# GAIT, BALANCE RECOVERY AND BALANCE CONFIDENCE AFTER TOTAL KNEE REPLACEMENT: DIFFERENCES BETWEEN YOUNGER AND OLDER PATIENTS

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## Abstract

Total knee replacement (TKR) is the gold standard treatment for improving mobility and relieving pain associated with end-stage knee osteoarthritis (OA) when other modalities have failed. Patients demonstrate significant improvements compared to pre-TKR levels, however deficiencies in function and mobility remain when compared to healthy controls. Recent national joint replacement registries have reported a substantial increase in the number of TKR procedures performed on younger patients. Over the last decade in Canada, the largest relative percent increase (≈300%) in TKRs has occurred to patients who were between 45-54 years of age. Although this younger patient group (<55 years old) is rapidly growing, the vast majority of the literature investigating TKR outcomes has been based upon the 'typical', older TKR patient (≥ 65 years old). This has created a therapeutic dilemma for clinicians, having little empirical data to formulate explicit statements or recommendations regarding how TKR will affect this younger population, and a concern with prosthesis failure and revision surgery, there is a hesitation to perform TKR on the younger knee OA patient.

Age-related deterioration in sensory information acquisition and musculoskeletal function has been observed between younger and older adults in the absence of knee OA and TKR, and has been linked to an increase in fall risk and falls. These age-related deficits observed in healthy adults may also distinguish younger and older TKR patients, which would have important implications to the surgical and rehabilitation practice. Currently, there are a limited number of published reports examining age-related differences in TKR patients and this gap in the literature warrants investigation. Therefore, the goal of this thesis is primarily to investigate the younger TKR patient and to compare their observations to that of the older, 'typical' patient and to their healthy age-matched controls. To do this, a convenience sample of 59 participants, including 29

primary knee replacement patients six-month post-TKR, provided informed consent from the following groups: 1) Younger TKR Patient (n=15 (11 F), age: 54.3 ± 7.9 years), 2) Younger Control (n=15 (13 F), age: 55.2 ± 4.0 years), 3) Older TKR Patient (n=14 (12 F), age: 76.9 ± 4.7 years), and 4) Older Control (n= 15 (11 F), age: 77.7 ± 4.1 years).

Falls have been shown to be elevated in knee OA patients and after TKR surgery, having a negative impact on the health of those who have fallen. Psychosocial factors have been shown to be associated with fall risk and falls. One of these factors, balance confidence, is associated with balance-impairment and reduced functional mobility in healthy older adults, and can distinguish fallers from non-fallers. The younger TKR group had significantly elevated balance confidence (Acitivities-specific balance confidence) scoring and functional mobility (Timed-up-and-Go test) compared to the older TKR group, but was not different to the healthy controls. It has also been shown that healthy older adults who have fallen report a higher propensity to consciously control or "reinvestment" in their movements compared to non-fallers. The results indicated that the younger TKR patient group reinvested in their movements significantly less compared to the older TKR patient group and that the amount of reinvestment was related to balance confidence and functional mobility scoring in TKR patients. These findings clearly demonstrate that the younger TKR patient, at six months post-surgery, is experiencing a better outcome than the typical, older TKR patient.

Persistent proprioceptive deficits after TKR have been reported and have been shown to be associated with limitations in lower limb mobility and postural control. Further, after TKR there is a reduction in obstacle avoidance success rate, compared to healthy controls, with the majority of these balance disturbances occurring in the forward direction. Using a tether-release method to replicate a forward fall it was observed that the younger TKR patients initiated lower limb movements earlier and employed a longer step than the older TKR group, which enabled a more efficient control of the forward translation of their centre of mass (COM), as the COM remained further behind the anterior boundary of the base of support at landing. Importantly, the younger TKR patient had a quicker step and larger moment arm associated with the longer step, which helped to create a larger restorative torque to counteract the forward momentum of the fall. As such, it was observed that the younger TKR patients recovered from the forward fall with a significantly smaller COM displacement to that of older TKR patients, but were similar to the healthy controls. No difference in peak anteroposterior COM falling acceleration (after magnet release to recovery step landing) was observed between groups, but the younger TKR patients demonstrated a significantly higher peak anteroposterior COM recovery acceleration (acceleration after recovery step landing) compared to the older TKR patients. To compensate and avoid falling, the older TKR patient employed a strategy of using additional recovery steps; logistic regression analysis demonstrated that increasing age and having undergone TKR significantly increased the odds ratio of requiring additional step from a forward fall. The number of steps required to recover balance from a forward fall has been related to the risk of falling, as such, these findings suggest that the younger TKR patient would have a similar fall risk to their healthy controls, but reduced to that of the older TKR patient.

There is evidence to suggest that after primary TKR there is a predictable pattern of deterioration in other major joints of the lower extremities, such as the contralateral knee. Asymmetrical gait patterns has been argued to be a compensatory strategy to reduce the forces and loading in the surgical limb, but as a consequence, may contribute to the initiation or progression of OA in joints of the contralateral limb. The results indicated that the older TKR group demonstrated an asymmetrical heel strike transient and knee adduction moment magnitude between the surgical and non-surgical limbs, the younger TKR group and control groups did not demonstrate this same asymmetrical pattern. Higher loading and moments at the non-surgical limb of the older TKR patient could create or further progress osteoarthritic degeneration in the non-surgical limb. The asymmetrical gait patterns observed in the older TKR patient may be due to a learned gait pattern which is not resolved despite treatment of the affected joint or could be a strategy to compensate for residual pain and functional impairment. Although, knee OA is a progressive aliment, the younger TKR patient may undergo a more acute degeneration and therefore may be less likely to adopt this asymmetrical gait pattern or more quickly in returned to a asymptomatic gait pattern after TKR than the older TKR patient.

The aggregate results of this thesis demonstrate that the younger TKR patient differs from the typical, older TKR patient in which the majority of the literature is based. The current findings begin to fill the gap and shed light into how age may affect the outcome after TKR. These findings would be clinically relevant for younger knee replacement patients who clearly demonstrate an elevated balance confidence and functional mobility, which suggests a reduction in fall risk compared to the typical TKR patient. This conclusion seems to be further supported by the stepping characteristics and superior centre of mass control observed for the younger TKR patient when recovering from a forward fall. Further, the results lend support to providing TKR to younger patients presenting with severe knee OA who would otherwise be indicated for TKR, as delaying surgery could lead to the adoption of gait patterns that may negatively affect the contralateral limb. Much more research is required, particularly those of longitudinal design, to support these current cross-sectional findings.

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## Dedication

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# CHAPTER ONE

# INTRODUCTION AND LITERATURE REVIEW

## *Epidemiology of Total Knee Replacement*

Osteoarthritis (OA) is the most common form of joint disbility (March & Bachmeier, 1997; Brooks, 2006) and the knee is the joint most affected by OA (Oliveria et al., 1995). The symptoms that occur with knee OA include pain (Creamer et al., 2000), reduction in range of motion (Oliveria et al., 1995), and impairments in functional balance (Gage et al., 2007, 2008). As the degeneration of the knee joint progresses and conservative treatment modalities are exhausted, with non-satisfactory results, total knee replacement (TKR) is often indicated (Jordan et al., 2003; Zhang et al., 2008). The primary indication for TKR is moderate to severe knee OA, as 94% of prosthesis recipients presented with knee OA (Katz et al. 2007). TKR has been accepted as a reliable and appropriate treatment option to reduce pain, restore function and improve health-related quality of life in patients suffering from knee OA (Anderson et al., 1996; Ewald et al., 1999; Scott et al., 2004; Richmond, 2008). Further, joint replacement surgery has been shown to provide a good cost-effectiveness ratio; total hip replacement costs have been reported to be less than $10,000 per quality-adjusted life year gained and may be further cost-saving if long-term care costs are included (Chang et al., 1996). Similar cost-effective research has yet to be done in regards to TKR, but are likely comparable to that of total hip replacement. In comparison, patients undergoing coronary artery bypass surgery for the treatment of severe coronary heart disease can expect a cost-effectiveness ratio of $8,132 per quality-adjusted life year gained (Magnuson et al., 2013).

The number of TKRs performed has risen dramatically since its introduction in the 1960's and 1970's (Richmond, 2008). In a ten year period from 1991 to 2000 the number of primary TKRs performed in the UK has doubled (Dixon et al., 2004) and has tripled in the United States (Kurtz et al., 2007). In Canada, for the period from 1994-2004, TKRs increased by 125% (annually by roughly 15%), and current data shows that over 40,000 TKRs are conducted each year (CJJR, 2012–2013). The incidence of TKR is higher in females than males; in 2004–2005, the rate of TKR for those aged 65-74 years was 555.5 women per 100,000 and 456.1 men per 100,000 (CIHI, 2005). Significant increases in the future number of knee replacement surgeries are also expected; statistical projections for the number of TKRs likely to be performed between 2005 and 2030 in the United States (currently more than 340,000) has been estimated to grow by 673% (Kurtz et al., 2007). The increased incidence of TKR surgery has been argued to occur because of changing demographics of the general population (e.g., rise in obesity and an aging population), however, another possible cause for this rise has been argued to be because the TKR procedures is being indicated to a more diverse population than previously (Crowninshield et al., 2006). Along with the increase in the number of joint replacement surgeries performed it has also been reported over the past decade that the demographics of the patient are changing to a younger patient, a trend that is argued to continue in the future. (Kurtz et al., 2007). Further, although the majority of joint replacement surgeries are performed in individuals over 65 years of age, a growing and substantial portion (approximately 120,000 or one-third) are performed in the United States on patients between the ages of 45–65 years (TAHRQ, 2002).

### *Patient Improvement Post-Total Knee Replacement*

After TKR it has been shown that pain scores improve much more rapidly than that observed in physical function; patients reach maximal improvements in the first 3–6 months after surgery (Kahn et al., 2013). In a systematic review of cohort studies by Ethgen & colleagues

(2004) it was concluded that TKR patients had substantial improvements in pain and function when compared to their preoperative levels. In addition to clinically-derived data, the use of patient-centered outcome measures is seen as an essential component of any long-term analysis of the success of TKR (Wright et al., 2004).  Health-related quality of life after TKR was evaluated and improvements were observed, although modest (Ethgen et al., 2004). Chronic pain has been shown to be the primary reason for knee OA sufferers to elect for TKR (Hawker et al., 1998); much research has been conducted to investigate how pain is affected after TKR. Using the WOMAC pain scale, a patient completed questionnaire, it was observed that mean preoperative WOMAC scores ranged from 40-45, postoperative scores after 6-months had improved to 76 (Jones et al., 2000). The WOMAC scores continue to improve in the long-term, a score of 82 (Lingard et al., 2004) and 88 (Wright et al., 2004) have been reported at 2 and 10-years after the TKR, respectively. However, although improved from their preoperative levels, patients still report pain amounts higher than that of their healthy controls. Similar results of improvement in pain and function after TKR were reported in another systemic review, although this review reported the proportion of people with an unfavourable long-term pain outcome was about 20% of patients (Beswick et al., 2012); further suggesting that persistent pain is a long-term factor for many TKR recipients.

### *Gait Characteristics Post-Total Knee Replacement*

After TKR patients generally expect there to be an overall improvement in their walking ability and an increased engagement in activities (Mancuso et al., 2001). Reports have shown that TKR patients demonstrate an improvement in knee range of motion (Misra et al., 2003) and have reduced activity restrictions (Heck et al., 1998) when compared to preoperative levels. When compared to age-matched individuals without knee disability, TKR patients demonstrate roughly 80% of their knee function 1-year after TKR (Finch et al., 1998). Even in the most clinically successful cases, many patients treated by TKR cannot achieve normal joint function to that observed in age-matched healthy cohorts (Finch et al., 1998; Lee et al., 1999). Further evidence of this detriment to knee joint function was reported by Smith et al. (2004), where in a longitudinal pre- and post-surgery study it was observed that gait patterns exhibited before surgery were retained up to 18-months after surgery. It has been argued that the reduction in pain and improvement in knee function post-surgery may not be sufficient to produce the return of a more normal gait pattern and that other contributors such as the previous gait strategies, prosthetic design, muscle weakness, reductions in postural control and degeneration of proprioceptive information prevent patients from regaining normal gait (Skinner, 1993). The reasoning for persistent gait deficits has been mainly speculative, as relatively little information is available regarding how impairments relate to gait deviations. Although, what is known, is that the intricate and complex interaction of ligaments, coordinated muscle activation and bony structures are disrupted when the knee joint is replaced with an artificial joint (Byrne & Prentice, 2003). Also, the very nature of OA as a degenerative disorder damages the tissue associated with the knee that cannot be replaced with a prosthetic.

