis towards the swing limb during gait would also increase the stance limb external hip adduction moment. However, recent knee OA studies investigating frontal plane hip joint mechanics have reported lower peak external hip adduction moments in groups with moderate and severe knee OA, compared to asymptomatic control participants (15;35;37;38). Thus, the role of hip mechanics in knee OA is not clear.

If hip abductor weakness could potentially lead to greater knee joint loading, then therapeutic interventions aimed at increasing the strength of the hip abductor muscles and controlling the pelvis in the frontal plane could reduce joint loading and have a possible disease-modifying effect (15;35). To our knowledge, an investigation of hip abductor strengthening as an intervention for individuals with knee OA has not been performed. Thus, the purpose of our study was to examine the influence of an 8-week home-based strengthening program for the hip abductor muscles on hip strength and the knee adduction moment in people with medial compartment knee OA. Given the functional importance of the hip abductor muscles, secondary objectives of the study were to determine if hip abductor strengthening exercises would improve physical function and knee symptoms in this sample of people with knee OA. Following the exercise program, we hypothesized that participants with medial compartment knee OA would demonstrate greater strength of the hip abductor muscles, a reduction in the external knee adduction moment, and improved physical function and knee symptoms.
moment during gait, improved physical functioning and decreased knee pain, compared to a matched control group of asymptomatic participants.

5.3 Sample and Methods

5.3.1 Participants

Forty individuals with medial compartment knee OA were recruited through newspaper advertisements and from the practices of orthopedic surgeons in Kingston, Ontario. Potential participants were included in the study if they met all of the following criteria (39;40): age \( \geq \) 40 years; self-reported pain in the knee(s) for most days of the month; physician diagnosis of knee OA; and one of the following applied: a) radiographic evidence of medial compartment knee OA; b) documented evidence of cartilage loss in the medial compartment by arthroscopy or magnetic resonance imaging. For those participants with bilateral medial compartment OA, the more affected side (as identified by radiographic OA grade) was selected as the test leg.

Participants were excluded if they presented with any of the following: intra-articular corticosteroid or visco-supplementation injection into either knee within the previous 3 months; other significant co-morbidities (including significant heart disease, stroke, and active treatment for cancer) that would be a contraindication for exercise and for gait and strength measures; OA from other types of arthritis, including rheumatoid arthritis and other systemic inflammatory arthropathies; history of avascular necrosis; prior periarticular fractures of the knee joint; Paget’s disease; villonodular synovitis; joint
infection; neuropathic arthropathy; acromegaly; Wilson’s disease; hemochromatosis; gout or recurrent pseudogout; or osteopetrosis (41). Individuals with known hip OA, previous trauma affecting one or both hips and previous replacement of any joint in the lower extremities were also excluded from the study. Finally, those who were receiving rehabilitation services for knee OA or performing a hip strengthening program at the time of testing were not eligible to participate.

Participants with knee OA were matched to a control group of individuals with no clinical diagnosis of knee OA, hip OA or rheumatoid arthritis and no reports of hip or knee pain or previous trauma. Control group participants were recruited through newspaper advertisements and posters displayed in churches and seniors’ centers in the Kingston area. Matching was attempted initially for gender, age (± 5 years), height (± 5 cm) and mass (± 5 kg). However, as the study progressed, gender and age became the primary criteria for matching as it was difficult to match for height and particularly body weight.

5.3.2 Sample Size

An estimate of sample size was obtained from two power calculations (two-tailed test, power = 80%, and significance level = 0.05) and 10% loss to attrition. One calculation used data from tests of isometric hip abductor strength before and after an exercise program in individuals with OA and lower extremity functional impairment (42). The second power calculation was computed using knee adduction moment data from a group of older adults with knee OA and a matched, asymptomatic group (43). Based on
these 2 power calculations, at least 35 participants per group were needed for the study (see Appendix C for a summary of the power calculations).

5.3.3 Data Collection

Design and Setting

The design of the study was a non-equivalent pretest-posttest control group design (44). A design incorporating participants with knee OA and a healthy control group was selected because few studies have compared the strength of the hip abductor muscles in those with knee OA to asymptomatic older adults. All testing was conducted in the Motor Performance Laboratory at Queen’s University, Kingston, Ontario, with the exception of knee radiographs which were completed in the Radiology Department at Kingston General Hospital. Testing sessions lasted approximately 2 - 2.5 hours. The study was approved by the University Health Sciences Research Ethics Board and all subjects gave informed consent before participating (Appendix A).

Alignment and Knee OA Grading

In situations where participants had recent weight-bearing radiographs of the knees (within 6 months of the date of testing), permission was requested to obtain digital images of these radiographs for use in the study. For all other participants bilateral radiographs of the knees in weight-bearing anterior-posterior views were obtained on initial visit, according to the hospital’s standardized protocol. Digital images of the
radiographs were received from the Radiology Department on anonymous compact discs with only the subject code to identify the participant.

Frontal plane knee alignment was measured from the digital images by means of a computer software program (Horizon Image Viewer, version 1.5, OAISYS Medical Inc.), which incorporates the use of electronic tools to define femoral and tibial bone landmarks on the digital images (45-48). A study investigator who had been trained in application of the software program completed all alignment measurements. Since the images in this study were of the knee joint only and not full-limb radiographs, an estimate of mechanical axis alignment (depicted as the hip-knee-ankle [HKA] angle) was obtained from measurement of the anatomic axis angle. The anatomic axis angle is the angle formed at the centre of the knee joint by the intersection of the femoral and tibial anatomic (shaft) axes (Figure 5.1). The femoral anatomic axis passes through the centre of the femoral shaft to the mid-condylar point of the distal femur and the tibial anatomic axis is formed by a line through the centre of the tibial shaft to the centre of the tibial plateau (interspinous midpoint) (49;50). The femoral mechanical axis was shown to be offset from the femoral anatomic axis by 4-5° (49;51-54). Thus, an estimate of mechanical axis alignment (the HKA angle) was derived by subtracting 5° from the measured anatomic axis angle.

Knee radiographs were graded according to the knee OA grading scheme of Cooke et al. (55) by an orthopedic surgeon who was involved in the study. The medial compartment was scored for joint space narrowing (0-3), femoral osteophytes (0-3), tibial
Figure 5.1. Anterior-posterior knee radiograph depicting the anatomic axis angle.  
Note: The femoral and tibial anatomic axes are drawn from the mid-shafts of the femur and tibia, respectively.
erosion (0-4) and subluxation (0-3). Tibial erosion was graded as the loss of bone, progressing from dishing to marginal destruction, subsequent fragmentation and, finally, gross bone damage. Subluxation was noted as a shift medially or laterally between the tibial spines and the femoral sulcus. According to this grading scheme, maximum knee damage would produce a total score of 13. Radiographic grading scores obtained with this scheme demonstrated excellent inter-reader reliability and were significantly correlated with alignment measures (55).

Gait Analysis

Testing in the Motor Performance Laboratory began with an evaluation of the participants’ level walking on an 8 m long walkway. Three-dimensional kinematic data (sampled at 100 Hz) were collected using 2 Optotrak optoelectronic motion tracking cameras (Optotrak 3020, Northern Digital Inc., Waterloo, ON, Canada) placed on either side of the walkway. Two AMTI force plates (Advanced Mechanical Technology Inc., Newton, MA) embedded in the centre of the walkway collected GRF data at a sampling frequency of 200 Hz. Spatial registration between the 2 cameras and the force plates was conducted just prior to each testing session to ensure that the Optotrak motion tracking system and the force plates were referenced to the same lab coordinate system.

Participants dressed in shorts and a loose fitting shirt for initial and final testing, and the same pair of comfortable walking shoes was worn at both sessions. Rigid marker clusters containing infrared light emitting diodes (IREDs) were positioned on the dorsum of the foot (over the metatarsal area), lateral shank, lateral thigh and sacrum, and over the
spinous processes of the 7th cervical/1st thoracic vertebrae. Figure 5.2 shows the standard configuration of marker clusters for the gait trials. The clusters were secured with Velcro straps and/or tape to avoid movement of the markers during the walking trials. Although markers were attached to both legs, only the test leg was analyzed. For control participants the test leg corresponded with the affected leg of the matched knee OA participants. Participants were instructed to ambulate along the walkway at their self-selected normal gait speed. After several practice trials, 5 good walking trials were obtained. Trials were considered successful if participants landed with one foot on each force plate and all IRED markers were visible by the cameras over the full course of the gait cycle to be analyzed. Appendix D includes the data collection sheets used for the testing sessions.

Following the gait trials, participants stood in view of the cameras and a series of reference trials were captured using a pointed probe fitted with 4 IRED markers (Figure 5.3). The tip of the probe was placed on specific bone landmarks to identify the location of the landmarks in relation to the marker clusters. Joint centres could then be approximated based on the location of these landmarks and the marker clusters. The bone landmarks selected for the reference trials included the 1st and 5th metatarsal heads, medial and lateral malleoli, medial and lateral femoral epicondyles, greater trochanters, a point directly vertical to the greater trochanter at the level of the mid-iliac crest bilaterally and the acromion processes of the scapula.

Visual three-dimensional (3-D) motion analysis software (C-Motion Inc., Rockville, MD) was used to process the gait data and produce a 3-D eight-segment model
Figure 5.2. Standard configuration of marker clusters for gait trials.
Figure 5.3. Pointed probe fitted with 4 infrared light emitting diode markers (IREDs) placed on bone landmarks during the reference trials.
(foot, shank and thigh segments bilaterally, and pelvis and trunk segments) (Figure 5.4).

Raw motion data and force plate data were filtered with a dual-pass Butterworth low-pass filter at a cut-off frequency of 6 Hz. The Visual 3-D program used an inverse dynamics approach to incorporate the force plate and Optotrak motion data, the landmarking reference trials and anthropometric parameters, in order to calculate frontal plane moments for the knee and hip during stance phase.

Net external hip and knee adduction moment data were exported from Visual 3-D to a Microsoft Excel® (Microsoft Office 2003, Microsoft Corporation, USA) worksheet, where the average moment waveforms were obtained for each participant. The stance phase of the test leg was divided into 100 points representing 100% of stance. Peak hip and knee adduction moment values in the first 50% of stance phase were calculated from the respective average moment waveforms. Excellent test-retest reliability results (ICC of 0.86) were obtained for peak knee adduction moment values in 31 persons with medial compartment knee OA (6). Peak values were selected as the highest peak in the first 50% of stance phase which was preceded by at least 5 values in ascending order and followed by 5 values in descending order. Peak hip and knee adduction moments were normalized to body weight and height (expressed in the units of %BW*Ht), to allow for comparison between participants.

