The assessment and treatment of dynamic balance in individuals with knee osteoarthritis

by

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Abstract

Introduction: Those with knee osteoarthritis report more falls than those without, and falls present serious economic, personal and public health consequences. Dynamic balance is an important factor associated with falls risk. Current clinical tests of balance in this population have limitations to their use. Further, interventions to improve dynamic balance have had mixed results in this population, possibly since more information on dynamic balancing ability is needed for better program design. This thesis examined the assessment and treatment of dynamic balancing ability in individuals with knee osteoarthritis.

Methods: The Community Balance and Mobility Scale (CB&M), an advanced test of dynamic balance, was examined for use in individuals with knee osteoarthritis. The convergent validity, construct (known groups) validity, and test re-test reliability of the scale was assessed (Chapter 2). Convergent validity was assessed by comparing to tests measuring similar constructs, such as the Berg Balance Scale. Construct validity was assessed by comparing scoring of those with and without knee osteoarthritis. Test re-test reliability was assessed one week apart. Clinically modifiable factors associated with dynamic balancing ability were then investigated (Chapter 3). These included muscle strength, knee joint proprioception, knee joint range of motion and anticipatory postural control. Finally, a ten week dynamic balance training program, designed using findings from Chapter 2 and 3, was assessed in Chapter 4. This was a randomized controlled trial, with dynamic balancing ability and self-reported physical function measured at baseline and follow-up.

Results: The CB&M was found to display moderate to strong convergent validity with other tests, strong construct validity and high test re-test reliability. Lower extremity strength, and to a lesser extent, knee range of motion were important factors associated with dynamic balancing ability. Ten weeks of training resulted in significant improvement in self-reported physical function but not in CB&M scores.

Conclusion: This dissertation provides new understanding of dynamic balance assessment and treatment in those with knee osteoarthritis. These findings highlight a valid and reliable clinical outcome measure for dynamic balance, as well as provide insights into balance training program designed to improve outcomes and maintain high adherence in this population.

Preface

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The Community Balance and Mobility Scale in Appendix A has been reprinted with the permission of Dr. Jo-Anne Howe and Liz Inness, the creators and copyright holders of this scale.

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List of Abbreviations

AIC	Akaike Information Criterion
ACL	Anterior cruciate ligament
APA	Anticipatory postural adjustment
BMI	Body mass index
BBS	Berg Balance Scale
CEEF	Concentric extension divided by eccentric flexion
COM	Centre of mass
COP	Centre of pressure
CB&M	Community Balance and Mobility Scale
EECF	Eccentric extension divided by concentric flexion
GUG	Get-Up-and-Go
ICC	Intraclass correlation coefficient
KL	Kellgren and Lawrence
LES	Lower extremity strength
MDC	Minimum detectable change
NRS	Numerical rating scale
OA	Osteoarthritis
PASE	Physical Activity Scale for the Elderly
SAFFE	Survey of Activities and Fear of Falling in the Elderly
TBI	Traumatic brain injury
TKA	Total knee arthroplasty

TUG	Timed-Up-and-Go
VIF	Variance inflation factor
WOMAC	Western Ontario and McMaster Universities OA Index

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Dedication

To Jerrad

Chapter 1: Introduction and background

1.1 Balance

Dynamic balance is a key element of physical function necessary for mobility and independent living (1, 2). In this thesis, static balance is defined as stability in non-moving postures such as standing or sitting, while dynamic balance is defined as locomotor stability during movement and is needed to complete tasks such as walking and changing direction (3). Adequate dynamic balance encompasses both balance and mobility (the ability to move the centre of gravity), which allows an individual to actively regulate the position of the body, for instance by responding to perturbations (4) such as trips, slips, and bumps, and is necessary to recover from unexpected perturbations experienced in the environment.

The sensory inputs for balance control are comprised of three systems: vision, vestibular sense, and the somatosensory system. These systems provide input on the location and movement of the body, and when integrated with the motor system, control balance by maintaining the relationship between the base of support and the centre of mass (COM) of the person (5). Vision is involved in planning movement and avoiding obstacles (2). The vestibular system senses linear and angular acceleration, and has an influence on balance correcting reactions (6, 7), while the somatosensory system provides input on the position and velocity of body segments in space (2, 8). While there is redundancy among systems, degeneration in one or more systems can result in difficulties with maintaining balance (6, 9). The sensory input is processed by the nervous system, with the response coordinated among muscles. Consequently, not only the input from sensory systems, but neuromuscular deficiencies surrounding the output of the balance response, can affect the success in maintaining one's balance. For instance, muscle weakness in either proximal or distal aspects of the leg strongly impacts the ability to control the COM and the resultant response to balance perturbation (9). Further, other neuromuscular deficits, such as impaired range of motion, have been suggested to impair balance control (10). Neuromuscular deficits, particularly those seen in knee osteoarthritis (OA) that may negatively affect dynamic balance control, were investigated in this thesis and are discussed in Section 1.2.5.

1.1.1 Balance and falls

Falls in older adults are a considerable public health concern. Among those 65 and older, falls are the leading cause of acute injury (11, 12). In one sample of over 5000 adults aged 65 years and older, more than 25% reported experiencing a fall in the past year, and two-thirds of those who fell were injured by the fall (13). Research has shown that 32% of older adults experiencing a fall will require help with activities of daily living after falling, severely limiting mobility and independence (14). The risk of mortality increases significantly with an increased frequency of falling (15).

Poor balance control is a significant contributor to functional disability (16) and the risk of falls (17, 18), while improvements in balance are associated with reduced falls risk and improvements in quality of life (19). Previous research has shown a significant difference in balance control between fallers and non-fallers (determined prospectively, $p = 0.008$), such as the amplitude of mediolateral centre of pressure (COP) displacement after an induced perturbation (18). Dynamic balance may be particularly important, as 41% of falls in the elderly occur during weight shifting, including when walking and turning (20). This suggests that it is important to understand dynamic balancing ability and the factors that contribute to dynamic balance when assessing individuals at risk of falls. However, dynamic balance is poorly understood, with few tools available to measure it and few interventions aimed at directly improving it.

Dynamic balance can be assessed using a variety of tests. Clinically, balance control (both dynamic and static) has been assessed using tests such as single-leg stance and the Timed-Up-and-Go (TUG), and composite measures such as the Berg Balance Scale (BBS), the Community Balance and Mobility Scale (CB&M). Clinical tests present many advantages to their use: they can be administered quickly, they require little equipment, and often have previous data pertaining to performance on the test by normative and clinical populations that can be used for comparison. This thesis focuses on some of the more commonly used clinical tests of balance.

1.1.2 Clinical tests of balance

Balancing ability is currently evaluated in the clinic using a variety of tests. Some of the more frequently used clinical tests including single-leg stance time, the TUG and the BBS are described below. The CB&M, a more comprehensive and advanced test of dynamic balancing ability used as a primary outcome in this dissertation, is also described. The validity and reliability of these measures are presented in Table 1.1.

Measures of single-leg stance time (21, 22) have been commonly used to evaluate static balance in older adults, because equipment is not needed and the test can be completed quickly. Tests of single-leg stance time require the participant to stand on one leg, without support from a wall or chair, and maintain the stance for a pre-determined amount of time, such as 10 or 30 seconds. The test is completed if the maximum time is reached, if the participant touches the free limb to the ground, or if there is excessive upper body or trunk movement (such as swinging the arms). However, dynamic balance is a key component of function necessary for activities such as walking and changing direction, and an outcome measure of static balance such as single-leg stance time does not adequately evaluate the balance and mobility necessary for ambulation and independent living.

The TUG requires participants to rise from a chair, walk as quickly as they can for three meters, turn around, return to the chair and sit down (23). The time to complete the task is measured in seconds, with a greater time signaling slower (worse) performance on the test. Completion of the TUG requires a chair, stopwatch, and enough space to walk three meters. While the TUG requires dynamic balance during this single task, it does not assess the dynamic balance needed during multiple tasks that are encompassed in ambulation in the community, including descending stairs or crouching.

The BBS consists of 14 items that include static tasks such as sitting and standing, and movements such as turning and bending. Tasks are scored on a scale of zero (unable to perform or needs assistance) to four (able to perform independently). Lower scores are given if participants are unable to meet time or distance requirements. Completion of the BBS requires two chairs, a ruler, a step or low stool, a bean bag and a stopwatch. While the BBS addresses basic balancing ability in multiple tasks, not all tasks (for example, sitting) require dynamic balancing ability.

The CB&M is comprised of 13 tasks including bending, turning, or looking while walking, single-leg standing, and stair descent. Tasks are rated by a trained assessor on a scale of zero (unable to perform) to five (proficient), with the exception of stair descent, where participants can earn a maximum of six points for completing the task while carrying a load. Lower scores are given if participants are unable to meet time requirements or use discontinuous movements. Tasks such as single-leg stance, walking and looking (over an eight meter distance), running (over an eight meter distance), and step-ups (performance of five step-ups onto a stair) are timed, with slower times resulting in fewer (or no) points on the task. Unilateral tasks such as single-leg stance or walking while looking at a target are performed on both sides. The maximum score is 96, with a minimum score of zero. For tasks that require a track on the CB&M, an eight meter track can be marked out on a level floor, such as in a hallway. Assessment of the CB&M takes approximately 15 minutes to complete by a trained assessor and requires minimal equipment, including two weighted bags, an eight meter track with a target on the wall, a stopwatch, a set of stair steps, and a bean bag. Further information of the individual tasks has been published by Rocque et al. (24). The CB&M was developed to assess community-level functional deficits in both balance and mobility in patients after traumatic brain injury (TBI) (25). The CB&M tests both balance and mobility. Dynamic balance, as defined above, encompasses both concepts. Thus, for the purposes of this thesis, the use of the term dynamic balance will encompass both the balance and mobility needed for tasks. Initial research suggests that the CB&M may be important in identifying those at risk of falling. This measure has been shown to discriminate between fallers and non-fallers, as well as multiple fallers, with a slightly better discriminatory capacity than other measures such as the BBS (26).

Table 1.1 Measurement properties of clinical tests of balance

Measure	Validity	Reliability	Ceiling Effect?
Single-leg stance time	Convergent validity with BBS in stroke (27)	Healthy elderly; ICC = 0.75 (28) Stroke; ICC = 0.92 (27)	No
TUG	Construct validity with known groups in knee OA (29, 30)	Knee OA; r = 0.75 (31)	No
BBS	Content validity in healthy elderly, construct validity in knee OA (29, 32, 33)	Healthy elderly; ICC = 0.98 (32)	Yes
CB&M	Content and construct validity in TBI, convergent validity in stroke (25, 34)	TBI; ICC = 0.90 (25) Stroke; ICC = 0.98 (34)	No

While there are many clinical tests of balance, few tests suitably identify dynamic balance deficits. This highlights the utility of tests such as the CB&M, which has been shown to avoid ceiling effects (see Table 1.1) and which comprises several tasks that require dynamic balance, in order to better identify deficits in balancing ability. The CB&M was used as a primary outcome measure in this thesis.

1.2 Osteoarthritis

1.2.1 Osteoarthritis epidemiology

Arthritis affects one in six adults (35). Of the known types of arthritis, OA is the most prevalent (36), and the knee is the most commonly affected weight-bearing joint. The global prevalence of knee OA is estimated at 3.8%, with hip and knee OA considered the 11th highest contributor to global disability among 291 conditions considered, as measured by years lived with disability (37). This highlights the pervasiveness of the disease, affecting the long-term quality of life for those burdened by the disease, but also influencing the lives of individuals on a daily basis. Some studies also suggest that the burden of OA may be underestimated due to factors such as under-reporting (37). With the aging of populations in developed countries, the prevalence and burden of knee OA is expected to rise, with concomitant increases in pressure on local and global healthcare systems.

1.2.2 Osteoarthritis economic burden

Due to the pervasive and chronic nature of the disease, OA is a costly condition. Over one quarter of the total cost of musculoskeletal diseases in Canada is attributed to arthritis, for an estimated $27.5 billion annually (36). Knee OA is costly on an individual level also. Studies suggest that the monthly cost of arthritis for people with mild to moderate knee OA is more than $1000/month, including indirect costs such as productivity loss and direct costs such as medical costs (38). For people that progress to joint replacement, the economic burden increases. In 2012, it was estimated that the total direct and indirect cost of each total knee arthroplasty (TKA) in Canada was just under $25,000, with patients bearing a third of that cost, in factors such as time off work, medication and travel costs (39). With the considerable economic and personal burden of knee OA, there is a need to better understand the disease-related limitations that arise, and to develop evidence-based, low-cost conservative therapies to target these burdens. The considerable cost of TKA is further motivation to devise therapies that can slow or prevent the functional decline and progression of the disease. For this reason, this thesis focuses on dynamic balance deficits and conservative treatment of these deficits in people with knee OA.

1.2.3 Osteoarthritis presentation

OA is a chronic degenerative joint condition that is characterized by a degradation of articular cartilage, sclerosis of subchondral bone, and osteophyte formation (40, 41). Radiographs are most commonly used to identify the severity of OA, with valid and reliable criteria for assessing the severity of knee OA developed by Kellgren and Lawrence (KL) (42). This rating system describes knee OA severity based on the presence of joint space narrowing, the number and size of osteophytes and the presence of bony sclerosis. Severity is rated from zero to four, where zero refers to no sign of OA, one indicates doubtful signs of OA, two indicates mild OA, three indicates moderate OA, and four indicates severe OA. Clinically, the condition is characterized by the presence of OA on radiograph as well as symptoms such as joint pain and stiffness (43).

One of the most common symptoms of knee OA is joint pain. This chronic pain is thought to be due to sensitization and activation of nociceptors in the joint, during the inflammatory process (44). Also, central sensitization and reduced inhibition of pain pathways further supports the chronicity of the pain experience (45). These factors combine to produce chronic knee pain, which can affect physical function, quality of life, and balancing ability.

Beyond joint pain and stiffness, this population appears to be at an increased risk of falls. Previous studies have highlighted the high incidence of falls in samples of elderly individuals with OA – over 50% (46-48). The risk of falls in those with knee OA is higher than that of healthy elderly individuals, as measured by the Physiological Profile Assessment, a battery of tests that measure the risk of falling (46, 49). The Physiological Profile Assessment does not measure dynamic balance, but assesses factors that prospectively contribute to balancing difficulties in healthy adults, such as muscle weakness and visual deficits. Compounding this is a greater fear of falls in individuals with knee OA compared to healthy controls (46). Given that falls are associated with large and unique healthcare costs and consequences, falling and the risk of falls represent a significant area of concern for people with knee OA and provide further economic and personal burdens to affected individuals. There is a need to better understand factors that affect falls risk in those with knee OA, including balancing ability.

1.2.4 Balance control and knee osteoarthritis

While aging results in alterations in balance control, further disruptions in balancing ability are seen in those with knee OA, above and beyond changes seen with aging. Those with knee OA score lower on clinical tests of balance than healthy adults, including timed single-leg stance, TUG, BBS, and CB&M. Scoring may also be affected by factors such as pain and swelling, which can alter sensory input and the ability to complete tests, due to factors such as muscular inhibition (10). Knee pain can indirectly impact balancing ability through avoidance and sedentary behaviour or more directly through interference of sensory and motor information. The following sections focus on how people with knee OA score on the clinical tests described above.

Single-leg stance time is used as a clinical measure of standing balance. Those with knee OA have demonstrated difficulty in maintaining single-leg stance for even small amounts of time – for instance, one third of participants with knee OA in one sample were unable to maintain single limb stance for ten seconds (22). Other studies have reported similar difficulties (50-52), highlighting the difficulty those with knee OA have with unilateral stance.

Those with knee OA also take longer to complete dynamic tests such as the TUG. One sample of individuals with moderate to severe knee OA completed the TUG in a mean time of 11s, while healthy controls in the same study completed the TUG in eight seconds (29). There was also a small but significant difference in TUG times between those with mild knee OA and those without knee OA (d = 0.4s, $p < 0.05$). This small difference may not be clinically meaningful but does conform to the trend of dynamic balance deficits in people with knee OA. It may be the case that performance on multiple tasks stressing dynamic balance is needed before clinical differences become apparent. Other studies have reported similar times for the TUG for people with knee OA [e.g. 9.1 s (53)], times that are higher than those reported for healthy adults.

Clinically, the BBS has been widely used to assess balance and mobility in many populations, including healthy elderly and those with knee OA (29, 54, 55). However, it has been shown that the BBS has a ceiling effect in individuals who can ambulate independently in the community, including those with mild knee OA (29, 56). BBS scores were lower in one study of older individuals with knee OA (mean age 62.9 years) waiting for knee replacement (mean BBS score = 46/56) than healthy older adults (mean age 60.3 years, mean score = 56/56), indicating that severe cases of knee OA can be identified with the BBS (29). However, more moderate disability or those who are ambulatory may not show deficits in dynamic balance on the tasks on this scale. For example, in the same study, those with mild knee OA reached a statistically similar mean score (54.6/56) to the group of healthy older adults (mean score 56/56) on the BBS. The items on the BBS do not capture the full spectrum of dynamic balancing ability needed to function independently in the community, including omitting assessment of advanced tasks such as stair descent.

The CB&M is a clinical test of dynamic balance, which assesses advanced tasks such as descending stairs, crouching, and turning while walking. To date, the CB&M has not been used to assess dynamic balance deficits for those with knee OA. Other clinical populations, such as those who have sustained a stroke, score significantly lower than healthy older adults. This scale may be more sensitive in assessing dynamic balance difficulties than previous measures such as the BBS. The inclusion of advanced tasks may help in identifying dynamic balance deficits in those who are higher functioning community-dwelling older adults with knee OA. Though the validity and reliability of the CB&M has been established in other patient populations (25, 34), these psychometric properties need to be assessed in the knee OA population to determine whether the CB&M can be used to evaluate balance and mobility deficits in this patient group. This will ultimately help to permit the development of interventions focused on targeted balance rehabilitation.

In summary, while it has been established that those with knee OA score lower on clinical tests of balance such as single-leg stance time, TUG, and BBS, these measures display limitations in fully evaluating the dynamic balance deficits present in higher functioning community dwelling older adults with knee OA. Further, the reason for dynamic balance deficits in those with knee OA is unknown. Individuals with knee OA demonstrate a number of neuromuscular deficits compared to healthy age-matched adults. It is possible that such factors may affect dynamic balancing ability. The role of potential neuromuscular factors in the dynamic balancing ability of those with knee OA will be discussed and explored next.

1.2.5 Possible factors that affect balancing ability

Neural and muscular changes that have been noted in those with knee OA include reduced joint proprioception, muscle weakness, and reduced joint range of motion. Other changes such as altered anticipatory postural control have also been suggested. These factors can all affect balancing ability in general, while some of these factors have been shown to influence balancing ability specifically in those with knee OA. Further, all of these factors have been shown to be modifiable, with some exhibiting positive effects on balancing ability when improved following treatment. Impairments in these factors in people with knee OA compared to healthy controls and the effect of such deficits on balancing ability are explored below. Where available data exists, the relationship of the factors to dynamic balance specifically in people with knee OA will be discussed.

1.2.5.1 Proprioception

Proprioception refers to a sense of limb position and movement (57). Proprioceptive changes directly affect balance responses to perturbation. This is evident in cases where proprioception is disrupted, as in those with full leg or lower leg proprioceptive loss. When proprioception is impaired, the balance response to a perturbation is affected. For instance, ankle torque onset is delayed in patients with lower leg proprioceptive loss (58) resulting in a reduced ability to adequately respond to perturbations. Muscle responses are delayed in total leg proprioceptive loss (where there is no proprioceptive input from the lower or upper leg), while this delay is not seen in individuals with lower leg proprioceptive loss who have intact trunk and hip proprioception (58, 59). Thus, loss of proximal proprioception may partly be responsible for the delays in stabilizing muscle response (for instance, in the tibialis anterior during toes up rotational perturbations). These studies highlight the importance of proprioception in balancing ability and in the avoidance of falls.

Proprioceptive training has also been shown to improve proprioception, as well as balancing ability. Proprioceptive training over 12 weeks resulted in improvements in knee joint position sense and static balancing ability (stability index using the Biodex Stability System) in a sample of adults after anterior cruciate ligament (ACL) reconstruction (60). Similarly, sixteen weeks of Tai Chi training for older adults resulted in a significant improvement in knee joint proprioception, as evidenced by improvements in the passive detection of motion test, as well as improvements in single-leg stance time (61). These results suggest that balancing ability may be modified by altering proprioceptive ability.

Studies have established deficits in knee joint proprioception in people with knee OA. In particular, those with knee OA display worse performance on joint repositioning tests (62, 63) than healthy age-matched controls. Joint repositioning tests require an individual to match a particular knee joint flexion angle to one that their knee was previously placed in. In one study, individuals with knee OA were successful in only 7.5% of joint repositioning trials, as compared to 53% on target for age-matched healthy individuals (63). Those with knee OA also have a much higher threshold for sensing joint movement (64) meaning a greater amount of movement occurs before it is detected. This lowered sensitivity to movement, and greater difficulty identifying joint positions, could result in a longer time to perceive, and recover from perturbations.

In people with knee OA, reduced joint proprioception has been suggested as a predictor of balancing ability (65). Bennell et al. (66) found that there was a small, but significant, correlation between knee joint position sense and TUG times ($r = -0.2$, $p < 0.01$) in people with knee OA, though this relationship may have been weak because the particular test of joint proprioception chosen in this study was a bilateral measure, unlike the unilateral test commonly used, which can isolate discrepancies per side. Further, proprioceptive training has positive effects on those with knee OA, resulting in a significant improvement in knee joint position sense, as well as static standing balance, with participants able to stand on one leg for longer after training (67). Similarly, six weeks of proprioceptive training improved stability index scores on the Biodex Stability System (68) in people with knee OA awaiting TKA. While few studies have assessed the role of proprioceptive training on dynamic balancing ability, a systematic review concluded that proprioceptive exercises can improve functional outcomes such as TUG times (69), which, while limited, do encompass some aspects of dynamic balance. This suggests that joint proprioception may influence dynamic balancing ability, as seen in cases where proprioceptive increases result in improved ability on tasks requiring dynamic balancing ability.

1.2.5.2 Muscle strength

Muscle weakness is associated with impairment in the response to perturbation and reductions in balancing ability, an important factor in avoiding falls. In contrast, strength gains through training have resulted in improvements in balancing ability, suggesting that not only is muscle strength related to balancing ability, but that strength gains can improve balance. Muscle weakness has been shown to result in kinematic alterations in the response to perturbation and increases in muscle response amplitudes. For instance, distal muscle weakness, such as in the lower legs, results in an inability to counteract body motion in response to perturbation (9). This results in large COM movement in response to perturbations in all directions, with resultant reductions in balance control.

Gains in strength and their effect on response to perturbation have been evaluated in resistance training studies in older adults. These studies tend to include ten to thirteen weeks of heavy resistance training that emphasize low volumes and high intensity. Strength training interventions have had conflicting results, as highlighted in one systematic review, which concluded that while strength training tends to improve balance, this is not consistent across balance types or groups of individuals (70). In one training intervention for older adults, an increase in mediolateral COM displacement in response to a small perturbation (4° over five seconds) with eyes closed was seen in the training group after 12 weeks of exercise (71). These results suggest that the training intervention undertaken had no positive effect on dynamic balance control, as greater COM movement is traditionally considered to equate to worse balance. An alternative explanation for this result is that the improvements in strength and balance from training may allow greater movement of the COM. In a similar training study, an increase in the peak ankle torque as well as the rate of torque production in response to perturbation was seen in one study of ten weeks of training of frail older adults (72). This positive change may help individuals recover and maintain balance when moving. Other studies have shown improvements in standing balance (COP sway) with strength training of healthy older adults (73).