Gait analysis has been shown to be of value in distinguishing between clinical outcomes of different types of knee surgery (Chassin et al., 1996; Dorr et al., 1988; Andriacchi et al., 1997) and predicting the outcome of knee surgery as it pertains to function (Prodromos et al., 1985; Wang et al., 1990; Hilding et al., 1999). Furthermore, gait analysis has been used by researchers to provide a more detailed evaluation of knee motion following TKR in comparison to healthy controls (Andriacchi et al., 1982; Simon et al., 1983; Brugioni et al., 1990; Chen et al., 1991;

Chassin et al., 1996; Wilson et al., 1996; Bolanos et al., 1998; Fuchs et al., 2002, 2003; Smith et al., 2004; Saari et al., 2005).

In the typical TKR patient group, spatiotemporal variables have been well researched (Andriacchi et al., 1982; Ouellet & Moffet, 2002; Smith et al., 2004; Yoshida et al., 2008). In a study conducted by Smith et al. (2004) it was observed that all participants undergoing TKR displayed significant improvements in all spatiotemporal parameters post-surgery compared to their pre-surgical values. For example, mean gait speed improved significantly from 0.97 ± 0.16 m/s at pre-surgery to 1.05 ± 0.12 m/s post-surgery. These findings indicate that the procedure provided improvement for patients; however, when compared to healthy age-matched controls (1.08 ± 0.14 m/s) the patients differed and this impairment can persist up to 50-months post-surgery (Andriacchi, 1993). Some of the gait patterns that typical TKR patients adopt to reduce gait speed is to walk with a reduced cadence and step length. In a study conducted by Simon et al. (1983) TKR patients spent approximately 30% more time in double-limb stance and had prolonged gait cycle times when compared to healthy age-matched controls. The available range of motion (ROM) in the sagittal plane of the knee following TKR is considered to be an important determinant of patients' functional abilities postoperatively, particularly for activities involving greater knee flexion, such as kneeling or ascending stairs (Myles et al., 2002; Andriacchi et al., 1997). Normal walking has been shown to require roughly 67° of sagittal plane motion about the knee (Brinkman & Perry, 1985; Scuderi & Insall, 1989, 1992); however, arthritic changes to the knee cause a decrease in this motion (Győry et al., 1976; Schurman et al., 1985; Messier et al., 1992). This decrease in motion has also been observed in TKR patients. Wilson et al. (1996) observed that the sagittal mean knee ROM during level walking in the TKR group (53°) was significantly lower than that observed in the healthy control group (61°).

The reason for many of the adopted gait changes observed in knee OA and TKR patients is not fully understood. However, one hypothesis is to employ a more cautious strategy, to decrease variability and thereby improve stability within their gait in an effort to reduce the occurrences of self-generated perturbations and the consequences of external perturbations (Dingwell & Marin, 2006; England & Granata, 2007). Another hypothesis that has been suggested is the altered gait strategies are adopted to alleviate pain caused by the associated impact forces during gait (Henriksen et al., 2006). However, TKR has been shown to significantly improve reported pain, therefore it is unknown if this strategy is adopted because low level pain still persists or if pre-surgery gait pattern is still continued post-surgery.

The forces that occur at the knee have been shown to affect the wear of the articular-bearing surfaces, as well as the integrity of the bone–implant interface and thereby the prosthesis survivorship (D'Lima et al., 2007). The typical TKR patient demonstrates kinetic measures that are different to their healthy age-matched controls (Nigg, 2003; Yoshida et al., 2008). During gait, vertical impact forces peak in the lower limbs at heel contact (Nigg, 2003); a transient stress wave develops at this stage, which moves up the lower kinetic chain (Chu et al., 1986). This heel strike transient and its magnitude has been suggested to possibly play a role in the aetiology and progression of knee OA (Radin et al., 1978; Collins & Whittle, 1989), as the ability to reduce the impulse forces produced by the heel strike transient is possibly hindered by the presence of OA (Voloshin & Woak, 1982). This force has been shown to be significantly lower in the TKR group for their surgically repaired limb compared to the healthy individuals at 12-months after TKR (Chu et al., 1986). The implications of this are of particular importance to patients who have undergone a unilateral TKR, as previous studies have shown gait alterations, including gait asymmetry, occur following knee replacement surgery (Mizner & Snyder-Mackler, 2005;

McClelland et al., 2007; Stacoff et al., 2007) and could affect the development or progression of OA in the contralateral knee. Levinger et al. (2005) reported significant differences between the operated and non-operated limbs for the heel strike transient magnitude. The asymmetrical load distribution between limbs for unilateral TKR patients has been shown to increase the likelihood of OA progression in the contralateral knee (Shakoor et al., 2002, 2003). It has been suggested by Levinger and colleagues (2005) that the asymmetrical gait pattern between limbs may occur as a compensatory strategy, reducing the load required to be distributed at the prosthetic knee by shifting the body weight over to the contralateral limb.

The typical TKR patient also shows a different hip, knee and ankle moment profile during weight acceptance from their age-matched healthy controls. Yoshida et al. (2008) has reported that during the weight acceptance phase TKR limbs have a larger contribution from the hip joint and a smaller contribution from the knee joint compared to controls. It was argued that TKR patients adopt a “stiff knee” movement strategy; as the hip extension moment dominated the support phase of the lower extremity, with a very small contribution from the knee extension moments compared to healthy controls. This similar hip and knee extension moment pattern has been observed in knee OA patients, as such it has been suggested that preoperative gait habits may still persist postoperatively (McGibbon & Krebs, 2002). Different kinetic lower limb patterns have also been observed for external flexion-extension joint moments in TKR patients (Brugioni et al., 1990; Wilson et al., 1996; Andriacchi, 1993; Smith et al., 2004). Smith & colleagues (2004) reported that peak external knee flexion moment at early mid-stance did not change significantly from pre- to post-surgery, however, the peak external knee extension moment at terminal stance increased significantly from pre-surgery (−0.06 Nm/kg) to post-surgery (−0.17 Nm/kg). Andriacchi (1993) found that the abnormal flexion-extension moments observed in TKR patients may be associated with anomalous phasing of quadriceps and hamstrings. The author argued that the TKR patients adopted a gait pattern that extended the knee throughout the stance phase, thereby decreasing the demands on the quadriceps. The decreased magnitude in the external knee flexion moment and the more extended knee has been argued to be a strategy to reduce the eccentric load on the quadriceps, as the quadriceps would be required to produce less of the force to counteract the diminished flexion moment (Milner, 2009). Therefore, one possible explanation for adopting a “stiff knee” pattern for TKR patients is to reduce the joint compression forces that the quadriceps produce around the knee to possibly alleviate pain or from remnant gait patterns before surgery. Changes in knee flexion moments during early stance are of importance as it has been associated with prosthesis failure (Hilding et al., 1996, 1999) and further anterior knee pain (Smith et al., 2004).

The external knee adduction moment (EKAM) during gait is a key variable in understanding the mechanical loading environment of those with medial compartment knee OA. Altered magnitude characteristics have been reported and associated with medial compartment loading (Baliunas et al., 2002; Lewek et al., 2004; Deluzio & Astephen, 2007; Newell et al., 2008) and knee OA progression (Lewek et al., 2004; Mündermann et al., 2005). The EKAM is the product of the frontal plane lever arm (perpendicular distance from the ground reaction force vector to the knee joint centre of rotation) and resultant ground reaction force in the frontal plane. It has been reported that both the EKAM and the frontal plane GRF exhibit a similar double hump waveform, one early and then again late during stance phase (associated with heel contact and toe-off, respectively). However, Hunt et al. (2006) and Street & Gage (2013a) have both reported that the frontal plane lever arm does not demonstrate this characteristic waveform; the lever arm showed little change in magnitude throughout the stance phase of gait. Although the components of the EKAM have been identified, only the moment itself has been investigated for TKR patients. Benedetti et al. (2008) found a significantly higher magnitude in the two characteristic peaks of the EKAM profile during the stance phase at 5, 12, and 24 months post-TKR compared to an asymptomatic control group. An analysis of the change after TKR in the EKAM was not done, as there was no preoperative evaluation. When Saari et al. (2005) investigated the EKAM it was observed that the preoperative levels were reduced compared to post-TKR. Milner & O'Bryan (2008) reported the first EKAM peak was higher in the non-operated limb when compared with the operated limb for a group of TKR pateints and with the healthy controls. The early stance peak has been suggested to be of most importance, as it has been shown to be higher in knee OA patients compared to healthy controls (Wada et al., 1998; Mündermann et al., 2005). Therefore, the higher early stance peak observed in the non-operated limb after TKR offers a possible mechanism for the predictable deterioration of contralateral knee after unilateral TKR, particularly in the medial compartment of the knee. Of note, Hilding et al. (1996) reported that TKR patients who demonstrated high EKAM values were associated with prostheses that were classified as ‘unstable’ by roentgen stereophotogrammetry (a highly accurate technique for the assessment of three-dimensional migration and micromotion of a joint replacement prosthesis relative to the bone it is attached to). The authors suggested that the higher frontal plane moment magnitudes may lead to premature component loosening and ultimately prostheses failure.

### *Balance Recovery Characteristics Post-Total Knee Replacement*

Human postural control is a complex sensorimotor function that includes components such as movement detection and generation and the control of coordinated voluntary and reflexive motor responses (Fransson et al., 2000). This response requires the central integration of multiple neurosensory afferent signals to generate a context-specific motor response to maintain upright posture and avoid falls (Keshner et al., 1987). The sensory integration of this information culminates in the central nervous system (CNS) and is derived from sensory information of the visual, somatosensory and vestibular systems (Akram et al., 2007). Sensory sources act to detect any disturbances to the upright posture and establish the timing and metrics employed in creating the balance correction (Allum et al., 1993). Upon a disturbance the somatosensory system detects motion and muscle stretch at the ankle, knee and trunk, and the vestibular sensory system detects linear and angular accelerations at the head (Allum et al., 1993). A balance correction response will follow, as modulation of the somatosensory and vestibular systems act to establish the amplitude pattern required in the muscle response (Forssberg & Hirschfeld, 1994; Horak et al., 1994; Allum et al., 1995). The contributions of the visual inputs have been shown to mainly influence later stabilizing reactions to the initial balance corrections (Allum & Pfaltz, 1985; Allum et al., 1993). However, it has also been shown that during quiet standing that somatosensory and visual inputs are sufficient to attenuate postural disturbances (Winter et al., 1998), as the sway-related accelerations are often inadequate to trigger the thresholds of vestibular organ sensation (Benson et al., 1986; Fitzpatrick & McCloskey, 1994). Notwithstanding, postural coordination and the role of different sensory systems change as a function of task constraints, in other words, the CNS must use different strategies to maintain stable balance control under different conditions (Allum et al., 1993). Optimally, the CNS integrates the information from each of the systems, which is then weighted according to the resulting balance difficulties, and the different afferent outputs are modified as needed (Peterka, 2002).