The temporal-spatial parameters of gait speed (m/s), stride length (m), stance time (s), double limb support time (s) and cadence (steps/min) were also calculated. Over the 2 testing sessions gait speed was controlled by ensuring that each participant’s final gait
Figure 5.4. Sample walking frame (lateral view) showing C-Motion computer-generated model with location of infra-red emitting diodes, force platforms and lab axes. Note: frontal plane is represented by the Y-axis.
speed was within ± 15% of the individual’s initial gait speed. This step was to control for gait speed as a potential confounding factor which could influence the knee adduction moment (14), in addition to the exercise intervention.

**Strength Measures**

Isometric and isokinetic concentric strength of the hip abductor muscles was measured using the Biodex System 3 Isokinetic Dynamometer, following recommended hip strength testing protocols in the literature (56;57). Reliability and validity of angular position, isometric torque and concentric velocity have been established for the Biodex dynamometer (58). The hip adductor muscles were also evaluated at this time, to obtain measures of isometric and isokinetic strength of the opposing muscle group. High test-retest intraclass correlation coefficients (ICCs) of 0.96 have been reported for standing isokinetic concentric testing of hip abduction and adduction (56). Participants stood in an upright position with their posterior trunk supported by a pillow placed against the back of the dynamometer chair. The trunk and pelvis were stabilized using Velcro straps. The axis of rotation of the dynamometer was aligned with the participant’s anterior superior iliac spine and the dynamometer pad was secured snugly with a Velcro strap around the lower thigh just proximal to the knee. Figure 5.5 shows the set-up for strength testing. Participants were instructed to lift the test foot slightly from the Biodex platform when performing all strength measures. The order of isokinetic hip abduction/adduction and the separate isometric tests of hip abduction and adduction were randomized. A rest period of 2 minutes was provided between each test. Data were sampled at 100 Hz.
Figure 5.5. Set-up for hip abductor and adductor isokinetic and isometric muscle strength testing using the Biodex System 3 Isokinetic Dynamometer.
Data processing was performed using a MATLAB® software (Math Works Inc, MS) program, which filtered the torque data with a 6 Hz low-pass filter (Butterworth, 6th order) to reduce the possibility of selecting incorrect peak torque values due to motion artifact. The Biodex isokinetic output was also windowed to remove torque data that were not obtained within the pre-set isokinetic velocity (59;60). The software program calculated mean peak isokinetic and isometric torque values for hip abduction and adduction, which were normalized to body weight (expressed in units of N\cdot m/kg) for comparisons between groups.

Isokinetic Testing

Concentric strength of the hip abductor and adductor muscles was measured at an angular velocity of 60°/s, as this velocity was most typically used in other studies evaluating strength of these muscle groups (57;61-64). Johnson et al. (57) also reported that both older and younger subjects complained of hip muscle soreness at a testing velocity of 30°/s in the standing position and that older adults had difficulty generating torque values consistently at 90°/s. Range of motion of the hip joint was set from 0° to approximately 30° of abduction (56;57). Participants completed a practice set of 3 sub-maximal concentric abduction/adduction repetitions prior to each test to ensure familiarization with the test procedures. This was followed by 5 consecutive repetitions of maximal concentric hip abduction and adduction, with verbal encouragement provided to facilitate maximum effort. Peak torque values were obtained for each repetition. The data from the first repetitions were omitted and the last 4 of the 5 peak torque values from
each test were averaged to obtain the mean peak torques for abduction and adduction (65;66).

Isometric Testing

The position of the hip joint for isometric testing was set at 0° of abduction. Three sub-maximal isometric contractions were completed for both hip abduction and adduction prior to the respective tests. For each direction, participants then performed 3 maximal isometric contractions held for 5 seconds, with a 10-second rest between contractions. Verbal encouragement was given to promote maximum effort. Peak torque values were obtained for each isometric contraction in both directions and were averaged to produce the mean peak torques for isometric hip abduction and adduction.

Assessment of Knee Symptoms, Physical Function and Activity Level

Knee symptoms and perceived disability experienced due to OA were assessed with the Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC); a disease-specific, self-administered questionnaire given in a Likert scale format (67). The WOMAC is a recommended outcome measure for evaluation of individuals with OA of the knee or hip (68;69), and the reliability, validity and responsiveness of WOMAC measures have been well-established in these populations (67;70). The WOMAC consists of 24 questions, probing the specific dimensions of pain (5 questions), joint stiffness (2 questions), and physical disability or functioning (17 questions). The questionnaire takes about 5-10 minutes to complete. A standard scoring system was used
in which the responses for each subscale were rated from 0-4, with 4 representing extreme pain, stiffness or difficulty in physical function. The scores were then summed to produce a total score for each of the three subscales (67).

The Five-Times-Sit-to-Stand Test (FTSST) was used as an objective measure of lower extremity physical function (71). This test measures the time required to rise from a chair and sit down for 5 repetitions. Participants were instructed to sit on an armless chair (43 cm height, 47.5 cm depth) with their arms across their chest and to position themselves initially so that their back was resting against the chair. Timing with a digital stopwatch began with the word "Go" and stopped when participants returned to sitting after the 5th stand. Participants were instructed to stand up fully between repetitions of the test and not to touch the back of the chair during each repetition (72;73). Test-retest reliability of FTSST measurements has been established in older adults living in the community (74-76) and the correlation of FTSST scores with walking performance, lower extremity muscle strength and self-reported physical functioning provides evidence of the validity of the test (74;77;78). Furthermore, in community-dwelling older adults, performance on the FTSST and 2 other tests of physical function was highly predictive of subsequent disability (72).

Participants also completed the Physical Activity Scale for the Elderly (PASE), a self-reported measure designed to assess occupational, household, and leisure activities typically performed by older adults (79). Respondents were asked to record the activity frequency for 12 types of activities over the previous week. The validity of the PASE has been established in community-dwelling older adults without physical limitation (79-81)
and with knee pain and physical disability (82). PASE scores also demonstrated good
test-retest reliability ($r = 0.75$) in 254 community-dwelling older adults (79). The
questionnaire can be completed in 5-10 minutes. A total PASE score for each participant
was computed by multiplying specific weighted values for each activity with the activity
frequency/week, then summing the products for all 12 types of activities (83;84). Higher
PASE scores indicate greater levels of physical activity. Total scores may range from
zero to 400 or more (83).

5.3.4 Exercise Intervention

Upon completion of the initial testing session all participants with knee OA were
taught a home-based strengthening program for the hip abductor muscles by a study
physical therapist. An exercise instruction booklet and graded resistance elastic bands
were supplied to the participants. Individuals were instructed in the following program:
1) sidelying isotonic hip abduction exercises, progressing to using resistance bands
positioned around the distal thighs; 2) single leg standing stabilization exercises,
progressing to isotonic hip abduction using resistance bands placed just proximal to the
ankles; 3) single leg standing exercise off the side of a 10 cm step (contracting the stance
limb hip abductor muscles and raising the free leg to level while keeping the stance knee
extended). Participants were instructed to perform the specified exercise program 3-4
times per week for 8 weeks, completing one set of each exercise to fatigue. All exercises
were performed for both legs. Progression to greater resistance levels occurred when
participants could perform the exercise correctly and without fatigue for 20 repetitions. Exercise instructions and figures are included in Appendix E.

Participants completed weekly exercise calendars in which they recorded the frequency and resistance levels of the exercises (Appendix E). Over the 8-week period, the physical therapist arranged 2 follow-up visits with each participant in the laboratory or the participant’s home for monitoring and progression of the exercises. These visits lasted approximately 30 minutes. The therapist provided telephone follow-up support every 2 weeks and participants were encouraged to call with any questions or concerns.

Participants in the control group were instructed to continue their daily activities and refrain from beginning any new exercise program over the 8-week period. At the end of the 8 weeks, both groups returned to the laboratory for re-evaluation of the gait, strength and physical function measures and completion of the questionnaires.

5.3.5 Statistical Analysis

Prior to analysis data were reviewed to determine whether the distribution was normal for each of the outcome measures. Very few of the measures from initial and final testing violated the assumptions of normality as determined by the Kolmogorov-Smirnov statistic. Those measures that did not meet the assumption of normal distribution were analyzed using the Friedman 2-way analysis of variance (ANOVA) non-parametric test. Since non-parametric and parametric methods produced the same results, for the sake of consistency only parametric statistics are reported (85).
Independent t-tests were employed to assess for significant differences in demographic and clinical characteristics between the OA and control groups at baseline. Changes in the WOMAC pain, stiffness and physical function scores between initial and final testing for the OA group were assessed with paired sample t-tests. Repeated measures ANOVA was used to determine the main effects and interactions of group and time for the outcome measures of hip abductor and adductor muscle strength, peak hip and knee adduction moments and time to complete the FTSST. Mean differences in scores from initial to final testing for each of the measures were also computed and independent t-tests were used to assess for significant differences in these change scores between groups. These analyses yielded the same results as the repeated measures ANOVA. Therefore, only the repeated measures analyses are presented. Statistical analysis was performed using SPSS software (Version 15.0.1, SPSS Incorporated, Chicago, Illinois, 2006) and the alpha level was set at 0.05 for significance testing.

5.4 Results

5.4.1 Baseline Characteristics of the Study Participants

Forty participants with knee OA (mean age 62.98 ± 9.73 years, 23 women) and 40 matched control participants (mean age 64.13 ± 9.04 years) completed the study. An additional 5 participants with knee OA completed the initial testing only; 3 participants had to discontinue their participation because of a death or illness in the family and 2
participants did not wish to continue after the initial testing session. Thirty-three of the 40 OA participants had bilateral medial compartment knee OA.

Baseline demographic and clinical characteristics for the 40 participants in each group who completed the study are displayed in Table 5.1. The OA group had higher values for weight and body mass index and greater varus alignment compared to the control group (p < 0.05). There were no significant differences in age or height between groups. The average grade of disease severity for the OA group was 3.7, indicating an overall moderate level of severity. On evaluation of temporal-distance gait measures the OA group had a slower gait speed, longer stance time, longer double limb support time and lower cadence (steps/min) at baseline. Paired t-tests confirmed that gait speed within subjects had been controlled for, as there were no significant differences in the participants’ gait speeds between initial and final testing in either group (p > 0.05). Gait speed at baseline was 1.00 ± 0.20 m/s for the OA group and 1.12 ± 0.19 m/s for the control group. On final testing, the OA group had a gait speed of 1.03 ± 0.22 m/s and the gait speed of the control group was 1.12 ± 0.20 m/s.