Eccentric strength training in particular has produced positive changes in balancing ability. Eccentric strengthening has been shown to improve standing balance, as measured by the stability index of the Biodex Stability System in those with achilles tendinopathy (74). Further, eccentric strength training has been shown to improve dynamic balance. In one study, older adults completing 11 weeks of eccentric training improved on measurement scales that included dynamic balance tasks, including the BBS and TUG (75). This improvement was significantly greater than a group participating in a traditional lower extremity resistance training program using free weights and weight machines. Importantly, the TUG times of those in the eccentric exercise group were lowered below the threshold for fall risk (14s), while those in the traditional training group were not.

While the research on strength training is overall positive, there are some factors that may account for the mixed results on balancing ability observed. Training interventions have not included muscles that act primarily in the frontal plane, such as hip abductors and adductors. These muscles have been hypothesized to be important in dynamic balance, particularly in controlling lateral stability, and are thought to be weakened in older adults (76). There may also be a minimum strength gain necessary before improvements in dynamic balance become apparent. More research is needed to understand the relationship of muscle strengthening and dynamic balancing ability in healthy individuals and especially those with musculoskeletal pathology.

Numerous studies have highlighted deficits in isometric and concentric quadriceps (77-79) and hip muscle (80) strength in those with knee OA compared to age-matched controls. This is compounded by a reduction in specific strength (force per unit muscle) as measured in the quadriceps, compared to age-matched controls (79). When eccentric muscle strength has been measured in those with and without knee OA, significant differences are also seen. People with OA produced 76% less quadriceps eccentric force than healthy age-matched controls, and this discrepancy is 20% greater than the deficit seen in concentric quadriceps strength (63). It has also been hypothesized that eccentric strength may be the predominant type of muscle contraction necessary for the recovery of balance after perturbation (81) as recovery of balance often consists of stabilizing the body against gravity. Thus, maintenance of eccentric strength could be particularly important for reducing falls risk.

In those with knee OA, muscle weakness is a known determinant of static balancing ability (22, 65) with those individuals with less quadriceps strength shown to stand on one leg for less time and with a longer COP path length (more sway). Jadelis et al. (82) showed that isometric knee extension strength can explain variance in standing balancing ability ($R^2 = 0.19$) in those with knee OA. While those with knee OA have been shown to have a higher risk of falling when assessed using the Physiological Profile Assessment, this difference arises largely from deficits in joint proprioception and isometric knee extension strength (46). This highlights the importance of muscle strength in falls risk, especially those with knee OA. Few studies have assessed the effect of strength training on balance in those with knee OA. Messier et al. (83) found that 18 months of strength training (3 months supervised and 15 months at home), which consisted of nine unspecified upper and lower body exercises with free weights performed three times per week, improved standing balance (reduced COP movement when eyes were closed). Similarly, Ratsepsoo et al. (84) showed a reduction in standing COP sway after six weeks of a home exercise program with resistance bands in a small group (n = 17) of people with knee OA. Others have seen a small (not statistically significant) improvement in BBS scores in those with knee OA following completion of a 12 week resistance training program consisting of eccentric and concentric exercises targeting the quadriceps muscle three times per week (85). Thus, it appears that muscle strength is associated with balancing ability, and that eccentric strength may play an important role in dynamic balancing ability in humans. However, the role of this factor in dynamic balancing ability of those with knee OA has not been clarified.

1.2.5.3 Knee joint range of motion

Reduced knee joint range of motion may hinder dynamic balance, potentially by increasing the difficulty of tasks that require large amounts of knee flexion. For instance, crouching to pick up objects requires more than 80° of knee flexion (86), and individuals that do not have this range of motion may adopt alternative, destabilizing strategies (such as stooping) to complete the task. Poor knee joint range of motion may thus affect the mobility and risk of falling of these individuals.

Reductions in knee joint range of motion are seen in individuals with knee OA compared to healthy controls (87). Flexion contracture in particular is common, with more than 50% of those with knee OA demonstrating an inability to fully extend the knee (88). Knee flexion, in particular, has been linked to the severity of knee OA, with reduced flexion being associated with more severe OA as evidenced by more osteophytes and greater joint space narrowing on radiograph (89).

Knee joint range of motion is related to standing balancing ability in those with knee OA (90). In particular, there is a correlation between COP velocity and the amount of active knee range of motion ($r = 0.41$) in a sample of women with knee OA (90). Joint range of motion has also been linked to disability on tasks such as walking and sitting to standing in people with knee OA (88), suggesting that some aspect of the ability to perform dynamic tasks may be compromised. However, the relationship of knee joint range of motion to tasks that require dynamic balance (more so than walking) has not been investigated. Exercise programs specifically targeting knee range of motion after TKA have found no evidence of improvement in static standing balance (91) – no change in COP area, distance, or velocity when standing, though the effect on dynamic balance has not been explored and should be investigated further.

1.2.5.4 Anticipatory postural control

Anticipatory postural control is an important element of dynamic balance (92). In particular, an appropriate anticipatory postural adjustment (APA) counteracts the destabilizing forces of voluntary movement and assists in movement initiation, with the goal of successfully completing the movement task. Importantly, alterations in anticipatory postural control, such as reductions in the magnitude and speed of the adjustment, are seen with aging, and with heightened fear (92, 93). These changes may jeopardize the successful initiation and/or completion of a movement by resulting in a loss of balance, highlighting the importance of an appropriate anticipatory postural control response in dynamic balance, and functional ability.

It is unknown whether those with knee OA show changes in anticipatory postural control, however some studies have suggested that APAs may be altered in knee OA. To date, one study has assessed differences in APAs in those with knee OA compared to healthy controls (94). These were individuals with end-stage disease who underwent TKA. The APA during an arm raise task was measured prior to TKA and at three and six months post-operatively. However, because no differences were seen with time, the data were collapsed over time and compared to the controls. The results showed reductions in the COP magnitude (smaller APAs) during a reaching task compared to healthy controls (94). The reduction in APA magnitude is similar to the changes in this parameter seen in those who express a fear of falling, where a reduction in magnitude and velocity of the APA, as measured by the COP during a rise-to-toes task has been demonstrated (93). Fear of falling has been previously noted as common in those with knee OA [half of participants report a fear of falling (95)], and this may further impact their anticipatory postural control if this characteristic is present.

The relationship of anticipatory postural control to dynamic balancing ability (including scores on clinical balance tests), has not been reported in those with knee OA. It is known that anticipatory postural control is a modifiable factor, with studies highlighting improvements with exercise in those with chronic low back pain (96, 97). The clinical implication of such changes is unknown. More information is needed about how anticipatory postural control affects dynamic balancing ability in those with knee OA, and the clinical implications of improvements in this parameter.

1.3 Treatment of balance impairment

1.3.1 Dynamic balance training

Recent research has assessed the effect of balance training in those with knee OA. Exercise programs targeting balance to reduce the risk of falling appear to be inconclusive, with some providing evidence of functional and symptomatic improvement (98, 99), while others show no significant differences between the treatment and control group (21, 100). Importantly, there have been few published studies that have examined the effect of exercise on dynamic balance in people with knee OA (see section 1.3.2 below). Further, with few studies examining factors influencing dynamic balance in this population, it is unknown if current balance training programs are targeting important aspects of overall balancing ability.

Currently, studies investigating balance training programs in those with knee OA have included some form of muscle strengthening such as knee extension, static balancing exercises such as standing on one leg, and functional activities such as stepping or walking. It is unknown if these types of exercises are focused or challenging enough to improve balance for those with knee OA. Current knee OA management guidelines do not address exercise programs targeting balance and falls risk, though some reviews have called for this inclusion (101) due to the deficits in balance and mobility seen in those with knee OA compared to healthy controls (29, 102, 103). Targeted dynamic balance training has been undertaken in other clinical populations such as those who have experienced a stroke or undergone ACL reconstruction, with favourable outcomes. If such outcomes could be achieved in those with knee OA, the risk of falling and the personal and economic burdens of the disease may be considerably reduced. In the subsequent paragraphs, evidence of the effects of balance training in healthy and clinical populations will be briefly presented, before a discussion of dynamic balance training in knee OA is provided.

Balance training interventions aimed at reducing the risk or rate of falls in elderly have been extensively studied in the literature. Many studies have focused on intervention components that are largely non weight-bearing, or that have a strong focus on static standing, with few studies assessing balance training interventions that are weight-bearing and dynamic. However, there is some evidence in the literature of the effect of dynamic balance training on balance and physical function. One such intervention is the Otago Exercise Program, designed to prevent falls in older adults (104). This program has been tested with clinical trials showing reductions in falls risk and rate with implementation (104-107). The program consists of weight bearing strength and dynamic balance exercises, such as standing calf raises, and turning while walking. However, the exercises have been found to be most effective for those over 80 or those who have suffered more than one fall, suggesting the program may not be advanced enough to challenge older adults who are under 80, who are highly functional, or those who show no previous history of falls. Other similar interventions have shown improvement in physical function and balance, including improved scoring on the BBS in a sample of adults who were on average 80 years old completing a 12 week balance and strength intervention (108). In this sample, the TUG times did not improve, and this may be because the exercises, while weight-bearing, were often completed in static standing – improvements in which would be captured in multiple tasks on the BBS, but not necessarily the TUG.

There is some evidence of the effect of targeted dynamic balance interventions in clinical populations. These have been shown to significantly improve dynamic balance control and physical function (109, 110). In a program based on the Otago Exercise Program, Kovacs et al. (111) saw improvements in physical function and mobility, including on the TUG, in a sample of cognitively impaired older adults. Importantly, this study consisted of a 12-month exercise program, with the length of intervention being one potential reason why positive results were seen. However, shorter, focused training interventions have also proven successful. In a small sample of stroke survivors (n = 10), an eight week dynamic balance training program involving exercises such as multidirectional stepping and walking, squats, and stepping on and off a step, resulted in significant improvements in TUG times and BBS scores (109). Further, in a group of young adults after ACL reconstruction, dynamic balance training involving exercises such as step downs, lunges, and jumps over six months resulted in significant improvements in self-reported pain and physical function (110). These studies together suggest that weight-bearing, dynamic balance training can improve functional ability, including significant improvement on tests that require dynamic balance, such as the BBS. If results similar to such clinical populations can be achieved in those with knee OA, such a program may produce a significant reduction in functional disability, reducing the risk of falls and improving quality of life.

1.3.2 Dynamic balance training in knee osteoarthritis

Few studies have examined the effects of dynamic balance training in those with knee OA. Of these, the interventions aimed at improving balance deficits in those with knee OA have had mixed results and have focused more on self-reported symptoms than on balance outcomes. Diracoglu et al. (99) found significant improvements in the Western Ontario and McMaster OA Index (WOMAC) physical function subscale, SF-36, and 10-m walk time after 24 sessions of balance and strength exercises compared to a strength-only group. However, Fitzgerald et al. (100) found no significant differences between a strength-and-balance and strength-only group in WOMAC (total and physical function subscale) and Get-Up-and-Go (GUG) test scores after 12 sessions. While the GUG test is similar to the TUG, it lacks the turn and return to sit down components of the TUG, and thus encompasses fewer components that require dynamic balance. No other dynamic balance outcomes, such as the BBS or CB&M, were reported in these studies. Thus, it is unclear what effect these training interventions had on overall dynamic balancing ability.

A systematic review investigating Tai Chi effectiveness in those with knee OA found that this mode of exercise (dynamic but controlled movements) was consistently effective in improving measures of physical function, such as the WOMAC physical function subscale and six minute walk times (112). However, with only one study investigating the effect of Tai Chi on standing balance (113), and none examining dynamic balance, the effect of Tai Chi on dynamic balancing ability is unknown. Song et al. (113) compared 22 individuals enrolled in 12 weeks of Tai Chi to a group of no exercise control (n = 21) and found those doing Tai Chi significantly increased the amount of time that they could stand on one leg for. Other studies investigating home-based dynamic balance training programs have found improvement in self-reported function as reported on the WOMAC physical function subscale, but changes in performance on objective measures such as GUG times did not reach significance (114, 115). However, Chaipinyo et al. (115) prescribed their exercise program for only a short time period of four weeks with five sessions per week. This volume of exercise, at 20 total bouts of exercise, is relatively low, with more bouts being employed in studies that showed improvement in subjective and objective measures of physical function. Further, the study by Rogers et al. (114) was underpowered, with a sample size of less than ten participants in each of four different treatment arms. While the improvements in physical function suggest that dynamic balance training may be beneficial, it is unknown whether the lack of improvement on objective measures is due to such limitations as low volume of exercise, or small sample sizes. Further, the improvement seen with balance training is similar to improvements in outcome measures seen with resistance or functional training alone (100, 115). Finally, it is important to note that all of the above-mentioned studies found clinically meaningful changes in self-reported physical function as measured by the WOMAC, defined as a 20% improvement or greater in scores (116). This suggests that dynamic balance training programs are indeed promising, and the effect on objective measures of physical function and on dynamic balancing ability need to be explored.

Promising, yet conflicting, results for exercise programs including dynamic balance are also apparent with other methods of exercise delivery. In an aquatic setting, Hinman et al. (117) found that six weeks of pool exercises with some dynamic balance focus (i.e. lunges, stepping) resulted in a significant improvement in self-reported function (measured using the WOMAC physical function subscale), but again, no change in objective measures such as the TUG. Other aquatic exercise programs with a dynamic balance component (118) have found no differences in self-reported physical function or standing balance when compared to a land-based exercise program or to a control group. While aquatic exercise appears to offer some benefits such as fewer adverse events than land-based exercise programs (118), the setting does not appear to enhance the results of dynamic balance training.

Dynamic balance training for those with knee OA after TKA has shown positive results. Liao et al. (98) found that additional dynamic balance exercises, such as side stepping and multi-directional walking after surgery resulted in significant improvements in TUG times and total WOMAC scores. These exercises were performed in addition to a functional exercise program that consisted of strengthening and functional exercise (such as isometric knee extension and stair ascent). It should, however, be noted, that the treatment group spent considerably more time exercising compared to the control group, who only received the functional exercise, and this increased exposure to exercise may have influenced the findings. However, in a smaller randomized controlled trial, those participating in a balance training program as a supplement to functional training after TKA (n = 21) showed no improvement in single-leg standing, walking, or timed chair-rise compared to those just participating in functional training (21).

Some of the contrasting conclusions, and lack of improvement in outcomes may be due to the poor understanding of dynamic balance deficits in those with knee OA (10). Dynamic balance limitations, and factors that influence dynamic balancing ability are inadequately understood, with no studies to-date investigating these relationships in those with knee OA. Consequently, dynamic balance and underlying determinants may not have been adequately targeted during previous training interventions. If determinants are not targeted, dynamic balance and the factors that influence it may not improve, and the balance training program may not be successful. A targeted balance intervention is needed, with consideration of known factors that influence dynamic balance control, in order to improve balance and mobility and reduce the risk of falling in people with knee OA. The focus of this thesis is the identification of factors that influence the dynamic balancing ability of those with knee OA, with the results incorporated into a clinical trial of dynamic balance training.

1.4 Thesis outline

The overall objective of the research is to investigate dynamic balance deficits in individuals with knee OA, with the goal of developing a targeted treatment for these deficits. To adequately measure dynamic balance, the first study examined the measurement properties of the CB&M in those with knee OA. Convergent validity, construct (known groups) validity, and test re-test reliability were examined. In order to better understand what factors influence dynamic balance, the second study explored factors that may influence dynamic balance, as measured by the CB&M, in individuals with knee OA. Neuromuscular measures such as muscle strength, knee joint proprioception, knee joint range of motion, and anticipatory postural control were collected and analysis was undertaken using multiple linear regression. The effect of descriptive measures including age, body mass index (BMI), knee pain and knee OA severity on CB&M scores were also explored in a second model. Finally, the third study examined the effect of dynamic balance training on dynamic balance and physical function in people with knee OA. Specifically, a randomized controlled trial comparing ten weeks of targeted balance training with a no-treatment control group was conducted.

1.4.1 Objectives and hypotheses

1.4.1.1 Chapter 2

Objective: The purpose of this study was to determine the convergent validity, construct validity and test re-test reliability of the CB&M in a knee OA population.

Hypothesis: We hypothesized that the CB&M would display moderate to strong convergent validity ($r > 0.5$) and high construct validity based on differences between groups ($p < 0.05$). We also hypothesized that the CB&M would display high test re-test reliability [Intraclass correlation coefficient (ICC) > 0.8] (119).

1.4.1.2 Chapter 3

Objective: The purpose of this study was to identify factors that influence dynamic balancing ability in those with knee OA. Multiple linear regression was used to examine the relationship of modifiable neuromuscular factors, as well as the influence of descriptive variables, on CB&M scores.

Hypothesis: We hypothesized that scores on the CB&M would be significantly related ($p < 0.05$) to neuromuscular factors, in particular muscle strength, proprioception, and knee joint range of motion.

1.4.1.3 Chapter 4

Objective: The purpose of this study was to examine the effect of ten weeks of targeted dynamic balance training on measures of dynamic balance and physical function in individuals with knee OA. We aimed to compare the effects of a training program to a no-treatment control group.

Hypothesis: We hypothesized that CB&M and WOMAC physical function scores would significantly improve ($p < 0.05$) after a ten week dynamic balance training intervention in the training group, with no change in the control group.

1.5 Methodological approach

1.5.1 Community Balance and Mobility Scale

Throughout all three studies in this thesis, the CB&M was used as a primary outcome measure. The CB&M is a valid and reliable measure of dynamic balance, with a maximum score of 96, and a minimum score of zero. Higher scores indicate better dynamic balance. Details of the CB&M can be found in Sections 1.1.2, and 1.2.4. The full scale is listed, with illustrations, in Appendix A. For all studies, the CB&M was administered by one of two trained assessors, and the testing of all participants was conducted in UBC Hospital. For tasks that included continuous walking (i.e. the eight meter walking and looking task), a track was marked out on the floor of a hallway. This same track was used for all participants in all studies in this thesis. For tasks that required stairs, an adjacent stairwell was used. While testing was being completed, the assessor ensured that no other individuals used the hallway or stairwell. The CB&M was completed in approximately 15 minutes for each testing session. The studies in Chapters 3 and 4 also included outcomes of lower extremity muscle strength, knee joint proprioception, and knee joint range of motion using the same protocol for each outcome in both studies. These protocols will be described here.

1.5.2 Lower extremity muscle strength

Maximal concentric and eccentric muscle strength (torque) of the knee extensors, flexors, and ankle plantarflexors were measured using an isokinetic dynamometer (Biodex Medical Systems, Shirley, NY). For strength testing of the knee extensor and flexor muscles, participants were seated with hip and knee joints flexed to 90° (Figure 1.1). The dynamometer attachment was secured to the lower leg two centimetres above the medial malleolus. Participants were instructed to push against the pad of the attachment during tests of knee extension, and to pull against the pad during tests of knee flexion. For strength testing of the ankle plantarflexor muscles, the seat was reclined 35° from the vertical and the lower leg was positioned parallel to the floor with the foot secured on the foot plate (Figure 1.2). Isokinetic eccentric and concentric strength were measured in three trials of maximal effort at 90°/s, as has been previously measured in those with knee OA (120). Three warm-up trials at 50% perceived maximal intensity were completed and adequate rest between maximal effort trials was provided. In order to minimize knee pain, the knee extensors were the last muscles to be tested. Maximum torque production relative to body weight (Nm/kg) from the three trials for each muscle group was recorded. Maximal isokinetic leg strength tests have been shown to be valid (121) and reliable (ICC = 0.9 and higher) in those with knee OA (122). Composite measures of lower body muscle strength were then calculated, which are further described in Chapters 3 and 4.

Figure 1.1 Isokinetic dynamometer setup for knee extension/flexion

Figure 1.2 Isokinetic dynamometer setup for plantarflexion

1.5.3 Knee joint proprioception

Knee joint proprioception was measured using a knee joint repositioning task, previously used in those with knee OA to assess knee joint proprioception (63). This task has been shown to be valid as a measure of joint position sense and reliable (ICC = 0.91) in the knee OA population (123, 124). Participants were seated on the same isokinetic dynamometer used for strength testing with hip and knee joints flexed to 90°. Participants were blindfolded for the repositioning task. The participants' limb was passively positioned and held for ten seconds in one of three target positions (15°, 30°, and 60° of knee flexion). Participants' knees were then returned to 90° and asked to actively match the position that their limb had been held in. Participants completed two blocked trials at each of the three randomly presented target positions, resulting in a total of six trials. Participants were allowed to practice the task with eyes open three times before data collection. The absolute difference between actual leg position and target position, in degrees, for each trial was calculated using the electrogoniometer of the dynamometer, and the mean difference of the six trials was taken.

1.5.4 Knee range of motion

Active knee joint range of motion was measured using a manual goniometer, similar to other studies of knee OA (87). Participants were asked to lie on their back and bend their knees by bringing their heel towards their buttock as much as possible for measures of knee flexion (Figure 1.3). They were then asked to straighten their knees as much as possible for measures of knee extension. Two measures were taken for each of flexion and extension, and the greater value of the two taken as the range of motion for each movement. For knee extension, negative values denoted lack of full extension, while positive values denoted hyperextension. The maximum flexion and extension values were then summed and expressed as the total available range of motion. Reliability of range of motion measures varies from moderate to good (ICC = 0.64 – 0.90), with higher reliability when instructions are standardized (125, 126).

Figure 1.3 Knee range of motion measurement

Chapter 2: Validity and reliability of the Community Balance and Mobility Scale in individuals with knee osteoarthritis

2.1 Introduction

Balance is a key element of function that allows individuals to maintain posture and respond to perturbations (1). Furthermore, sufficient mobility, often defined as the capacity to ambulate, is also needed to navigate or avoid obstacles and is intrinsically related to independent living (127). Importantly, older adults with mild mobility impairment are at a high risk of falls (127) and exercise interventions that improve mobility can reduce the risk of falling (128, 129). These studies are suggestive of the important role of balance and mobility in reducing the prevalence and risk of falls. Both adequate mobility and balance are needed in order to ambulate independently in the community.

Several outcome measures have been used to evaluate static standing balance in those with knee OA such as functional reach tests (130), measures of single-leg stance time (21, 22), and single-leg (22, 131) or double-leg (132-134) static standing tests that assess variations in COP. However, dynamic balance [defined as locomotor stability during movement (3)] requires both balance and mobility and is a key component of function necessary for activities such as walking and changing direction, and such static outcome measures may not adequately evaluate the dynamic balance necessary for ambulation and independent living.

Measures of dynamic balance and function, such as the BBS, the TUG, and measures of gait speed have been used previously. Clinically, the BBS has been widely used to assess dynamic balance in many populations, including healthy elderly and those with knee OA (29, 54, 55). However, it has been shown that the BBS has a ceiling effect in individuals who can ambulate independently in the community, including those with mild knee OA (29, 56). For example, Kim et al. (29) found that all healthy older adults that they tested (n=40) scored a perfect 56 on the BBS, with a similar mean score for those with mild knee OA (54.6/56). The high scores by both healthy and patient populations make identification of individuals in need of further treatment difficult when using the BBS. The TUG has been used frequently as a valid measure of mobility (and a limited measure of dynamic balance, as discussed above in Section 1.1.2) in both healthy individuals and those with knee OA (29, 30), and gait speed is also often evaluated as a measure of lower limb physical function and mobility (23, 30, 135). Measures of gait speed are valid and reliable (30) and can discriminate between different levels of function (135). However, the test of gait speed does not assess the balance needed during different tasks or change in continuous movement in the community independently. A dynamic test of both balance and mobility (a dynamic balance test) is needed to better assess functioning and dynamic balance in those with knee OA.