Patients suffering from knee OA have demonstrated greater body sway during standing than healthy controls (Hurley et al., 1997; Wegener et al., 1997; Hassan et al., 2001). It has been argued by Hassan et al. (2001) that the increased body sway of knee OA patients is the product of proprioceptive deficits, muscle weakness, and knee pain brought about by articular degeneration of the knee joint. Several studies have supported the hypothesis of pain having an association with standing postural instability. Tjon et al. (2000) investigated arthritic patients and found a relationship between increase pain and lateral centre of pressure (COP) velocity and it was argued that this could be an adopted strategy to unload painful joints. Hassan et al. (2001) reported that knee pain and quadriceps strength were significant predictors of increased postural sway. Another possible cause for the altered balance patterns adopted by knee OA sufferers is the diminished joint sensation that may precipitate degenerative changes. Swanik et al. (2004) and Andriacchi et al. (1982) reported a strong association between decreased proprioception and function in patients with knee OA. Although joint sensation is decreased in arthritic knees, it has been reported that joint-position sense improves after TKR when compared with that of the contralateral limb (Barrett et al., 1991; Warren et al., 1993), to an osteoarthritic control group (Koralewicz & Engh, 2000) and prospectively, six months following TKR surgery (Attfield et al., 1996). The mechanism for restoring joint sensation after TKR seems to involve the elimination of several deleterious factors in the elderly and osteoarthritic patients (Kokmen et al., 1978; Barrack et al., 1983; Kaplan et al., 1985; Skinner & Barrack, 1991). This may be achieved through joint space and soft-tissue tension being re-established and the reductions in pain and chronic inflammation after TKR. Thereby, the TKR procedure may modify mechanoreceptors response characteristics in both capsuloligamentous and musculotendinous structures, enhancing the perception of joint motion and position (Ferrell et al., 1992) and possibly enhancing motor coordination and functional stability of the knee (Swanik et al., 2004). Although the TKR procedure restores the intra-articular geometry of the knee, neuromuscular impairment still persists (Attfield et al., 1996) and could explain why some patients after TKR exhibit balance recovery strategies which, although approach normal, remain compromised (Viton et al., 2002; Wada et al., 2002; Swanik et al., 2004; Gage et al., 2007, 2008; Mandeville et al., 2008). It was reported by Gage et al. (2007) that although peak center of mass displacement was not affected by TKR, that the TKR group demonstrated alterations in the knee joint kinematics and lower limb muscle activity, in both the surgical and non-surgical limbs. The TKR patient group demonstrated lower muscular activity than the control group for gastrocnemius, tibialis anterior and rectus femoris, as well as a 34% lower peak knee joint angular displacement compared to the control group. It was argued that the observed reduction in muscle activity is consistent with a strategy implemented to unload the post-surgical knee. Although these changes were observed in both limbs, possibly suggesting a central reorganization of the balance response (Gage et al., 2007). This previous study specifically looked at sagittal plane changes, however, it has been reported for both older individuals and those suffering from a pathological disorder that balance control is affected more in the frontal plane (McIlroy & Maki, 1996; Allum et al., 2002; Helbostad & Moe-Nilssen, 2003; Gage et al., 2008). Gage et al. (2008) reported that TKR patients demonstrated larger movements of the whole body centre of mass (COM) in the frontal plane following movement of a support surface. The patient group tended to demonstrate a reduced knee flexion and knee joint angular velocity in flexion (43% less) compared to the control group.  The TKR patient group also demonstrated differences in the temporal organization and amplitude of muscle activity (tibialis anterior, gastrocnemius, and rectus femoris). It was suggested by the authors that differences observed in knee joint angular velocity, EMG onsets and activity amplitudes may be used by the patient group to reorganize their motor response to increase the biomechanical stiffness, thereby simplifying the demands of the response to the perturbation.

### *Falls and Balance Confidence Post-Total Knee Replacement*

Falls are among the most common cause of injury and hospitalisation for older adults, with an estimated one-third of the older community-dwelling population falling each year (O'Loughlin et al., 1993; Tromp et al., 2001; Friedman et al., 2002; Means et al., 2005). Falls are one of the most common and problematic issues among older adults (Li et al., 2003). It was reported that falls were the leading cause of injury-related visits to emergency departments in the United States (Fuller, 2000), producing a negative impact upon fallers' quality of life and a strong predictor for placement in institutional care (Cumming et al., 2000). Many of the associated risk factors observed in the older adult who report falling are also observed in older adults with self-reported lower limb arthritis (Sturnieks et al., 2004). Factors commonly associated with knee OA, such as pain and neuromuscular deficits, may therefore be important underlying contributors to falls in this population (Lamb et al., 2000; Arden et al., 2006; Foley et al., 2006). It has also been shown that OA is an important risk factor for falls (Blake et al., 1988; Campbell et al., 1989; Lawlor et al., 2003; Sturnieks et al., 2004; Leveille et al., 2009), where greater than 50% of individuals with knee OA reported falling in the past year (Williams et al., 2010). Moreover, persistent pain and neuromuscular deficits after joint replacement may cause TKR patients to remain at an elevated risk of falling. Levinger et al. (2011) reported that TKR patients are at an elevated risk of falling both prior to and following their surgery, suggesting the primary cause was due to deficits in knee extension strength and lower limb proprioception. Although the follow-up period in this study was only 4-months postoperatively, therefore full recovery of strength and proprioception may not have been achieved. Swinkels et al. (2009) found that those who have undergone TKR, who have fallen prior to surgery, 45% of patients fall again in the 1-year following surgery. However, it was observed that of the 24% of patients who fell in the preoperative quarter (3-months) just 12% fell in each of the four postoperative quarters (up to one year post-surgery), suggesting a positive impact of TKR on the rate of falls. TKR may also lead to a reduction in the prevalence of falls, as there was a change in the distribution of fallers/non-fallers; with 54% of preoperative fallers becoming non-fallers after surgery.

It would then make sense that among individuals who fall, many would have a concern of falling again. Researchers investigating psychological factors associated with falls have used various concepts such as falls-related self-efficacy, balance confidence and fear of falling as constructs. Although they are frequently used interchangeably, these concepts have been shown to have distinct features. For example, although measures of falls-related self-efficacy and fear of falling were associated, falls-related self-efficacy was much more strongly associated with functional status than fear of falling in a cohort of community-dwelling older adults (Tinetti et al., 1994). There has been a focus on the construct of confidence associated with falling, suggesting that it is the individual’s loss of confidence in his or her balance abilities that may contribute to the avoidance of activities (Tinetti et al., 1988). Measures of balance confidence have been developed to quantify the psychological component of balance-related behaviour. The concepts of falls-related self-efficacy or balance confidence have been investigated using two main measurement tools: the Falls Efficacy Scale (Tinetti et al., 1993) and the Activities-specific Balance Confidence Scale (Powell & Myers, 1995). The authors Powell & Myers (1995) have argued that although the Falls Efficacy Scale is often referred to as a measure of “falls-related self-efficacy” and the Activities-specific Balance Confidence Scale is a measure of “balance confidence," both scales measure the same construct of perceived balance ability. These measures are based on Bandura's theory of self-efficacy, which is defined as the confidence a person has in his or her ability to successfully perform a specific behaviour (Bandura, 1986). In this context, balance confidence refers to the degree of confidence a person has in keeping his or her balance while performing activities of daily living.

The Activities-specific Balance Confidence Scale is a 16-item questionnaire asking respondents to score their level of confidence in performing situation-specific activities. Each question is framed as such: "rate the amount of confidence you have in avoiding a fall when you have to…", "Pick up an object from the floor" or "Walk on icy sidewalk"? Each item is scored from 0% to 100%, with 0% being no confidence and 100% having full confidence in the ability to perform the activity without losing balance. The Activities-specific Balance Confidence Scale was found to demonstrate a strong test-retest reliability (*r*=.92), and good convergent validity (*r*=.63) with the physical activity subscale of the Physical Self-Efficacy Scale (Powell & Myers, 1995). Importantly, the Activities-specific Balance Confidence Scale has been shown to have better scale responsiveness than the Falls Efficacy Scale when used with community-dwelling older adults aged 65 to 95 years (Powell & Myers, 1995).

A number of studies investigated balance confidence have demonstrated strong links between balance confidence and physical and social functioning in older adults (Myers et al., 1996; Tinetti et al., 1994). Epidemiological studies have also shown a high prevalence of balance confidence impairment in older adults (Schepens et al., 2010; Seematter-Bagnoud et al., 2010). Low balance confidence has been shown to be predictive of functional decline and activity avoidance (Mendes de Leon et al., 1996; Myers et al., 1996). Self-efficacy has also been shown to be predictive of functional performance in participants with knee OA (Rejeski et al., 1996) and participants suffering from knee pain (Rejeski et al., 2001). Balance confidence has only recently been investigated in individuals who have undergone knee replacement surgery. Webster et al. (2006) reported that women (80.1 ± 12.6) after TKR had a significantly lower total Activities-specific Balance Confidence Scale score (less confidence) than men (96.9 ± 5.2), and the balance confidence scores were significantly correlated with functional scoring (American Knee Society knee score, r = .62; walking speed, r = .59). This study was cross-sectional in nature and did not include a healthy control group for comparison, so how TKR affects the level balance confidence of TKR patients and how they may differ from healthy individuals is unknown. It seems reasonable to hypothesize that balance confidence could be a factor that influences the overall outcome in this population, as altered gait patterns and sensory deficits are often associated with TKR patients (Skinner, 1984). There has been very little focus on TKR patients and their level of balance confidence, as such, there is a significant need to conduct further research examining patients after joint replacement and comparing their levels to healthy controls.

### *Reinvestment and Fall Risk*

Additional cognitive components could also have a role in the elevated risk of falling and reduced balance confidence for knee replacements patients. The term reinvestment has been used to describe the conscious control of a motor skill (Masters & Maxwell, 2008). It has been argued that individuals who tend to reinvestment more would be more likely to attempt conscious control of their movements. Importantly, it is generally believed that once a motor skill (e.g., walking) is mastered and performed automatically that the completion of that movement will be optimally performed without conscious control (Magill, 2004). The movement Specific

Reinvestment Scale (MSRS) was specifically developed to measure the tendency to consciously control one's movement (Masters et al., 2005). The MSRS has two subscales that measure movement self-consciousness (MSC) and conscious motor processing (CMP). MSC reflects the amount of worry or concern an individual has while performing a movement, while CMP reflects the amount of conscious control one invests in their movements. The MSRS has been used to quantify differences in trait reinvestment between different clinical populations. Orrell et al. (2009) found that stroke patients reinvest more than age-matched controls, where CMP and time spent in rehabilitation were significant predictors of functional impairment following stroke. Wong et al. (2008) reported that elderly fallers had a higher propensity to consciously control their movements than elderly non-fallers. The authors also found that the CMP subscale was a better discriminator between fallers and non-fallers than the MSC subscale. Therefore, the CMP may be of more importance than MSC in determining motor skill performance. In Parkinson's disease patients it was shown that duration of disease was associated with a higher reinvestment score, suggesting that patients appeared to become more aware of the mechanics and actions with disease progression (Masters et al., 2007). Therefore, TKR patients may also have an increased propensity to consciously control their movements and this conscious control could alter movement mechanics and decrease balance confidence, ultimately increasing fall risk and falls. No study to date has investigated either knee OA or TKR patients for this cognitive measure.

### *The Growing Population of "Younger" Total Knee Replacement Patients*

One subset of the knee replacement population that has received relatively little focus is the younger patient. TKR has had proven clinical success, as well as having predictable pain relief and functional improvement in elderly patients and younger patients who were treated for rheumatoid arthritis (Insall et al., 1983; Ewald & Chrisite, 1987; Goldberg et al., 1988; Vince et al., 1989; Ranawat et al., 1993; Colizza et al., 1995). Early reports of higher failure rates in the younger total hip replacement population led to the expectation of elevated failure rates in knee replacement patients (Dorr et al., 1994; Joshi et al., 1993; Torchia et al., 1996). This has led many surgeons to be apprehensive about the long-term outcome of TKR in this younger patient population (Stern et al., 1990). However, studies looking at the younger hip population have reported better than expected outcomes; moreover, there was early reports in the literature of success with the younger TKR population as well (Ranawat et al., 1993). TKR has been shown to be effective in younger patients (Ewald & Christie, 1987; Stuart & Rand, 1988; Hungerford et al., 1989; Stern et al., 1990), but there is still concern for surgeons regarding the possibility of aseptic loosening due to wear debris generated by a younger, and possibly more active patient (Windsor et al., 1989; Blunn et al., 1991; Feng et al., 1994). Moreover, younger TKR patients have the potential for additional revision operations in the course of a lifetime, as such TKR has generally been reserved for patients who are at least sixty years old (Insall, 1985; Rand & Ilstrup, 1991). Without consensus there has been the development of a therapeutic dilemma (Stulberg, 1995) for surgeons and a more cautious decision making process when contemplating whether to proceed with TKR in the younger patient presenting with a painful osteoarthritic knee.