### 5.4.2 Compliance

Adherence to the home exercise program was assessed by means of the self-completed, weekly exercise calendars. Participants were determined to be compliant with the exercise program if they performed at least 75% of the prescribed exercise sessions over the 8-week period. According to this criterion, 31 of the 40 OA participants (78%) were compliant with the exercise program. When only the group of 31 compliant
Table 5.1. Baseline demographic and clinical characteristics of participants completing the study.

<table>
<thead>
<tr>
<th></th>
<th>OA Group</th>
<th>Control Group</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n = 40</td>
<td>n = 40</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mean (SD)</td>
<td>Mean (SD)</td>
<td></td>
</tr>
<tr>
<td>Age (yr)</td>
<td>62.98 (9.73)</td>
<td>64.13 ± 9.04</td>
<td>0.59</td>
</tr>
<tr>
<td>(Range: 46-90)</td>
<td>(Range: 47-84)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>82.31 (20.0)</td>
<td>69.71 (11.03)</td>
<td>0.001*</td>
</tr>
<tr>
<td>Height (m)</td>
<td>1.73 (0.11)</td>
<td>1.70 (0.86)</td>
<td>0.23</td>
</tr>
<tr>
<td>Body mass index (kg/m²)</td>
<td>27.38 (5.47)</td>
<td>24.04 (3.24)</td>
<td>0.001*</td>
</tr>
<tr>
<td>Knee alignment (°)</td>
<td>-4.1 (4.3)</td>
<td>-2.2 (1.9)</td>
<td>0.014*</td>
</tr>
<tr>
<td>Grade of OA Severity b</td>
<td>3.7 (2.1)</td>
<td>0.4 (0.80)</td>
<td>0.000*</td>
</tr>
</tbody>
</table>

Temporal-distance gait parameters:

<table>
<thead>
<tr>
<th></th>
<th>OA Group</th>
<th>Control Group</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n = 40</td>
<td>n = 40</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mean (SD)</td>
<td>Mean (SD)</td>
<td></td>
</tr>
<tr>
<td>Gait speed (m/s)</td>
<td>1.00 (0.20)</td>
<td>1.12 (0.19)</td>
<td>0.006*</td>
</tr>
<tr>
<td>Stride length (m)</td>
<td>1.19 (0.16)</td>
<td>1.26 (0.15)</td>
<td>0.08</td>
</tr>
<tr>
<td>Stance time (s)</td>
<td>0.84 (0.11)</td>
<td>0.75 (0.07)</td>
<td>0.000*</td>
</tr>
<tr>
<td>Double limb support time (s)</td>
<td>0.39 (0.08)</td>
<td>0.33 (0.05)</td>
<td>0.001*</td>
</tr>
<tr>
<td>Cadence (steps/min)</td>
<td>97.36 (10.48)</td>
<td>104.60 (9.29)</td>
<td>0.003*</td>
</tr>
</tbody>
</table>

SD=standard deviation

* Negative alignment values represent varus

b Radiographic grading scale from 0-13 (Cooke et al.(55))

(*) significant differences between groups (p < 0.05)
participants and their matched controls were included in the statistical analyses of the measures, the same results were obtained as with the group of 40 participants. Therefore, the results are presented for all participants.

5.4.3 WOMAC Scores

Mean total WOMAC scores for the subscales of pain, stiffness and physical function at baseline and on final testing are presented in Table 5.2. WOMAC knee pain scores were lower in the OA group on final testing after the 8-week period (borderline significant at p = 0.05). There were no significant changes in the WOMAC stiffness or physical function total scores from baseline to final testing in the OA group.

5.4.4 Outcome Measures

Table 5.3 presents the initial and final means and standard deviations for the outcomes of hip isokinetic and isometric muscle strength, peak hip and knee adduction moments and time to complete the FTSST. There were no significant differences in isokinetic strength of the hip abductor muscles between the OA and control groups. Improvement in isokinetic hip abductor strength occurred over time in both groups and the significant interaction effect indicated a greater change in the OA group compared to the control participants (F = 4.565, p = 0.036) (Figure 5.6). Tests of isometric hip abduction showed no significant changes within or between groups over the 8-week period (Figure 5.7).
Table 5.2. Comparison of mean WOMAC subscale scores from initial to final testing for the OA group.

<table>
<thead>
<tr>
<th></th>
<th>Initial Testing</th>
<th></th>
<th>Final Testing</th>
<th></th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n=40 Mean (SD)</td>
<td>n=40 Mean (SD)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WOMAC Pain</td>
<td>5.55 (2.87)</td>
<td>4.78 (3.43)</td>
<td>0.05</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WOMAC Stiffness</td>
<td>3.08 (1.80)</td>
<td>2.95 (1.77)</td>
<td>0.55</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WOMAC Physical Function</td>
<td>19.60 (11.77)</td>
<td>18.15 (12.78)</td>
<td>0.23</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

SD = Standard Deviation  
WOMAC = Western Ontario and McMaster Universities Osteoarthritis Index. Higher scores on the WOMAC subscales indicate greater severity of pain, stiffness and difficulty in physical function.  

\(^a\) WOMAC Pain Subscale: total score from 0-20  
\(^b\) WOMAC Stiffness Subscale: total score from 0-8  
\(^c\) WOMAC Physical Function Subscale: total score from 0-68
Table 5.3. Initial and final means and standard deviations for hip muscle strength, peak hip and knee adduction moments and chair rise rise time in OA and control groups.

<table>
<thead>
<tr>
<th></th>
<th>Group</th>
<th>Initial Testing Mean (SD)</th>
<th>Final Testing Mean (SD)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isokinetic hip abductor muscle strength (N.m/kg)</td>
<td>OA</td>
<td>0.75 (0.42)</td>
<td>1.00 (0.41)</td>
<td>0.036*</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>0.96 (0.43)</td>
<td>1.06 (0.43)</td>
<td></td>
</tr>
<tr>
<td>Isokinetic hip adductor muscle strength (N.m/kg)</td>
<td>OA</td>
<td>0.45 (0.31)</td>
<td>0.74 (0.45)</td>
<td>0.53</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>0.72 (0.50)</td>
<td>0.94 (0.58)</td>
<td></td>
</tr>
<tr>
<td>Isometric hip abductor muscle strength (N.m/kg)</td>
<td>OA</td>
<td>0.95 (0.28)</td>
<td>1.03 (0.38)</td>
<td>0.26</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>1.07 (0.31)</td>
<td>1.08 (0.33)</td>
<td></td>
</tr>
<tr>
<td>Isometric hip adductor muscle strength (N.m/kg)</td>
<td>OA</td>
<td>0.83 (0.38)</td>
<td>0.99 (0.41)</td>
<td>0.097</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>1.07 (0.41)</td>
<td>1.13 (0.49)</td>
<td></td>
</tr>
<tr>
<td>Peak knee adduction moment (%BW*Ht)</td>
<td>OA</td>
<td>2.97 (0.87)</td>
<td>2.96 (0.90)</td>
<td>0.52</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>2.47 (0.62)</td>
<td>2.52 (0.67)</td>
<td></td>
</tr>
<tr>
<td>Occurrence of peak knee adduction moment (% stance)</td>
<td>OA</td>
<td>28.80 (6.02)</td>
<td>29.03 (6.32)</td>
<td>0.98</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>26.17 (4.65)</td>
<td>26.37 (4.33)</td>
<td></td>
</tr>
<tr>
<td>Peak hip adduction moment (%BW*Ht)</td>
<td>OA</td>
<td>4.55 (0.78)</td>
<td>4.50 (0.83)</td>
<td>0.52</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>4.53 (0.75)</td>
<td>4.39 (0.78)</td>
<td></td>
</tr>
<tr>
<td>Occurrence of peak hip adduction moment (% stance)</td>
<td>OA</td>
<td>30.31 (5.97)</td>
<td>30.74 (5.56)</td>
<td>0.79</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>27.60 (3.77)</td>
<td>27.78 (3.52)</td>
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<tr>
<td>FTSST (s)</td>
<td>OA</td>
<td>15.21 (8.51)</td>
<td>12.52 (6.06)</td>
<td>0.021*</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>10.09 (2.97)</td>
<td>9.31 (2.80)</td>
<td></td>
</tr>
<tr>
<td>PASE score</td>
<td>OA</td>
<td>196.18 (66.26)</td>
<td>200.90 (80.48)</td>
<td>0.065</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>165.03 (64.98)</td>
<td>147.33 (60.24)</td>
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</tbody>
</table>

*a n= 40 participants in each group
FTSST: Five-Times-Sit-to-Stand Test
PASE: Physical Activity Scale for the Elderly
(*) significant interaction effect (p < 0.05)
Isometric Hip Abductor Muscle Strength (N.m/kg)

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<th>OA Group</th>
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<td>Final Test</td>
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Figure 5.6. Means and standard deviations of isokinetic hip abductor muscle strength: comparison between initial and final tests for OA and control groups. Note: Significant time and interaction effects (p < 0.05)

Isometric Hip Abductor Muscle Strength (N.m/kg)

<table>
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<th>OA Group</th>
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<td>Initial Test</td>
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<td>Final Test</td>
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Figure 5.7. Means and standard deviations of isometric hip abductor muscle strength: comparison between initial and final tests for OA and control groups. Note: No significant group, time or interaction effects (p > 0.05).
Analysis of hip adductor muscle strength measures revealed similar findings for both isokinetic and isometric testing. A main effect of group was found, with the OA group showing decreased hip adductor strength compared to the control group (p = 0.017 and p = 0.04 for isokinetic and isometric testing, respectively). Both the OA and control groups demonstrated significant improvements in isokinetic and isometric hip adductor strength over time and there were no interaction effects (Figures 5.8 and 5.9).