The CB&M has been developed to assess community-level functional deficits in both balance and mobility (25). This scale was designed to assess advanced dynamic balance activities such as rapid direction changes and dual tasking, originally in young patients after TBI. Importantly, the CB&M has been validated in healthy individuals (24) and other patient populations, including TBI (25) and stroke (34) to accurately assess dynamic balance. The CB&M is sensitive to change (34) and does not suffer from ceiling effects commonly seen when using other tools such as the BBS and TUG to assess dynamic balance (24, 34). The validity and reliability of the CB&M in those with knee OA needs to be assessed to determine whether the CB&M can be used to evaluate dynamic balance deficits in the knee OA population to permit focused rehabilitation. Therefore, the purpose of this study was to examine the convergent and known groups validity and test re-test reliability of the CB&M in older adults with knee OA. The reliability of other tests of balance and mobility is presented for comparison.

2.2 Methods

2.2.1 Participants

Individuals aged 50 years and older with and without knee OA were recruited from the local community using print advertisements and a laboratory database of previous study participants. Presence or absence of knee OA was confirmed with radiographs (see below). Exclusion criteria for the knee OA group consisted of: articular cartilage degradation in the lateral tibiofemoral compartment greater than the medial; an inflammatory arthritic condition; history of previous lower extremity joint replacement surgery (including hip or knee replacement); or recent (within six months) arthroscopic knee surgery. Exclusion criteria for the control (no knee OA) group consisted of: any knee pain; any evidence of knee OA on radiographs; or other musculoskeletal abnormality that would affect balance and mobility. Ethics approval was obtained from the clinical research ethics board, and written informed consent was provided by all participants.

2.2.2 Study procedure

Interested participants were screened by a study coordinator and those eligible were referred for radiographic investigation. Evidence of knee OA was determined using the KL (42) rating scale, with knee OA defined as definite osteophytes (minimum KL2). Healthy controls had to have KL0 or KL1 (no definitive radiographic OA). Those with knee OA were tested on two separate occasions within two weeks (14 days), while healthy controls were assessed in a single testing session only. Participant characteristics that were collected included age, height and body mass.

Those with knee OA completed the WOMAC, Physical Activity Scale for the Elderly (PASE), and Survey of Activities and Fear of Falling in the Elderly (SAFFE) for descriptive purposes. The PASE is a measure of self-reported physical activity that displays construct and convergent validity with activity monitor counts and other tests of physical function such as the six-minute walk (136), and has shown moderate (ICC = 0.75 – 0.77) test re-test reliability (137, 138). The SAFFE is a measure of fear of falling used because it describes behavior change (i.e. activity restriction) with respect to fear of falling. SAFFE scores for health elderly are 0.5 on average, with scores ranging from zero to three (139). Higher scores indicate greater fear. While there is currently no reliability data available, the survey does display convergent and criterion validity (139, 140). KL grade of knee OA was determined by consensus agreement of two independent raters (JT and MAH) from postero-anterior standing radiographs taken within the last six months. All participants were asked to rate the amount of knee pain felt on average during the past week on a numeric rating scale from 0 – 10 (0 = 'no pain', 10 = 'worst possible pain'). Validity and reliability (ICC = 0.89 – 0.98) for NRS pain scales has been established in this and other populations (141, 142). At each testing session, participants completed the CB&M, BBS, TUG, and tests of single-leg stance time and gait speed. All tests were administered by the same assessor, and participants completed the tests in the same standardized order during all testing sessions. This was to try to minimize the confounding effect of knee pain.

2.2.3 Outcomes

2.2.3.1 Community Balance and Mobility Scale

The CB&M was assessed as described in Sections 1.1.2 and 1.5.1 above.

2.2.3.2 Berg Balance Scale

The BBS consists of 14 tasks that include static movements such as sitting and standing, and movements such as turning and bending (see Section 1.1.2 above). The BBS was administered by a trained assessor using published guidelines (32).

2.2.3.3 Timed-Up-and-Go

Participants completed the TUG in the same hallway used for completion of the CB&M. When completing the TUG, participants were instructed to rise from their chair without using the hand rests, walk as quickly as they could three meters, which was marked by a line of tape, turn around once they crossed the tape, return to the chair and sit down (23). The chair height used for all tests was 41 cm, and time required to complete the TUG was recorded in seconds. Though permitted, no participants used gait aids during the TUG or during any other tests.

2.2.3.4 Single-leg stance time

Participants were asked to stand on one leg for a maximum of 90 seconds. The arthritic knee was used for the knee OA group except in cases of bilateral involvement, in which case the more symptomatic leg was chosen as the stance limb. For healthy controls, the stance limb was randomly selected. Participants were instructed to bend the knee of the free limb up to 90° and hold the position with their arms by their sides. Participants were instructed to maintain their balance on the standing leg for as long as they could, to a maximum of 90 seconds. The test was completed if the participant touched the free limb to the ground, performed excessive upper body or trunk movements (for example, swinging arms) or completed the 90 seconds. Participants were allowed to try the single-leg stance twice, if they were unable to maintain balance for more than ten seconds during the first attempt, and the maximum time was recorded.

2.2.3.5 10m walk test

Gait speed was assessed using the 10m walk test (23). Participants were asked to walk at their natural pace for 14m, of which the middle 10m was timed. The test was completed twice, and the mean of the two trials was calculated to determine the normal walking speed of the participant. The same test was repeated with participants asked to walk at a fast walking pace ('walk as quickly as you can, but safely'). Time was recorded in seconds, and converted to m/s.

2.2.4 Statistical analysis

Differences on tests of balance and mobility, and in age and BMI between those with and without OA were assessed using independent t-tests. For all analyses of validity, data from the first test session in those with knee OA were used to compare with the single session of data from the healthy controls. Normal distributions of data were assessed using histograms and the skewness statistic, where skewness scores outside the range -1.0 – 1.0 indicate a non-normally distributed variable (143). Ceiling effects of the CB&M and BBS were calculated as the percentage of participants scoring the maximum possible score on the test.

To assess convergent validity of the CB&M, Pearson product-moment correlation coefficients between the CB&M and other tests of balance and mobility were calculated.

Significance of correlations was assessed by hypothesis testing where the null hypothesis was that there is no correlation between outcome measures. Spearman's rank correlation coefficient was used in instances where data were not normally distributed. Correlations < 0.5 were considered weak to fair, 0.5 – 0.75 were considered moderate, and > 0.75 were considered strong (144). Known groups validity of the CB&M was assessed by comparing scores on the CB&M and the other tests of balance for individuals with knee OA to healthy controls using independent t-tests. In instances of non-normality, the Mann-Whitney U test was used. Reliability of the CB&M and other tests of balance in the knee OA group was assessed by calculating intra-class correlation coefficients ($ICC_{2,1}$), and standard error of measurement (SEM). ICC was calculated using a two-way random effects model with absolute agreement. ICC values > 0.4 were considered moderate and > 0.8 were considered a high level of reliability (119). SEM was chosen to test absolute reliability, and was calculated as follows:

SEM = $s_X\sqrt{1 - ICC}$, where s_X = the standard deviation of the measurement (145). A high SEM indicates a high level of error and implies non-reproducibility of the measurements. Confidence intervals at 95% were calculated around ICC and SEM estimates. A Bland and Altman plot of CB&M scores comparing testing sessions was constructed to visually inspect the data. The minimum detectable change (MDC) at 95% confidence was calculated to provide clinical interpretation as follows:

$$MDC = SEM * 1.96 * \sqrt{2}$$

Results were considered statistically significant if $p < 0.05$. All statistical analyses were conducted using SPSS v21.0 (IBM Corporation, Armonk, NY).

2.3 Results

Participant demographics can be found in Table 2.1. Groups were sex-matched, with no significant differences in age between groups (p= 0.69). Those with knee OA had a significantly higher BMI than those without ($p < 0.01$). Most people in the OA group had mild (KL2, n = 14) or moderate (KL3, n = 9) knee radiographic OA, with the remaining participants exhibiting severe (KL4, n = 2) knee OA. All data were normally distributed with the exception of the BBS, which was analyzed using Spearman's rank correlation coefficient when examining correlation and with the Mann-Whitney U test when comparing groups. There was no ceiling effect experienced on the CB&M for individuals with knee OA with the highest score being 93/96, and only 12% of healthy controls scored the maximum score on this test. For the BBS, there was a considerable ceiling effect for both individuals with (64%) and without knee OA (92%).

Table 2.1 Participant characteristics

Descriptive Data	OA (n = 25)	Healthy (n = 25)
Age (years)	62.5 (7.4)	63.3 (6.2)
Sex (M/F)	11/14	11/14
BMI (kg/m^2)	29.2 (6.6)	24.6 (4.0)*
Knee Pain (0 – 10)	3.3 (2.4)	0(0)
WOMAC Total Score	28 (19)	N/A
PASE Score	254.1 (98.1)	N/A
SAFFE Score	0.5 (0.5)	N/A
KL0	0	11 (44)
KL1	0	14 (56)
KL2	14 (56)	0
KL3	9 (36)	0
KL4	2 (8)	0

Mean (SD) provided. For each grade of OA, the number (%) of participants per group are provided. * indicates significant differences.

2.3.1 Validity

For those with knee OA, scores on all balance and mobility tests were significantly correlated with CB&M scores, with correlations ranging from 0.52 – 0.74 (Table 2.2), indicating moderate convergent validity.

Table 2.2 Correlation matrix for measures of balance and mobility

Measure	CB&M (OA)	CB&M (Healthy)
BBS	0.52**	0.31
TUG (s)	-0.74**	-0.62**
Single-leg stance time (s)	0.71**	0.63**
Self-selected gait speed (m/s)	0.61**	0.21
Fast gait speed (m/s)	0.69**	0.47*

Tests of balance and mobility were correlated with the total score on the CB&M. * indicates significant correlation at the 0.05 level. ** indicates significant correlation at the 0.01 level.

The CB&M correlated most strongly with the TUG, and least strongly with the BBS (Figure 2.1). For healthy controls, correlations ranged from 0.21 – 0.63, with the CB&M correlating most strongly with the measure of single-leg stance time and least strongly with self-selected gait speed.

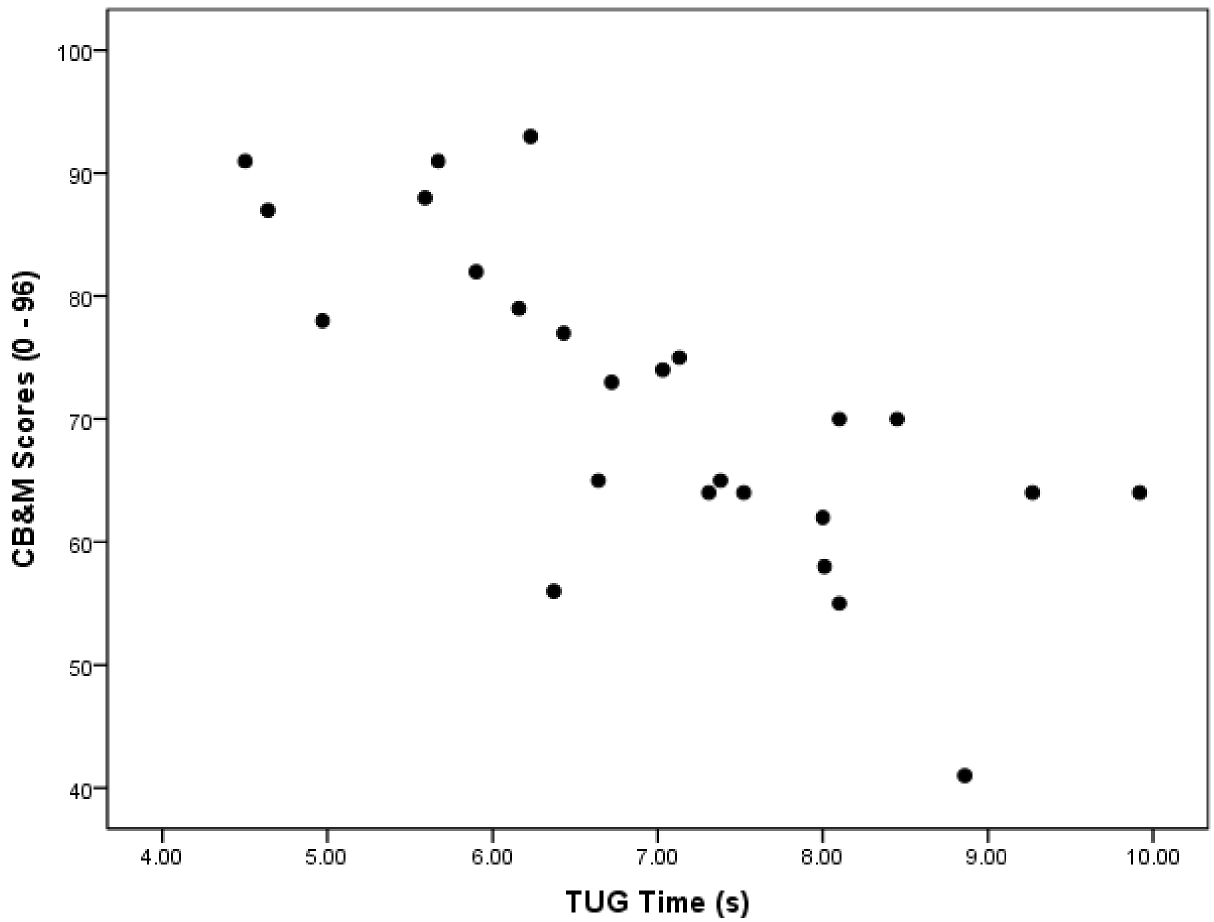

Figure 2.1A. CB&M scores were moderately correlated with TUG times for people with knee OA (r = -0.74; n = 25)

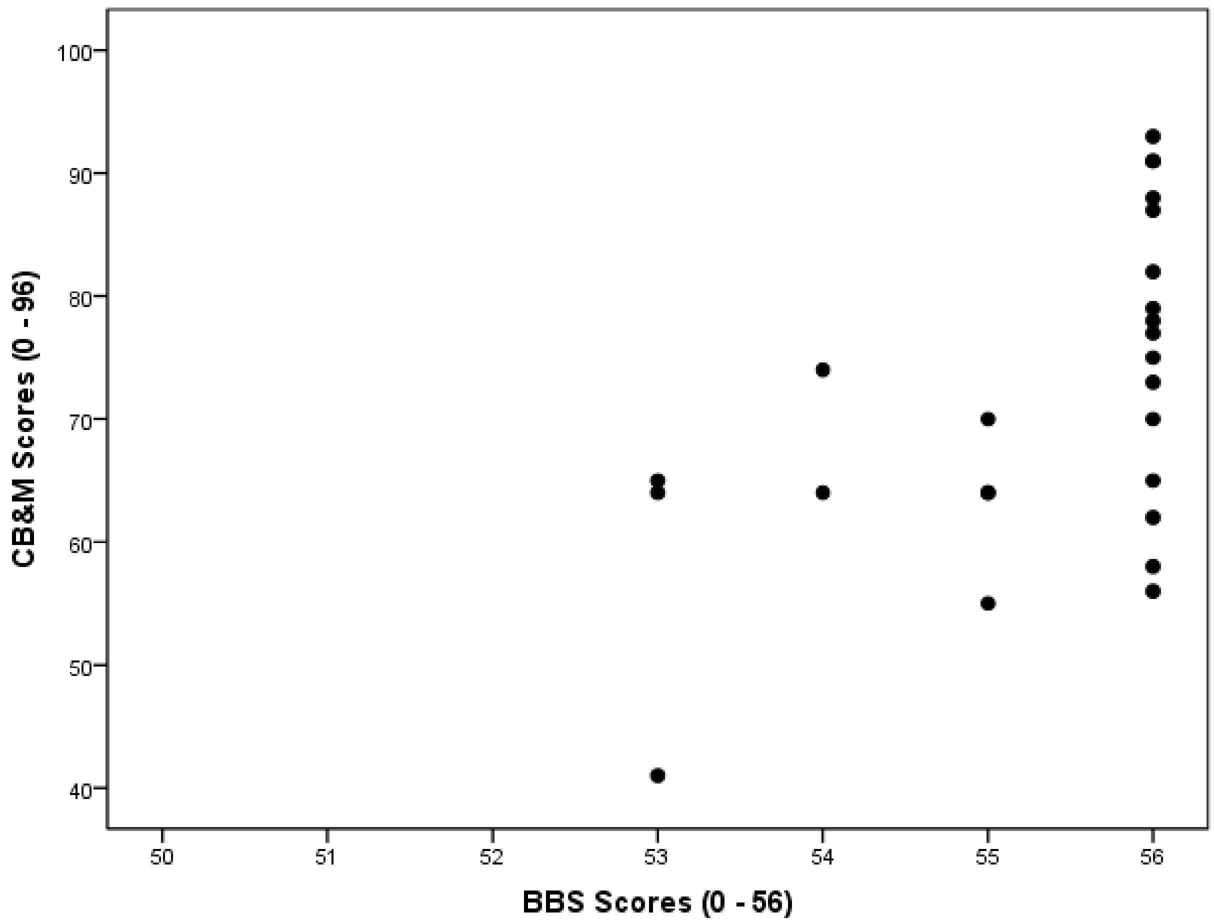

Figure 2.1B. CB&M scores were moderately correlated with BBS scores for people with knee OA (rho = 0.52; n = 25)

Those with knee OA scored significantly lower on all tests of balance and mobility than healthy controls, except on the BBS and 10m walk test of fast walking speed (Table 2.3). Participants with knee OA scored on average (SD) 71 (13) points on the CB&M, while healthy controls scored 85 (10) points. This significant difference in test scores on the CB&M – individuals with knee OA scoring on average 14 points lower than healthy controls ($p < 0.001$) – indicated known groups validity.

Table 2.3. Participant scores on the measures of balance and mobility

Measure	OA (n = 25)	Healthy (n = 25)	P-Value
Community Balance and Mobility (/96)	71 (13)	85 (10)	< 0.001*
Berg Balance Scale+ (/56)	56 (53-56)	56 (53-56)	0.09
Timed-Up-and-Go (s)	7.0 (1.4)	5.7 (0.9)	< 0.001*
Single-leg stance time (s)	41.7 (33.2)	66.1 (30.7)	0.01*
Self-selected gait speed (m/s)	1.40 (0.19)	1.55 (0.19)	0.01*
Fast gait speed (m/s)	1.97 (0.22)	1.86 (0.27)	0.10

Mean (SD) for normally distributed scores, median (range) for others. Non-normally distributed data are designated by a +. Significant differences are noted by a *.

2.3.2 Reliability

Test-retest reliability was conducted on a subsample of 20 individuals with knee OA, as five of the participants were unable to return within the test re-test timeframe (mean = 8.0; range = 4, 14 days). Scores on each test for these individuals for each session are presented in Table 2.4. Test-retest reliability of the CB&M was high: ICC = 0.95 (95% CI 0.70 – 0.99), SEM = 3 (95% CI 2.68 – 4.67). A Bland and Altman plot for CB&M scores is presented in Figure 2.2, and further supports the reliability of this scale. Table 2.4 displays ICC and SEM values with 95% confidence intervals, the relative SEM values (SEM %) as well as the 95% MDC. ICC values were greatest for the CB&M, and lowest for the BBS (ICC = 0.59, 95% CI -0.07 – 0.84). With the exception of the BBS and TUG (which displayed moderate reliability), all other tests of balance and mobility (gait speed, CB&M) exhibited high test-retest reliability (ICC > 0.8). The

95% MDC value for CB&M scores was 9.45, and for the BBS was 2.82. For all other MDC values see Table 2.4.

Table 2.4. Participant scores per session for those included in the reliability analysis (n = 20), ICC, SEM, and MDC at 95% level of confidence is presented for each test of balance and mobility.

Measure	Session 1 Mean (SD)	Session 2 Mean (SD)	ICC (95% CI)	SEM (95% CI)	SEM%	MDC at 95%
CB&M (/96)	73 (13)	76 (12)	0.95 (0.70 – 0.99)	3 (2.68 – 4.67)	5	9.45
BBS^{+} (/56)	55 (53-56)	55 (48-56)	0.59 (-0.07 – 0.84)	1 (0.80 – 1.40)	2	2.82
TUG (s)	7.0 (1.4)	7.0 (1.3)	0.66 (0.11 – 0.87)	0.83 (0.66 – 1.14)	11.9	2.31
Single-leg stance time (s)	44.4 (33.5)	46.4 (33.6)	0.91 (0.78 – 0.97)	11.72 (9.23 – 16.06)	25.8	32.48
Self-selected gait speed (m/s)	1.41 (0.16)	1.44 (0.17)	0.85 (0.63 – 0.94)	0.07 (0.06 – 0.10)	5.1	0.20
Fast gait speed (m/s)	1.86 (0.25)	1.84 (0.26)	0.90 (0.74 – 0.96)	0.10 (0.08 – 0.13)	5.3	0.27

Non-normally distributed data are designated by a +. Single-leg stance time is the maximum time the participant can maintain single limb stance, up to 90s. Gait speed was measured using the 10m walk test.

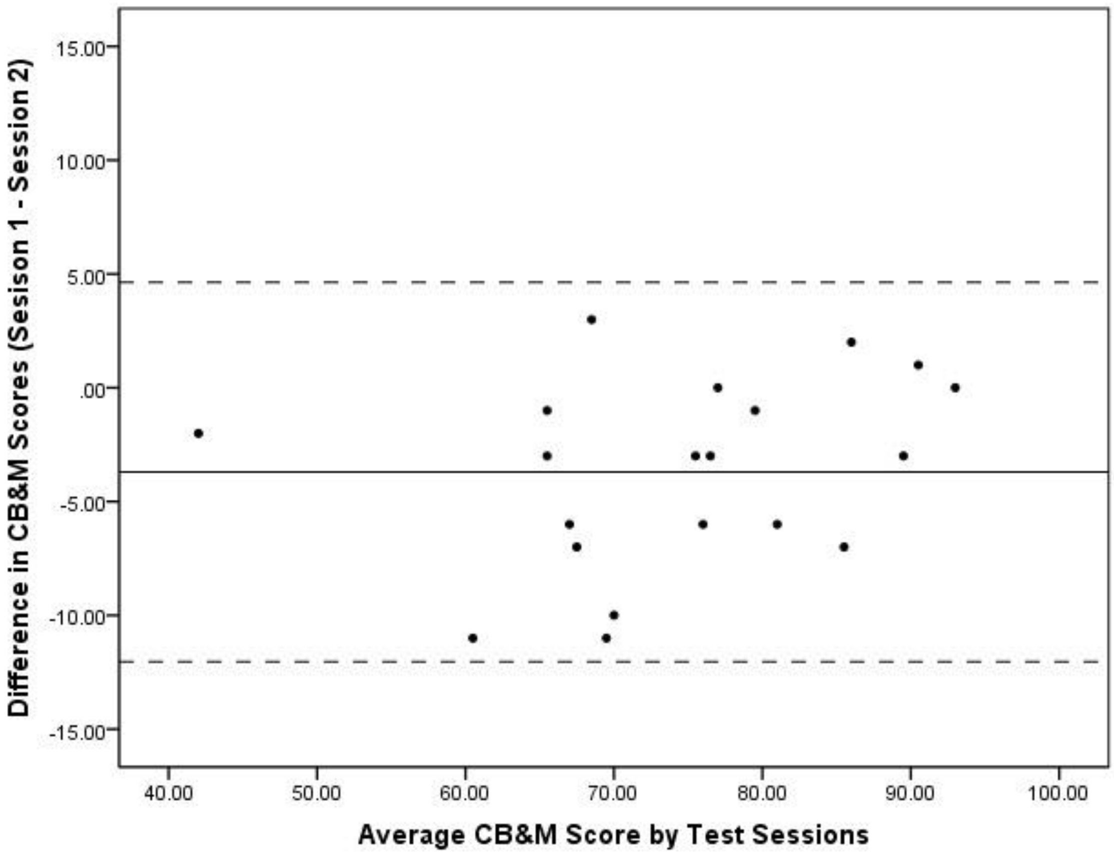

Figure 2.2. Bland and Altman plot representing comparisons between the two test sessions for the CB&M score. Solid line indicates the mean difference between sessions, and dashed lines indicate limits of agreement (+/- 2 SD)

2.4 Discussion

The purpose of this study was to assess the validity and reliability of the CB&M in individuals with knee OA. The CB&M displayed moderate convergent validity with all administered tests of balance and mobility. Scores on the CB&M for healthy controls were significantly higher than those with knee OA ($p < 0.001$) indicating excellent known groups validity. Test-retest reliability of the CB&M was also high. The observed power for the study was 0.96, indicating the study was adequately powered to answer the research question. These results indicate that the CB&M is a valid and reliable tool for assessing dynamic balance in individuals with knee OA.