Although knee OA is most common among the those over 65 years and the prevalence increases with age, OA can develop early in middle age (~35 years of age), especially in persons with predisposing factors such as heredity, obesity, muscle weakness and/or joint damage. It was reported by Kopec et al. (2008) that over the previous decade the largest number of new cases of OA occurred in the age group of 50–54 years for both sexes. A similar trend for TKR procedures has also been observed. In the Canadian Joint Replacement Registry 2008–2009 annual registry it was reported that compared to the 1996–1997 reported knee replacement procedures, the largest relative percent increase was in the 45-to-54 age group for both males and females (271% and 337% increase, respectively). This trend has also been reported in other national joint registries as well. During the past 10 years, knee surgery for OA (i.e. high tibial osteotomy and knee replacement) in patients less than 55 years of age has doubled in Sweden (Swedish Knee Arthroplasty Register, 2013). In Australia, the current mean age of patients undergoing TKR is 70 years, however the proportion of patients aged less than 65 years at the time of surgery has been increasing recently, reaching 32% in 2007 (Australian Orthopaedic Association National Joint Replacement Registry, 2008). Moreover, it is anticipated that the demand for TKR surgery will at least double within the next decade and the average age at surgery will continue to decrease (Wells et al., 2002; Dixon et al., 2004). Although the cause for this increase in younger TKR patients is unknown. Demographic factors such as the increased prevalence of obesity may have a consequence. Furthermore, factors involving the evolution and innovation in materials, design, instrumentation and surgical techniques have resulted in better outcomes from TKR in relatively early stages of OA (Gidwani & Fairbank, 2004). This improvement has led to the broadening of the indication for the TKR procedure as surgeons have gained confidence in the surgical treatment of TKR for a more diverse population, including younger patients (Deshmukh & Scott 2001, Pennington et al., 2003, Lisowski et al., 2004, Price et al., 2005, Argenson & Parratte 2006, Berend et al., 2007, Mullaji et al., 2007, Emerson & Higgins 2008).

### *The Outcome Post-Total Knee Replacement of the ‘Younger’ Patient*

There is a slight increase in the risk of failure 10-years after implantation in patients aged 50 years and younger compared to patients aged 70 years or older (Hofmann et al., 2002; Rand et al., 2003). The reason for this occurrence is still unclear, but the increased rate and magnitude of loading due to higher activity levels in the younger patient could play a role. Notwithstanding, favourable results have been reported for younger knee OA patients (Swedish Knee Arthroplasty Register 2013) and younger patients with rheumatoid arthritis who underwent TKR (Ranawat et al., 1989; Dalury et al., 1995; Duffy et al., 1998). To date, studies that have investigated the younger TKR patients are limited. Moreover, the age described as "younger" within the literature have ranged from younger than 50 to younger than 75 years of age (Santaguida et al., 2008), this wide spread in age brings into question the homogeneity of the established data for comparison. There are also a larger proportion of studies that had a majority of the younger TKR sample presenting with rheumatoid arthritis with very few that exclusively looked at OA patients (Ewald & Christie, 1987; Stuart & Rand, 1988; Hungerford et al., 1989; Dalury et al., 1995). The younger OA patient is not satisfied with the reduced function that can accompany a stiff, painful arthritic knee and they are looking to TKR to improve their function. The hypothesized higher activity levels of the younger TKR patient may have played a role in some of the poor outcomes observed above. Although, Keeney et al. (2014) reported that sustained high activity levels are not likely to be a principal cause of revision surgeries among younger patients when considering age and diagnosis alone. Further research to determine the effect of activity on survivorship of the prosthesis is needed and should be based on measured functional activity instead of using age as proxy for activity levels. In a systemic review by Santaguida & colleagues (2008) it was reported that younger age was associated with greater risk for revision ranging from two to ten years postoperatively. The magnitude of how age affected revision was estimated to be an odds ratio of 0.82 (Heck et al., 1998) and 0.97 (Robertsson et al., 2001). More recently, W-Dahl & colleagues (2010) confirmed this finding; after unicompartmental knee replacement, patients less than 65 years of age had a higher risk of revision than patients who were 65 or older, and patients less than 55 years had a cumulative revision rate of 20% at seven years. It has also been reported that both males and females who received TKR prior to the age of 60 years had significantly increased mortality (Julin et al., 2010). However, it was speculated that the finding of a higher morality rate in the younger TKR patient group could be indicative that there was a correlation between an early progression of OA and some other co-morbidity causing premature death (Robertsson et al., 2001). It has also been argued that many of the negative outcomes observed in the younger TKR patient group may have influence from other confounding factors; when prosthesis failure rates were adjusted for sex, diagnosis, patellar resurfacing, TKR-type, and fixation method the rate of revision in the younger age group decreased. As many factors associated with poorer prosthesis survival (e.g., male sex and the diagnosis of secondary OA) are observed in the younger patients (Julin et al., 2010).

Early results of TKR in younger patients showed promise; as there was not a significant increase in failure rates from aseptic loosening observed (Stuart & Rand, 1988; Ranawat et al., 1989; Stern et al., 1990). Further, there are reports that contradict the poor revision rates in younger TKR patients. Dalury et al. (1995) reported on 103 TKR for patients younger than 45 years old, with an average follow-up of seven years, there were no reported revisions from a loose prosthesis. In a longer follow-up (ten years; range, five-eighteen years) Gill et al. (1997) reviewed 68 TKR in 50 patients who were 55 years old or younger, there were only two revisions for aseptic loosening and one for infection. The previous studies had a majority of younger TKR patients presenting with rheumatoid arthritis, however, in a study conducted by Diduch et al. (1997), it was reported that of 108 TKR (patients <55 years old), presenting with post-traumatic OA, the overall rate of survival of the prosthesis was 94% after eighteen years. More recently, Tai & Cross (2006) carried out a prospective study of 118 TKR in patients who were ≤ 55 years of age (presenting with severe OA), with an average follow-up period of 8 years; only three revisions reported (two because of aseptic loosening and one case of polyethylene wear). At twelve years, the overall rate of implant survival was 97.5%, it was concluded by the authors that polyethylene wear, osteolysis and loosening of the prosthesis were not major problems for younger, active patients. Of particular note, the rate of infection that causes revision among TKR patients ≤ 65 years was nearly 10% lower than patients > 65 years (17, 26%, respectively). However, much more research is needed to determine if and how the younger patients' activity levels affect the survivorship of the prosthesis.

Another important factor to consider when measuring the benefits of TKR in younger patients is the improved activity levels that may occur with the reduction in pain and improved function after TKR (Dalury et al., 1995). The benefit of increased physical activity following TKR is undeniable; increased psychological satisfaction that patients gain when able to take part in physical activity, as well as the improved muscle strength, coordination, balance, endurance, and proprioception, all of which contribute to an overall healthier individual. Studies have shown that cardiovascular fitness is positively affected by exercise after both hip and knee replacement, with significant improvements shown for exercise duration, maximum workload, and peak oxygen consumption two years postoperatively (Ries et al., 1996, 1997). Studies also support the conclusion that TKR may allow people to return to high levels of activity and recreational exercise. In a study conducted by Diduch et al. (1997), it was reported that of 108 TKR (patients <55 years old), the average activity score (Tegner & Lysholm, 1985) was 1.3 points (range, 0 to 4 points) preoperatively and 3.5 points (range, 1 to 6 points) postoperatively. This improvement is equivalent to a change from sedentary, desk-type work with limited walking on even ground to an occupation that involves light labour, such as nursing or truck-driving, and some recreational activities, such as cycling, cross-country skiing, or swimming. Moreover, individuals who were relatively sedentary prior to joint replacement often increased their activity levels post-joint replacement (Visuri & Honkanen, 1980; Diduch et a1., 1997). A study by Visuri & colleagues (1980) showed that patients significantly increased their participation in low-impact activities, such as exercise walking, cycling, swimming, and cross-country skiing, after total hip replacement, while Diduch & colleagues (1997) demonstrated that patients nearly tripled their activity scores after TKR. The increased activity levels that accompany joint replacement may then have an effect on decreasing the likelihood of individuals developing chronic diseases (e.g., heart disease and diabetes) in the future.

There is also evidence that the younger TKR patient shows improved function post-TKR (Ranawat et al., 1989; Ranawat et al., 1993; Colizza et al., 1995). Stern et al. (1990) reported that of the 68 TKRs, 55 had excellent results (81%) and 13 had good results (19%) at an average of six years after TKR. Diduch et al. (1997) reported the average Hospital for Special Surgery knee score for function (reporting on 103 knees) had improved from 55 points (range, 22 to 80 points) preoperatively to 92 points (range, 75 to 100 points) postoperatively. The postoperative score for all 103 knees represented a good or excellent rating. Furthermore, these results were similar to those reported in older patients (Insall et al., 1983; Goldberg et al., 1988; Colizza et al., 1995). Odland et al. (2011) in a retrospective review of 59 patients TKR patients with an average age of 48.5 years (minimum follow-up period of ten years) reported post-operative scores of 11.8 for pain, 31.1 for stiffness, and 24.9 for function (using the Western Ontario McMaster Universities Osteoarthritis Index). A recently published multicenter study, assessed residual symptoms and functional deficits in 661 younger patients (mean age of 54 years) at one to four years after primary TKR (Parvizi et al. 2014). Their results showed that 89% of patients were satisfied with their ability to perform normal daily living activities.

It has been projected that younger adults (<55 years old) will become the majority indicated for TKR during the next two decades in the USA (Kurtz et al., 2009). Although this younger patient group is rapidly growing, the vast majority of the literature investigating the functional outcome after total knee replacement has been derived from the ‘typical’ older TKR patient (≥ 65 years old). It must be noted that, in addition to the pain and dysfunction of the affected knee and lower limb, the typical patient may differ functionally from the younger patient in measures of neuromuscular control, which decline with age. Studies have identified that ageing affects sensory systems and the speed with which information is processed by the CNS to yield appropriate and coordinated movements (Allum et al., 2002). Healthy older adults show a reduction in the proprioceptive capacity as well as a reduced central processing capacity of afferent information (Erni & Dietz, 2001; Marigold & Patla, 2002). These reductions may have a negative consequence on both reactive as well as predictive adjustments when performing a balance correction response (Bierbaum et al., 2010). Other age-related changes include; reductions in muscle strength (Grabiner et al., 2005; Karamanidis et al., 2008), modifications of the muscle activation timing (Thelen et al., 1997) as well as lower muscular contraction velocities (Thoroughman & Shadmehr, 1999). The consequences of these aforementioned age-related changes have been observed in studies testing participants balance recovery, where elderly participants had an increased induced sway (Stelmach et al., 1989), delayed onsets and amplitude changes of automatic postural responses in ankle muscles (Nardone & Schieppati, 1998), delayed and slightly weaker torques about the ankle joint (Gu et al., 1996) and abnormal compensatory stepping reactions (McIlroy & Maki, 1996). These age-related changes could be further exacerbated by degeneration of the knee joint that persist after TKR in the older patient, although this is only speculative. Recent research has shown that younger patient do differ from the typical, older patient for perceived knee function after TKR. Street et al. (2013b) found that the largest improvement in perceived knee function after joint replacement surgery was observed to occur in the youngest patient group (50-59 years old); importantly, the mean Oxford Knee Score did not differ significantly to that of the clinician assessed functional score (Khanna et al., 2011; Hamilton et al. 2012). To date, there has not been any investigation into how this rapidly growing younger TKR patient functions; how or if TKR affects the mechanics when walking or during a balance recovery response differently for the younger patient compared to the typical patient, and post-TKR is balance confidence different for the younger patient compared to the typical patient and healthy controls.

The absence of any published data on the function of the younger TKR patient warrants investigation. An understanding of how TKR affects younger patients is crucial to both the surgical and the rehabilitation practice. It is not known if the younger TKR patient acts more like the typical TKR patient or more closely to their healthy aged-match controls. The goal of this thesis is to investigate the younger TKR population and to shed light on if, and possibly why, the younger patient differs from the typical, older TKR patient; to impact current gaps in policy decisions when indicating an intervention and on the rehabilitation programs implemented for the younger TKR patient.