On analysis of the kinetic gait parameters, the OA group had higher peak knee adduction moments (F = 8.019, p = 0.006) than the control group (Table 5.3), but there was no significant change in the peak knee adduction moment over time and no interaction effect (Figure 5.10). Figure 5.11 illustrates the average knee adduction moment waveforms for the OA and control groups across the stance phase of the gait cycle during both initial and final tests. The peak hip adduction moments did not change within or between groups over the duration of the study. The occurrences of the first peak hip and knee adduction moments were later in the stance phase of gait for the OA group (p = 0.005 and p = 0.017 for hip and knee adduction moments, respectively), compared to the control group. However, there were no significant changes over time in the occurrences of the first peak hip and knee moments and there was no interaction effect.

Analysis of physical function measures revealed that the OA group performed the FTSST more slowly than the control group (F = 12.339, p = 0.001) (Table 5.3). Although an improvement in sit-to-stand time was observed for both groups over time, the improvement in the OA group was significantly greater than in the control group (F =
Figure 5.8. Means and standard deviations of isokinetic hip adductor muscle strength: comparison between initial and final tests for OA and control groups. Note: significant group and time effects (p < 0.05); no interaction effect (p > 0.05)

Figure 5.9. Means and standard deviations of isometric hip adductor muscle strength: comparison between initial and final tests for OA and control groups. Note: significant group and time effects (p < 0.05); no interaction effect (p > 0.05)
Figure 5.10. Mean peak external knee adduction moments: comparison between initial and final tests for OA and control group (means ± standard deviations). \( \% \text{BW} \times \text{Ht} \) = Percentage body weight times height

(*) significant difference from respective control group at \( p < 0.05 \)

Note: Both initial and final mean peak moments for the OA group were higher than initial and final mean peak moments for the control group.

Figure 5.11. Average knee adduction moment waveforms for the OA and control groups across the stance phase of the gait cycle, on both initial and final testing. The waveforms were obtained by averaging across participants at each percent of stance, such that data were normalized across time to 100% of stance phase.
Figure 5.12. Means and standard deviations of time to complete the Five-Times-Sit-to-Stand Test: comparison between initial and final tests for OA and control groups.
Note: significant group, time and interaction effects (p < 0.05)
5.55, p = 0.021) (Figure 5.12). From the evaluation of the PASE scores, the OA group demonstrated higher total scores for physical activity compared to the control group (F = 9.057, p = 0.004) (Table 5.3). There were no significant changes in physical activity level over time for either group and no interaction effect was found.

5.5 Discussion

The primary findings of the current study were that a home-based strengthening program targeting the hip abductor muscles resulted in a significant increase in isokinetic hip abductor strength, but had no effect on reducing the knee adduction moment during gait, in people with medial knee OA who were compared to an asymptomatic control group. Hip abductor strengthening led to an improvement in functional performance on the sit-to-stand test and a trend towards reduced knee pain in the sample with knee OA.

5.5.1 Muscle Strength Measures

Results of our study revealed that there were no significant differences in isokinetic or isometric hip abductor muscle strength measurements between OA and control groups. This finding did not support our hypothesis that those with knee OA have weakness of the hip abductor muscles, which leads to drop of the pelvis towards the swing limb during gait and greater loading through the knee joint (15;35). Similar to our findings, Yamada et al. (36) reported no difference in isometric hip abductor muscle strength between individuals with medial compartment knee OA and healthy control
participants. Our participants with OA were active in leisure, household and occupational activities, which may be one explanation for a lack of hip abductor muscle weakness in this sample. Mean total PASE scores for the OA group were 196.18 ± 66.26 on initial testing and 200.90 ± 80.48 at the final visit. These values were higher than the mean total PASE scores for sedentary older adults (131.3 ± 70.4) (86) and older adults with knee pain and functional limitations (131.4 ± 71.1) (82) reported in the literature. The high activity levels of our participants with knee OA indicated that they were continuing to engage in physical activities despite their disease and symptoms.

A significant improvement in isokinetic strength of the hip abductor muscles occurred over time in the OA group receiving the 8-week exercise intervention. However, there was no significant change in isometric hip abductor strength over time. The dynamic nature of the hip strengthening exercises may have resulted in more pronounced changes in isokinetic than isometric strength. Compliance with the exercise program was moderately high at 78% and the home program was reviewed and progressed at regular intervals by the study physical therapist during the period of the intervention.

Few other studies have incorporated hip strengthening as part of exercise programs for persons with knee OA or included hip muscle strength as an outcome measure in this population. McGibbon et al. (42) randomly assigned a group of 15 elderly individuals with lower extremity impairment, including OA but not isolated to knee OA, to one of two 6-week intervention programs. The strength training intervention included resisted proprioceptive neuromuscular facilitation exercise patterns for all lower
extremity muscle groups using graded resistance bands. The functional training intervention consisted of exercises simulating activities of daily living (including gait, rising from a chair, stepping and squatting down) performed at 3 different speeds and progressing in difficulty. Significant improvements in isometric hip abductor muscle strength (16.42% with functional training and 13.75% with strength training), as measured in the sitting position by a hand-held dynamometer, were found in both groups following the exercise interventions.

The OA participants in the current study demonstrated lower values for isokinetic and isometric hip adductor strength as compared to the healthy age-matched control group. Yamada et al. (36) did not find a difference in isometric hip adductor strength between persons with knee OA and control participants. However, higher adductor to hamstring ratios were reported in those with medial compartment OA and varus alignment, and these ratios increased with higher knee OA disease severity scores. The authors suggested that strength of the hip adductor muscles may have increased over time to resist varus angulation of the limb and reduce the knee adduction moment. Our findings do not support this hypothesis. The study by Yamada et al. (36) included females only and involved different positioning and instrumentation for isometric strength testing, thus making comparisons between studies difficult. Also, the increased adductor to hamstring ratios may have related to lower hamstring strength observed in the OA group with increasing disease severity, in the study by Yamada et al. (36). However, given the finding of hip adductor weakness in our OA group on both static and dynamic testing and the potential role of these muscles in contributing to frontal plane knee
stability, further studies to quantify hip adductor strength and function in persons with knee OA are warranted.

The improvement in isokinetic and isometric strength of the adductor muscles in both groups over time may indicate a testing effect, rather than an intervention effect. Participants may have become familiar with the equipment and test protocol, and, as a result, they may have performed the strength testing more effectively at the final visit. We chose to test the hip muscles in standing as a functional position. Cahalan et al. (56) reported high test-retest reliability coefficients of 0.96 for standing isokinetic concentric tests of hip abduction and adduction at velocities of 30, 90, 150 and 210°/s in healthy younger and older adults. Other studies have evaluated isokinetic hip muscle strength at 60°/s in healthy adults positioned in side-lying and obtained varying levels of test-retest reliability (ICC values from 0.59 to 0.88) (61-64). Kea et al. (63) found that averaging isokinetic hip strength measures over 2 test occasions (ICC, type 2,2) was necessary to achieve excellent test-retest reliability coefficients in young athletes tested in side-lying. Future studies evaluating hip adductor strength in people with knee OA may need to consider increasing the number of practice repetitions or incorporating two initial hip strength testing sessions to permit familiarization with the equipment and protocol.

5.5.2 Knee and Hip Adduction Moments

Gait analysis revealed that peak knee adduction moments in the first 50% of stance phase were higher in our sample of participants with knee OA compared with the control group. These results are consistent with reported findings in the literature. The
mean peak knee adduction moment of 2.97 ± 0.87 % BW*Ht for the OA group at baseline is comparable to peak adduction moment values reported in studies of those with less severe knee OA (6;8;10;14), and is lower than values reported for those with more severe knee OA and greater varus alignment (1;2;8;10;14).

There were no changes in the peak knee adduction moment over time in either group. Thus, strengthening the hip abductor muscles did not influence the knee adduction moment in our participants with medial knee OA. Other studies investigating the effect of lower extremity strengthening on the knee adduction moment have also failed to demonstrate a change in the knee moment during gait. In an 8-week pilot study by Thorstensson et al. (87), 13 persons with early knee OA participated in an exercise program which involved lower extremity muscle strengthening (including the hip abductor and adductor muscles), trunk strengthening and weight-bearing functional activities. Following the exercise program, the peak knee adduction moment in the shock-absorption phase of gait (approximately 10% of the gait cycle) was not significantly reduced, but was significantly lower during one-leg rise. It was suggested that the peak knee adduction moment during the more demanding task of one-leg rise may be more sensitive to change than the peak moment during gait (87). This pilot study with small sample size, lack of control group and low statistical power was considered preliminary in nature.

Lim et al. (88) evaluated the effect of quadriceps strengthening on the knee adduction moment in a 12-week randomized controlled trial of 107 persons with medial knee OA. Participants were stratified into two groups according to varus malalignment
or more neutral alignment. Each group was then randomly assigned to a supervised, home-based, quadriceps strengthening program or no intervention. No significant change in the knee adduction moment was observed in the groups with more varus malalignment or neutral alignment following the exercise intervention (88).

No differences in mean peak hip adduction moments in the first 50% of stance phase were found between the OA and control groups in the current study. This result compares with the findings of Mundermann et al.(15), who reported that those with less severe knee OA (K/L grades \( \leq 2 \)) had hip adduction moments that were similar to their matched control subjects. In contrast, other studies have reported lower first peak hip adduction moments in those with moderate and severe knee OA compared to control participants (15;35;37;38). Reasons for the disparity between our findings and the results of these studies may be related to differences in our study group, including lower overall disease severity, high activity levels and relatively mild knee symptoms. Another possible explanation is that the moderate to severe OA groups in the other studies may have used gait strategies which have been shown to reduce the knee adduction moment, such as lateral trunk lean towards the stance limb and increased toe-out angle. These strategies would also decrease the hip adduction moment during gait. Participants in our OA group may not have required the same degree of compensatory gait strategies. However, lateral trunk lean and toe-out gait were not measured in any of these studies or in the current study, so these speculations could not be confirmed.

Our study also demonstrated no significant change in the hip adduction moment following the exercise intervention. Although it has been suggested in the literature that
strengthening the hip abductor muscles could potentially prevent drop of the pelvis to the swing side during stance phase of gait (15;35), which would decrease the external hip adduction moment, hip strengthening produced no effect on the hip adduction moment in our sample of participants with medial knee OA.

The peak knee and hip adduction moments occurred later in the gait cycle in the OA group compared to the control group. These findings may be related to more cautious loading of the limb by participants with knee OA as an adaptive strategy to reduce knee pain. The later occurrence of the hip and knee peaks corresponds to the slower gait speed, longer stance time and longer period of double limb support time found in the OA group.