High convergent validity of a measure indicates that participants score similarly on tests designed to measure the same construct. The validity of several tests of balance and mobility has been assessed for those with knee OA. For instance, tests of normal and fast walking speed are valid measures of mobility (146), and have been used to measure change in mobility in individuals with knee OA before and after surgery (147). The TUG is similarly valid for assessing mobility, and to a lesser extent dynamic balance, in those with knee OA (30, 148). Scores on the CB&M were highly correlated with all of these valid measures of mobility, particularly the TUG ($r = -0.74$). This relationship is similar in other studies that have assessed the validity of the CB&M in other populations. For example, in individuals with stroke, scores on the CB&M are also correlated with the TUG ($r = -0.75$), indicating that these two tests may measure similar constructs (34). While the TUG is often used as a single measure of dynamic balance, the CB&M measures dynamic balance on multiple tasks. Thus, the CB&M can be considered a more comprehensive test of the dynamic balance needed for independent function in the community. The CB&M displayed the lowest correlation with the BBS (r = 0.52), likely due to the finding that the BBS exhibited a substantial ceiling effect. Previous studies have highlighted possible ceiling effects in the BBS in several populations including knee OA (29, 34, 149). In the current study, scores on the BBS ranged from 53 – 56, with a median score of 56 (the maximum) both for those with and without knee OA. In one other study, individuals with knee OA scored on average 55 out of 56 on the BBS (29), similar to our results. This may be due to the fact that the BBS was originally designed to measure balance in elderly residents at a care facility (32). This lack of appreciable spread on the data may have resulted in the lower correlation between the CB&M and BBS found in the current study.

Those with knee OA scored considerably lower on most tests of balance and mobility than the healthy control group, except the BBS and 10m fast walking test. Previous literature has indicated that those with knee OA display various deficits in balance (50, 102), in line with current results. When assessing balance and mobility, tests that are able to identify deficits in dynamic balance are needed. The CB&M displayed significant differences between groups in dynamic balance. These differences are similar to the group differences seen in some of the other tests of balance and mobility (such as single-leg stance time and the TUG) in this and other studies (150, 151). Interestingly, the 10m test of fast walking speed, where participants were asked to walk as quickly as they could, did not show significant differences between those with and without OA. This is contrary to previous literature that has shown small but significant differences in fast walking speeds (152). The self-selected walking speed for both groups was elevated (mean speed of 1.4 m/s for those with OA, 1.5 m/s for those without; $p < 0.01$), highlighting the faster than usual speed of individuals with knee OA (153). In the current study, all but two individuals with knee OA had mild to moderate levels of disease and were highly functional (as evidenced by the fast walking speed, high BBS scores and low TUG times). It is possible that the individuals with knee OA, when asked to increase their walking speed to their maximum, simply had the functional capacity to considerably increase their speed to a magnitude similar to the healthy controls.

Test-retest reliability of an instrument is a key property allowing researchers and clinicians to administer a test repeatedly to participants to assess change over time. The CB&M displayed very high test-retest reliability (ICC = 0.95, SEM% = 5) in this sample of individuals with knee OA. Other tests of balance or mobility displayed moderate (ICC = 0.4 – 0.8) and high (ICC > 0.8) reliability here (Table 2.4) and elsewhere, such as the TUG (r = 0.75) (31). Self-selected walking speed (r = 0.9) (146, 154) and the BBS are highly reliable in older adults (23), though reliability of the BBS has not been assessed previously in those with knee OA. Reliability as calculated by ICC coefficients of the BBS in our population was moderate but lower than all other tests of balance and mobility (ICC = 0.58), possibly owing to the low variance of the sample, as most individuals scored the maximum on the test. However, the SEM of the BBS was low, indicating high absolute reliability and further confirming low individual variation. Since both relative and absolute reliability of measures is important when interpreting findings, the high reliability of the CB&M (both ICC and SEM) makes it an attractive tool for assessing changes in dynamic balance over time.

The MDC values presented in Table 2.4 suggest, for instance, that for 95% of stable patients with similar characteristics to the current study, the score on the CB&M would change by less than ten points upon reassessment in our laboratory. Further, if the CB&M score of an individual with knee OA was 71, and after treatment improved to 83, we can be quite confident that the observed change in dynamic balance as measured by the CB&M is a true change, because the change exceeds the MDC of ten points. This MDC is less than one standard deviation of the CB&M, indicating that small changes can be true changes in balance and mobility, further supporting the reliability of the CB&M in those with knee OA.

There is growing evidence that some current measures of dynamic balance, such as the BBS, may have ceiling effects – where scores cluster around the maximum possible score with little variance – in some older populations that are more functional, such as those with knee OA. By contrast, no ceiling effect was seen for the CB&M in the current study. Participants in the current study scored between 41 and 93, with no participants with knee OA scoring the maximum 96 on the CB&M. In addition, the lowest score on the CB&M was 41, indicative that no floor effect was present either (minimum score of zero possible). Further, those without knee OA were challenged by the tasks on the CB&M, with only three participants scoring the maximum 96 points. A test of dynamic balance that is sufficiently challenging allows researchers and clinicians to evaluate change over time, such as improvement in dynamic balance due to a training intervention.

There are some limitations to the present study. First, all participants performed the CB&M in their own comfortable flat footwear (as per questionnaire guidelines). Since different shoes may have different coefficients of friction, certain tasks on the CB&M may be more difficult to perform (such as foot scooting) for individuals who wear shoes with more traction. However, allowing participants to wear their own shoes increases the generalizability of the tasks and the scoring of their dynamic balancing abilities. In addition, most individuals who participated in the study were mobile and highly functional. Only two individuals with KL4 (severe) OA participated, and it is possible that those who have more severe grades of knee OA may have lower levels of function and the relationship of dynamic balance test scores may have been altered.

Our results indicate the CB&M is a valid and reliable test with no indication of floor or ceiling effects. The tool displayed moderate convergent validity when compared to other tests of balance and mobility and excellent known groups validity was established by demonstrating significant differences between those with and without knee OA. Test–retest reliability for the CB&M was very high. These findings indicate that the CB&M can be used as a valid and reliable tool to assess dynamic balance deficits in those with knee OA. Future research should assess what factors are associated with CB&M scores in people with knee OA.

Chapter 3: Factors associated with dynamic balance in people with knee osteoarthritis

3.1 Introduction

Dynamic balance, or locomotor stability during movement (3), is critical for independence and balance deficits have been linked to the risk of falling (18). Those with knee OA demonstrate impairments in dynamic balancing ability, such as significantly lower scores than healthy elderly on the CB&M (155). It is hypothesized that this reduced dynamic balancing ability may be attributed to neural and muscular deficits linked to impairments associated with the disease, and beyond the neuromuscular changes normally experienced with healthy aging (10, 49).

Neuromuscular deficits seen in those with knee OA which may affect dynamic balance include increased muscle weakness, impaired proprioception, altered postural control, and reduced knee joint range of motion. Muscle weakness is a known risk factor for falls and studies suggest a marked difference in lower body strength between older fallers and non-fallers (156). Numerous studies have highlighted deficits in concentric quadriceps (77-79) and hip muscle (80) strength in those with knee OA. Individuals with knee OA also produced 76% less eccentric quadriceps force than those without (63). Further, previous studies have shown that knee and ankle strength values are correlated in people with knee OA, suggesting that ankle plantarflexor strength may also be reduced (82, 157). Those with knee OA also have greater difficulty with joint repositioning (proprioception) tests than healthy controls (62), and poor proprioception has been associated with an increased risk of experiencing multiple falls (63, 158). Anticipatory postural control is also an important element of dynamic balance (92). An appropriate APA counteracts the destabilizing forces of voluntary movement and assists in movement initiation.

Alterations in anticipatory postural control can jeopardize the successful completion of a movement by resulting in a loss of balance. Other impairments seen in individuals with knee OA compared to healthy controls include reductions in knee joint range of motion (87), which may drive individuals to adopt alternative, destabilizing strategies (such as stooping instead of crouching) to complete daily tasks requiring dynamic balance. Further, knee range of motion has been shown to be associated with standing balance in those with knee OA ($r = 0.41$) (90). Taken together, these findings highlight the multiple neural and muscular deficits which may contribute to impaired dynamic balance and an increased falls risk in those with knee OA.

While many neuromuscular factors appear to influence dynamic balance and the risk of falls, the specific factors associated with dynamic balance have not been reported in those with knee OA. In contrast, factors associated with static standing balance, including muscle weakness and knee pain (22, 134), have been identified. While static balance deficits have been linked to falling, a large portion of falls occur during movement (20). There is a need to better understand the factors that may contribute to poor dynamic balance control, as it is linked to falling. Though it is possible that similar factors drive dynamic balancing ability as static balancing ability, this has not been assessed in the literature. Further, understanding what drives dynamic balancing ability will allow the development of balance training programs that target important modifiable risk factors that contribute to poor dynamic balance and the risk of falls. Thus, the purpose of this exploratory study was to identify modifiable neuromuscular factors associated with dynamic balance – as quantified by the CB&M – in individuals with knee OA.

3.2 Methods

3.2.1 Participants

Individuals aged 50 years and older with osteoarthritic changes on radiograph [KL grade 1 or higher (42)] were recruited from the local community using print advertisements and a laboratory database of previous participants. Individuals underwent radiographic screening to confirm the presence and grade of knee OA. Participants with KL1 were included, in order increase the generalizability of the study results to those with any osteoarthritis changes observed on radiographic analysis (KL1 indicates possible osteophytes and/or joint space narrowing). Grading on radiograph was carried out by two experienced raters (JT and MAH), who reached consensus agreement on all ratings prior to participant inclusion in the study. Participants were excluded if they had: articular cartilage degradation in the lateral tibiofemoral compartment greater than the medial, an inflammatory arthritic condition, pain originating predominantly from the patellofemoral joint, a history of knee or hip replacement surgery, a history of recent arthroscopic surgery or corticosteroid use (within six months), or were unable to ambulate without a gait aid (as gait aid use results in automatic scoring of zero on the CB&M task in question). Participants were also excluded if they had a neurological or musculoskeletal condition that affected their balance or movement (i.e. Parkinson's, multiple sclerosis). All participants provided informed consent prior to testing, and the study was approved by the university clinical research ethics board.

Sample size was calculated based on previous research where regression was used to predict standing balance (134). Using an expected $R^2 = 0.55$, $\alpha = 0.05$, and statistical power of 80%, a sample size of 50 participants was required (144).

3.2.2 Study procedure

Participants attended a single testing session at the university. Baseline descriptive characteristics, including age, height, body mass, knee pain [pain over the previous week using an 11-point numerical rating scale (NRS) (0 = no pain; 10 = maximum pain)] and fear of pain [using the Brief Fear of Movement Scale (159)] were collected. Potential neuromuscular factors associated with dynamic balance including muscle strength, joint proprioception, anticipatory postural control, and knee joint range of motion were also measured. Dynamic balance was evaluated using the CB&M. Measures are described below. The order of testing was standardized and consistent across all participants.

3.2.3 Outcomes

3.2.3.1 Community Balance and Mobility Scale

The CB&M was used to evaluate dynamic balance as described above in Sections 1.1.2 and 1.5.1.

3.2.3.2 Muscle strength

Concentric and eccentric muscle strength (torque) of the knee extensors, flexors, and ankle plantarflexors were measured using an isokinetic dynamometer. The protocol for strength testing has been described above in Section 1.5.2. In order to reduce the number of variables available in the regression model, four composite measures were calculated: two lower extremity strength (LES) scores, and two quadriceps-hamstrings strength ratios. LES is the sum of knee extensor, flexor and ankle plantarflexor peak strength. Concentric and eccentric LES scores were calculated, separately. LES score has been used previously as a measure of global strength in healthy older adults and patient populations (160). Two knee extensor-flexor strength ratios were also calculated by dividing the peak torque produced by the knee extensors by the peak torque from the knee flexors (161-163), using functional ratios previously described in the literature and used in OA populations (120): 1) eccentric extension divided by concentric flexion (EECF), and 2) concentric extension divided by eccentric flexion (CEEF). These ratios have been proposed as indices of muscle strength balance around the knee joint that also provide information about agonist and antagonist strength relevant to a specific movement (for instance, EECF expresses strength during knee flexion) (120).

3.2.3.3 Joint proprioception

Knee joint proprioception was measured using a knee joint repositioning task on the same isokinetic dynamometer used for strength testing. The protocol has been described above in Section 1.5.3.

3.2.3.4 Anticipatory postural control

The reaction to internal perturbation was measured using a toe rise paradigm (93). Participants were asked to stand quietly on a force platform (Advanced Mechanical Technology Inc., Watertown, MA) with arms at their sides, head facing forward, and feet slightly apart (the participant's foot length). Participants completed five rise-to-toes movements as quickly as possible, and were instructed to maintain the new position for three seconds. Unsuccessful trials (excessive body compensation, arm waving, or stepping) were discarded and repeated. Each rise-to-toes movement was recorded separately. Participants were allowed to practice the procedure five times prior to data collection. Ground reaction force data were collected at 1200 Hz and

COP coordinates were calculated from the raw force platform data. During the rise-to-toes task, there is an initial APA where the COP travels posteriorly (indicated by negative values), prior to the COP moving anteriorly as the participant rises to their toes (Figure 3.1). While COP movement during a rise-to-toes task has not been extensively measured in those with knee OA, reliability data is available for other similarly challenging tasks. One such task is standing on one leg, where COP movement is measured using a force platform in this population similar to the rise-to-toes task, with moderate to high reliability (ICC = 0.54 – 0.87) (52). Previous research indicates that COP velocity during the APA is reduced with heightened fear of falling, and with age (92, 93). Therefore, COP APA peak velocity (in m/s) was analyzed, as an average of the five rise-to-toes movements.

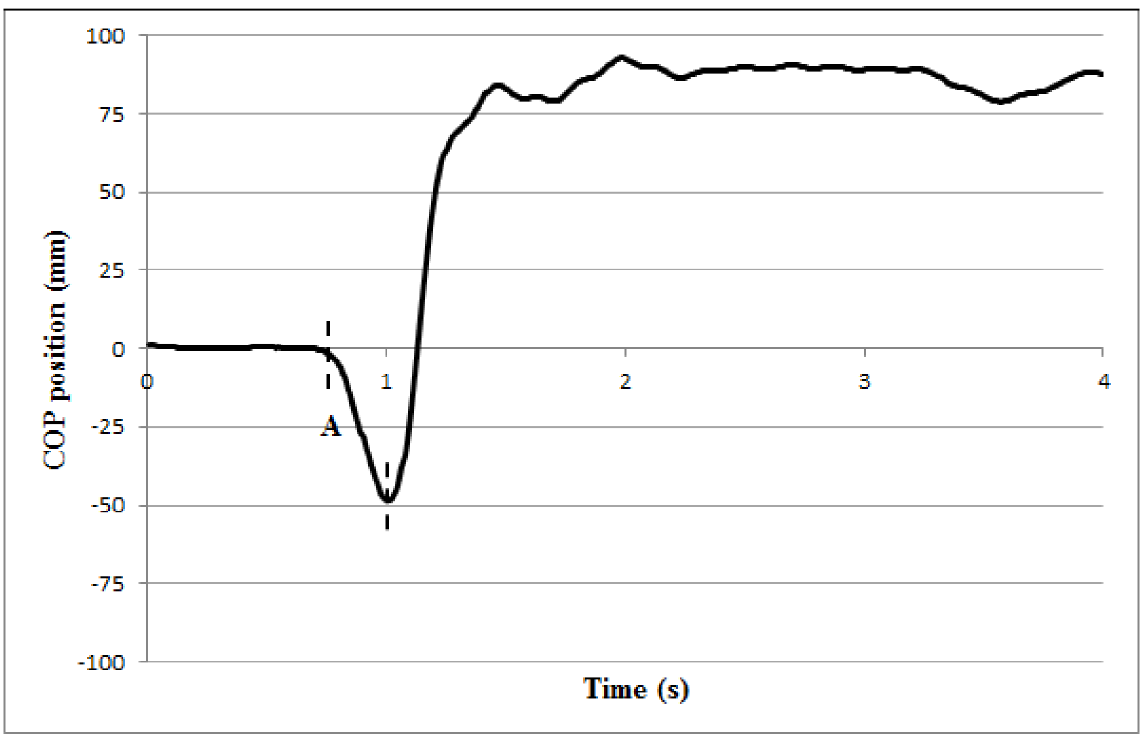

Figure 3.1. COP trace during the rise-to-toes task of a representative participant, with the area denoted by dotted vertical lines and "**A**" representing the APA.

3.2.3.5 Range of motion

Active knee joint range of motion was measured with the participant supine. This protocol has been described above in Section 1.5.4.

3.2.4 Statistical analysis

Descriptive statistics were calculated for group descriptors and study variables. Multiple linear regression was used to calculate explained variance in CB&M scores. Only neuromuscular variables that may be modifiable (for example, strength but not age) by clinicians in an exercise program were included in the first model, termed ‘neuromuscular variables’. A second model included the neuromuscular variables that were in the first model as well as adjusting for variables that described the population such as age, BMI, and knee pain, termed ‘descriptive variables’. Only variables that were correlated with CB&M scores ($p < 0.1$) were included in either model. A backwards stepwise regression model with the Akaike Information Criterion (AIC) was used for variable selection for both models (164), where lower scores indicate a better model choice. The AIC can be used to assess the goodness-of-fit of a model, while accounting for the complexity of the model and the error due to multiple comparisons (164). Assumptions of linearity, normality and equality of variances were examined using residual plots, skewness statistic and histograms. Skewness < 1 was considered satisfactory (165). Multicollinearity of independent variables was assessed using the variance inflation factor (VIF), where a VIF < 5 was considered satisfactory (165). Interactions between independent variables in the final model were assessed using hypothesis testing of cross-product terms (165). All statistical analyses were conducted using SPSS v21.0.

3.3 Results

Fifty-two individuals participated. Descriptive data can be found in Table 3.1. Of these individuals, 11 exhibited KL1 knee OA, 17 had KL2, 15 exhibited KL3, and nine exhibited KL4.

Table 3.1. Participant characteristics

	Mean (SD)
Age (years)	65.1 (8.9)
Sex (M/F)	24/28
BMI (kg/m^2)	26.3 (3.8)
Knee pain (0 – 10)	3 (2)
Fear of pain (6 – 24)	12 (5)

The mean (SD) score on the CB&M was 73 (14) out of 96 with a range of 45 - 95. Two participants were unable to complete knee extension, and one was unable to complete ankle plantarflexion resulting in LES data for 49 individuals and EECF and CEEF data for 50 individuals, used in analysis. Eccentric LES scores for participants were 4.5 (1.4) Nm/kg, and concentric LES scores were 3.4 (1.4) Nm/kg. EECF and CEEF were 2.0 (0.8) and 0.9 (0.3) respectively, indicative of hamstring weakness when compared to quadriceps strength. Participants produced a mean absolute error of 5.5 (2.3)° during the tests of proprioception. The COP APA peak velocity was -0.1 (0.06) m/s. Participants were able to produce a total knee joint range of motion of 125 (10)°, of which flexion accounted for 128 (8)°, and extension accounted for -3 (4)°. The negative extension value signifies that, on average, participants were unable to completely straighten their knee joint. The association of each variable (both descriptive and neuromuscular) with CB&M scores can be found in Table 3.2, with the variables chosen for inclusion in each model indicated in the table.

Table 3.2. Pearson correlation of potential factors with CB&M scores, with decision of inclusion in models.

	Correlation with CB&M	*P*-value	Inclusion in model: first/second/both
Descriptive variables			
Age	-0.39	0.004	Second
Sex†	-0.06	0.66	
BMI	-0.57	<0.001	Second
Knee pain	-0.55	<0.001	Second
Fear of pain	-0.22	0.11	
Knee OA severity†	-0.27	0.05	Second
Neuromuscular variables			
Eccentric LES	0.66	<0.001	Both
Concentric LES	0.64	<0.001	
EECF	-0.03	0.83	
CEEF	0.29	0.05	Both
Knee joint proprioception	-0.06	0.68	
APA velocity	-0.14	0.33	
Knee joint range of motion	0.45	0.001	Both

† indicates non-continuous data, correlation performed using Spearman's ρ.

Since eccentric and concentric LES were highly correlated (r = 0.9), two separate models were run first, one containing each LES score separately. The AIC and R^2 of each final model were examined to determine which approach was optimal. It was concluded that the analysis containing eccentric LES, but not concentric LES resulted in a higher R^2 and lower AIC (R^2 = 0.50, AIC = 222.4 for eccentric, vs. R^2 = 0.46, AIC = 225.8 for concentric), and thus concentric LES was not included in further analysis. The final first model for explaining variance in CB&M scores consisted of eccentric LES and knee joint range of motion and explained 50% of the variance in CB&M scores (Table 3.3). Knee joint range of motion was not a significant factor on its own (p = 0.15), but was considered an important variable for inclusion in the model due to the model selection criteria (lowest AIC suggesting optimal model). The relationship between CB&M scores and independent variables are plotted in Figure 3.2. The regression coefficients indicated that higher scores on the CB&M were associated with greater eccentric LES (β = 6.1); and greater range of motion (β = 0.22).

The second model, adjusting for age, BMI, and knee pain, resulted in eccentric LES (β = 2.7, p < 0.05) being the sole neuromuscular variable associated with CB&M scores (R^2 = 0.68, AIC = 205.3). In order to better understand the individual contribution of LES to the second model, post-hoc analysis examined the R^2 of this variable alone. The contribution of LES R^2 in the second model was 0.09. Table 3.3 displays both the first and second models for comparison. The beta coefficients indicate that for every one unit increase in the independent variable, while holding all other variables constant, the CB&M score is predicted to increase by the beta coefficient value. There were no significant interactions amongst variables. Residual plots indicated no violation of the principles of linearity or equality of variance. Skewness statistics indicated no issues with non-normality, and the histogram of CB&M scores revealed no departure from normality. VIF indicated no issues with multicollinearity (largest VIF = 2.1). Confirmatory (forward and mixed stepwise) analysis confirmed the findings are model-independent.

Table 3.3. Final models determined by AIC using backwards stepwise multiple linear regression of the CB&M scores.

Variable	Beta coefficient (95% CI)	Standardized Beta	*P*-value	VIF
First Model				
B (constant)	73 (70, 76)		< 0.001	
LES	6.1 (3.7, 8.4)	0.6	< 0.001	1.2
Range of motion	0.2 (-0.08, 0.5)	0.2	0.15	1.2
Second Model				
B (constant)	73 (71, 76)		<0.001	
Age	-0.6 (-0.9, -0.3)	-0.4	<0.001	1.2
BMI	-0.9 (-1.7, -0.08)	-0.3	0.03	1.8
Knee pain	-1.6 (-2.8, -0.4)	-0.3	0.008	1.3
LES	2.7 (0.2, 5.2)	0.3	0.03	2.1

First model: AIC = 222.4, R^2 = 0.50; Second model: AIC = 205.3, R^2 = 0.68. Lower extremity strength (LES) and knee joint range of motion were the variables that rendered the highest R^2 in the first model. After adjusting for age, BMI, and knee pain, eccentric LES rendered the highest R^2 in the second model. In the second model, LES R^2 = 0.09.