As such, this thesis will investigate the following research questions;

1. Do younger TKR patients have a similar balance confidence as the typical, older TKR patients or more closely to that of their healthy age-matched controls?

    a) Does a TKR patient's age affect balance confidence?
    b) Does a TKR patient's age affect the relationship between movement reinvestment and measures of balance confidence and functional mobility?
    c) Can age predict changes in balance confidence for TKR patients?
2. When responding to an external perturbation do younger TKR patients employ strategies that differ from that of the older, typical TKR patient?
    a) If so, are the balance response strategies employed by the younger TKR patient more effective at controlling COM displacement than those of the older TKR patient?
3. Do younger TKR patients behave similar during gait as the typical, older TKR patients or more closely to that of healthy age-matched controls?
    a) Does the heel strike transient, kinematics and joint moments of the knee during level walking of the younger TKR patient demonstrate a similar asymmetry pattern between their surgical and non-surgical limb as that observed in the typical, older TKR patient?

# CHAPTER TWO

## A COMPARISON OF BALANCE CONFIDENCE AND THE EFFECTS OF COGNITIVE REINVESTMENT BETWEEN YOUNGER AND OLDER TOTAL KNEE REPLACEMENT PATIENTS

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## Preface

Demographic changes have recently been observed in regional and national epidemiology reports of joint replacement registries; reporting a substantial increase in the number of younger individuals undergoing total knee replacement (TKR). Importantly, little data currently exists on how these younger patients will function after TKR. Elevated activity avoidance after TKR has been reported, a possible risk factor for activity avoidance in TKR patients is a decrease in balance confidence, which has been associated with chronic illness and fall risk. It has been shown that healthy older adults who have fallen report a higher propensity to consciously control or “reinvestment” in their movements compared to non-fallers and this could have a similar influence on balance confidence for TKR patients. Balance confidence and the influence of movement reinvestment for this quickly growing “younger” TKR patient population (<55 years old) may differ from the typical, older patient (>65 years old), which would have important clinical implications. Therefore, the purpose of this project is three-fold. First, investigate balance confidence among the younger TKR patient, and compare the observations to that of the typical, older TKR patient and their healthy age-matched controls. Second, determine if there is a relationship between age, movement reinvestment, balance confidence and functional mobility for TKR patients. Lastly, determine if there are variables that can predict balance confidence in TKR patients. The Activities-specific Balance Confidence scale (ABC), the Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC), Oxford Knee Score (OKS), the Timed Up and Go (TUG) test, and the Movement-Specific Reinvestment Scale (MSRS) were collected from a convenience sample of 59 participants, including 29 primary unilateral knee replacement patients six month post-TKR from the following groups; 1) Younger TKR Patient (n=15 (11 F), age: 54.3 ± 7.9 years), 2) Younger Control (n=15 (13 F), age: 55.2 ± 4.0 years), 3) Older TKR

Patient (n=14 (12 F), age: 76.9 ± 4.7 years), and 4) Older Control (n= 15 (11 F), age: 77.7 ± 4.1 years). Balance confidence and functional mobility was significantly higher in the two younger groups compared to the two older groups. Interestingly, ABC and TUG test scores observed for the younger TKR group was much closer to their age-matched healthy controls rather than the typical TKR patient. These findings suggest that after TKR balance confidence and functional mobility are at levels that are not statistically different between younger TKR patients and healthy controls, possibly elevating engagement in physical activity for younger TKR patients compared to the typical, older TKR patients. If the younger TKR patient is in fact more active, it could help explain the increase in revision rates that have been reported among younger TKR patients compared to the typical TKR patient. Also, the younger TKR patient group reinvested in their movements significantly less compared to the typical, older TKR patient group and the MSRS scale was shown to be related to both the ABC and TUG test. The younger TKR patient has a balance confidence, functional mobility and movement reinvestment level that more closely matches healthy controls, suggesting that younger TKR patient would be at a reduced risk of falling compared to the typical, older TKR patient and therefore age should not be a barrier when indicating knee replacement surgery.

## 1. Introduction

Knee osteoarthritis (OA) is generally considered to only affect older adults, but signs and symptoms of OA are observed in patients in their 30s and 40s, and it has been reported that over the last decade the largest increase in new knee OA cases reported in Canada occurred in the 50-54 age group (Kopec et al. 2008). Total knee replacement (TKR) is a common surgical procedure used for the management of moderate to severe knee OA with more than 40,000 TKR procedures performed in Canada each year (CJRR, 2009). TKR has been shown to provide pain relief and improve physical function and quality of life for patients with knee OA (Hawker et al. 1998; Cushnaghan et al. 2009); however, deficiencies in joint function and mobility persist when compared to healthy controls (Wada et al., 2002; Gage et al., 2008; Swinkels et al., 2009). Over the last decade in Canada, the largest relative percent increase (≈300%) in TKR surgeries occurred in the 45-54 age group (CJRR, 2009). Although this younger TKR patient group (<55 years old) is rapidly growing, the vast majority of the literature investigating TKR outcomes has been based upon the ‘typical’, older TKR patient (≥ 65 years). This has created a therapeutic dilemma for surgeons (Stulberg, 1995). With little empirical data on how younger patients will function after TKR coupled with the fear of earlier and multiple revision surgeries, there is a hesitation to indicate TKR to the younger knee OA sufferer.

Falls have been shown to be elevated in knee OA patients (Blake et al., 1988; Campbell et al., 1989; Lawlor et al., 2003; Sturnieks et al., 2004; Leveille et al., 2009; Williams et al., 2010) and after TKR surgery (Swinkels et al., 2009; Levinger et al., 2011). Thus, a concern related to falling, including a fear of falling or low balance confidence, may affect these individuals that have fallen in the past. Unver et al. (2014) reported that TKR patients had a higher fear of falling (Tampa Scale for Kinesiophobia; 17-item self-report questionnaire, using a

4-point Likert scale) up to 6-months post-TKR compared to healthy controls and that there was a significant correlation between fear of falling, functional mobility, and pain scores. Fear of falling was originally developed and measured as a dichotomous variable, as you were either fearful or not. This simple presence or absence of fear made it difficult to determine if any variability existed when completing a motor task, as simply expressing a concern about falling does not necessarily categorize someone as "fearful," even when they may modify their behaviour to avoid falling (Maki et al., 1991; Tinetti et al., 1994). To overcome this, researchers have employed the concept of self-efficacy (Bandura, 1986) to the context of mobility, where it is defined as the degree of confidence a person has in keeping his or her balance while performing activities of daily living. Currently, two measurement tools have been used to investigate self-efficacy associated with falling: the Falls Efficacy Scale (Tinetti et al., 1990) and the Activities-specific Balance Confidence Scale (Powell & Myers, 1995). Although the Falls Efficacy Scale is often referred to as a measure of "falls-related self-efficacy" and the Activities-specific Balance Confidence Scale (ABC) is a measure of "balance confidence," both scales measure the same construct of perceived balance ability (Powell & Myers, 1995). Balance confidence has been shown to be associated with physical and social functioning in older adults (Tinetti et al., 1994; Myers et al., 1996). To date, only a single cross-sectional study has investigated balance confidence for TKR patients. Webster et al., 2006 reported that women had a significantly lower ABC Scale score (less confidence) than men after TKR, and that balance confidence was significantly correlated with functional scoring. The cross-sectional nature of this study and the exclusion of a healthy control group for comparison, leaves a significant gap in the literature on how TKR affects the level balance confidence of TKR patients and how they may differ from healthy individuals.

A decrease in balance confidence may be associated with a shift from an automated control to a more conscious control when performing a motor task, such as walking. The term “reinvestment” has been used to describe this shift to a more conscious control of one’s movements (Masters & Maxwell, 2008), and it has been suggested that reinvestment would cause a decrease in performance when completing a motor skill (Masters et al., 1993). Increased movement reinvestment has been observed in stroke patients compared to healthy controls (Orrell et al. 2009), and elderly fallers are found to reinvest more in their movements compared to elderly non-fallers (Wong et al. 2008).  It has also been observed that when in an environment of elevated postural threat (e.g., standing on a raised platform) healthy younger adults report changes in movement reinvestment that are significantly correlated with changes observed in postural control (Huffman et al. 2009). This adoption of a more conscious control has been linked to increased falls (Orrell et al. 2009). Whether TKR patients demonstrate changes in movement reinvestment has not been examined. Also, it is not known if the rapidly growing younger TKR population differ in their balance confidence from the typical TKR patients and if the adoption of a more conscious control or self-consciousness when moving is related to a decrease in balance confidence in either of these patient populations. This significant gap in the literature warrants investigation.

The first purpose of this study was to investigate the effect of age on measures of balance confidence, functional mobility and movement reinvestment in a group of younger TKR patients and compare them to what is observed in the typical, older TKR patients, and each group's age-matched healthy controls. The second purpose of this study was to investigate the effect of the TKR patient’s age on the relationship between movement reinvestment and measures of balance confidence and functional mobility. Lastly, this study examined the effect of the TKR patient’s age on predictors for changes in balance confidence for TKR patients. It was hypothesized that balance confidence would be reduced with age. Additionally, it was hypothesized that functional mobility would be reduced with age after TKR in accordance with previous findings that reported younger healthy adults demonstrated higher levels of functional mobility compared to older healthy adults (Walsh et al., 1998; Boonstra et al., 2008). It is also hypothesized that a participant's age would be a significant predictor of balance confidence.

## 2. Methodology

### 2.1 Participants

A convenience sample of 59 participants, including 29 primary knee replacement patients, consisting of four groups volunteered to participate in this study: 1) Younger TKR patient (n=15 (11 F), age: 54.3 ± 7.9 years), 2) Younger control (n=15 (13 F), age: 55.2 ± 4.0 years), 3) Older TKR patient (n=14 (12 F), age: 76.9 ± 4.7 years), and 4) Older control (n= 15 (11 F), age: 77.7 ± 4.1 years). Prior to their participation, each participant provided informed consent to the potential risk factors associated with their participation. Approval of this study was provided by the Human Participants Review Committee (HPRC) at York University, Toronto, Ontario, Canada and Southlake Regional Health Centre, Newmarket, Ontario, Canada.

Inclusion criteria for the patient groups included: successful recovery following unilateral TKR, and at least six months post-surgery prior to testing. A total of 19 right knees and 10 left knees were operated on, and the date of surgery was 6.2 (± 0.6) months prior to testing. Exclusion criteria for the patient groups included: diagnosed arthritis in any other joint of the lower body, any other orthopaedic injuries or scheduled surgeries, post-operative infection related to the primary joint replacement, vestibular or any other balance disorder, and diabetes or any other peripheral neuropathic conditions. Prior to undergoing testing, the referring orthopaedic surgeon confirmed that each patient had returned to their normal daily activity, and that the post-surgical knee had completely recovered following the operation. It was understood that patients may experience discomfort at other joints, but that they had not been diagnosed with osteoarthritis or any other joint disorder at the time of testing, nor were any of them receiving any form of treatment for pain or discomfort at any other joint, or been told that they would need surgery on any other joint in the future. All participants in the two control groups reported that they had no history of orthopaedic injury or surgery, vestibular of other balance-related disorders, diabetes or any other peripheral neuropathic conditions.

## 2.2 Procedure

Each participant completed the following questionnaires: the Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC), the Oxford Knee Score (OKS), the Activities-specific Balance Confidence scale (ABC), and the Movement-Specific Reinvestment Scale (MSRS). Each participant also completed the Timed Up and Go (TUG) test. Each of the questionnaires and tasks were presented in a random order for each participant.

## 2.3 Dependent Measures

### 2.3.1 Perceived Pain, Stiffness, and Physical Function

The Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC) consists of 24-items divided into 3 subscales. The first subscale is pain, consisting of 5-items: pain during walking, using stairs, in bed, sitting or lying, and standing. The second subscale, stiffness, consists of 2-items: stiffness after first waking and later in the day. The last subscale is physical function and is made up of 17-items: what degree of difficulty do you have using stairs, rising from sitting, standing, bending, walking, getting in/out of a car, shopping, putting on/taking off socks, rising from bed, lying in bed, getting in/out of bath, sitting, getting on/off toilet, heavy household duties, light household duties. The WOMAC is scored on a Likert scale, using the following descriptors for all items: none, mild, moderate, severe, and extreme. These correspond to an ordinal scale of 0-4. The scores were summed for items in each subscale, with possible ranges as follows: pain=0-20, stiffness=0-8, physical function=0-68. A higher score in each subscale indicates worse pain, stiffness, and functional limitations. The test-retest reliability of the WOMAC for patients diagnosed with knee OA has been shown to have an intra-class correlation coefficient of 0.74, 0.58, and 0.92, for pain, stiffness, and physical function subscales, respectively (Roos et al., 1999).