5.5.3 WOMAC Pain Scores

The mean total WOMAC pain score (5.55 ± 2.87) in our group of OA participants at baseline is lower than other WOMAC subscale scores reported in the literature. Studies of large sample sizes which used a Likert scale format (total pain scores from 0 - 20) and included individuals with similar mean ages and a range of OA disease severities were compared. In these studies total WOMAC pain scores were higher, ranging from 6.45 to 12.40 (37;89-92). WOMAC pain scores indicated a trend towards decreased knee pain over time (borderline significant at 0.05) in our group of OA participants. The lack of a more definite reduction in pain over the 8-week intervention period may have been related to the relatively low intensity of knee pain which characterized our sample at baseline.
5.5.4 Physical Function Measures

Functional performance on the FTSST was decreased in our participants with knee OA, compared to the control group. This finding revealed that those with knee OA experienced limitations in lower limb physical function, despite being active in recreational, household and occupational activities. Mean total scores for the sit-to-stand test at baseline (15.21 ± 8.51 s) are higher than those reported in studies of healthy older adults which followed the same sit-to-stand protocol (60 to 69 yr: ranges from 8.4 to 12.7 s; 70 to 79 yr: ranges from 9.8 to 13.7 s) (74;76;93-95).

The OA group demonstrated a significant improvement (18%) in time to complete the sit-to-stand test over the 8-week intervention period. The FTSST has been shown to relate to lower extremity strength, particularly quadriceps muscle strength, and balance control (74;96). Although strength of other muscle groups was not measured in our study, it is likely that the weight-bearing exercises performed as part of the hip strengthening program produced co-contraction of other lower extremity and trunk muscles. Thus, overall lower extremity strength and pelvic stability may have increased with the exercise program, leading to improved functional performance on the sit-to-stand task. In addition, participants may have completed the FTSST at a faster speed because of decreased knee pain.

The mean total WOMAC physical function subscale score of 19.60 ± 11.77 (total possible range from 0 to 68) at baseline was relatively low in our group of OA participants, indicating that they reported little difficulty in functional tasks. In comparison, large sample studies of older adults with knee OA which included a range of
disease severities reported WOMAC physical function scores from 19.51 to 41.09 (37;90-92). Subjective reports from our participants of greater ease in ambulating, climbing stairs and rising from a chair following the exercise program correspond with the objective improvements in function on the sit-to-stand test. However, these verbalized functional improvements were not reflected in increased WOMAC self-reported physical function scores over the 8-week period. The subscale may not have been responsive enough to detect small changes in function over time in this group of OA participants that was functioning at a relatively high level and was active in physical activities.

5.5.5 Limitations and Recommendations

One limitation of our study was that gait strategies which may have affected the knee adduction moment, including lateral trunk lean, were not evaluated for change over time in this study. Hip abductor muscle strengthening may have increased trunk stability, thus decreasing lateral trunk lean and potentially nullifying a reduction in the knee adduction moment that might have occurred as a result of the exercise intervention. In addition, strength of the knee muscles was not assessed in this study. It is possible that the improvements in functional performance on the sit-to-stand test and the decrease in knee pain were more closely correlated with knee muscle strength gains from the functional weight-bearing exercises than increased hip abductor strength. Finally, our participants with knee OA were highly active in recreational, household and occupational
activities, as shown by the PASE scores. Therefore, the results from this study may not be generalizable to the average OA population.

Our results suggest the need for further studies to investigate the effects of hip abductor strengthening on improvement of physical function and reduction of symptoms in persons with medial knee OA. Randomized controlled trials with larger cohorts are recommended. Furthermore, accumulating evidence suggests that the local mechanical environment, including knee OA disease severity, lower limb alignment and varus-valgus knee laxity, may influence whether responses to exercise interventions are favourable in persons with knee OA (88;97;98). Stratification according to biomechanical factors would provide insight as to whether hip abductor strengthening is more effective in subgroups of persons with knee OA. Future studies of hip abductor strengthening in those with knee OA should also incorporate measures of knee muscle strength and lateral trunk lean during gait, to better elucidate relationships between factors and to clarify the biomechanical and functional benefits of this intervention.

5.5.6 Conclusions

In summary, an 8-week strengthening program for the hip abductor muscles resulted in increased isokinetic hip abductor muscle strength, reduced knee pain and improved functional performance on a sit-to-stand task in 40 participants with medial knee OA, compared to an asymptomatic control group. There was no change in the knee adduction moment with the exercise program. Further research is required to investigate whether hip abductor strengthening would be an effective intervention for slowing
disease progression and protecting against functional decline in people with medial knee OA.

Acknowledgements

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5.6 References


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6.1 Thesis Overview

“New knowledge of osteoarthrosis must be gained if the later years of our lengthening lives are not to be plagued by increasing pain and disability.”

~ J.H. Kellgren, 1961 (1).

The intent of this thesis was to advance understanding in the field of knee OA from muscular and biomechanical perspectives, with a focus on exercise intervention and measurement reliability. The primary objective was to investigate the effects of a home strengthening program targeting the hip abductor muscles on the knee adduction moment, hip muscle strength, physical function and knee symptoms in persons with medial knee OA (Chapter 5). Secondary objectives were to evaluate the reliability of: (a) measurements of knee muscle strength within a single testing session in a group of older adults with knee OA, and (b) measures of lower limb alignment obtained with the application of an established bone landmarks approach using a computer software program (Chapters 3 and 4).
6.2 Reliability of Knee Muscle Strength Measures in Persons with Knee Osteoarthritis

In Chapter 3 the main findings were that concentric isokinetic knee muscle strength measures at 3 commonly used velocities of 60°/s, 90°/s and 120°/s and isometric tests of the quadriceps and hamstring muscles were highly reliable within a single testing session in a sample of 40 persons with knee OA. For each of the strength measures, there were no significant differences in peak torque values between repetitions. Knee pain during strength testing did not correlate with mean peak torque values for isometric or isokinetic tests.

From a review of the literature pertaining to muscle strength testing in persons with knee OA prior to this study, it became clear that a variety of measures (both isometric and isokinetic) were employed. Discrepancies within trials for isokinetic testing at a velocity of 120°/s were also apparent from the literature (2-5). Thus, the study presented in Chapter 3 aimed to investigate the reliability of isometric and isokinetic measures of knee muscle strength for a single test session, with a particular focus on three angular velocities which were commonly used for isokinetic testing in knee OA studies.

The general isokinetic strength literature also provided recommendations for obtaining accurate and consistent trials, which we applied to our study in Chapter 3. These recommendations included eliminating the first of 5 trials for isokinetic testing (6;7) and filtering and windowing the data to avoid selecting erroneous peak torque values from motion artifact and end range torque spike oscillations (8;9).
reliability of isokinetic knee flexion and extension in a study of healthy volunteers was significantly improved after windowing the data (8). Our findings of high reliability coefficients for all knee muscle strength measures within a single testing session may have been related, in part, to the application of the above recommendations during data processing. We applied the same principles when evaluating the data from isokinetic tests of the hip abductor and adductor muscles in the study which comprises Chapter 5. However, no investigations were performed in either study to quantify differences between results obtained with and without the application of these steps during data processing.

Given that arthritic knees are often stiff and painful and that strength measures may produce or increase pain momentarily during test movements, a secondary purpose of the study in Chapter 3 was to evaluate the influence of knee pain experienced with the strength tests on the consistency of the measures. We found that knee pain occurring with strength testing did not detract from the consistency of the strength measures, given that all isometric and isokinetic strength measures were highly reliable for a single testing session. In addition, knee pain during strength testing did not correlate with any of the strength measures. This finding may have been related to the low VAS pain scores at baseline, the lower overall pain scores on the WOMAC pain subscale and considerable variability in pain responses during the strength measures from our sample of persons with knee OA.

While cross-sectional studies may require only a single testing session, intervention studies and longitudinal evaluations may employ repeated tests of lower
extremity muscle strength. Therefore, test-retest reliability of isometric and isokinetic strength measures is important to address in knee OA research. Isometric tests of knee flexion and extension (10;11) and isokinetic knee muscle testing at various angular velocities (2;12) demonstrated good test-retest reliability in samples of individuals with knee OA.

6.3 Reliability of Manual and Computer-Assisted Measures of Alignment

In Chapter 4 of this thesis our study showed that there were no significant differences between manual and computer-assisted measures of lower limb alignment from schematics of limb deformities drawn with the use of AutoCAD® software. For each of the measures of limb angles and bone lengths, computer-assisted analysis showed either similar or higher reliability in comparison to the manual method. When the computer program was applied to a large sample of full-limb digital radiographs of persons with, or at risk for developing, knee OA, all alignment measures demonstrated high inter- and intra-reader reliability.

Lower limb malalignment is a key factor influencing disease progression and functional decline in persons with knee OA (13;14). Malalignment has been shown to mediate the impact of other risk factors, including obesity, on the development and progression of knee OA (15-17). Furthermore, there is increasing evidence that the local mechanical environment, particularly the degree of lower limb malalignment, may affect individual responses to exercise interventions (18-20). Thus, it is imperative that
alignment measurements be included in research investigating biomechanical factors in knee OA and that these measurements exhibit good evidence of reliability. In addition, digital radiographs are rapidly replacing traditional radiographic film, requiring that alignment be measured from digital images with the aid of computer software programs.

The study outlined in Chapter 4 of this thesis provided a two-part evaluation of the reliability of lower limb alignment measures obtained with computer-assisted analysis. We applied an established approach (21-25), involving the selection of 10 bone landmarks on the femur and tibia, to obtain limb angles and bone lengths for a systematic evaluation of these measures. This approach defines the extent of femoral and tibial contributions to overall alignment in order to provide a comprehensive picture of knee joint geometry. The computer-assisted method was first compared to measures obtained manually using schematics of limb deformities drawn with AutoCAD® software. While these drawings were only simulations of various patterns of malalignment, they provided an optimal setting to test the program. Under these conditions, problematic issues such as poor visibility of landmarks due to radiographic underexposure or overexposure were removed.

The computer method was then evaluated using a large number of full-limb radiographs of persons with, or at risk for developing, knee OA. In addition to the mechanical axis angle, other angles of the femur and tibia and bone lengths demonstrated good inter- and intra-reader reliability. The computer software program provided electronic tools, including circle, ruler and midline tools, which aided the reader in selecting the 10 femoral and tibial bone landmarks. Other features of the software
program were image magnification and enhancement (enabling alterations to the brightness and contrast of the image), which allowed the femur and tibia to be visualized clearly when marking the bony points. Each of these features likely contributed to the high reliability coefficients obtained with the computer measures.