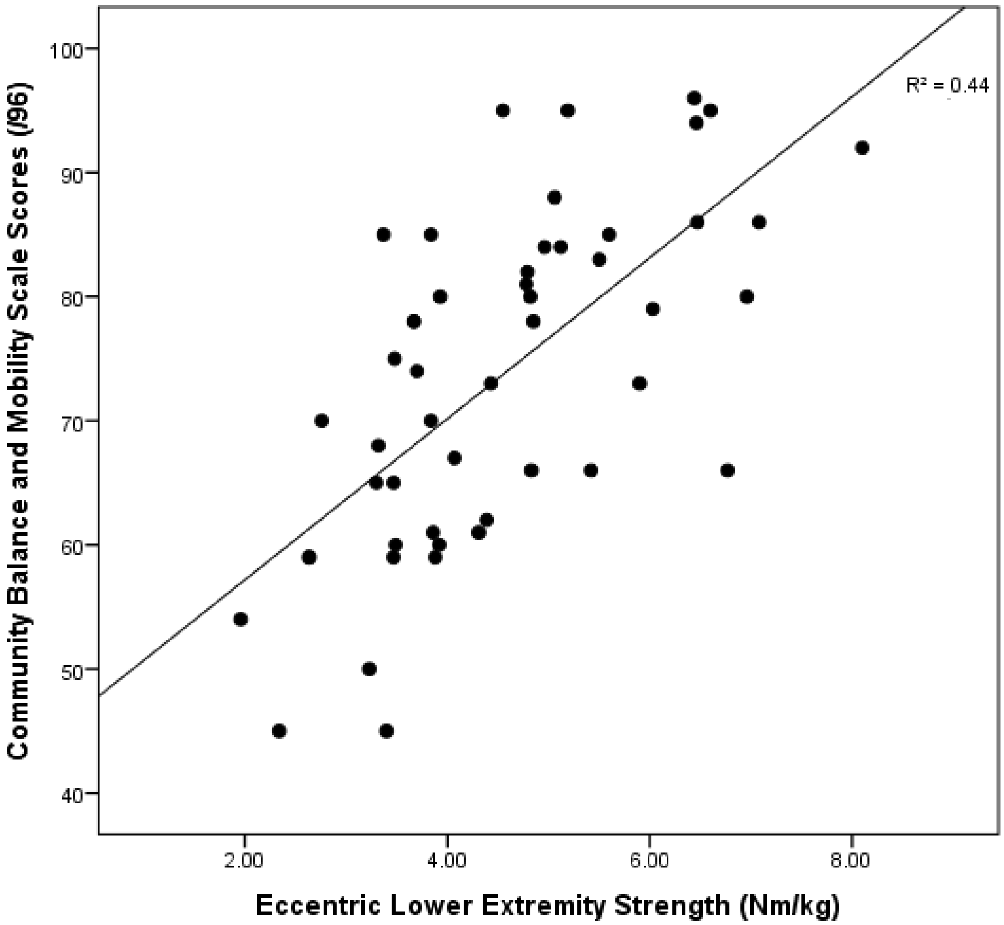

Figure 3.2A. Scatter plot of CB&M scores and eccentric lower extremity strength score.

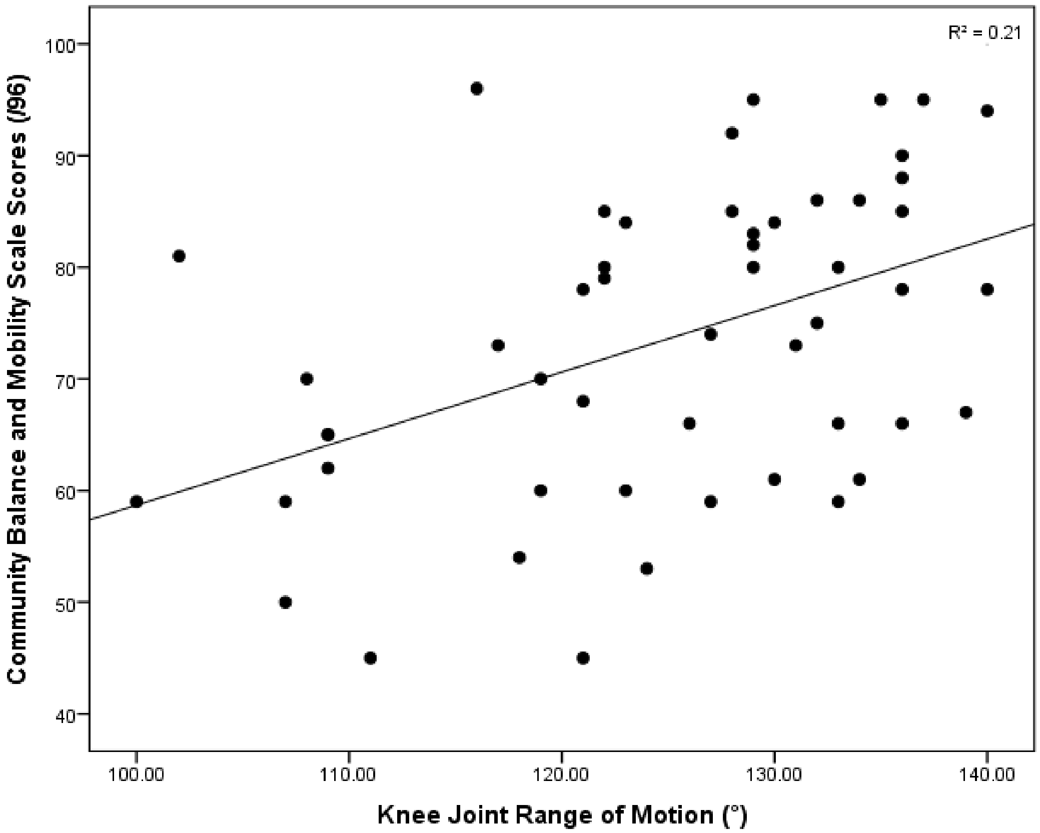

Figure 3.2B. Scatter plot of CB&M scores and knee joint range of motion.

3.4 Discussion

Lower extremity muscle strength was important in explaining variance in CB&M scores in people with knee OA, with the first model suggesting that knee joint range of motion may also be considered in further study. While the second model was able to explain 68% of the variance in CB&M scores, the first model involving only modifiable neuromuscular factors explained 50%, suggesting that the modifiable variables are important in determining dynamic balancing ability. However, the second model highlighted clinical characteristics, including age, BMI and knee pain that should be considered when assessing balancing ability. These findings are in agreement with available literature examining predictors of static standing balance that have identified similar neuromuscular factors, including isometric and isokinetic strength (22, 65, 134).

Muscle strength has been suggested to be particularly important for the recovery of balance from a perturbation (81), where the task is dynamic in nature. Indeed, many tasks on the CB&M require adequate muscle strength to complete, such as stair descent. In this study, eccentric LES explained a significant proportion of the variance in dynamic balancing ability, while EECF and CEEF were not able to explain variance, which may be because they were not able to provide more information beyond what was already provided by LES in the model. Eccentric LES had the largest beta coefficient in the first model ($\beta = 6.1$, $p < 0.001$), and while lowered, was the only neuromuscular variable in the second model ($\beta = 2.7$, $p = 0.3$). For every one unit (Nm/kg) increase in LES while holding all other variables constant, CB&M score was predicted to increase by more than six points. The MDC for the CB&M for people with knee OA is nine points (155), suggesting that a strength gain of approximately 1.5 Nm/kg (33% improvement based on the current study) could be associated with clinically significant changes on the CB&M. While substantial, previous reports recording strength gains of approximately 20 – 40% over baseline (166, 167) in knee extensors due to strength training in people with knee OA suggest that this may be a feasible increase. While literature has highlighted the importance of isometric muscle strength in static balancing ability (22, 134), this is the first study to examine the role of eccentric muscle strength in balancing ability of people with knee OA. Our results suggest that eccentric muscle strength explains considerable variance in balancing ability, and it may be important to target such strength during training. That said, since concentric and eccentric strength magnitudes were highly correlated and produced similar amounts of explained variance in CB&M scores, it is likely that improvements in either concentric or eccentric strength will result in changes in dynamic balance ability.

Knee joint range of motion may be another important factor in dynamic balancing ability. Limitations in range of motion may drive individuals to adopt destabilizing, alternate strategies for completing dynamic tasks, such as stooping instead of crouching when picking up objects. Our results show that knee joint range of motion was an important factor in the first model (β = 0.2), but not in the second model. The beta coefficient in the first model suggests that large changes in CB&M performance would not be evident without moderate or large improvements in range of motion (for instance, an increase of 20° would only result in an improvement of four points on the CB&M, which is below the MDC). Tasks on the CB&M such as crouching or lateral dodging are influenced by the knee joint range of motion available to the individual, yet only when the limitation is so great that the person is unable to bend or straighten their knee enough to complete the task, such as being unable to crouch and reach the bean bag. Further, range of motion was not a factor associated with CB&M scores in the second model, possibly owing to the descriptive variables, such as age and BMI, explaining variance that was also explained by range of motion. These results suggest that further study of individuals with moderate or severe limitations in range of motion, and the effect of such limitation on dynamic balancing ability, is warranted.

While proprioception is an important sensory system used to maintain postural control, it was not associated with dynamic balance ($r = -0.06$). This is in contrast to previous studies assessing static balance (65). The lack of relationship with CB&M scores may be because 1) tasks on the CB&M allow visual input, reducing the reliance on proprioception; and 2) the proprioceptive task used in this study was a non-weight-bearing test, while tasks on the CB&M

are weight-bearing. Postural control was also not able to explain significant variance in CB&M scores. This may be because the anticipatory phase of voluntary movements, at the beginning of each CB&M task, makes up a small portion of each task (i.e. less than one second at the beginning of the walking eight meters while looking task).

In the second model, the descriptive factors age, BMI, and knee pain explained significant amounts of variance in CB&M scores. This is consistent with previous findings that found impaired balance with increasing age (168), BMI (169), and knee pain (170). Reasons for these known associations include the impairment of postural control systems with age, such as proprioceptive ability, and the higher biomechanical difficulty in controlling larger body mass. Further, knee pain could indirectly impact balancing ability through avoidance and sedentary behavior or more directly through interference of sensory and motor information. Accordingly, these additional factors should be considered when assessing and treating balance or delivering balance interventions. Further, factors such as knee pain could affect other neuromuscular factors, such as muscle strength through inhibition. Thus, knee pain should be considered as an important factor both independently and in association with other factors.

There are some limitations to the current study. To assess knee joint proprioception, a non-weight-bearing test of joint position sense was used. While weight-bearing tests would be more similar to the tasks on the CB&M, the feasibility and validity of weight-bearing tests in this population are unknown. Further, non-modifiable factors such as age, and disease severity, which may predict balancing ability, were not included in the first model. While they were included in the second model, this second model initially contained seven variables in total, and due to the exploratory nature of the study, this may reduce the power of the model and any conclusions that can be drawn. Finally, only individuals with medial tibiofemoral knee OA were recruited to participate, and thus the results of the study can only be generalized to this sub-group of the overall knee OA population, and not to those with other forms of knee OA (for instance, patellofemoral knee OA).

Lower extremity muscle strength was able to explain a significant amount of variance in dynamic balancing ability as measured by the CB&M, in both models, while range of motion also contributed to the first model. Age, BMI, and knee pain were important descriptive factors in the second model and may contribute to a broader understanding of those with knee OA experiencing dynamic balance difficulties. To the authors' knowledge, this is the first study to consider modifiable neuromuscular factors that may influence dynamic balancing ability in people with knee OA. Further research on the impact of strength and range of motion training on dynamic balancing ability should be considered.

Chapter 4: Effects of a dynamic balance training intervention for individuals with medial knee osteoarthritis: A randomized controlled trial

4.1 Introduction

With research suggesting that those with knee OA show deficits in dynamic balance above and beyond those seen with healthy aging, there is a need for dynamic balance training programs to ameliorate these deficits. Currently, the evidence for dynamic balance training in those with knee OA is conflicting. For instance, Diracoglu et al. (99) found significant improvements in self-reported and objective measures of function, such as the WOMAC physical function subscale and the 10-m walk, after an eight week balance and strength intervention compared to a strength only group. However, Fitzgerald et al. (100) found no significant differences between strength-and-balance and strength-only groups in WOMAC physical function subscale and GUG scores following six to eight weeks of supervised training and a further four months of home training. Other studies investigating home-based dynamic balance training in people with knee OA have found improvement in self-reported function as reported on the WOMAC (physical function and total score), but performance on objective measures such as improvement in GUG times did not reach significance (114, 115). Both studies compared balance training to strength training, with Rogers et al. (114) including a third group (control – inert lotion application) and twice as long an intervention (eight weeks compared to four weeks). Even with these differences, there was still no improvement in objective measures of function in the dynamic balance training group (6.8% improvement vs 6.6% for control in GUG times, both statistically non-significant). However, there was a small, significant improvement in the strength training group (8% improvement in GUG time, $p = 0.02$). Of note, no other dynamic balance outcomes, such as the BBS or CB&M (which are more comprehensive measures of dynamic balance) were reported in these studies. Thus, it is unclear what effect these types of training interventions have on overall dynamic balancing ability in this patient population.

Results are less contradictory in other clinical populations. Eight weeks of dynamic balance training after TKA resulted in significant improvements in TUG times and WOMAC total scores compared to usual care in one randomized controlled trial (98). In another, Kovacs et al. (111) saw improvements in physical function and mobility, including on the TUG, in a sample of cognitively impaired older adults after 12 months of targeted dynamic balance training. Despite the limitations in the TUG with respect to overall dynamic balance ability described above, these results suggest that there is potential for gains in physical function and dynamic balance in populations with impaired balance, such as those with knee OA.

A few issues need to be considered when examining the results of balance interventions in the knee OA population and when designing dynamic balance training programs for these individuals. While previously published training programs appear to target dynamic balance, as evidenced by the inclusion of exercises such as walking on toes and crossover stepping which require balance but are weight-bearing, dynamic, and multi-directional, previous studies have often omitted objective evaluation of dynamic balance, or have used tests that encompass a single task (99, 100). Therefore, while dynamic balance may have improved, there is limited evidence to support that claim. Studies also differ in the volume of training prescribed, with programs containing more exercise bouts (24 or more, regardless of supervision) often showing more favourable results (99). Importantly, recent research in those with knee OA has highlighted the importance of strength, particularly eccentric strength, in balancing ability (65, 171), and this should be considered when choosing exercises aimed at improving dynamic balance. Although it was previously found that both concentric and eccentric strength were factors in balance in people with OA (Chapter 3), only one previous study has included eccentric strengthening exercises (99) among the stepping and balancing activities prescribed, and this may further explain why significant improvements were found with this particular program where others have seen no differences.

The inclusion of comprehensive dynamic balance assessment and exercises aimed at improving dynamic balance, such as strengthening exercises, may produce beneficial outcomes more closely aligned with those seen in other clinical populations. However, to date no study has included these components when investigating the effect of a dynamic balancing intervention in individuals with knee OA. Therefore, the purpose of this study was to investigate the effect of a dynamic balance training program, informed by previous evidence, on dynamic balance and physical function in people with knee OA.

4.2 Methods

4.2.1 Participants

Individuals aged 50 - 80 years with radiographically-confirmed medial tibiofemoral knee OA (KL grade ≥ 2) (42) and knee pain were recruited to participate in a ten week randomized controlled trial. A maximum age criteria was used to reduce the risk of exercise-induced complications, such as injury and tolerance to exercise. Community-dwelling individuals were recruited from our laboratory participant database and via advertisements in print media. Exclusion criteria consisted of: articular cartilage degradation in the lateral tibiofemoral compartment greater than the medial, inflammatory arthritic condition, history of knee or hip replacement, recent use of corticosteroids or arthroscopic surgery (within the last six months), pain originating predominantly from the patellofemoral joint or lateral tibiofemoral compartment, inability to ambulate without a gait aid (as gait aid use results in an automatic score of zero on the CB&M task it is used for), planning to start an exercise program within three months, or unable to attend eight sessions at the University. Individuals with any neurological, musculoskeletal or other condition that affected their lower extremity movement ability, balance, or maximal strength testing ability (i.e. stroke, diabetes, Parkinson's, recent heart attack, multiple sclerosis, fibromyalgia) were also excluded.

Prior to baseline testing, interested participants were screened for balance and physical function deficits. All individuals completed the CB&M and WOMAC, and only those that scored 75 or lower (out of 96) on the CB&M as well as 18 or higher on the WOMAC physical function subscale (out of 68) were included. This was done in order to allow for the possibility of improvement on each outcome measure. Ethical approval was obtained from the local Clinical Research Ethics Board and all participants provided written informed consent.

Based on the results of a previous study (100), an effect size of 0.5 on one of the primary outcomes (WOMAC physical function subscale) was anticipated for this intervention. Including this effect size, $\alpha = 0.05$, and a power of 80%, it was calculated that 16 participants per group was required (144). To conservatively account for 20% attrition, it was calculated that approximately 20 participants per group would need to be recruited to obtain statistically significant results in our primary outcomes (CB&M and WOMAC physical function subscale). Thus, a total sample size of 40 participants was targeted.

4.2.2 Study procedure

The setting for this study was a University biomechanical laboratory for baseline and follow-up testing, and a University exercise facility for balance training visits, with all other training completed at the participant's home. Interested participants were initially screened for inclusion and exclusion criteria over the telephone and eligible individuals underwent an initial physical screening to assess balance and physical function deficits as described in Section 4.2.1. Eligible participants were then referred for radiographic evaluation. Standing, semi-flexed, postero-anterior radiographs were obtained and graded for disease severity using the KL OA classification system (42), with Grade 2 or higher classified as exhibiting knee OA. Grading on radiograph was carried out by two experienced raters (JT and MAH), who reached consensus agreement on all ratings prior to participant inclusion in the study. Participants who successfully passed all screening procedures were invited to participate.

Participants were assessed at baseline (prior to treatment assignment) and after treatment by the same blinded assessor. Following the baseline assessment, participants were randomly allocated to either the dynamic balance training group (treatment) or no intervention (control) group for ten weeks. The randomization schedule of random permuted blocks of four to six was produced using a computerized random number generator by a researcher not involved in testing or training. The randomization allocation for each participant was placed in consecutively numbered, sealed, opaque envelopes and opened immediately after baseline testing. Ten weeks was chosen as the ideal time frame to optimize participant adherence and to observe clinically meaningful changes in dynamic balance and related constructs (99).

Baseline and follow-up testing consisted of the same laboratory measurements, and in the same testing order. Descriptive data including age, height, body mass, falls history, and length of time reporting symptoms were collected at baseline, with descriptive measures including knee pain and fear of pain collected again at follow-up. Participants completed the following self-report questionnaires: an 11-point NRS for knee pain (0 = "no pain"; 10 = "worst possible pain"), the Brief Fear of Movement Scale, the PASE (136), and the WOMAC OA Index (172).

The PASE is a measure of self-reported physical activity during occupational, household, and leisure activities, with validity and reliability described in Section 2.2.2. Values on the scale can range from zero to 400, with those with knee OA scoring around 200, though there is a wide range in scoring. Higher scores indicate more self-reported physical activity. The Brief Fear of Movement Scale contains six questions that evaluate fear of pain, movement and re-injury and has been validated in individuals with OA (159). Scores range from zero to 24, with higher scores indicating a greater fear of pain and injury. Scores above 12 indicated moderate, and higher levels of fear of pain. This novel scale is based on the Tampa Scale of Kinesiophobia, and while reliability of this scale has not yet been investigated, the questions on the Tampa Scale (which are repeated on this scale) have been deemed reliable (ICC = 0.75 – 0.81) (173, 174). Participants then completed the CB&M, and knee joint proprioception, muscle strength, and knee joint range of motion were measured.

4.2.3 Outcomes

4.2.3.1 Community Balance and Mobility Scale

Dynamic balance was assessed using the CB&M as described in Sections 1.1.2 and 1.5.1.

4.2.3.2 Self-reported physical function

Self-reported physical function was measured using the physical function subscale of the

WOMAC. The WOMAC is a valid (172) and reliable (175), widely used clinical scale in knee OA research. It contains 24 questions that assess pain (five questions), stiffness (two questions), and physical function (17 questions) in three subscales. For this study, questions were answered on a five-point Likert scale (none = 0, through to extreme =4 pain, stiffness or difficulty), with a maximum score of 96 and minimum score of 0. Higher scores indicate worse pain, stiffness, or physical function.

Overall perceived change in physical function at follow-up compared to baseline was assessed using a 15-point Likert scale, ranging from -7 ("a very great deal worse") to +7 ("a very great deal better") (176) with improvement deemed *a priori* as +3 ("somewhat better") or higher.

4.2.3.3 Proprioception

Knee joint proprioception was measured using a knee joint repositioning task, previously used in those with OA to assess joint proprioception (63, 171). The protocol has been described above in Section 1.5.3.

4.2.3.4 Muscle strength

Maximal eccentric muscle strength (torque) of the knee extensors, flexors, and ankle plantarflexors were measured using the same isokinetic dynamometer as for the knee joint repositioning task. The protocol for strength testing has been described above in Section 1.5.2. The sum of eccentric knee extensor, flexor and ankle plantarflexor peak strength was then calculated, termed the lower extremity strength score (LES). LES score has been used previously as a measure of global strength in healthy older adults and patient populations (177-179) and has been shown to predict dynamic balancing ability in knee OA (171).

Given the potential for core activation to influence balancing ability (180-182), participants were asked to complete the trunk stability test (TST), a measure of core stability during dynamic movements (183, 184). While reliability data on this task does not currently exist, this task was chosen as it has been previously used in similar clinical populations, can easily be administered in a clinic and holds clinical relevance, and expresses content validity (183). Participants were asked to lie on a plinth and maintain their neutral spine while they progressed through a series of movements that involved lifting and extending their legs. There are five levels of difficulty to the task, progressed by asking the participant to lift instead of slide the leg along the plinth, and by engaging both legs. The highest level the participant was able to complete while maintaining a neutral spine and pelvis was recorded.

4.2.3.5 Knee range of motion

Range of motion was measured using a goniometer, similar to other studies of knee OA (87). This protocol has been described above in Section 1.5.4.

4.2.4 Targeted dynamic balance training

Dynamic balance training consisted of progressive exercise training over three phases, with exercises emphasizing dynamic balance control, lower limb muscle strength, and core stability (Table 4.1 and Appendix B). Exercises were phased in order to maintain exercise challenge over the duration of the training program (with more difficult exercises introduced later), as well as to motivate participants with varied exercise. Phase one consisted of exercises including squats or chair sits, calf raises and side stepping. Difficulty was progressed in phase two by including exercises that were unilateral, such as step down, and exercises that were dynamic, such as toe walking. Finally, phase three included dynamic exercises with a reduced base of support, such as lunges, and dynamic exercises with direction changes, such as skate stepping (side-to-side unilateral movement). Exercises were performed as 2 – 3 sets of 8 – 12 repetitions, and were individually prescribed by an experienced kinesiologist. Difficulty of exercise was monitored using an 11-point NRS (0 = no difficulty; 10 = maximum difficulty). Exercises were progressed through the phases when the self-reported difficulty dropped below 3/10, or when the trainer deemed that the exercise had been mastered.

Participants were asked to perform the exercises four times per week, for a total of 40 exercise sessions over ten weeks, and they were asked to record completion of exercises in a log book. Participants completed six supervised training sessions at the University (during weeks 1, 2, 3, 5, 7, and 9) that were included in the total number of sessions for each week. The goals of the supervised training sessions were to introduce the exercises, ensure correct performance, modify and progress the exercises. All other training sessions were performed at home. All equipment necessary to complete the exercises was provided to participants, and consisted of four cones, painter’s tape, and a one lb weight.