### 2.3.2 Perceived Knee Joint Function

The Oxford Knee Score (OKS) is a 12-item patient-reported outcome specifically designed and developed to assess perceived function and pain after TKR surgery (Dawson et al., 1998). The original OKS questionnaire was based on 12-items, each answered on a Likert scale, with 5 response categories scored from 1 to 5, for a total of 60, with higher scores indicating a more symptomatic knee (Dawson et al., 1998). For this study, modification to the original scoring system of the OKS was used, which has been advocated for ease of use and to make the scoring more intuitive for the patient (Murray et al., 2007). The same 12-items were used, but each question was scored between 0 and 4, for a total score of 48 and a higher score is recognized as a healthier, less symptomatic joint. This scoring system has been reported in previous publications (Harcourt et al., 2001; Street et al., 2013). The OKS is very reliable, with a Cronbach's alpha total score of 0.918, and is highly correlated with the SF-36 subscale of physical function with a Pearson's correlation coefficient (r) of -0.72 (Charoencholvanich &

Pongcharoen, 2005). A minimal clinically important difference of 5.0 (95 % CI 4.4-5.5) was reported to occur between pre-operative and 1-year post-operative OKS for 505 patients undergoing a primary TKR for knee OA (Clement et al., 2013).

### 2.3.3 Perceived Balance Confidence

The Activities-specific Balance Confidence scale (ABC) is a 16-item self-report measure in which patients rate their balance confidence when completing activities of daily living. All of the 16 questions stem from the use of a specific lead when each activity is considered: "How confident are you that you will not lose your balance or become unsteady when you..." (Powell & Myers, 1995). Examples from the questionnaire include: “when walking around the house?” and “when walking up and down stairs?” Items are rated on a scale ranging from 0 – 100 %, where 0 reflects “I do not feel at all confident”, 50 reflects “I feel moderately confident”, and 100 reflects “I feel completely confident”. The overall score was calculated by adding item scores and then dividing by the total number of items, for a percentage out of 100%. A score of > 80% is considered to represent someone who would have a high level of physical function, 50-80% a moderate level, and < 50% a low level (Myers et al., 1998). Lajoie & Gallagher (2004) reported that a score of < 67% accurately classified older adults who were fallers 84% of the time.

### 2.3.4 Functional Mobility

The Timed Up and Go (TUG) test was used to assess the functional mobility of the participants. The test was administered based on published protocols (Podsiadlo & Richardson, 1991). The test assesses a person's mobility and requires both static and dynamic balance. Participants were asked to rise from a chair, walk three metres, turn around, walk back to the chair, and sit down. The total time to complete the TUG test was measured for each participant over five trials; the mean of those trials was calculated for each participant and used in the analysis. During testing, the person wore their regular footwear and used any mobility aids that they would normally require. The TUG test has excellent reliability (ICC = 0.99) and correlates with gait speed (r = -0.55) and the Berg Balance Scale (r = -0.72) (Ng et al., 2005). The initial authors of the test (Podsiadlo & Richardson, 1991) have reported that scores of < 10 seconds indicate normal mobility. A cut-off score of ≥ 13.5 seconds was shown to predict falls in community-dwelling frail older adults and scores of ≥ 30 seconds correspond with functional dependence in people with pathology (Rockwood et al., 2000; Bischoff et al., 2003).

### 2.3.5 Movement Reinvestment

The Movement-Specific Reinvestment Scale (MSRS) was developed to measure the tendency for individuals to consciously control their movement (Masters et al., 2005; Masters & Maxwell, 2008). The MSRS has two subscales: movement self-consciousness (MSC) and conscious motor processing (CMP). MSC reflects an individual's worry or concern about how his/her movement looks, while CMP reflects an individual's tendency to consciously monitor and control his/her movements. The MSRS comprises 10-items: five that relate to MSC (e.g., ''I am self-conscious about the way I look when I am moving'') and five that relate to CMP (e.g., ''I am aware of the way my body works when I am carrying out a movement''). Participants rated each item on a 6-point Likert scale from ''strongly disagree'' to ''strongly agree.'. Thus, cumulative scores ranged from 10 to 60 points, with higher scores indicating individuals with a higher propensity for reinvestment. The summed score for the total MSRS, as well as for the two subscales were recorded. The MSRS has been used to measure trait reinvestment with both CMP and MSC subscales showing acceptable test–retest reliability (r = 0.76) and internal reliability (r = 0.71) (Masters et al., 2005).

## 2.4 Statistical Analysis

Difference between groups in terms of age, BMI and height were evaluated using a two-factor ANOVA (*age* [younger/older] x *group* [patient/control]) with participants nested in both factors. Differences between groups in terms of the number of participants of each sex were evaluated using chi-squared analysis. Independent t-tests were used to assess the differences in the WOMAC and OKS questionnaires between the younger and older TKR groups. To address the first purpose of this study, the effect of age on measures of balance confidence, functional mobility and movement reinvestment in the younger and older TKR patients and their age-matched healthy controls, the following analysis was conducted: a two-factor ANOVA (*age* [younger/older] x *group* [patient/control]) with participants nested in both factors; Bonferroni adjusted tests were then used to assess differences when a significant interaction was observed. To address the second purpose of this study, the effect of the TKR patient′s age on the relationship between movement reinvestment and measures of balance confidence and functional mobility, Pearson's correlation coefficients were calculated. To address the third purpose of this study, the effect of the TKR patient′s age on predictors for changes in balance confidence for TKR patients, the following analysis was conducted: a multiple regression model to predict balance confidence results in the two patient groups was used, with age, WOMAC pain, WOMAC stiffness, WOMAC function, OKS, CMP, MSC, and TUG test as predictors.

## 3. Results

Participant characteristics are shown in Table 1. Analysis of age differences between the groups revealed no interaction effect of *age* x *group* ($F_{1, 55} = 0.63$, $p = 0.430$) or effect of *group* ($F_{1, 55} = 0.01$, $p = 0.944$). A significant effect of *age* was observed ($F_{1, 55} = 438.6$, $p < 0.001$). The older participants were significantly older than the younger participants. Analysis of the height and BMI revealed no interaction effect of *age* x *group* ($F_{1, 55} = 0.50$, $p = 0.483$; $F_{1, 55} = 0.01$, $p = 0.906$, respectively), effect of *group* ($F_{1, 55} = 0.83$, $p = 0.370$ $F_{1, 55} = 0.03$, $p = 0.860$, respectively) or effect of *age* ($F_{1, 55} = 2.97$, $p = 0.091$; $F_{1, 55} = 3.02$, $p = 0.088$, respectively). The groups were not significantly different in their respective ratios of females:males ($X^2$ (3, N = 59) = 1.345, $p = 0.697$).

### 3.1 Perceived Pain, Stiffness, and Physical Function

*The Western Ontario and McMaster Universities Osteoarthritis Index*: Perceived pain, stiffness, and physical function were different between the two patient groups and are presented in Table 2. The older TKR patient group reported a significantly higher total WOMAC score compared to the younger TKR patient group ($t_{27} = -10.28$, $p < 0.001$). Analysis of the three subscales of the WOMAC revealed that the older TKR patient group reported greater pain ($t_{27} = -8.11$, $p < 0.001$), stiffness ($t_{27} = -5.90$, $p < 0.001$), and reduced physical function ($t_{27} = -5.55$, $p < 0.001$) when compared to the younger TKR patient group.

### 3.2 Perceived Knee Joint Function

*Oxford Knee Score*: The older TKR patient group reported significantly reduced perceived knee joint function ($t_{27} = -3.81$, $p = 0.001$) compared to the younger TKR patient group (Table 2).

### 3.3 Perceived Balance Confidence

*Activities-specific Balance Confidence scale:* The mean and standard deviation values for the total ABC score for the four groups are presented in Table 2. The results showed that there was no interaction effect of *age* x *group* ($F_{1, 55} = 2.48$, $p = 0.121$), but a significant main effect of *age* ($F_{1, 55} = 37.55$, $p < 0.001$) and *group* ($F_{1, 55} = 6.64$, $p = 0.013$). The younger participants reported a mean balance confidence score that was 16.65% higher than that of the older participants. Further, the control group participants reported a mean balance confidence score that was 8.5% higher than that of the patient group participants.

### 3.4 Functional Mobility

*The Timed Up and Go test:* Table 2 shows the mean and standard deviation values for the TUG test time duration for the four groups. The results showed that there was no interaction effect of *age* x *group* ($F_{1, 55} = 2.55$, $p = 0.116$), but a significant main effect of *age* ($F_{1, 55} = 17.49$, $p < 0.001$) and *group* ($F_{1, 55} = 9.50$, $p = 0.003$). The younger participants had a mean TUG time that was 2.35 seconds faster than that of the older participants. Further, the control group participants had a mean TUG test time that was 1.75 seconds faster than that of the patient group participants.

### 3.5 Movement Reinvestment

*Movement-specific Reinvestment Scale:* The mean and standard deviation values for the total MSRS and the two subscales for the four groups are presented in Table 2. The analysis for MSRC revealed that there was a significant interaction effect of *age* x *group* ($F_{1, 55} = 5.43$, $p = 0.02$), a significant main effect of *age* ($F_{1, 55} = 60.03$, $p < 0.001$) and a significant main effect of *group* ($F_{1, 55} = 82.41$, $p < 0.001$). The older TKR patient group reported MSRS scores that were significantly higher than all of the other groups ($p < 0.001$).The younger TKR patient group and older control group reported similar MSRS scores ($p = 0.264$). However, the younger control group reported MSRS scores that were significantly less than the younger TKR patient ($p < 0.001$) and older control ($p = 0.002$) groups.

*Conscious motor processing (CMP) and movement self-consciousness (MSC):* ANOVA analysis for both CMP and MSC subscales revealed that there was a significant interaction effect of *age* x *group* ($F_{1, 55} = 8.32$, $p = 0.001$; $F_{1, 55} = 7.39$, $p = 0.003$, respectively), and significant main effects for both *age* ($F_{1, 55} = 60.99$, $p < 0.001$ and $F_{1, 55} = 44.81$, $p < 0.001$, respectively) and for *group* ($F_{1, 55} = 54.99$, $p < 0.001$ and $F_{1, 55} = 67.51$, $p < 0.001$, respectively). The CMP and MSC subscales showed that the younger TKR patient group and the older control group did not differ in the amount they consciously controlled or felt self-conscious about their movements ($p = 0.992$ and $p = 0.649$, respectively). However, it was observed that the younger control group reported conscious control and self-conscious about their movements was significantly less than the younger TKR patient ($p < 0.001$) and older control ($p = 0.002$) groups. The older patient group reported significantly higher amounts of conscious control ($p = 0.011$, $p < 0.001$ and $p = 0.005$, respectively) and self-consciousness ($p < 0.001$, $p < 0.001$ and $p = 0.003$, respectively) in their movements compared to the younger patient, younger control and older control groups.

### 3.6 Movement reinvestment relationship with balance confidence, functional mobility and age

Table 3 shows the relationships between movement reinvestment, balance confidence, functional mobility and age for all participants. The observed MSRS value was significantly related to that of the ABC ($r = -0.460$, $p = 0.01$) and the TUG test ($r = 0.646$, $p = 0.01$). An increase in movement reinvestment was related to feelings of less balance confidence and reduced functional mobility. There was also a significant negative relationship observed between the ABC and the TUG test (r = -0.459, p = 0.01); decreased balance confidence was associated with an increase in the time to complete the TUG test. Age was significantly related to ABC (r = -0.491, p = 0.01), TUG test (r = 0.498, p = 0.01), MSRS (r = 0.809, p = 0.01), CMP (r = 0.751, p = 0.01), and MSC (r = 0.822, p = 0.01); increased age was associated with decreased balance confidence, decreased functional mobility, and increased movement reinvestment.