To our knowledge, this study was the first to investigate the reliability of a full range of alignment measures using multiple readers. For each of the readers all measures demonstrated excellent reliability, indicating that the bone landmarks approach and the custom software program could be applied effectively to alignment measurements with training.

6.4 Hip Abductor Strengthening in Persons with Medial Compartment Knee Osteoarthritis

In the final study (Chapter 5) we concluded that an 8-week, home-based strengthening program for the hip abductor muscles resulted in increased isokinetic hip abductor strength, improved functional performance on a sit-to-stand task and a trend towards reduced knee pain in 40 participants with medial compartment knee OA, compared to a control group without OA. There were no changes in the knee adduction moment following the exercise program. This finding did not support the hypothesis that hip abductor strengthening could reduce knee joint loading by controlling frontal plane pelvic stability.

The study in Chapter 5 was initiated in response to the proposition in the literature that hip abductor muscle weakness and altered biomechanics at the hip and pelvis could
influence knee joint loading in people with medial compartment OA (26;27). The purpose of this study was to investigate the influence of a home program of strengthening exercises for the hip abductor muscles on hip muscle strength and the knee adduction moment in a sample of participants with knee OA, when compared to an asymptomatic control group that received no intervention. Secondarily, we evaluated whether the home exercise program would have effects on physical function and knee symptoms in the group with OA.

Previous studies evaluating frontal plane hip biomechanics during gait have indicated that individuals with medial knee OA may have weakness of the hip abductor muscles, which could lead to drop of the pelvis to the swing side during stance phase of gait (26;27). This action could cause a shift in the centre of mass towards the swing limb, which could increase the magnitude of the frontal plane lever arm, resulting in greater loading through the medial compartment of the knee. We did not find evidence of hip abductor weakness in our participants with knee OA, although this group was highly active in leisure, household and occupational activities. Studies of sedentary older adults with knee OA may reveal hip abductor weakness in this population. Given that knee muscle weakness is generally present (5;28-31) and that lower extremity function is often reduced (32-35) in those with knee OA, it is possible that hip muscle strength would also be decreased.

We chose to test the antagonist muscle group, the hip adductor muscles, based on the suggestion of Yamada et al. (36) that the hip adductor muscles may play a role in providing frontal plane knee stability during gait. The hip adductor muscles appear to
have an integral function as part of the global muscle sling system contributing to pelvic and hip stability (37;38). The anterior oblique sling is described as containing the external oblique abdominal muscle and the anterior abdominal fascia in connection with the contralateral internal oblique muscle and hip adductors. The lateral sling contains the gluteus medius/minimus, the tensor fascia lata and the contralateral hip adductor muscles as the primary stabilizers of the hip joint. Our study participants with knee OA demonstrated weakness of the hip adductor muscles. Given the potential stabilizing function of these muscles, the role of the hip adductors should be explored further in knee OA studies.

Results of this study also revealed that a hip abductor strengthening program had no effect on the knee adduction moment during gait in our group with knee OA. This finding was in contrast to the hypothesis in the literature that hip abductor strengthening could lead to improved pelvic stability in the frontal plane and reduce the knee adduction moment. Peak gluteus medius electromyographic (EMG) activity during gait has been reported to range from 23% of maximum voluntary contraction in young adults to an average of 46% of maximum in healthy elderly (39). Thus, even with age-related weakness or weakness associated with decreased functional capacity in older adults with knee OA, the hip abductor muscles may still be capable of controlling the pelvis in the frontal plane unless muscle strength declines below the threshold necessary for pelvic control. Electromyographic activity of the hip abductor muscles during gait was not evaluated in our study. It would be beneficial to assess with use of EMG whether gluteus
medius functions more effectively as a frontal plane stabilizing muscle in stance phase following a hip abductor strengthening program.

The knee adduction moment is strongly implicated as an indirect measure of medial compartment knee joint loading (40-42). Thus, strategies or interventions that reduce the adduction moment could be effective in slowing the rate of structural OA progression. One potential gait strategy is lateral trunk lean over the stance limb, a maneuver that would, in theory, shift the ground reaction force vector laterally and decrease the magnitude of the frontal plane lever arm, thereby reducing the knee moment (43). Hunt et al. (43) reported that first and second peak knee adduction moments demonstrated significant negative correlations with lateral trunk lean during gait in a study of 120 persons with medial compartment knee OA. The extent of lateral trunk lean was not evaluated in our study and is a factor that could have affected our results. Hip abductor muscle strengthening may have led to increased trunk stability and decreased lateral trunk lean during gait as a result. This change at the trunk may have potentially nullified a reduction in the knee adduction moment that could have occurred as a result of the hip strengthening program.

Other strategies that influence the knee adduction moment, such as increased toe-out angle during gait, were not evaluated. Furthermore, we did not consider whether the hip abductor strengthening intervention produced any changes in sagittal plane kinetics.

The current study showed that functional performance on a sit-to-stand task improved in the OA group following the exercise intervention. In addition, there was a trend towards decreased knee pain at the end of the 8-week intervention period.
Increased frontal plane pelvic stability as a result of strength gains in the hip abductor muscles may have contributed to the improvement in function. Our exercise program also incorporated functional weight-bearing exercises which challenged neuromuscular control and facilitated co-contraction of other lower extremity muscles. Thus, it is possible that the improvements in functional performance on the sit-to-stand test and the decrease in knee pain in the OA group were related to knee muscle strength gains rather than increased hip abductor muscle strength. As strength of other muscle groups was not evaluated in our study, we cannot determine the extent of general lower extremity muscle strengthening and enhanced neuromuscular control that occurred as a result of the exercise program.

Factors linked to structural changes in the knee joint have been shown to differ from factors influencing the physical disability associated with knee OA (32;44-46). Increased understanding of factors which may protect against functional decline would provide insight regarding potential interventions that could prevent or minimize disability (47). Strong hip musculature may be one such factor which positively influences functional outcomes in persons with knee OA. Further investigation of hip abductor muscle strengthening as an exercise intervention for improving lower extremity function and knee symptoms is warranted.

6.5 Recommendations

Several methodological and clinical recommendations have developed from the research presented within this thesis and are summarized below.
1. Careful examination of peak torque data from isometric and isokinetic lower extremity strength testing is recommended, to determine if the first isokinetic trials should be omitted from subsequent analyses and to avoid selecting incorrect peak torque values. Filtering of the strength data, including windowing, may be beneficial for obtaining consistent results.

2. Studies requiring repeated strength testing for the hip muscles should incorporate several practice repetitions prior to testing or two initial testing sessions to permit familiarization with the equipment and protocol. These steps may reduce the potential for testing effects, which could threaten the internal validity of the measures.

3. Based on the preliminary findings from the intervention study in Chapter 5 of hip adductor weakness in the OA group and improved functioning following a hip strengthening program, it is recommended that clinicians evaluate hip abductor and adductor muscle strength during consultations with individuals diagnosed with medial compartment knee OA. The inclusion of functional hip strengthening exercises as part of rehabilitation programs may be beneficial for increasing lower extremity physical performance and reducing symptoms in those with medial OA.
6.6 **Future Research**

Recommendations for future research have arisen primarily from our preliminary intervention study targeting the hip abductor muscles in persons with knee OA. This research has generated questions and hypotheses that require further investigation.

1. Given the findings of hip adductor weakness in our sample of participants with knee OA and contrasting results presented in the literature, additional exploration of the contribution of the hip adductor muscles to frontal plane stability is warranted.

2. A natural follow-up to this research would be the administration of a randomized controlled trial to investigate further whether hip abductor strengthening would improve pain and function in persons with medial knee OA.

3. Given that lower limb malalignment and varus-valgus laxity may mediate the effects of exercise interventions in persons with knee OA, randomized controlled trials which stratify participants according to factors such as disease severity, alignment and/or knee joint laxity are recommended. Stratification according to local mechanical factors would provide insight as to whether hip abductor strengthening is more effective in subgroups of persons with knee OA.
4. Future studies investigating the effects of hip abductor strengthening on lower extremity function and pain should incorporate other measures, including lateral trunk lean, knee muscle strength and sagittal plane kinetics, to better elucidate the influence of these factors and to clarify the functional benefits of this intervention.

6.7 Conclusions

The studies in this thesis have answered some questions related to measurement reliability and the influence of hip abductor strengthening as an intervention for persons with knee OA. These studies have also generated directions for further exploration in knee OA research. In particular, investigations of conservative interventions which could have a potential disease-modifying effect and delay functional decline are urgently needed, in view of the enormous impact of knee OA and the epidemic of knee symptoms in society.
6.8 References


(20) Sharma L. Examination of exercise effects on knee osteoarthritis outcomes: why should the local mechanical environment be considered? Arthritis Rheum 2003 Apr 15;49(2):255-60.


Appendix A
Consent Forms
Human Mobility Research Centre
Kingston General Hospital and Queen’s University
Kingston, Ontario

CONSENT FORM

Principal Investigator:  Dr. Sandra Olney
          Professor and Director, School of Rehabilitation Therapy
          Phone:  (613) 533-6102

Title of the Project:  A comparison between isometric strength testing and different velocities of isokinetic testing in patients with knee osteoarthritis

Background Information
Overview of the Study:
You are being invited to participate in a research study directed by Dr. Sandra Olney and researchers at the Human Mobility Research Centre. People with knee osteoarthritis vary considerably in the range of their symptoms and limitations for daily function and we do not understand fully why some people experience worsening of their symptoms. Muscle weakness is one of the factors suggested to contribute to pain and limited function in patients with knee osteoarthritis. Therefore, strength of the knee muscles is often evaluated in studies investigating the factors contributing to progression of knee symptoms. However, the most reliable protocol for testing knee muscle strength in people with knee osteoarthritis, without aggravating knee symptoms, has not been clearly identified.

Aim of the Study:
The purpose of this study is to compare knee muscle strength testing at different speeds and while resisting without moving the limb in order to determine the most reliable and most comfortable settings for testing muscle strength in people with knee osteoarthritis.

We invite you to participate if you are 40 years of age or older, have knee pain on most days of the month, and have been diagnosed by your doctor with knee osteoarthritis. Elizabeth Sled, a doctoral student in the School of Rehabilitation Therapy at Queen’s University, will read through this consent form with you. She will describe procedures in detail and answer any questions you may have.