Participant adherence was measured as the number of exercises sessions completed, divided by the total number of exercise sessions (maximum 40), converted to a percentage. Attendance was measured as the number of supervised exercises sessions attended at the University (to a maximum of six, converted to a percentage). Adverse events, such as injury or pain, experienced due to the intervention were recorded weekly by participants in the log books provided. Treatment and medication changes made by participants during the study period were also recorded in the log books.

Table 4.1 Training group exercises prescribed in each phase

Phase	Exercise	Description
One	Sitting rotation	In a seated position, participant engages core while rotating a small weight in arms from one side of the body to the other. Legs are kept still
	Chair sit/squat	Participant slowly lowers into, or hovers above, a chair, then rises. Difficulty dependent on ability.
	Calf raise	While standing, participant slowly rises onto toes, then lowers back down
	Side stepping	While keeping knees slightly bent, participant side steps for prescribed number of steps
	Stepping pattern	Participant places two pieces of intersecting tape on floor to make a plus sign. They then complete given stepping patterns
Two	Standing rotation	In a standing position, participant engages core while rotating a small weight in arms from one side of the body to the other. Legs are kept still
	Step down	Standing on a step, participant lowers one leg to the ground, before rising back up. Step height varies based on ability
	Toe walking	While standing on toes, participant slowly walks prescribed number of steps
	Lateral step-up	Participant steps sideways onto step, rising to touch the top with both feet, then lowering back down
	Stepping pattern	Same as above, but with an alternate foot pattern requiring more steps prescribed
Three	Stepping rotation	In a standing position, participant engages core while rotating a small weight in arms from one side of the body to the other. While rotating, participant is instructed to take a step
	Lunge	Once positioned in a wide step, participant lowers into lunge, then rises

Phase	Exercise	Description
	Mini-hop	Participant instructed to start and end each hop with bent knees
Three	Skate stepping	Participant places two pieces of tape parallel but 30 cm apart. They then alternate stepping to the outside of the tape while the other foot touches down behind the front foot
	Cone walking	Participant positions four cones in a square. They then complete figure eight walking patterns around pairs of cones. Distance between cones is dependent on ability

4.2.5 Control group

The no-treatment control group attended the same two testing sessions (baseline and follow-up) twelve weeks apart as the balance training group, with no other visits to the University. During this period, participants were asked to maintain their usual level of activity and refrain from trying new treatment programs or medications. Participants were asked to record any changes to their usual activity routine, any change in knee or other joint pain, and any new treatments or medications in a weekly log book.

4.2.6 Statistical analysis

Data were analysed by a researcher not directly involved in the collection of data. Variables at baseline including age, BMI, knee pain, and fear of pain were examined for differences between groups. Independent two-tailed t-tests were run to evaluate baseline differences for all variables, except sex, which was analysed using the chi-square test. Variables found to be statistically significantly different ($p < 0.05$), with differences deemed clinically important between groups were included as covariates and adjusted for in the final analysis. For examining the treatment effect, change scores were calculated for each outcome measure (follow-up minus baseline), and independent t-tests were run on the change scores between group. A Bonferroni correction of k = 3 (for CB&M, WOMAC physical function subscale score, and LES) was employed to correct for multiple comparisons. Thus, $p < 0.017$ was considered significant. Assumptions of normality and equality of variances were assessed using skewness statistic, histograms and Levene's test. Outcomes that did not meet assumptions of normality were analysed using the Mann-Whitney U Test. Missing primary outcome data from the four participants to drop out were inspected to ensure that the missing at random assumption was reasonable. Multiple imputation was then used to estimate missing values of the primary outcome variables (CB&M score and WOMAC physical function score). Ten iterations were imputed using the Markov Chain Monte Carlo method (185, 186). Pooled data sets were then re-analyzed to investigate the validity of the results. All statistical analyses were conducted using SPSS v21.0 (IBM Corp, Armonk, NY).

4.3 Results

A total of 221 individuals were screened between May 2014 and September 2015 (Figure 4.1). Of these, 117 underwent the initial physical screening, and 47 were then sent for radiographic screening. The most common reason for exclusion at the initial physical screening was insufficient physical dysfunction, as indicated by WOMAC physical function subscale scores that exceeded our maximum threshold for inclusion (>18). Forty individuals underwent baseline testing, and were then randomized to one of the two conditions. A total of four individuals dropped out of the study after baseline data were collected, three due to medical problems unrelated to the intervention, and one in the control group who had a knee flare-up and was unwilling to attend the follow-up testing [n = 4; 2 males; 2 KL2, 2 KL4; age 68.1 (8.5) years; BMI 32.2 (4.74) kg/m^2]. The three individuals that left the training program all left the study in the first week. Descriptive characteristics of all study participants can be found in Table 4.2.

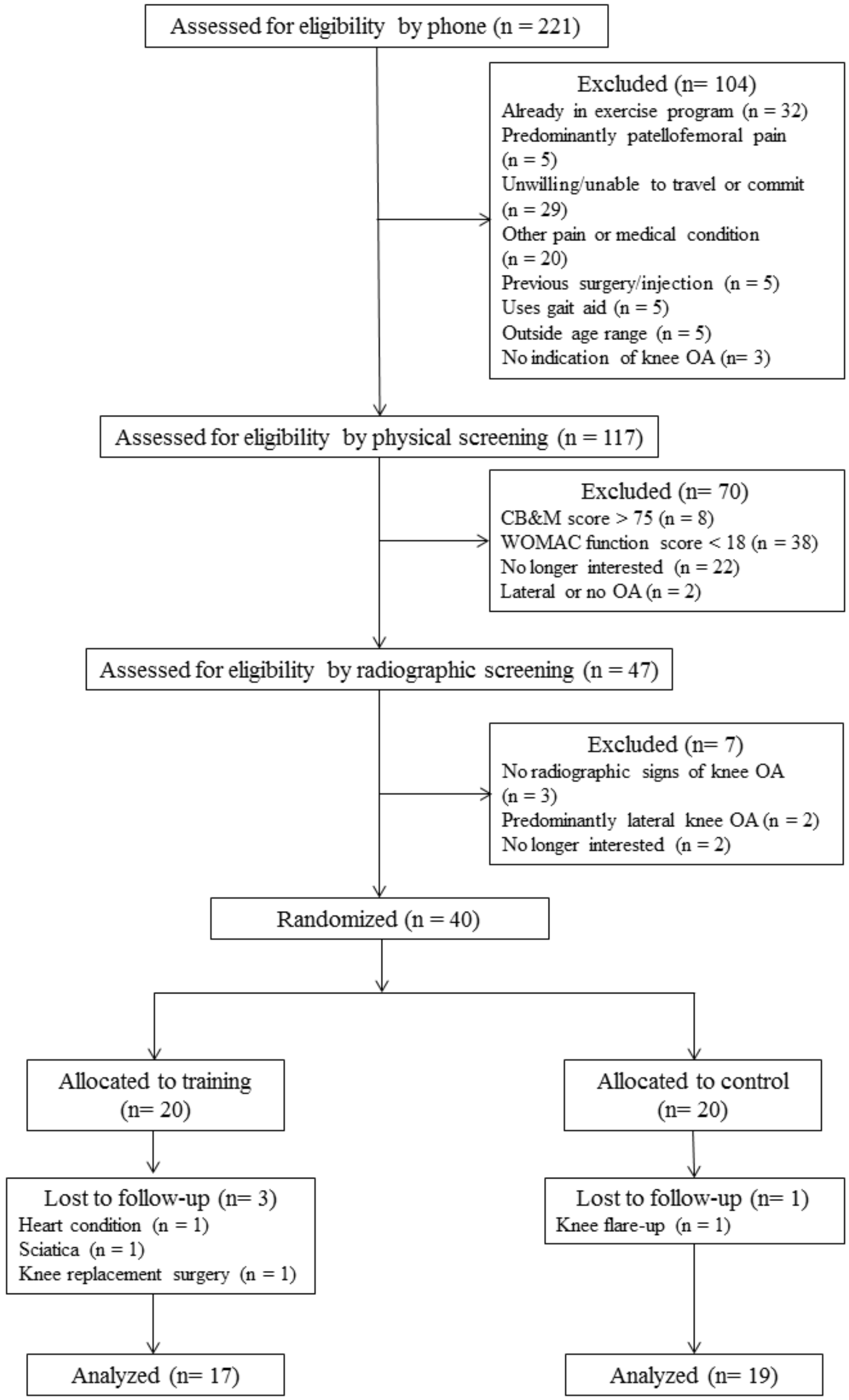

Figure 4.1 Flow diagram of participant recruitment and enrollment

Table 4.2 Mean (SD) baseline participant characteristics

Descriptive Data	Training (n = 20)	Control (n = 20)
Age (years)	66.1 (8.7)	67.1 (5.4)
Sex (M/F)	1/19	7/13
BMI (kg/m^2)	28.5 (5.4)	28.9 (4.5)
Knee pain (0 – 10)	5.1 (1.8)	4.9 (2.2)
WOMAC total score	41.5 (9.3)	41.7 (13.9)
Fear of pain (0 – 24)	13.3 (4.0)	13.6 (4.6)
PASE Score	187.9 (68.6)	213.0 (85.4)
0 previous falls	13 (65)	14 (70)
1 previous fall	7 (35)	5 (25)
2 previous falls	0 (0)	1 (5)
KL2	8 (40)	8 (40)
KL3	6 (30)	8 (40)
KL4	6 (30)	4 (20)

For each grade of OA and number of previous falls reported, the number (%) of participants per group are provided.

Overall, assumptions of normality and equality of variance were met for all variables except proprioception and TST. Proprioception at baseline and follow-up was found to exceed the acceptable amount of skewness (baseline = 2.4, follow-up = 2.8). Visual inspection of data showed an outlier in both cases that was 3.5 SDs greater than the group mean. After removal, proprioception values reflected a normal distribution and skewness was reduced (baseline = 0.5, follow-up = 0.6), and was thus analysed as previously described. TST was non-normal, and was analysed using the Mann-Whitney U test. At baseline, there were no statistically or clinically significant differences between groups in any variables, with the exception of sex (chi-square = 5.6, $p = 0.02$) showing more males enrolled in the control group. No adjustments were performed in the final analysis.

There was no change in any outcome in the control group from baseline to follow-up. There was a significant improvement in the WOMAC physical function subscale score in the training group when compared to the control group (mean difference = -8; $p = 0.016$), with no difference in any other outcome. Post-hoc confirmatory analysis using ANCOVA co-varying for baseline data confirmed the above findings of a significant improvement in WOMAC physical function in the training group but not the control group, with no difference between groups in CB&M scores. Differences between follow-up and baseline values for each group can be found in Table 4.3. Pooled results from analyses of data sets generated using multiple imputation confirmed the above findings for CB&M score (mean difference = 0, $p = 0.91$) and for the WOMAC physical function subscale (mean difference = -7, $p = 0.01$). Seven of 17 participants in the exercise group indicated a positive global change in self-reported physical function (+3 or higher), though only three indicated a perceived negative change, with the rest (n=7) indicating no change in overall function. In the control group, five indicated a positive change, with the majority (11 of 19) indicating no change, and the remainder (n=3) indicating a negative change.

Table 4.3 Outcomes at baseline and follow-up for each group

	Training Within-Group Differences			Control Within-Group Differences				
	Baseline (n = 20)	**Follow-up (n = 17)**	**Mean Difference (95% CI)**	**Baseline (n = 20)**	**Follow-up (n = 19)**	**Mean Difference (95% CI)**	**Between-Group Differences (95% CI)**	**Between-Group P-value**
CB&M (0-96)	53 (14)	56 (15)	1 (-3,4)	50 (15)	50 (14)	0 (-3, 4)	0 (-5, 5)	0.91
WOMAC physical function score (0-68)	30 (7)	20 (11)	-9 (-14, -4)	30 (10)	28 (10)	-1 (-6, 3)	-8 (-14, -2)*	0.016
Proprioception (°)	6.4 (2.4)	6.9 (3.0)	0.8 (-0.6, 2.3)	6.2 (2.7)	5.9 (3.1)	0.1 (-1.9, 2.0)	0.8 (-1.6, 3.2)	0.52
LES (Nm/kg)	3.2 (0.8)	3.6 (1.1)	0.3 (-0.1, 0.7)	3.5 (1.0)	3.3 (1.3)	-0.2 (-0.7, 0.3)	0.5 (-0.1, 1.1)	0.12
TST† (0 – 5)	0 (1)	0 (2)	0 (0, 0)	1 (2)	0 (2)	0 (-1, 1)	0 (0, 1)	0.14
ROM (°)	115.3 (12.3)	120.9 (12.3)	3.8 (-0.3, 7.8)	119.2 (8.0)	118.2 (8.4)	-0.4 (-1.9, 1.1)	4.2 (-0.1 8.4)	0.053

†TST was analysed using the Mann-Whitney U test. Values displayed for TST are median (IQR), and median difference (CI). * indicates significant difference at $p < 0.017$. Proprioception in the control group was analysed with n = 19 values at baseline and n = 18 values at follow-up.

Participants in the training program spent a mean (SD) 3.3 (0.7) weeks in phase one, 4.6 (0.9) weeks in phase two, and 2.1 (1.1) weeks in phase three of the program. Participants rated the average difficulty of the exercises, as a whole, as moderate (3.4/10), with phase one (rated 3.4/10) being judged similar to phase 2 and 3 (both rated 3.3/10). Adherence to the exercise program was high, with an overall adherence of 82.2% (559 of 680 total sessions; median 39 of 40 sessions, minimum 11 sessions; maximum 40 sessions). This involved a mean completion rate for home exercise sessions of 79.2% (mean 27 of 34 required sessions). Attendance at university exercise sessions was much higher at 92.2% (mean 5.5 of 6 required sessions). Post-hoc analysis performed in order to further explain results examined the lack of change in CB&M scores and associations with adherence or time spent exercising. There was no significant association between change in CB&M scores and adherence ($r = -0.1$; 95% CI = -0.7 – 0.3) or change in CB&M scores and time spent in any of the phases (Phase 1: $r = 0.3$, 95% CI = -0.2 – 0.7; Phase 2: $r = -0.4$, 95% CI = -0.7 – 0.01; Phase 3: $r = 0.2$, 95% CI = -0.3 – 0.7).

Seven participants reported an adverse event during the exercise program. These adverse events ($n = 9$ total across the seven participants) included two instances of back pain lasting no more than two weeks, four instances of knee pain or soreness lasting one to two weeks, one instance of hip pain lasting two days, one instance of foot pain lasting three weeks, and one report of overall stiffness lasting one week. Only the instance of foot pain required additional treatment (prescription pain medication from physician). Participants in the training group did not report use of any co-interventions. Three participants in the control group reported a total of four instances of use of a co-intervention. This consisted of two bouts of physiotherapy lasting one or two sessions, one bout of hydrotherapy lasting 2 weeks, and one bout of exercise circuit training lasting three weeks. Seven participants reported making a change in medication use, all aimed at pain relief (training n = 4, control n = 3).

4.4 Discussion

A ten week dynamic balance training program for people with knee OA had a significant effect on self-reported physical function, as measured on the WOMAC physical function subscale, though there was no change in dynamic balance, as measured on the CB&M. This study showed that a ten week training program focused on dynamic balance and factors known to be associated with dynamic balance, such as eccentric strength, can improve self-reported outcomes with minimal adverse effects.

Self-reported physical function, as measured on the WOMAC physical function subscale, was a primary outcome and improved significantly in the training group from baseline to follow-up compared to the control group ($p = 0.016$). These results are similar to other studies of balance training in knee OA that have also seen improvements in self-report measures, including the WOMAC physical function subscale, in their samples (99, 100, 114). Similar to previous studies, a decrease in knee pain (a descriptive measure collected at baseline and follow-up) over the ten weeks was also noted in the training group compared to the control group (mean difference = -2), suggesting that not just physical function but other self-reported measures also improved. As knee pain can affect balance and physical function, the interpretation of changes in self-reported physical function should consider the reduction in knee pain. Importantly, the improvements in self-reported physical function seen in this study are some of the largest (30%) among those previously reported, which range from 8.5% (115) to 34% (100) and indeed, this is the largest absolute improvement in score seen in all studies (more than a nine point improvement in the training group). This change in self-reported physical function is considered a clinically important change on the WOMAC physical function subscale, as it is larger than the 21% change considered the minimum clinically important improvement (187).

This promising finding can be due to several factors. First, the study design followed ACSM guidelines for exercise prescription, with a total of 40 sessions prescribed and a goal of maintaining exercise difficulty above 3/10, in order to increase the chance of adaptation from exercise. With an overall adherence of 82.2%, this means that on average, participants completed 32 sessions over 10 weeks, which is more than the ACSM recommended 2-3 sessions per week (188). As well, the average difficulty of exercises was rated as 3.4/10 during the university exercise sessions, which is above the goal of 3/10, though the difficulty of exercises performed at home was not measured. These measurements highlight that participants were likely exercising at a high enough volume and intensity to see change in physical function, but not dynamic balance. Further, the high level of adherence could be due to several aspects of the program. The mixed nature of the program (home and supervised), the game-like nature of some exercises meant to increase enjoyment, such as moving around cones and completing stepping patterns, may have increased the likelihood that a participant attends a session and completes the exercises. The length of each exercise session may also have contributed, as the session length was 30-45 minutes at the university and reported to be shorter at home. These short exercise sessions may seem less daunting and may be easier to fit into a participant's busy day than longer bouts. In addition, the exercise journal participants were asked to complete may also have served as a motivational tool and reminder to participants to exercise. Taken together, these factors support an adherence rate that is higher than other studies of balance training [such as (100)], and thus favourable improvement in physical function.

It is promising to note that adherence was associated with improvement in the WOMAC physical function subscale score (r = -0.45; not reported above), confirming a likely relationship between adherence and improvement in outcomes. There was also an inverse relationship between overall adherence and time that the knee has been symptomatic for (r = -0.40), suggesting that those who have been symptomatic for longer may adhere less to the program, and these individuals could potentially be targeted during interventions to improve their outcome. In addition, factors such as fear of pain, self-efficacy, anxiety and confidence may have changed throughout the program, and improvements in these could lead to improvements in self-reported physical function (189, 190). Fear of pain, measured using the Brief Fear of Movement Scale, was collected as a descriptive measure at baseline and follow-up. Fear of pain decreased in the exercise group compared to the control group (mean difference = -3), suggesting that fear of pain, or other psychological factors, are amenable to change and indeed may change with exercise. Other factors, such as self-efficacy with exercise, anxiety and confidence were not measured, but it is possible that they may have improved in the training group and may explain some of the changes in self-reported physical function seen here. Finally, it is possible that the participation of males in the exercise program would alter the results, as previous studies have shown some differences, such as increased strength gains for men, in the response of men and women to exercise (191, 192). As no men completed the exercise program, the results of this study should not be generalized to that population.

There was no change in any other objective measure collected, including the CB&M, and secondary outcomes including muscle strength, knee joint proprioception, and knee joint range of motion. As per the discussion above, we believe that the design of the study, combined with the favourable adherence, did provide the stimulus necessary for change. It is possible, however, that not enough emphasis was placed on a certain factor, such as muscle strength. Indeed, previous studies have highlighted the importance of eccentric strength in dynamic balancing ability (10, 81). While eccentric exercise was included in the training program, for instance in the exercises step downs and lunges, only one of the five exercises in each phase focused expressly on eccentric strength, with strength often a component but not a focus in the other exercises.

In this study, lower extremity strength improved 9.4%. Our results from Chapter 3 suggest that a change of 33% is needed to see a clinically significant change (9 points) in CB&M score. While our change was not significant, further exercises targeting eccentric strength may have resulted in greater strength gains, which may translate into dynamic balance improvements. Also, our program included supervised exercise visits as well as a home program. More supervised sessions may result in greater motivation, better form, and greater adherence to exercise, thus a better outcome. Indeed, a difference in adherence was seen between the supervised (92%) and home (79%) exercise sessions in this study. However, the cost and accessibility of supervised exercise can be prohibitive, and thus designing a training program that can successfully be completed at home, and that produces substantial improvements in dynamic balancing ability, is paramount. Further work needs to be done on dynamic balancing exercise, particularly how it may be carried out successfully at home or in a low cost manner. It may be possible, with technology, to augment the home program with virtual supervision, while keeping costs low, and this, or other methods of low cost motivation and supervision as a means of improving outcomes, should be further investigated.

This study highlights a discrepancy between self-reported and objective outcomes, with only self-reported outcomes showing an improvement over the training program. Previous studies in the literature examining balance training in knee OA have shown similar findings

(100, 114). We have hypothesized some of the reasons why this might be, including changes in psychological variables, such as fear of pain, fear of falling, self-efficacy, anxiety or confidence, many of which were not measured in this study, leading to changes in self-reported outcomes. In addition, it is possible that exercises were performed differently, at lower intensity, or with different form when performed at home, in a non-supervised environment. While the low cost nature of the home program is one of its strengths, the lack of supervision is a weakness as it is unknown how the training program was truly carried out at home. In order to see changes in objective outcome measures, the amount, intensity, and focus of exercise, as well as performance of the exercise at home should be taken into account. The length of intervention, or more specifically, time spent doing the most difficult phase of exercises, may also have contributed to the discrepancy in improvement of outcomes seen here.

We believe the CB&M is well-suited to measuring change in dynamic balancing ability – it is valid and reliable in this population, and has no demonstrable ceiling effect. The CB&M scores in our sample hold to this pattern, with no participant scoring the minimum (0) or maximum (96) score. Previous studies have found change on the CB&M with exercise (193), and have shown that the CB&M is sensitive to change (34). The change on the CB&M in the current study was only one point in the training group, while the minimum detectable change has been cited to be nine points (155), and sensitivity analysis suggests a large effect size of 0.83 (34). These measurement properties of the CB&M suggest that it does respond to change, and that in this case, true change was not seen. There was also moderate correlation between the difference in CB&M score from baseline to follow-up, and the severity of knee OA (spearman's rho = 0.53), suggesting that those with more severe knee OA may not respond in the same manner to intervention.

There are some limitations to the current study. First, participants were randomized to the training or control group, and by chance, no male participants completed the exercise program. One male participant randomized to the training program dropped out prior to the start of the program. As such, as stated above, the results of the training program cannot be generalized to males. Future studies in this area may benefit from stratification based on sex prior to randomization. Also, there were a much larger number of women than men enrolled in the study. While this is partly due to the greater prevalence of knee OA in women, the low number of men enrolled may also be due to sampling method (more women in previous studies invited to participate here, and perhaps more women responding to local advertisements). Further, the control group in this study was a no-treatment control group. An active control group may have allowed the examination of the training program with respect to a more general exercise program, however, this was not possible due to limitations in funding. However, this study does provide further information on dynamic balance training in those with knee OA, with results that can improve on the design of such programs as well as their outcomes in the future. Finally, the study sample size was powered using a previous effect size estimate for the WOMAC. For this reason, it is unknown whether the sample size was large enough to see changes in CB&M score.

In conclusion, we found that ten weeks of dynamic balance training resulted in a significant improvement in self-reported physical function. Further research is needed to investigate how exercise may result in improvement on objective measures of dynamic balance, such as the CB&M. Also, the use of technology such as real-time video or messaging allowing investigators to monitor and motivate participants completing home programs, while maintaining the benefits of the home program (low cost and accessibility) should be further examined. The impact of such technologies on home exercise performance and adherence may increase the chance of improvement on objective outcomes, as well as maintaining exercise safety through low-cost supervision. While self-reported improvement is clinically important, further changes in more objective outcomes may help to lessen the risk of falling and further improve clinical outcomes.