### 3.7 Predictive model with regards to balance confidence status for younger and older knee replacement patients

Table 4 shows the relationships between ABC, WOMAC subscales, OKS, MSRS subscales and the TUG test for all patients. A significant negative correlation was observed between ABC and WOMAC stiffness ($p < 0.05$ level; 2-tailed), and the ABC with age, WOMAC pain, WOMAC function, OKS, CMP, MSC and the TUG test ($p < 0.01$ level; 2-tailed). Therefore, for example, lower age among patients was associated with increased balance confidence. No correlation was observed between MSC and OKS (r = 0.304, $p > 0.05$), and MSC and ABC (r = 0.319, $p > 0.05$). For all the remaining variables a significant positive correlation was observed ($p < 0.05$ level; 2-tailed). The observed correlation showed that age and WOMAC pain had the highest correlation with the ABC (r = -0.676, $p > 0.01$ and r = -0.635, $p > 0.01$, respectively)

Regression modeling was performed in order to understand the underlying contribution of factors that may affect balance confidence. The predictors entered into the regression model analysis included age, WOMAC pain, WOMAC stiffness, WOMAC function, OKS, CMP, MSC and TUG test time. The regression analysis showed that five predictors contributed significantly to the prediction of balance confidence, accounting for 78% of the variance in ABC Scale scores.

These included age, WOMAC pain, WOMAC function, CMP and TUG time. Table 5 displays the regression coefficients (B), the standard errors (S.E) and corresponding p-values for the predictor variables. For the significant predictor of age, it was observed that balance confidence decreased by 1.84% for each year as patient got older. Also, as a patient′s pain (WOMAC pain) was reduced by one unit their balance confidence increased by 1.03%. The significant predictors for both perceived function and functional mobility (WOMAC function and TUG time) revealed that as functional scoring improved by one unit, or the time to complete the TUG test was reduced by one second, balance confidence increased by 1.7% and 4.6%, respectively. Lastly, for the significant predictor CMP, it was shown that balance confidence improved by 2.3% for each unit of improvement in the measure of conscious control of movement.

## 4. Discussion

The use of TKR has increased substantially during the past two decades, particularly among younger patients (Amstutz et al., 1984; Bellamy et al., 1988; Bozic et al., 2010). Although TKR is performed with increasing frequency on younger adults, very little data on the younger TKR patient beyond clinical scores and prosthesis durability have been published. Unless there is a greater understanding of how TKR affects this rapidly growing younger patient, it is inappropriate to formulate explicit statements or recommendations regarding how TKR will affect this population. The results from this current study indicate that the younger TKR patient report lower levels of pain, joint stiffness, and movement reinvestment, and elevated levels of physical function, functional mobility and balance confidence compared to the typical TKR patient. These findings suggest that the younger TKR patient is at a reduced risk of falling and have less activity restrictions, and that at six months post-surgery, the younger TKR patient is experiencing a better perceived outcome then the typical older TKR patient.

Data were collected at six months post-surgery; as it is well known that the majority of maximum functional gains in terms of balance and locomotion are achieved in the first six months following TKR surgery (Unver et al., 2005; Kennedy et al., 2008). Consistent with previous studies that have investigated TKR patients, many more females than males (23/29, 79% female), composed the current sample (Unver et al., 2005; Rossi et al., 2006; Yoshida et al., 2007; Kennedy et al., 2008; Bade et al., 2010; Unver et al., 2014). The mean age of the older participants was significantly greater (22.6 years) than the mean age of the younger participants. No significant difference was observed between any of the groups for height or BMI. All of the groups (BMI between 30 and 35) would be categorized as Obese Class I or moderately obese (World Health Organization, 2006). Similar BMI values, when TKR patients are stratified for age, have been reported previously (Williams et al., 2013).

### 4.1 Younger total knee replacement patients report less perceived pain, stiffness and elevated function compared to the typical older patient.

In this study the total WOMAC score observed in the typical, older patient group was significantly higher than that of the younger patient group. The difference between the groups in the reported overall WOMAC score exceeds the minimal clinically important difference (MCID) of 15 points for TKR patients six months after surgery (Escobar et al., 2007). This difference between older and younger patient groups is reflective of scores that have been argued to create a meaningful difference in a patient’s life (Cook, 2008), suggesting that at six months post-surgery the younger TKR patient is experiencing a better perceived outcome then the typical older TKR patient. The younger TKR group also reported significantly better pain, joint stiffness, and function scores for the WOMAC subscales, compared to the older patient group. In another study that looked at age as an independent factor, it was found that increasing age was correlated with worse scores in both the WOMAC stiffness and WOMAC pain subscales for TKR patients

(Escobar et al., 2007). Alzahrani et al. (2011) reported pre-surgical and one year follow-up assessments using the WOMAC, and found that age was a factor in post-TKR outcome. Alzahrani et al. (2011) categorized patients into two groups: “no improvement” or “improved”, according to the minimal clinically important improvement for the WOMAC after TKR. Logistic regression modeling showed age to be an independent predictor of “no improvement” on the WOMAC scale one year after surgery, such that for every year of age older at the time of surgery, the patient was 6% more likely to show no improvement at one year post-TKR.

The older TKR group reported an OKS of 35.7 (± 7.4) similar to previous data published for the typical TKR patient six months after surgery (Dawson et al., 1998; Wylde et al., 2009; Scott et al., 2010; Alzahrani et al., 2011; Street et al., 2013). The OKS reported by the younger TKR group was 43.4 (± 8.7), showing that the younger TKR group reported a significantly less symptomatic knee than the older TKR group. Similar OKS in younger TKR patients have been reported in previous publications (Alzahrani et al., 2011; Street et al., 2013; Williams et al., 2013). William et al. (2013) reported postoperative OKS that were comparable across age groups (< 55; 56-64; 65-84; ≥ 85 years), but a linear trend of progressively lower levels of improvement in OKS with increasing age was observed. Further, a clinically significant improvement in OKS was observed in 879 patients (87.2%) two years after surgery, but the proportion of patients achieving a clinically meaningful improvement was greater in the younger groups. The difference in OKS between the younger and older TKR patients in the current study was 7.7 points; this value exceeds the MCID of five points (Clement et al., 2013), suggesting that this difference in perceived knee function between TKR groups is sufficient to impact the perceived outcome post-TKR. In a retrospective study, Street et al. (2013) investigated the effects of TKR and age on OKS among 240 TKR patients, stratified by age into four groups (50-59; 60-69; 70-

79; 80-89 years). It was found that the largest improvement with joint replacement was observed to occur in the youngest patient group (50-59 years old), and that the degree of improvement diminished as the patient age increased. TKR has generally been reserved for patients who are at least sixty years old (Insall, 1985; Rand & Ilstrup, 1991), as the lack of data on the younger patient has created a therapeutic dilemma (Stulberg, 1995) for surgeons when contemplating whether to proceed with TKR in the younger patient. The current findings clearly demonstrate that the younger TKR patients at six months post-surgery are experiencing a better perceived outcome then the typical older TKR patient. Therefore, the results from the current study provide further support to the conclusion by Bourne et al. (2007), Escobar et al. (2007) and Street et al. (2013) that age should not be a barrier when indicating knee replacement surgery.

### 4.2 After total knee replacement younger patients report balance confidence and functional mobility values similar to healthy controls

Psychosocial factors have been associated with fall risk and received increased attention throughout the past decade. However, to date, very little research has been conducted on balance confidence and TKR patients. Lower balance confidence scores have been shown to be associated with balance-impairment and reduced functional mobility in mildly balance-impaired older adults (Cho et al., 2004). Lajoie & Gallagher, (2004) reported that balance confidence scoring was related to falls in older adults and could distinguish fallers from non-fallers. Balance confidence scoring has also been shown to be significantly lower in older adults who have reported falling compared to older adults who have reported no history of falling (Schepens et al., 2010). A consequence of reduced balance confidence is activity avoidance, which can then lead to further balance deterioration (Myers et al., 1996), and create a self-degenerating cycle. In this current study the older TKR and older control groups reported a balance confidence score that was 16.65% lower than that of the younger TKR and younger control groups. Interestingly, the younger TKR and younger control groups only differed by 5.8%, whereas the younger TKR group reported a balance confidence score that was 17.8% higher to that of the older TKR patient. Webster et al. (2006) is one of the few studies to investigate balance confidence and TKR patients; it was reported that women after TKR had a significantly lower ABC Scale score (less confidence) than men, and the balance confidence scores were significantly correlated with functional scoring (American Knee Society knee score, r = .62; walking speed, r = .59). This study did not include a healthy control group for comparison, but the ABC scoring are similar to that of the ABC scoring of the older TKR group of this current study.

The reported balance confidence of the younger control, younger TKR and older control groups from this current study all would represent a population who would be considered to have a high level of physical function (> 80%), whereas the older TKR group reported a balance confidence score (50-80%) which would represent a population with only a moderate level of physical function (Myers et al., 1998). Importantly, this distinction between patient groups may represent a difference in fall risk (Morris et al., 1987). The results from this current study seem to suggest that younger TKR patients are more confident when performing tasks of daily living and would have a reduced risk of falling compared to the typical TKR patient. Further, the elevated balance confidence of the younger patient may lead to an increase in physical engagement, this may have negative consequences on prosthesis survivorship and may help explain the elevated revision rates that have been reported among younger TKR patients compared to the typical TKR patient. Conversely, increased physical activity could also diminish the occurrence of chronic diseases associated with a more sedentary lifestyle. Future research should look to investigate the activity levels of the younger patient and its implications on patient health and prosthesis degeneration and survivorship.

Maximizing functional mobility is a key goal of TKR surgery. Functional performance in patients one year after TKR remains lower than healthy adults, with reports of an 18% slower walking speed, 51% slower stair-climbing speed, and deficits of nearly 40% in quadriceps strength (Walsh et al., 1998). The Timed-Up-and-Go (TUG) test has been commonly used to evaluate function after TKR (Steffen et al., 2002; Thomas et al., 2003; Kennedy et al., 2006; Rossi et al., 2006; Yoshida et al., 2007; Kennedy et al., 2008; Bade et al., 2010), as the test is simple to administer and reliable (Thomas et al., 2003; Bade et al., 2010). In this current study the younger TKR and control groups completed the TUG test 2.35 seconds faster than the older TKR and control groups. A 1.75 second difference in TUG test time was also observed between control and patient groups. This is consistent with the results of previous studies by Walsh et al. (1998) and Boonstra et al. (2008), who found increased TUG test times at one year or more after TKR compared to healthy adults. In contrast, Yoshida et al. (2007) found that one year after TKR, patients had equivalent TUG test times compared to healthy adults. However, patients were matched to healthy adults using BMI, not sex and age, which in my opinion decreases the generalizability of their results. Ouellet & Moffet (2004) reported that individuals two months post-TKR were 6.3 seconds slower completing the TUG test compared with healthy controls. The differences reported in this current study are much lower between patient and control groups and may be related to the time of assessment after surgery compared with the current study as one would expect functional performance to improve between two and six months.

Age-related differences in functional testing have been reported previously (Steffen et al., 2002). Steffen et al. (2002) reported mean TUG test times of eight seconds for the youngest group (60-69 years old), nine seconds for the middle group (70-79 years old) and eleven seconds for the oldest group (80-89); showing a trend of age-related decline for the TUG test, for both male and female older community-dwelling adults. In the current study a similar trend is observed, as there was a significant difference between the younger and older groups. However, no significant difference was observed between the two younger groups, suggesting, like with what was observed for balance confidence, functional mobility improves to the point that there is no statistical difference between younger controls and patients. Interestingly, published studies have pointed to cut-off scores for the TUG test between ten and twelve seconds (Trueblood et al., 2001), indicating a threshold where the risk for falling increases. Only the older TKR group took longer than twelve seconds to complete the TUG test. Thus, compared with the other groups, including the younger TKR group, the older TKR group would be considered at an increased risk of falling.