Description of the Testing
This study will involve one visit lasting approximately 75 – 90 minutes.

1) Questionnaires:  You will be asked to complete two brief questionnaires which ask questions about your knee pain and stiffness and your physical activities. You will also
be asked to rate the intensity of your knee pain prior to testing by placing a mark on the line of a pain scale.

2) **Knee Muscle Strength Testing:** You will sit in the chair provided by the muscle strength testing device. Padded straps will be used to stabilize your trunk, thigh and lower leg. You will be asked to bend and straighten your knee with maximum effort for five repetitions. A 2-minute rest break will be allowed between tests. You will complete the testing at three different speeds of movement and while resisting without moving your leg. After each test you will again be asked to rate the intensity of your knee pain.

3) **Physical Performance Measures:** You will be asked to perform two simple common daily tasks. These tasks will include:
   a) rising from a regular chair and then sitting again and repeating these tasks as fast as you can for 5 repetitions;
   b) walking for 6 minutes in a corridor at a comfortable speed.

**Risks**
There are no known risks associated with the procedures used in this study. You may experience some mild muscle soreness and fatigue with muscle strength testing and the physical performance measures.

**Benefits**
While you may not benefit directly from this study, results from this study may help us to determine the most reliable and comfortable protocols for knee muscle strength testing to be used for subsequent research in knee osteoarthritis. Thus, the results of this study may benefit those with knee osteoarthritis in the future.

At the end of the session you will also receive an educational pamphlet providing instructions for a few simple mobility exercises and strengthening exercises which have been shown to be effective in the management of knee osteoarthritis. The researcher performing the testing will be a physical therapist experienced in bone and joint disorders. She will review the educational material with you and be available to answer questions. You may benefit as a result of the information and exercises provided.

If you are interested, we will send you by mail a summary of the results of the study once the project is completed.

**Confidentiality**
All information obtained during this study will be strictly confidential. Your anonymity will be protected at all times. A file number will be assigned to your data and this information will be kept in a secure location. You will not be identified in any publication or reports.
Voluntary Nature of Study / Freedom to Withdraw or Participate
Your participation in this study is voluntary. You may withdraw from this study at any
time and your withdrawal will not affect your future medical care with your physician or
at Kingston General Hospital or Hotel Dieu Hospital.

Statement of Subject and Signature
I have read and understand the consent form for this study. I have had the purposes,
procedures and technical language of this study explained to me. I have been given
sufficient time to consider the above information and to seek advice if I chose to do so. I
have had the opportunity to ask questions which have been answered to my satisfaction.
I am voluntarily signing this form. I will receive a copy of this consent form for my
information.

If at any time I have further questions, problems or adverse events, I can contact:

   Dr. Sandra Olney, Principal Investigator, at (613) 533-6103

OR

   Dr. Elsie Culham, Associate Professor and Chair, Physical Therapy Program,
   School of Rehabilitation Therapy, Queen’s University, at (613) 533-6727

If I have questions regarding my rights as a research subject I can contact:

   Dr. Albert Clark, Chair, Research Ethics Board, at 533-6081

By signing this consent form, I am indicating that I agree to participate in this
study. I am aware that I may refuse to participate or withdraw at any time for any
reason without any penalty to the care I will receive.

_________________________  _________________  
Signature of Subject        Date

_________________________  _________________  
Signature of Witness        Date
Statement of Investigator:
I have carefully explained to the subject the nature of the above research study. I certify that, to the best of my knowledge, the subject understands clearly the nature of the study and demands, benefits, and risks involved to participants in this study.

________________________  _________________
Signature of Investigator    Date
CONSENT FORM

TITLE OF PROJECT: The influence of a home program of hip abductor exercises on gait parameters and muscle strength in persons with knee osteoarthritis

BACKGROUND INFORMATION
Overview of the Study:
You are being invited to participate in a research study directed by Elizabeth Sled, PhD candidate, and Dr. Elsie Culham, Faculty Advisor, in the School of Rehabilitation Therapy. This study will examine the influence of a home program of hip exercises on walking patterns and hip muscle strength in people with knee osteoarthritis. The muscles of the hip and thigh may have an effect on the forces acting at the knee joint by controlling the position of the pelvis and/or by acting as lateral stabilizers for the knee. Research suggests that the function of the hip muscles during walking may be decreased in people with knee osteoarthritis. Therefore, strengthening the hip muscles may be an effective strategy for reducing stress on the arthritic knee.

Elizabeth Sled will read through this consent form with you. She will describe procedures in detail and answer any questions you may have.

DETAILS OF THE STUDY
Aim of the Study: to determine the influence of an eight-week home program of exercises for the hip muscles on walking patterns and hip muscle strength in people with knee osteoarthritis.

We invite you to participate as part of the knee osteoarthritis group if you have been diagnosed with knee osteoarthritis by your doctor, are 40 years of age or older, have knee pain on most days of the month and have at least some difficulty in daily function due to your knee pain. You are invited to participate as part of the control group if you have no diagnosis of knee or hip osteoarthritis and no history of hip or knee injury or pain.

Description of the Testing
Initial Testing Session: Testing will be conducted in the Motor Performance Laboratory at the School of Rehabilitation Therapy and in the Radiology Department at Kingston General Hospital. The initial testing session will last approximately 2 – 2.5 hours and will involve the following measures:
1) **Questionnaires:** You will be asked to complete two brief questionnaires which will obtain information about your physical activities and your knee pain during daily function.

2) **Baseline measurements:** Your weight and height will be measured using a regular weigh scale and tape measure.

3) **Walking Performance:** You will be asked to wear shorts for the walking tests. Surface markers will be positioned on your skin at the foot, ankle, knee, hip, lower back and base of the neck, and straps will be used to hold the markers in place. You will be asked to walk along an 8-metre indoor walkway at a comfortable speed wearing your normal footwear. Two large camera systems will detect the movement of the markers as you walk across the floor. You will be provided with rest breaks in between walking trials. We will collect five good walking trials from each side of the body.

4) **Hip Muscle Strength Testing:** You will stand with your back supported against the muscle strength testing device. A padded cuff will be positioned around your lower thigh just above your knee. You will be asked to keep your knee straight and to take your leg out to the side and back to the midline in a small range of movement while providing maximum effort against the resistance of the machine. Testing will be performed at a comfortable speed and 5 repetitions will be completed. You will also be asked to push against the cuff without any movement of your leg, holding for 5 seconds 3 times. The tests will then be repeated for the opposite leg. You will be given a 2-minute rest between tests.

5) **Physical Performance Measures:** You will be asked to rise from a regular chair and then sit again as fast as you can for 5 repetitions.

**Exercise Program:** If you are a participant in the group with knee osteoarthritis you will be taught a home exercise program. An additional 30 minutes will be required after the testing for one of the researchers, a physical therapist, to teach you several simple exercises for the hip muscles. You will be instructed in how to contract your hip muscles during walking, stepping up on a step and standing on one leg. You will also be taught a sidelying leg lift exercise using elastic tubing around your lower thigh to provide resistance. You will be asked to perform these exercises four times per week (on alternate days) for 8 weeks.

For those participating in the exercise program, two follow-up visits with the physical therapist will occur in the laboratory or in your home (your preference) during the 8-week program. These visits will last about 30 minutes. The physical therapist will review your exercise program with you and teach you how to progress the exercises. You are also encouraged to contact the physical therapist by phone if you have any questions or concerns during the 8-week exercise period.
If you are part of the control group of participants without knee osteoarthritis you will be instructed to continue your daily activities, but not to begin any new exercise program, over the 8 weeks after the initial testing session.

**X-rays:** If you have not received a recent knee X-ray, you will be asked to have an X-ray taken on the date of your first visit or on a separate day at Kingston General Hospital. You will be required to stand on a turntable with your knees ahead and your feet positioned on markers. Your hips will be supported by adjustable pads to help maintain the position. A hand rest is available for support. You will be asked to distribute your weight evenly on both legs and to keep still during the sequence of X-rays. Front views of your knees will be taken. We will use these X-rays to grade the level of arthritis in your knee joint and to determine how your knee is aligned. The X-rays from the control group will be used to confirm the absence of knee osteoarthritis (as osteoarthritis may be present in people without knee pain) and to obtain the measures of knee alignment for comparison with those with osteoarthritis.

If you have had a recent knee X-ray, with your consent we will view these X-rays to grade the level of knee arthritis and determine your knee alignment.

**Final Testing Session:** All participants will be asked to return to the Motor Performance Laboratory 8 weeks after the initial testing session. You will complete the questionnaires again. We will also re-test your walking performance, hip muscle strength and sit-to-stand performance.

**Risks**
There are no known risks associated with the procedures used in this study. The radiation dosage for knee X-rays is well within safe limits, provided that participants have not been exposed to large amounts of radiation over the past year. You may experience some mild muscle soreness and fatigue with strength testing of the hip muscles and measurement of your walking performance. If you are participating in the home exercise program you may also experience mild muscle soreness and fatigue with the hip exercises.

**Benefits**
If you are participating in the home exercise program you may experience a decrease in knee pain and/or improved ability to perform your daily activities as a result of the exercises. The findings from this study may improve our understanding of the role of hip strengthening exercises as part of rehabilitation programs for people with knee osteoarthritis. Thus, the results of this study may benefit those with knee osteoarthritis in the future. There are no expected benefits for those participating as part of the control group.

**Exclusions**
You will not be considered for this study if you present with any of the following: corticosteroid injection into either knee within the previous three months; other
significant medical problems (including significant heart disease, stroke, and active
treatment for cancer) that would prevent you from being able to perform a hip exercise
program or to participate in tests of walking performance and hip muscle strength; known
osteoarthritis or previous trauma affecting one or both hips; and previous replacement of
any joint in the lower extremities. You will not be considered if you are receiving
rehabilitation services for knee osteoarthritis or performing a hip strengthening program
at the time of testing.

Confidentiality
All information obtained during this study will be strictly confidential. Your anonymity
will be protected at all times. A file number will be assigned to your data and this
information will be kept in a secure location. Data will be stored in locked files and will
only be available to the Principal Investigator and Faculty Advisor. You will not be
identified in any publications or reports.

Voluntary Nature of Study / Freedom to Withdraw or Participate
Your participation in this study is voluntary. You may withdraw from this study at any
time and your withdrawal will not affect your future medical care with your physician or
at Kingston General Hospital or Hotel Dieu Hospital.