Chapter 5: General discussion

5.1 Overview

The results of this thesis provide a greater understanding of dynamic balance assessment and treatment in people with knee OA. Specifically, the measurement properties of a clinical tool to assess dynamic balance were investigated, factors that were associated with dynamic balance performance on this scale were explored, and the effects of a dynamic balance exercise program were examined. This thesis advances the understanding of dynamic balance assessment in this patient population in Chapter 2, with the investigation of the test re-test reliability, convergent validity and construct validity of the CB&M. The results indicate that the CB&M is a valid and reliable clinical tool in this population. This is then built upon in Chapter 3, where clinically modifiable factors that may affect dynamic balance were investigated. This study found that eccentric muscle strength, and to a lesser extent knee range of motion, were associated with dynamic balance, which was measured by the CB&M. Chapter 4 examined a balance training program for people with knee OA, and found that ten weeks of exercise significantly improved self-reported physical function, but not dynamic balance as measured by the CB&M. The evidence from Chapters 2 and 3 was important in designing the study in Chapter 4. Chapter 2 provided a valid and reliable outcome measure that can be used to measure change in dynamic balance before and after an intervention, while Chapter 3 contributed important factors to consider when designing an exercise program meant to target dynamic balance control in this population. Chapter 4 furthers our understanding of exercise in this population aimed at improving dynamic balance control, and contributes important information and suggestions for future programs that can help improve future outcomes. Taken together, these studies offer insight into dynamic balance assessment and treatment in people with knee OA. Further, the results of these studies provide avenues for further research and insights to help improve on exercise prescription in this population.

5.2 CB&M as a clinical tool for people with knee OA

The CB&M was designed to measure dynamic balance required during advanced tasks, similar to ones that may be necessary in order to maintain independence in the community (25). This scale was designed with input from clinicians and patients to capture the dynamic balance needs during daily tasks as comprehensively as possible. This scale was originally designed for use with individuals who have experienced TBI. However, it has been used in other populations, including stroke (34), healthy older adults (194), and children with cerebral palsy (195), suggesting the scale may be able to assess dynamic balance control in a wide range of populations. To date, there are few clinical scales that assess dynamic balance control. There are even fewer that have been used in a knee OA population. Further, those that have been used, such as the BBS, often present significant limitations to their use (i.e. ceiling effects). In a search for a valid clinical tool that could reliably measure dynamic balance in the knee OA population, we investigated the use of the CB&M. We examined the measurement properties of the scale in a knee OA sample, and a sample of individuals without knee OA.

The CB&M is a valid and reliable tool for dynamic balance control assessment. We found the CB&M displayed convergent validity, as indicated by moderate relationships with other clinical scales measuring dynamic balance, standing balance, and mobility. The CB&M also displayed known groups (construct) validity, showing a difference in scoring between those with and without knee OA, and high test re-test reliability when tested in those with knee OA within 14 days.

In study 3, both the CB&M and WOMAC were collected as primary outcomes. The CB&M and WOMAC physical function subscale, while similar in some tasks, assess different outcomes. The WOMAC subscale primarily assesses self-reported difficulty on simple tasks such as taking socks off and getting in and out of a car, while the CB&M assesses objective difficulties with more advanced tasks. Some tasks overlap, for instance, both measures refer to crouching and rising type movements. Thus, while this diversity is a strength of the study, it may also be a limitation with respect to the applicability of the WOMAC effect size used for sample size calculation in study 3.

While the CB&M appears to assess dynamic balance, it is clear from further investigation (carried out in Chapter 3, and from observation), that there may be other factors that contribute to dynamic balance control and scoring on the CB&M (i.e. strength). It is important that clinicians using a tool understand fully not just the measurement properties, but what factors contribute to scoring on a scale. In order to better understand this, another sample of individuals with knee OA were assessed using the CB&M, and modifiable clinical factors such as strength, proprioception, and range of motion were included in a multiple linear regression. Lower extremity eccentric strength, and less so, knee range of motion, were associated with dynamic balance as measured by scoring on the CB&M. These results provide greater understanding of the CB&M, and dynamic balance control, in the knee OA population. However, there are still some questions regarding the CB&M. First, as the scale was originally designed for individuals after a TBI, there may be tasks not well suited to assessing dynamic balance control in people with musculoskeletal impairment, such as knee OA. Knee OA presents a different set of limitations, such as knee pain and restriction that are not present in populations such as TBI, that may alter the strategies used while performing tasks, thus affecting scoring. Modification of the scale for the knee OA population may provide an even more powerful, and sensitive measure of dynamic balance. Indeed, in the stroke population, a Rasch analysis has suggested that a modified version of the CB&M may better encompass dynamic balance control in that population (196). Second, in order to perform many tasks fully on the CB&M, participants are required to execute multiple movements (i.e. walking, turning, and continuing backwards). The complicated nature of the tasks, while more realistic to everyday activities, may necessitate other factors (such as range of motion or strength) in order to complete a task with full points. A factor analysis in this population may be warranted to better understand what factors may contribute to each individual task. Further exploration of the CB&M is also warranted, including with individuals that are not well represented in the current studies, such as those with severe knee OA (KL4). Indeed, more individuals with mild, or moderate, knee OA participated in the studies in this thesis than those with severe knee OA, and thus their performance on this scale is not well understood.

5.3 Balance exercise for people with knee OA

Exercise to improve balance and reduce the risk of falls is important and emphasized in the healthy older adult literature, but this is not the case in knee OA investigation. While it has been found that those with knee OA report more falls than older adults without knee OA (47), and that aspects of balance control are reduced in this population, such as proprioception and strength, few studies have investigated dynamic balance treatment in this population. The importance of this area has been recognized, and recently, there have been calls to include balance exercise in knee OA treatment guidelines (101). Of the few studies that have investigated balance exercise in a knee OA population, results are conflicting. Our work in Chapter 4 highlights that clinically significant self-reported improvements in physical function can be seen with dynamic balance training. However, changes in objective outcome measures were not seen, and this area needs further investigation to better understand what stimulus is needed to see improvements in outcomes. Our work in Chapter 4 also highlights an evidence-based study design that produces high levels of adherence, while maintaining a moderate level of difficulty of the intervention. This is particularly important, as many studies see low levels of adherence, meaning the benefit of exercise is not being received by these participants. Indeed, in the work by Fitzgerald et al. (100), 53% of participants had an adherence rate below 80%. Based on our results, and the previous work, we recommend designing interventions using multiple sessions per week for ten weeks or more, in line with ACSM guidelines, in order to maximize the likelihood of seeing results. We further recommend virtual or in-person supervision of the exercises. It is hoped that these recommendations for future investigation will help to better understand dynamic balance, as well as improve dynamic balance, particularly on objective dynamic balance measures in those with knee OA.

5.4 Limitations

There are some limitations in the studies contained with this thesis. These include generalizability of some results, drawbacks of currently available clinical proprioceptive outcome measures, limitations of a no-treatment control group, and difference in the sample from Study 1 and 2 to Study 3. These are detailed below.

1) Few people with severe knee OA (KL 4) participated in this work. Further, the investigation was only aimed at those with medial tibiofemoral knee OA, and those with OA

predominantly in other parts of the knee, such as the patellofemoral joint, were excluded from the studies. Participants who are more functionally able with less severe knee OA may be more likely to volunteer to participate in a study, and thus those with severe knee OA may be unwilling, or unable to participate. As such, the results of the studies cannot fully be generalized to those with severe knee OA. As well, the exclusion of those with lateral tibiofemoral knee OA, or patellofemoral knee OA, means results cannot be generalized to these populations and the understanding of dynamic balance assessment and treatment gained from this work applies only to those with tibofemoral knee OA.

2) Proprioception was measured using an established measure: passive joint position sense. During this test, participants are blindfolded, and while sitting, asked to try and match their knee position to one in which it was previously held. While this is a widely used test, it is limited in its measurement of proprioception as it is not weight-bearing. It was expected that scores on the CB&M, a measure of dynamic balance, may be associated with knee joint proprioception, as literature would suggest; however, we found no association in Chapter 3, and no change with balance exercises in Chapter 4. This may be due to differences in how proprioception was measured (sitting), and actual proprioceptive use during the CB&M (weight-bearing standing or moving). It is unknown whether this discrepancy may be responsible for the lack of association, or whether there truly is no association of proprioception with dynamic balance control. A more functional test, when devised, may produce different results.

3) In the Chapter 4 study, a no-treatment control group was included. The use of a no-treatment control allows determination of any placebo effect of the baseline or follow-up testing sessions, or effect of the intervening ten weeks. However, the control group was not an active control. As such, it is unknown what difference there may be between the treatment group, who

are completing dynamic balance exercise, and a general exercise or other active control group. This type of comparison would provide further insight into clinically important outcomes for care.

4) Finally, the individuals in Study 1 and 2 were highly mobile and functionally able, as characterized by low TUG times, fast walking speeds, and CB&M scores of 71 and 73 on average. However, in Study 3, the average score on the CB&M was 53, in order to allow for improvement. This difference in CB&M score and functional ability between studies may mean that the generalizability of the results from Study 1 and 2 to the Study 3 sample should be done with caution. Further research is needed on individuals at all functional levels with knee OA with respect to dynamic balancing ability.

5.5 Implications and future directions

The above chapters highlight investigations in dynamic balance control in people with knee OA, an important area of study. The CB&M, a tool used to clinically assess dynamic balance control, has not previously been validated in a knee OA population. This investigation adds new knowledge particularly useful for clinical practice. Further, regression modelling was used to assess factors associated with dynamic balance in knee OA. This process has only previously been used to assess factors associated with static balance in individuals with knee OA (22, 65), and this approach provides new understanding of factors associated with dynamic balance control. Importantly, factors identified can be modified clinically and may be targeted in treatment, helping to refine outcomes and improve quality of life. Finally, the training program was the first to measure the change in dynamic balancing ability on the CB&M with ten weeks of dynamic balance training, with results suggesting subjective but not objective improvement. These results can inform future training programs with the aim of continued improvement.

The CB&M has been shown to be a valid and reliable measure of dynamic balancing ability. As mentioned earlier, more information about the scale, via factor analysis or other investigation may provide more information to clinicians about what is being measured, as well as provide guidance in scale modification. Future research should also consider quantification of falls, as this is a primary concern in health care. In particular, the prospective association or predictive capacity of the CB&M of falls in the knee OA population should be examined. This would further inform clinicians of falls risk when assessing an individual on the CB&M.

Further refinement of balance exercise, as well as of overall training programs, should also be undertaken. Future studies could investigate whether eccentric lower extremity strengthening exercise is a key component in programs for those with knee OA. The difficulty of exercises should also be considered, with time spent on more targeted exercises. Finally, future studies may consider sub-analysis of training interventions by knee OA severity, or even approaching balance training differently for different knee OA severities, in order to improve on current outcomes. For instance, those with more severe knee OA may benefit from more supervised sessions, or potentially a longer intervention, where more time can be spent in certain phases of the exercise program. If possible, the rate of falls after a training program should also be collected. This would allow a better understanding of how the training program influences the risk and rate of falls, with the overall goal of improving dynamic balancing ability, and reducing the risk of falls.

Finally, the advent of accessible and cost-effective technologies such as real-time video or messaging may improve our ability to support participants as they complete exercise programs at home. The use of these technologies should be explored, as they may help improve outcomes in several ways. First, improved monitoring of home programs may allow investigators to help participants maintain appropriate technique and difficulty of exercises, improving the outcomes of the exercise program. Second, increased contact with investigators in this way may serve to motivate participants to complete the exercises through increased feedback, maintaining high adherence rates. Finally, this technology may help to make exercise programs more accessible to those who need them most (for instance, those with limited mobility, live in rural or remote settings or have lower socioeconomic status), thus improving outcomes for those who may otherwise be unable to participate. The benefits, and any drawbacks of this technology, should be further examined.

5.6 Conclusion

This thesis provides novel insight into dynamic balance assessment and treatment in people with knee OA. Importantly, the CB&M was found to be a valid, reliable measure of dynamic balancing ability for the knee OA population, with eccentric lower extremity strength and, to a lesser extent, knee range of motion associated with CB&M scoring. Also, ten weeks of dynamic balance training was found to improve on subjective outcomes but not objective outcomes. This program provides insight for further refinement of balance training in knee OA. Future research is needed to more comprehensively assess and treat dynamic balance control in knee OA.

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Appendix A: Community Balance and Mobility Scale

CB&M

CB&M

Community Balance & Mobility Scale

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UHN Toronto General Toronto Western Princess Margaret Toronto Rehab

VELUT ARBOR ÆVO

INTRODUCTION

The consequences of postural dyscontrol are pervasive and have a significant impact on activities of daily living, community mobility and social, work and leisure pursuits. The Community Balance and Mobility Scale (CB&M) was designed to evaluate balance and mobility in patients who, although ambulatory, have balance impairments which reduce their full engagement in community living.

The following is a brief summary of the key measurement properties of the CB&M established to date with individuals with traumatic brain injury (TBI). Content validity was obtained by the involvement of patients with TBI (n=7) and clinicians (n=17) during the item generation process. The CB&M demonstrates intraclass correlation coefficients (ICC's) of 0.977 for both intra- and inter-rater reliability, 0.898 and 0.975 for test-retest reliability (5-day and immediate, respectively) and Cronbach's alpha of 0.96 for internal consistency.[1]

Additional studies have shown that in ambulatory patients with TBI, the CB&M is less susceptible to a ceiling effect than the commonly used Berg Balance Scale and better able to capture change in this higher functioning group.[2]

The construct validity of the CB&M was supported by associations with laboratory measures of dynamic postural control and measures of community integration and balance confidence.[2] Statistically significant correlations were demonstrated between the CB&M and spatiotemporal measures of gait including walking velocity, step length, step width and step time (r values ranging from 0.38 to 0.87). Importantly, variability in step length and step time, used as a marker of dynamic stability, also correlated significantly with CB&M scores (r values ranging from 0.46 to 0.70). Significant associations were also achieved with self-report measures of balance confidence and participation in the community using the Activities-specific Balance Confidence (ABC) scale (r=0.60) and the Community Integration Questionnaire (r=0.54), respectively.

The CB&M has been able to capture the decline in balance that occurs with aging in healthy individuals supporting the validity and sensitivity of the scale.[3] Healthy age-referenced data across the decades is available from the authors to assist in interpretation of patient scores. Determining if patients are within the range of healthy values for their age group is helpful in identifying the presence and degree of balance impairment.

Clinical feedback and user reports have indicated that the scale is also appropriate for high-functioning clients with diagnoses other than traumatic brain injury but further studies are warranted.

The positive results support that the CB&M is a reliable and valid clinical outcome measure for detecting dynamic instability and evaluating change in ability in the higher functioning ambulatory patient with TBI.

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Community Balance & Mobility Scale (CB&M) Administration And Scoring

PHYSICAL SETTING

Much of the testing of the CB&M is designed to occur within a clinic setting upon a measured track. (The set-up is outlined below.) The therapist must also have access to a full flight of stairs (minimum 8 steps).

The following materials are required for testing:

- stop watch (digital preferred)
- average size laundry basket or large rigid box of same dimension
- 2 lb. & 7 ½ lb. weights
- visual target used in Item 8
  (a paper circle 20cm in diameter with a 5cm diameter black circle in the middle)
- bean bag

CLOTHING

The patient should wear comfortable clothing and enclosed, flat footwear. Footwear should be consistent on subsequent testing. The patient is allowed to use whatever orthotic is customarily worn at the time of testing.

RATING PROCEDURE

Use of Ambulation Aides: All tasks are to be performed without ambulation aides (with one exception in Item 12 - Descending Stairs).

Timed Tasks: The clock beside the title of an item indicates that the task is timed.

Demonstration of Tasks: To ensure understanding of the task, the therapist should demonstrate all tasks while instructing the patient.

Standardized Starting Position: Unless otherwise indicated, the following starting position should be used: standing feet slightly apart, arms at sides, head in neutral position with eyes forward, toes touching start line.

Scoring Patient Performance: Score on the first trial. In cases where it is clear that the individual did not understand the task, only then is re-instruction and a second trial allowed.

The therapist should judge the patient's performance in comparison to a young adult with a normal neuro-musculoskeletal system.

Scale descriptors are detailed and precise. It is recommended that the grading criteria be reviewed well, including criteria for when the 'test is over' prior to performing the tasks.

Patient Safety: If in the therapist's clinical judgment the patient would be unsafe in performing part or all of a task, the patient should not attempt it. Score according to the guidelines if part of the task is attempted or "0" if it is not attempted.

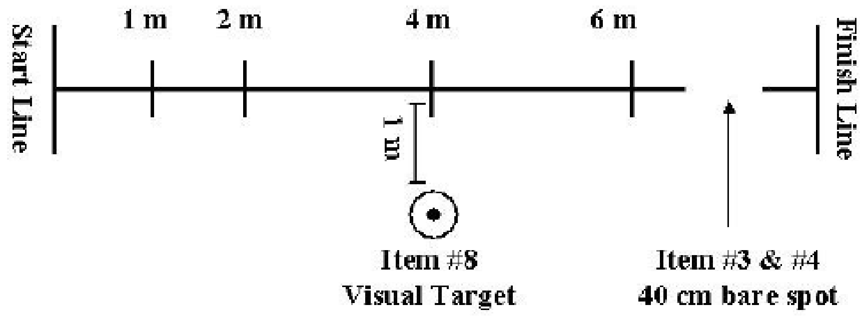
Rest Periods: Rest periods are acceptable between tasks, as required.

DEFINITION OF TERMS

Equilibrium Reactions: For the purpose of this measure, the term equilibrium reactions is defined as the use of movement strategies of the trunk and limbs to maintain centre of mass within the base of support.

THE TRACK

Set-up: The total area recommended for testing is 10 metres by 2 metres. The track is an 8 metre line with a perpendicular start and finish line. It may be applied to the floor with paint or duct tape, 5cm wide. The 1m, 2m, 4m, and 6m points should be indicated. A 40cm bare spot for items #3 and #4 as the diagram shows below is recommended if tape is used. The visual target for Items 8 and 11 is placed at the 4m mark, at patient's eye level and 1m from the outside edge of the track.



Use of the track for measurement:

The track is used in two ways for measurement of the balance items:

i) as a direct measurement, when foot placement on the line is part of the scoring criteria e.g. Tandem Walking,

ii) as a reference to indicate whether the patient maintains a straight course or veers from a straight trajectory during the task e.g. Walking & Looking.

COMMUNITY BALANCE & MOBILITY SCALE (CB&M) SCORE SHEET

Full CB&M guidelines must be reviewed to ensure accurate administration and scoring. To score 5, actions must appear coordinated and controlled without excessive equilibrium reactions.

CB&M Tasks	Notes	Initial	Mid	D/C
1. UNILATERAL STANCE 0 unable to sustain 1 2.00 to 4.49 sec. 2 4.50 to 9.99 sec. 3 10.00 to 19.99 sec. 4 ≥ 20.00 secs. 5 45.00 sec., steady and coordinated	"Look straight ahead" Test is over if stance foot moves from start position or raised foot touches ground.	Left		
		Right		
2. TANDEM WALKING 0 unable 1 1 step 2 2 to 3 consecutive steps 3 > 3 consecutive steps (levels 2 & 3: heel-toe distance < 3″ *(for levels 2 &3 only)*) 4 > 3 consecutive steps 5 7 consecutive steps (levels 4 & 5: in good alignment = heel-toe contact and feet straight *(for levels 4 & 5 only)*)	"Look ahead down the track, not at your feet."			
3. 180° TANDEM PIVOT 0 unable to sustain tandem stance 1 sustains tandem stance but unable to unweight heels or initiate pivot 2 initiates pivot but unable to complete 180° turn 3 completes 180° turn but discontinuous pivot (e.g. pauses on toes) 4 completes 180° turn in a continuous motion but can't sustain reversed position 5 completes 180° turn in a continuous motion and sustains reversed position	Test is over if touches heels down or steps out of position.			
4. LATERAL FOOT SCOOTING 0 unable 1 1 lateral pivot 2 2 lateral pivots 3 ≥ 3 pivots but < 40 cm 4 40 cm in any fashion and/or unable to control final position 5 40 cm continuous, rhythmical motion with controlled stop.	Test is over if patient hops or opposite foot touches down.	Left		
		Right		
5. HOPPING FORWARD 0 unable 1 1 to 2 hops, uncontrolled 2 2 hops, controlled but unable to complete 1 metre 3 1 metre in 2 hops but unable to sustain landing (touches down) 4 1 metre in 2 hops but difficulty controlling landing (hops or pivots) 5 1 metre in 2 hops, coordinated with stable landing	Test is over if opposite foot touches down.	Left		
		Right		
6. CROUCH AND WALK 0 unable to crouch 1 able to descend only 2 descends and rises but hesitates, unable to maintain forward momentum 3 crouches and walks in continuous motion, time ≤ 8.00 sec. protective step 4 crouches and walks in continuous motion, time ≤ 8.00 sec. excess equilibrium reaction 5 crouches and walks in continuous motion, time ≤ 4.00 sec.				

7. LATERAL DODGING 0 unable to perform 1 cross-over in both directions without support 1 1 cross-over in both directions in any fashion 2 1 or more cycles, but does not contact line every step 3 2 cycles, contacts line every step 4 2 cycles, contacts line every step 12.00 to 15.00 sec. 5 2 cycles, contacts line every step < 12.00 sec. coordinated direction change	"Do this as fast as you can yet at a speed that you feel safe."			
8. WALKING & LOOKING 0 unable to walk and look e.g. stops 1 performs but loses visual fixation at or before 4 metre mark 2 performs but loses visual fixation after 4 metre mark 3 performs and maintains visual fixation between 2-6 metre mark but protective step 4 performs and maintains visual fixation between 2-6 metre mark but veers 5 performs, straight path, steady and coordinated ≤ 7.00 sec.	"Walk at your usual pace."	Left Right		
9. RUNNING WITH CONTROLLED STOP 0 unable to run 1 runs, time > 5.00 sec. 2 runs, time > 3.00 but ≤ 5.00 sec., unable to control stop 3 runs, time > 3.00 but ≤ 5.00 sec., with controlled stop, both feet on line 4 runs, time ≤ 3.00 sec., unable to control stop 5 runs, time ≤ 3.00 sec., with controlled stop, both feet on line, coordinated and rhythmical	"Run as fast as you can." Hold position on finish line.			
10. FORWARD TO BACKWARD WALKING 0 unable 1 performs but must stop to regain balance 2 performs with reduced speed, time > 11.00 sec. or requires 4 or more steps to turn 3 performs in ≤ 11.00 sec. and/or veers during backward walking 4 performs in ≤ 9.00 sec. and/or uses protective step during or just after turn 5 performs in ≤ 7.00 sec., maintains straight path	"Walk as quickly as you can yet at a speed that you feel safe."			
11. WALK, LOOK AND CARRY (Score same as #8 Walking and Looking)	"Walk at your usual pace."	Left Right		
12. DESCENDING STAIRS 0 unable to step down 1 step, or requires railing or assistance 1 able to step down 1 step with/without cane 2 able to step down 3 steps with/without cane, any pattern 3 3 steps reciprocal or full flight in step-to pattern — no railing 4 full flight reciprocal, awkward — no cane 5 full flight reciprocal, rhythmical and coordinated +1 bonus for carrying basket				
13. STEP-UPS X 1 STEP 0 unable to step up, requires assistance or railing 1 steps up, requires assistance or railing to descend 2 steps up and down (1 cycle) 3 completes 5 cycles 4 completes 5 cycles in > 6.00 but < 10.00 sec. — unacceptable to look at feet 5 completes 5 cycles in ≤ 6.00 sec., rhythmical	"Do this as quickly as you can. Try not to look at your feet."	Left Right		
TOTAL SCORE		/96	/96	/96

Signature(s)______________ Date(s)______________

1. UNILATERAL STANCE

i) Test to be performed on right leg
ii) Test to be performed on left leg

Starting position: Standardized starting position.