Statement of Subject and Signature
I have read and understand the consent form for this study. I have had the purposes,
procedures and technical language of this study explained to me. I have been given
sufficient time to consider the above information and to seek advice if I chose to do so. I
have had the opportunity to ask questions which have been answered to my satisfaction.
I am voluntarily signing this form. I will receive a copy of this consent form for my
information.

If at any time I have further questions, problems or adverse events, I can contact:

Elizabeth Sled, Principal Investigator, (613) 533-6000, ext. 75593

OR

Dr. Elsie Culham, Acting Director and Faculty Advisor, School of Rehabilitation
Therapy
Queen’s University, at (613) 533-6727

If I have questions regarding my rights as a research participant I can contact:

Dr. Albert Clark, Chair, Research Ethics Board, at 533-6081
By signing this consent form, I am indicating that I agree to participate in this study. I am aware that I may refuse to participate or withdraw at any time for any reason without any penalty to the care I will receive.

__________________________________________  ________________________
Signature of Subject                                Date

__________________________________________  ________________________
Signature of Witness                                Date

Statement of Investigator:
I have carefully explained to the participant the nature of the above research study. I certify that, to the best of my knowledge, the participant understands clearly the nature of the study and demands, benefits, and risks involved to participants in this study.

__________________________________________  ________________________
Signature of Investigator                            Date
Appendix B

Types of Intraclass Correlation Coefficients
Types of Intraclass Correlation Coefficients

The intraclass correlation coefficient (ICC) is a commonly used coefficient for statistical measurement of reliability. Different equations may be used to calculate the ICC, depending on the purpose and design of the reliability study and the types of measurements (1).

Three models of the ICC have been described by Shrout and Fleiss (2). Portney and Watkins (1) have summarized the three models in the context of a reliability study with rater as the aspect of interest:

**Model 1 (Random Effect):** In this model each subject/condition is evaluated by a different set of raters. The raters are considered to be randomly chosen from the larger population of raters.

**Model 2 (Random Effects):** Each subject/condition is evaluated by the same set of raters. Subjects/conditions and raters are both random effects. The studies in Chapter 3 and 4 of this thesis used Model 2 to calculate ICCs in almost all cases.

**Model 3 (Mixed Model):** In this design, one factor is considered a random effect and the other factor is considered a fixed effect. The study in Chapter 3 of this thesis used Model 3 to calculate ICCs for evaluating the reliability of manual and computer measures of lower limb alignment. In this case, the condition (manual or computer-assisted measures) was treated as a fixed effect.
Each of the ICC models may be expressed as 2 forms (single or average ratings). Form 1 is used when reliability measures are calculated from individual ratings. In Form 2, the mean of several raters or ratings is used for the calculation of the ICC (1)

Types of ICCs are classified according to both the model and the form of ICC. Two numbers in parentheses are used to designate the type of ICC. The first number indicates the model used (1, 2 or 3). The second number in parentheses signifies the form, either a single measurement (1) or the mean of several measurements ($k$), where $k$ is the number of scores used to obtain the mean. In the study in Chapter 3, one aspect of data analysis involved averaging the data for the 4 repetitions of isokinetic strength tests to calculate the ICC. In this situation, $k = 4$ (ICC [type 2,4]).

In summary, ICC (type 2,1) was used in most cases in this thesis (Chapters 3 and 4). Other types used were ICC (type 2,4) in Chapter 3 and ICC (type 3,1) in Chapter 4.

References


Appendix C

Power Calculations for Estimate of Sample Size for Study in Chapter 5
An estimate of sample size for the study in Chapter 5 was obtained from 2 power calculations and 10% loss to attrition.

1) One calculation used data from tests of isometric hip abductor strength before and after a functional strengthening program in 15 individuals with osteoarthritis (OA) and lower extremity functional impairment (1). The percentage change in isometric hip abductor strength from baseline to final testing was 16.42 ± 22.82%.

   One goal of the proposed study is to test the null hypothesis that the two population means are equal. The criterion for significance (alpha) has been set at 0.050. The test is 2-tailed, which means that an effect in either direction will be interpreted. With a proposed sample size of 32 in each group, the study will have power of 80.9% to yield a statistically significant result. This computation assumes that the mean difference is 16.4% and the standard deviation is 22.8%.

   This effect was selected as the smallest effect that would be important to detect, in the sense that any smaller effect would not be of clinical or substantive significance. It is also assumed that this effect size is reasonable, in the sense that an effect of this magnitude could be anticipated in this field of research.

   On average, a study of this design would enable us to report the mean difference with a precision (95.0% confidence level) of ± 11.33%. For example, an observed difference of 16.4% would be reported with a 95.0% confidence interval of 5.07 to 27.73.
2) The second power calculation was computed using peak knee adduction moment data from a group of 10 older adults with knee OA and a matched group of 10 asymptomatic older adults (2). The mean peak knee adduction moments during gait were as follows: OA group: 0.25 ± 0.06 N·m/kg; Control group: 0.33 ± 0.06 N·m/kg. The percentage difference was -24.2% (p = 0.35; effect size = 0.44).

One goal of the proposed study is to test the null hypothesis that the two population means are equal. The criterion for significance (alpha) has been set at 0.050. The test is 2-tailed, which means that an effect in either direction will be interpreted. With a proposed sample size of 10 in each group, the study will have power of 80.5% to yield a statistically significant result. This computation assumes that the mean difference is -0.080 (corresponding to means of 0.250 versus 0.330) and the common within-group standard deviation is 0.060.

This effect was selected as the smallest effect that would be important to detect, in the sense that any smaller effect would not be of clinical or substantive significance. It is also assumed that this effect size is reasonable, in the sense that an effect of this magnitude could be anticipated in this field of research.

On average, a study of this design would enable us to report the mean difference with a precision (95.0% confidence level) of ± 0.055 points. For example, an observed difference of -0.080 would be reported with a 95.0% confidence interval of -0.135 to -0.025. With a proposed sample size of 32 in each group, the study will have power of 100% to yield a statistically significant result.
References


Appendix D
Data Collection Sheets
KNEE OA STUDY
DATA COLLECTION SHEET: INITIAL TESTING

Participant Code:___________  Date of Birth: ___________  Age: _____
Weight (kg): ___________  Height (m): ___________  Leg Tested: __________

Gait Data Collection:

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Five-Times-Sit-to-Stand Test (FTSST) time: _______________________
KNEE OA STUDY
DATA COLLECTION SHEET: FINAL TESTING

Participant Code: ____________________

Weight (kg): _______________  Leg Tested: _______________

**Gait Data Collection:**

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Five-Times-Sit-to-Stand Test (FTSST) time: ____________________
Appendix E

Hip Abductor Strengthening Program and Sample of Exercise Calendar (Log)
HOME EXERCISE PROGRAM

The primary muscle you will target with the exercises is the *gluteus medius* muscle. This hip muscle helps to keep the pelvis level when walking. The gluteus medius muscle is located towards the back of each hip, at approximately the outer edge of the back hip pockets. The muscle attaches into the bony prominence at the side of each hip.

To feel the muscle working, stand on your affected leg and press with your fingers in the area of the hip pocket above the bony prominence of the hip. You should feel a tension in the muscle under your fingers.

You may feel muscle fatigue or mild muscle soreness in the area of the back hip pocket after performing the following exercises. However, if any of the exercises produce hip or knee pain, stop the exercises and contact the study physiotherapist, Elizabeth Sled, at 533-6000, ext. 75593.

Exercise #1: Side-Lying Leg Lift

Lie on your side with the leg to be exercised on top. Your bottom knee should be bent slightly and your top leg should be straight. Rotate your pelvis forward slightly so that the hip bone faces up towards the ceiling. Pull in the abdominal muscles to stabilize yourself in that position. Extend the top leg back behind the bottom leg.

SLOWLY LIFT the top leg about 10 inches (to horizontal), HOLD for a count of 5 seconds, then SLOWLY LOWER the leg back to the starting position. Watch that the top leg does not come forward and that your pelvis does not roll backwards.

Repeat this exercise until tired, gradually working up to 15-20 times.
Perform once per day.
Perform 4 days per week (every other day).

Progression:
Tie tubing snugly around both thighs just above your knees. Then repeat Exercise #1 above, lifting your leg against the resistance of the tubing.
Repeat this exercise until tired, gradually working up to 15-20 times if you are able.
Perform once per day.
Perform 4 days per week (every other day).
Exercise #2: Standing on One Leg

Stand sideways close to the kitchen counter or a chair. Lightly grasp the counter or top of the chair for balance if needed.

Stand on the leg to be exercised. Pull your abdomen in. Keep the pelvis level; don’t let your hip drop on the opposite side. Hold until tired, gradually working up to a 20-30 second hold. Repeat this exercise 5 times. Perform once per day. Perform 4 days per week (every other day).

Progression:

Tie tubing snugly around both ankles. Stand on the leg to be exercised. Take the other leg out to the side, tightening the tubing. Hold 5 seconds. Keep the pelvis level and the upper body tall and still. Repeat this exercise until tired, gradually working up to 15-20 times if you are able. Perform once per day. Perform 4 days per week (every other day).
Exercise #3: Step Exercise

The leg you are exercising will be standing on the step. The other leg is hanging freely at the side. Keeping the standing leg straight (no knee bending!), allow the free leg-side hip to drop down slightly. The whole leg should lower with the hip as it drops.

Then focus on using your standing leg gluteus medius muscle to pull the free-leg hip back up to a level position. You can place your fingers over the gluteus medius muscle to feel the tension in this muscle.

** Watch that you don’t ‘cheat’ by pulling up with the trunk muscles on the side of the free leg, rather than using the hip muscles of the standing leg.
** Try to keep the pelvis square at the front; don’t let it rotate.
** It helps to do this exercise facing a mirror, with your waist-line visible.

Repeat this exercise until tired, gradually working up to 15-20 times if you are able. Perform once per day. Perform 4 days per week (every other day).

Posture Correction:

Finally, focus on good posture whenever you are standing and walking. Keep your ears, shoulders and hips in a straight line. Keep your head up and your abdomen pulled in. Gently squeeze the gluteus medius muscles as you walk and stand upright. Perform as often as possible throughout the day.

If you have any questions, feel free to contact Elizabeth Sled, PT, at 533-6000, ext. 75593.
## WEEKLY EXERCISE LOG
### Week 1

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### Sample

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