Instructions to Patient: *Stand on your right/left leg and hold for as long as you can up to 45 seconds. Look straight ahead.*

Instructions to Therapist: Begin timing as soon as the patient's foot leaves the ground. Do not allow the patient to brace the elevated leg against the supporting leg.

Test is over: Stop timing if stance foot moves from starting position or opposite foot touches ground.

GRADING:

0 unable to sustain unilateral stance independently, i.e. able to unweight leg for brief moments only

1 able to sustain unilateral stance for 2.00 - 4.49 sec.

2 able to sustain unilateral stance for 4.50 - 9.99 sec.

3 able to sustain unilateral stance for 10.00 - 19.99 sec.

4 able to sustain unilateral stance for $\geq$ 20.00 sec.

5 able to sustain unilateral stance for 45.00 sec. in a steady & coordinated manner
NOT Acceptable: excessive use of equilibrium reactions

2. TANDEM WALKING

Starting position: Standardized starting position with one foot positioned on the 8m line.

Instructions to Patient: *Walk forward on the line, heel touching toes. Keep your feet pointing straight ahead. Look ahead down the track, not at your feet. I will tell you when to stop.*

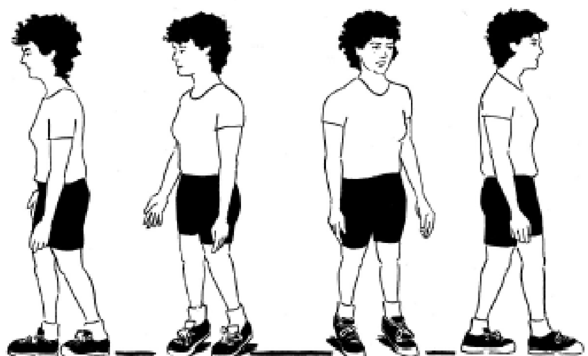
Instructions to Therapist: If able, allow the patient to take a maximum of 7 steps. For your scoring, count only those consecutive steps for which the heel is on the line and the heel-toe distance is $\leq$ 8cm (3 inches).

GRADING:

0	unable to complete 1 step on the line independently, i.e. requires assistance, upper extremity support, or takes a protective step
1	able to complete 1 step independently, acceptable to toe out
2	able to complete 2 or 3 steps consecutively on the line, acceptable to toe out
3	able to complete more than 3 steps consecutively, acceptable to toe out
4	able to complete more than 3 steps consecutively, in good alignment (heel-toe contact, feet straight on the line, no toeing out), but demonstrates excessive use of equilibrium reactions
5	able to complete 7 steps consecutively, in good alignment (heel-toe contact, feet straight on the line, no toeing out), and in a steady & coordinated manner. **NOT Acceptable:** excessive use of equilibrium reactions looking at feet

3. 180° TANDEM PIVOT

Starting position: Tandem Stance on bare spot in track (see set-up diagram) – aligned heel to toe, no toeing out, arms at sides, head in neutral position and eyes forward. Patient allowed to choose either foot in front and may use assistance or upper extremity support to achieve, but not sustain, tandem stance.



Start Action Finish

Instructions to Patient: *Lifting your heels just a little, pivot all the way around to face the opposite direction without stopping. Put your heels down and maintain your balance in this position.*

Instructions to Therapist: When right foot is in front in tandem position, patient to turn towards left. When left foot is in front in tandem position, patient to turn towards right. Therapist may assist patient to assume starting position.

Test is over: When patient puts heels down or steps out of position.

GRADING:

0	unable to sustain tandem stance independently, i.e. requires assistance or upper extremity support
1	able to sustain tandem stance independently, but unable to unweight heels and/or initiate pivot
2	able to initiate pivot, but unable to complete 180° turn
3	able to complete 180° turn but discontinuous, i.e. pauses on toes during pivot
4	able to complete 180° turn in a continuous motion, but unable to sustain reversed position **NOT Acceptable:** heel-toe distance > 8cm (3 inches)
5	able to turn 180° in a continuous and coordinated motion and sustain reversed position (Acceptable to have feet slightly angled out in reversed position) **NOT Acceptable:** heel-toe distance > 8cm (3 inches); excessive use of equilibrium reactions

4. LATERAL FOOT SCOOTING

Lateral foot scooting is defined as alternately pivoting on the heel and toe of one foot while moving sideways.
i) move to the right when performing on right leg
ii) move to the left when performing on left leg

Starting position: Standing on the line beside the bare spot in unilateral stance on right/left foot, arms at sides. Foot is perpendicular to the track.

Instructions to Patient: *Stand on your right/left leg and move sideways by alternately pivoting on your heel and toe. Keep pivoting straight across until you touch the line and maintain your balance in this position.*

Instructions to Therapist: The patient moves laterally along the length of the bare spot (40cm). For the grading, one lateral pivot is defined as either pivoting on heel, moving toes laterally OR pivoting on toes, moving heel laterally.

Test is over: When patient steps, hops, or touches opposite foot to floor.

GRADING

0	unable to sustain unilateral stance independently, i.e. requires assistance or upper extremity support
1	able to perform 1 lateral pivot in any fashion
2	able to perform 2 lateral pivots in any fashion
3	able to perform $\geq$ 3 lateral foot pivots, but unable to complete 40cm
4	able to complete 40cm in any fashion, acceptable to be unable to control final position
5	able to complete 40cm in a continuous and rhythmical motion, demonstrating a controlled stop briefly maintaining unilateral stance **NOT Acceptable:** pausing while pivoting to regain balance veering from a straight line course excessive use of equilibrium reactions excessive trunk rotation while pivoting

5. HOPPING FORWARD

i) to be performed on right leg
ii) to be performed on left leg

Starting position: Unilateral stance on right/left with entire foot on the track. Heel placed on inside edge of starting line.

Instructions to Patient: *Stand on your right/left foot. Hop twice straight along this line to pass the 1m mark with your heel. Maintain your balance on your right/left leg at the finish.*

Instructions to Therapist: It is recommended that the therapist assess safety prior to commencing task by having the patient hop in one spot. Patient is successful in completing 1m when the heel of the foot is touching or beyond the 1m line.

Test is over: If patient touches down with suspended foot between hops.

GRADING	
0	unable to sustain unilateral stance independently or hop, i.e. requires assistance or upper extremity support
1	able to perform 1 or 2 hops with poor control, i.e. unable to sustain 1 foot landing for even brief moments, unable to complete 1m
2	able to perform 2 hops sequentially in a controlled manner, unable to complete 1m
3	able to complete 1m in 2 hops, but unable to sustain 1 foot landing, i.e. touches down or steps with opposite limb upon landing. Acceptable to deviate from the line
4	able to complete 1m in 2 hops, but difficulty controlling landing, i.e. hops or pivots on stance foot to maintain landing. Acceptable to deviate from the line **NOT Acceptable:** touching down or stepping with opposite limb to achieve stability on landing
5	able to complete 1m in 2 hops in a coordinated manner and sustain a stable landing **NOT Acceptable:** deviate from line excessive use of equilibrium reactions

6. CROUCH AND WALK

Starting Position: Standardized starting position. Bean bag is placed to right or left side of the 2m mark considering which hand the patient will use to pick it up.

Instructions to Patient: *Walk forward and, without stopping, bend to pick up the bean bag and then continue walking down the line.*

Instructions to Therapist: This task is performed using only half of the track. Start timing when the patient's foot leaves the ground. Stop timing when both feet cross the 4m line.

Patient should use the less affected upper extremity for the task. This will avoid downgrading the score due to limitations of upper extremity function as opposed to balance function.

GRADING

0 unable to crouch (descend) to pick up bean bag independently, i.e. requires assistance or upper extremity support

1 able to crouch (descend), but unable to maintain crouch to pick up bean bag or rise to stand independently, i.e. requires assistance or touches hands down to floor

2 able to crouch to pick up bean bag and rise to stand independently but must hesitate at any time during activity, i.e. unable to maintain forward momentum

3 able to crouch and walk in a continuous motion (i.e. maintaining forward momentum) with time $\leq$ 8.00 seconds and demonstrates protective step at any time during the task

4 able to crouch and walk in a continuous motion with time $\leq$ 8.00 seconds and/or uses excessive equilibrium reactions to maintain balance at any time during the task
NOT Acceptable: veering off course

5 able to crouch and walk in a continuous and rhythmical motion with time $\leq$ 4.00 seconds
NOT Acceptable: veering off course
excessive use of equilibrium reactions

7. LATERAL DODGING

Starting Position: Standing at the 2m mark with feet perpendicular to the track. The toes of both feet should cover the track

Instructions to Patient: *Move sideways along the line by repeatedly crossing one foot in front of and over the other. Place part of your foot on the line with every step. Reverse direction whenever I call "Change!" Do this as fast as you can, yet at a speed that you feel safe.*

Instructions to Therapist: Patient moves laterally back and forth along the line, between the 2m and 4m marks by repetitively crossing one foot <u>over and in front</u> of the other.

It is acceptable for the patient to look at the line to monitor foot placement.

One cross-over includes crossing one leg over to land beside the other and returning the back leg to an uncrossed position.

One cycle requires the patient to cross-over for a 2m distance and return. The test requires that the patient perform two of these cycles (a total of 8m). Begin timing as soon as the patient's foot leaves the ground. Stop timing when both feet cross over the final mark. To cue the patient to change direction, call out "Change!" when one foot passes the 2 and 4m marks. The patient should believe direction changes are random.

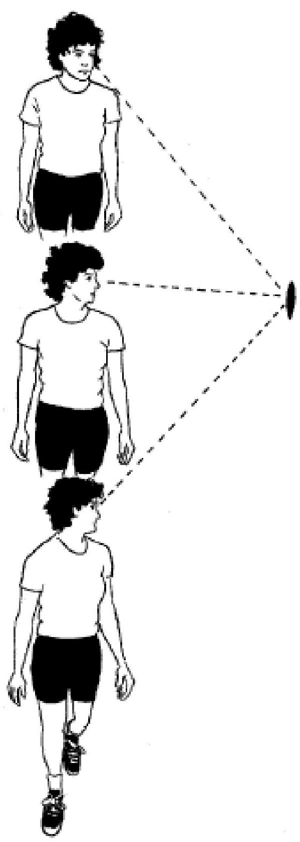
GRADING

0	unable to perform one cross-over in both directions without loss of balance or use of support.
1	able to perform one cross-over in both directions without use of support, but unable to contact the line with part of the foot.
2	able to cross-over for 1 or more cycles to and from the 2m mark, but unable to contact the line with every step.
3	able to perform 2 cycles in any fashion (to the 2m line and back <u>twice</u>) and one part of each foot must contact the line during each step.
4	performs 2 cycles as described in level 3 in 12.00 to 15.00 sec.
5	performs 2 cycles in less than 12.00 sec. in a continuous, rhythmical fashion with coordinated direction changes immediately after verbal cue.

8. WALKING & LOOKING

i) to be performed looking right
ii) to be performed looking left

Starting position: Standardized starting position. (See set-up diagram for placement of visual target.)



Instructions to Patient: *Walk at your usual pace to the end of the line. I will tell you when to look at the circle. Keep looking at it while you walk past it. I will then tell you when to look straight ahead again. Try not to veer off course while you walk.*

Instructions to Therapist: Score client as defined in the guidelines, irrespective of the underlying limiting impairments, e.g. decreased neck or trunk rotation. Start timing when the patient's foot leaves the ground. Stop timing when both feet cross the 8m finish line.

1. At the 2m mark, ask the patient to "Look at the circle."

2. Cue the patient to "Keep looking at the circle" as they look back over their shoulder until they reach the 6m mark.

3. At the 6m mark, ask the patient to "Look straight ahead and continue walking until the end of the line."

Stand in a location where the patient's ability to maintain fixation can be assessed, that is, beside the target. Thus, a second person may be needed to walk with the patient to ensure safety. It is acceptable to continue to remind the patient of where they should be looking at each segment.

To score in the opposite direction, repeat task starting from opposite end of the line.

8. WALKING & LOOKING (CONTINUED)

GRADING

0 unable to walk and look, i.e. has to stop to look, or requires assistance or upper extremity support at any point during the test

1 able to continuously walk and initiate looking, but loses visual fixation on circle at or before 4m mark

2 able to continuously walk and look, but loses visual fixation on circle after 4m mark, i.e. while looking back over the shoulder

3 able to continuously walk and fixate upon the circle between the 2m and 6m mark, but demonstrates a protective step.

4 able to continuously walk and fixate upon the circle between the 2m and 6m mark, but veers off course at any time during task.

5 able to continuously walk and fixate upon circle between the 2m and 6m mark, maintains a straight path, in a steady and coordinated manner, time $\leq$ 7.00 sec.
NOT Acceptable: inconsistent or reduced speed
looking down at feet

9. RUNNING WITH CONTROLLED STOP

Starting position: Standardized starting position.

Instructions to Patient: *Run as fast as you can to the end of the track. Stop abruptly with both feet on the finish line and hold this position.*

Instructions to Therapist: Begin timing when initial foot leaves ground. Stop timing when both feet reach the finish line. It does not matter whether the feet land consecutively or simultaneously on the finish line.

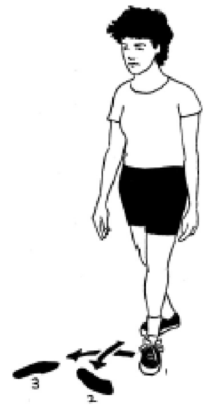
GRADING

0	unable to run (with both feet off ground for brief instant), rather demonstrates fast walking or leaping from foot to foot
1	able to run in any fashion, time > 5.00 sec.
2	able to run in any fashion, time > 3.00 sec. but ≤ 5.00 sec., but is unable to perform a controlled stop with both feet on the line, i.e. uses protective step or excessive equilibrium reactions
3	able to run in any fashion, time > 3.00 sec. but ≤ 5.00 sec., and perform a controlled stop with both feet on the line **NOT Acceptable:** excessive use of equilibrium reactions
4	able to run in any fashion, time ≤ 3.00 sec., but is unable to perform a controlled stop with both feet on the line, i.e. uses protective step(s) or excessive equilibrium reactions
5	able to run in a coordinated and rhythmical manner and perform a controlled stop with both feet on the line, time ≤ 3.00 sec. **NOT Acceptable:** excessive use of equilibrium reactions

10. FORWARD TO BACKWARD WALKING

Starting position: Standardized starting position.

Instructions to Patient: *Walk forwards to the halfway mark, turn around and continue to walk backwards until I say "Stop." Try not to veer off course. Walk as quickly as you can, yet at a speed that you feel safe.*



Instructions to Therapist: Start timing when the patient's foot leaves the ground. Stop timing when both feet cross the 8m finish line. The patient is to turn at the 4m mark. It is acceptable for the subject to turn in any direction s/he chooses.

- When counting the steps required to turn 180°:
  - i) the first step in the turn is angled away from the forward trajectory,
  - ii) the last step in the turn completes the 180° turn and is oriented towards the starting line, initiating backwards walking.
- It is also acceptable to pivot on one foot rather than stepping around.

GRADING

0	unable to complete task, i.e. requires assistance or upper extremity support
1	able to complete task independently, but must stop to maintain/regain balance at any time during this task
2	able to complete the task without stopping but must significantly reduce speed, i.e. total time is > 11.00 sec., AND/ OR requires 4 or more steps to complete the turn
3	able to complete task with time $\leq$ 11.00 sec. and/or veers from straight path during backwards walking
4	able to complete task in a continuous motion, time $\leq$ 9.00 sec., and/or uses protective step(s) during or just after turn
5	able to complete the task in a continuous motion with brisk speed, time $\leq$ 7.00 sec. and maintaining a straight path throughout

11. WALK, LOOK & CARRY

i) to be performed looking right
ii) to be performed looking left

Starting position: Standardized starting position, but carrying a plastic grocery bag in each hand by the handle, with a 7 ½ lb. = 3.4 kg weight inside each bag. (See set-up diagram for placement of visual target.)

Instructions to Patient: *Walk at your usual pace to the end of the line carrying the grocery bags. I will tell you when to look at the circle. Keep looking at it while you walk past it. I will then tell you when to look straight ahead again. Try not to veer off course while you walk.*

Instructions to Therapist: Same instructions as in Item 8 Walking & Looking. Patient to carry only one grocery bag if unable to perform bilaterally due to motor control problems of the upper extremity. Indicate on the score sheet if patient carried only one bag.

GRADING

0 unable to walk and look, i.e. has to stop to look, or requires assistance or upper extremity support at any point during the test

1 able to continuously walk and initiate looking, but loses visual fixation on circle at or before 4m mark

2 able to continuously walk and look, but loses visual fixation on circle after 4m mark, i.e. while looking back over the shoulder

3 able to continuously walk and fixate upon the circle between the 2m and 6m mark, but demonstrates a protective step. Acceptable for patient to demonstrate inconsistent or reduced speed

4 able to continuously walk and fixate upon the circle between the 2m and 6m mark but veers off course. Acceptable for patient to demonstrate inconsistent or reduced speed

5 able to continuously walk and fixate upon circle between the 2m and 6m mark, maintains a straight path, in a steady & coordinated manner, time $\leq$ 7.00 sec.
NOT Acceptable: inconsistent or reduced speed
looking down at feet

12. DESCENDING STAIRS

Starting position: Quiet standing at top of staircase (minimum 8 steps). Depending on patient's skill on the stairs, may begin by descending from the first or third step at the bottom of the flight.

Instructions to Patient: *Walk down the stairs. Try not to use the railing.*

Instructions to Therapist: Depending on patient's skill on stairs, may use a cane as in level 1 and 2.

GRADING

0	unable to step down 1 step OR requires the railing or assistance
1	able to step down 1 step with/without use of cane **NOT Acceptable:** use of railing (from this level onwards)
2	able to step down 3 steps in any pattern with/without the use of cane, i.e. step-to pattern with/without cane or reciprocal pattern with cane
3	able to step down 3 steps in a <u>reciprocal</u> pattern, <u>without</u> cane OR able to step down a full flight in a step-to pattern, without cane **NOT Acceptable:** use of cane (from this level onwards)
4	able to step down a flight in a reciprocal pattern but awkward, uncoordinated*
5	able to step down a flight in a reciprocal pattern in a rhythmical and coordinated manner*

***BONUS**

If the patient achieves a score of 4 or 5, and if deemed safe by the rating therapist, the patient is asked to repeat the task and descend stairs while carrying a weighted basket (laundry basket with 2 lb. weight in it). It is acceptable for the patient to intermittently look at the steps.

Add one bonus point to the score of 4 or 5 if the patient can descend the stairs safely while carrying the basket without the need for continuous monitoring of their foot placement. If the patient is unable to hold the basket with one or both arms, they are not eligible for the bonus point.

Instructions to Patient: Hold this basket, keeping it in front of you at waist level. Walk down the stairs and try not to look at your feet. You may look at the steps once in a while for safety.

13. STEP UPS x 1 STEP

i) to be performed leading with right leg
ii) to be performed leading with left leg

Starting position: Standardized starting position in front of step at bottom of stairs.

Instructions to Patient:
i) Step up and down on this step as quickly as you can until I say "Stop." The pattern is Right-Left Up and Right-Left Down. Try not to look at your feet.
ii) Step up and down on this step as quickly as you can until I say "Stop." The pattern is Left-Right Up and Left-Right Down. Try not to look at your feet.

Instructions of Therapist: Start timing when the patient's foot leaves the ground. Stop timing after the completion of 5 cycles. A cycle is one complete step up and down.

GRADING

0	unable to step up independently, requires assistance and/or railing to ascend
1	able to step up independently, but unable to step down independently, i.e. requires railing and/or assistance to descend
2	able to step up and down (1 cycle) independently without railing or assistance. Acceptable to look at feet
3	able to complete 5 cycles. Acceptable to demonstrate incoordination or inconsistent speed/rhythm **NOT Acceptable:** to look at feet
4	able to complete 5 cycles in > 6.00 but < 10.00 sec. Acceptable as in Level 3 **NOT Acceptable:** as in level 3
5	able to complete 5 cycles in $\leq$ 6.00 sec. in a rhythmical and coordinated manner **NOT Acceptable:** to look at feet

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Appendix B: Dynamic balance training exercises

Phase One

Exercise 1a – Sitting rotation

Exercise 2a – Chair sit/squat

Exercise 3a – Calf raise

Exercise 4a – Side stepping

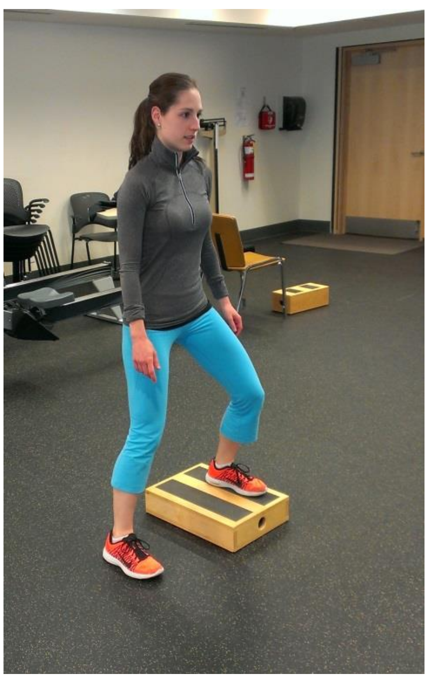
Exercise 5a – Stepping pattern

Phase Two

Exercise 1b – Standing rotation

Exercise 2b – Step down

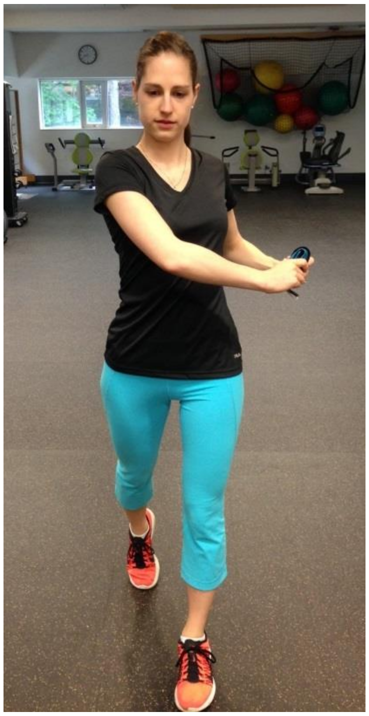
Exercise 3b – Toe walking



Exercise 4b – Lateral step-up

Exercise 5b – Stepping pattern

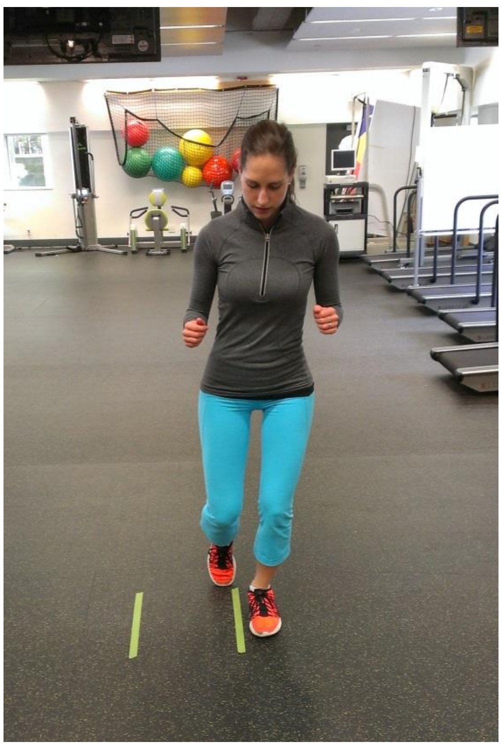
Phase Three



Exercise 1c – Stepping rotation

Exercise 2c – Lunge

Exercise 3c – Mini-hop



Exercise 4c – Skate stepping

Exercise 5c – Cone walking