### 4.3 Movement reinvestment is associated with balance confidence and functional mobility in total knee replacement patients

The propensity to try to control movements by consciously directing attention to the current motor task can be estimated using a questionnaire called the movement-specific reinvestment scale. The scale also assesses the propensity to be self-conscious about one′s movements. There is evidence to suggest that those with movement disorders, such as Parkinson′s disease or stroke, show a strong predisposition to direct attention to their movements and is associated with greater functional impairments (Masters et al., 2007; Orrell et al., 2009). In this current study, we found that the younger TKR, younger control and older control groups reinvested in their movements significantly less compared to the older TKR group, but that the younger TKR group and the older control group did not differ. A similar trend for the MSRS subscales (CMP & MSC) was also observed between groups. Wong et al. (2008) found that elderly fallers scored significantly higher than elderly non-fallers on both subscales of the MSRS

(CMP and MSC), arguing the MSRS shows potential as a clinical tool with which to predict falls in the elderly. In a cross-sectional questionnaire survey study (Orrell et al., 2009), 148 stroke patients and 148 age-matched controls were investigated for their propensity to reinvest in their movements. It was observed that scores were greater in the stroke group compared to the control group for both subscales of the MSRS, and scores on the CMP subscale were observed to be greater than that observed for the MSC subscale, which match what was observed for TKR patients in the current study. In a study investigating movement reinvestment in individuals with Parkinson's disease, it was found that the propensity for movement reinvestment increases with disease progression (Masters et al., 2007). The authors argued that constant uncertainty and reduced motor performance may cause Parkinson's disease patients to habitually monitor their movements, suggesting a self-protective mechanism to prevent falling. Older TKR patients seem to employ a similar strategy; the progressive nature of OA, with the associated pain and loss of function, may contribute to a "conscious movement" adoption over time with OA progression, disrupting the automaticity of their movements (Masters, 1992). This increased conscious control when moving could then create a scenario of increased fall risk where the older TKR patient (concerned with falling) overloads their limited working memory capacity by dividing attention between internally monitoring their limbs and externally monitoring the environment (Masters et al., 1993).

A correlation analysis was conducted to investigate if a relationship between movement reinvestment and balance confidence, functional mobility and age existed for all of the participants. The results indicated that the MSRS had a significant and positive correlation (r = .646, p = 0.01) with the TUG test time, showing that as movement reinvestment increased there was a decrease in functional mobility. Huffman et al. (2009) reported a similar finding when investigating elevated postural threat of healthy adults at different platform heights, where a higher reinvestment score was related to poorer balance. In the current study, it was found that there was a negative correlation between balance confidence and functional mobility (r = -.459, p = 0.01), showing that a rise in balance confidence is related to a rise in functional mobility; Ingemarsson et al. (2000) and Salbach et al. (2006) have reported similar results. When the subscales of the MSRS were examined it was shown that both CMP and MSC had significant negative correlation with balance confidence (r = -.488, p = 0.01; r = -.414, p = 0.01) and a positive correlation with functional mobility (r = .715, p = 0.01; r = .588, p = 0.01). The CMP subscale was shown to be a stronger correlate than the MSC with the ABC and TUG test, suggesting that for TKR patients in general, the decline in balance confidence and functional mobility is more affected by the amount of conscious control, rather than the amount of worry or concern regarding their movements. This finding has been reported in previous publication of younger and older healthy adults as well as in stroke patients (Wong et al. 2009; Huffman et al., 2009; Orrell et al., 2009). Age was significantly correlated across all variables; ABC (r = -.488, p = 0.01), TUG (r = -.414, p = 0.01), CMP (r = -.488, p = 0.01), MSC (r = -.414, p = 0.01) and MSRS (r = -.414, p = 0.01). These findings clearly show that with increased age there is a corresponding decline in balance confidence and functional mobility, and an increase in the propensity to reinvest when moving. An important novel finding from this analysis is that for TKR patients older age has a stronger correlation with the MSC subscale of reinvestment, rather than the CMP, which shows the elevated reinvestment that occurs in the older TKR groups is more because of worry or concern regarding their movements.

### 4.4 Balance confidence can be predicted from functional mobility, pain, conscious motor processing and age in total knee replacement patients

A multiple regression model was performed using the predictors age, WOMAC pain, WOMAC stiffness, WOMAC function, OKS, CMP, MSC, and the TUG test to predict balance confidence scoring in the two patient groups. The results indicated that age, WOMAC pain, WOMAC function, CMP and TUG test were all significant predictors in the model. WOMAC stiffness, OKS and MSC were not significant in predicting balance confidence levels in TKR patients. Age of the patient had a negative and significant ($r = -.676$, $p < 0.01$) correlation with balance confidence, showing that for every year the patient was older, there was a 1.84% decrease in their balance confidence scoring. Legters et al. (2005) stated that the effect of aging did not have a significant impact on ABC scoring. However, the discrepancies between the current results and the results of Legters and colleagues can be explained by the fact that a different patient population and different grouping for age was studied. Myers et al. (1996) found that balance confidence had a negative and significant correlation with age in a population of community-dwelling ambulatory older adults (aged 65-95), supporting the findings in this study. Increased pain was related to balance confidence ($r = -.635$, $p < 0.01$), where a decrease in one unit of the WOMAC pain subscale resulted in a 1.03% increase in balance confidence for TKR patients. Swinkels et al. (2009) also found a significant correlation between pain and balance confidence in a prospective observational study of falling before and after knee replacement surgery. Pain has also been associated with a greater propensity to trip on an obstacle and fall in OA patients (Pandya et al., 2005; Foley et al., 2006) and TKR patients (Swinkels et al., 2009). It was observed in this current study that a negative and significant correlation was observed between balance confidence and the CMP subscale ($r = -.486$, $p < 0.01$), showing that a unit decrease in the conscious control when moving would reflect a 2.56% increase in balance confidence. A similar correlation has been observed in older community-dwelling adults, where it was observed that older adults that reported lower confidence in performing daily activities reinvest more in their movements (Wong et al., 2009). The regression model determined that functional mobility was a significant predictor for balance confidence in TKR patients; for every second decrease in the TUG test there was 4.6% increase in balance confidence. Hatch et al. (2003) found the TUG test scores to be highly correlated with balance confidence scores, reporting that a relationship exists between balance confidence and functional mobility in community-dwelling elderly people. Swinkels & Allain (2013) have recently reported similar correlation values between the ABC and TUG test ($r = -0.67$, $p = 0.001$), where the lower the balance confidence, the greater the time taken to complete the TUG test was observed in TKR patients. More needs to be learned about other possible predictors of balance confidence in TKR patients.

## 5. Conclusion

Younger TKR patients report lower levels of pain, joint stiffness, and elevated physical function, functional mobility and balance confidence that exceed the minimal clinically important difference, when compared to the older typical TKR patient. Movement reinvestment was shown to be related to balance confidence and functional mobility in TKR patients and to be elevated in the older TKR patients, compared to younger TKR patients. The current findings clearly demonstrate that the younger TKR patients at six months post-surgery are experiencing a better outcome then the typical older TKR patient. Therefore, the results from the current study provide further support to the conclusion that age should not be a barrier when indicating knee replacement surgery. These findings may also play a role in the elevated physical activity engagement for the younger TKR patient, possibly impacting prosthesis degeneration and explaining the observed increase in revision rates for this population. Future research should investigate the affects of balance confidence on the activity levels of TKR patient and its implications on patient health and prosthesis degeneration and survivorship.

**Table 1.** Participant Characteristics. Mean (SD).

BMI = Body mass index; n = number; YP = Younger patient, YC = Younger control, OP = Older patient, OC = Older control.
Age values are expressed in mean (range)

* Significantly older compared to the older participants ($p < 0.001$).

| **Variable** | **Age/Group** | | | |
|---|---|---|---|---|
| | **YP**<br>**n=15** | **YC**<br>**n=15** | **OP**<br>**n=14** | **OC**<br>**n=15** |
| Age, y | 54.3(51-64)* | 55.2(53-66)* | 76.9(72-85) | 77.7(71-86) |
| Surgical limb, left/right | 5/10 | - | 5/9 | - |
| Female, % (n) | 73(11) | 73(11) | 86(12) | 80(12) |
| Height, m | 1.67(0.11) | 1.66(0.12) | 1.60(0.8) | 1.64(0.8) |
| BMI, kg/m$^2$ | 32.12(6.8) | 31.2(5.9) | 30.1(4.4) | 29.7(6.1) |

**Table 2.** Differences in perceived pain, stiffness, physical function, knee function, and balance confidence, functional mobility and reinvestment between the two patient and control groups.YP = Younger patient, YC = Younger control, OP = Older patient, OC = Older control.WOMAC Western Ontario and McMaster University Osteoarthritis Index, ABC Activities-specific balance confidence scale, TUG Timed Up and Go test, CMP Conscious motor processing, MSC Conscious motor processing, MSRS Movement-Specific Reinvestment Scale.
* Significantly different to the old patient group ($p < 0.05$). † Significantly different to the old control group ($p < 0.05$). § Significantly different to the younger patient group ($p < 0.05$) .

| **Parameters** | **Age/Group** | | | |
|---|---|---|---|---|
| | **YC** | **YP** | **OC** | **OP** |
| **Pain, stiffness, and physical function** | | | | |
| WOMAC pain | - | 1.4(1.3)* | - | 8.6(3.2) |
| WOMAC stiffness | - | 1.2(0.8)* | - | 3.2(1.1) |
| WOMAC function | - | 6.3(3.7)* | - | 18.7(7.8) |
| WOMAC total | - | 9.2(4.4)* | - | 29.5(6.1) |
| **Oxford knee score** | - | 43.4(8.7)* | - | 35.7(7.4) |
| **Balance confidence** | | | | |
| ABC | 98.1(1.9)*† | 92.3(8.1)* | 84.2(10.6)* | 74.5(11.3) |
| **Functional mobility** | | | | |
| TUG | 8.7(1.1)* | 9.6(2.3)* | 10.2(2.0)* | 12.8(2.7) |
| **Reinvestment** | | | | |
| CMP | 5.3(0.5)*†§ | 8.3(2.8)* | 8.6(2.7)* | 15.6(3.5) |
| MSC | 5.5(0.9)*†§ | 11.6(3.7)* | 9.5(3.5)* | 18.0(3.0) |
| MSRS total | 10.8(3.4)*†§ | 20.0(6.3)* | 18.1(5.6)* | 33.3(6.0) |

**Table 3**. Reinvestment relationship with balance confidence, functional mobility and age for the four experimental groups.

ABC Activities-specific balance confidence scale, TUG Timed Up and Go test, CMP Conscious motor processing, MSC Conscious motor processing, MSRS Movement-Specific Reinvestment Scale.
* Correlation is significant at the 0.01 level (2-tailed).

| **Parameters** | CMP | MSC | MSRS | ABC | TUG | Age |
|---|---|---|---|---|---|---|
| CMP | - | .900* | .970* | -.488* | .715* | .751* |
| MSC | - | - | .979* | -.414* | .588* | .822* |
| MSRS | - | - | - | -.460* | .646* | .809* |
| ABC | - | - | - | - | -.459* | -.491* |
| TUG | - | - | - | - | - | .498* |
| Age | - | - | - | - | - | - |

**Table 4.** Correlation among the balance confidence predictor variables for the two patient groups.

W. p Western Ontario and McMaster University Osteoarthritis Index pain subscale, W. s Western Ontario and McMaster University Osteoarthritis Index stiffness subscale, W. f Western Ontario and McMaster University Osteoarthritis Index function subscale, OKS Oxford knee score, ABC Activities-specific balance confidence scale, TUG Timed Up and Go test, CMP Conscious motor processing, MSC Conscious motor processing and TUG Timed Up and Go test.
* Correlation is significant at the p < 0.05 level (2-tailed).
** Correlation is significant at the p < 0.01 level (2-tailed).

| **Parameters** | Age | W. p | W. s | W. f | OKS | ABC | CMP | MSC | TUG |
|---|---|---|---|---|---|---|---|---|---|
| Age | - | .842** | .751** | .730** | .591** | -.676** | .766** | .701** | .545** |
| W. p | - | - | .717** | .872** | .516** | -.635** | .565** | .484** | .450* |
| W. s | - | - | - | .730** | .403* | -.431* | .653** | .561** | .414* |
| W. f | - | - | - | - | .510** | -.594** | .475** | .399* | .449* |
| OKS | - | - | - | - | - | -.474** | .434* | .304 | .476* |
| ABC | - | - | - | - | - | - | -.486** | -.319 | -.505** |
| CMP | - | - | - | - | - | - | - | .891** | .656** |
| MSC | - | - | - | - | - | - | - | - | .487* |
| TUG | - | - | - | - | - | - | - | - | - |

**Table 5.** Predictive model with regards to balance confidence status between younger and older knee replacement patients.

WOMAC pain, stiffness and function Western Ontario and McMaster University Osteoarthritis Index subscales, TUG Timed Up and Go test, OKS Oxford knee score, CMP Conscious motor processing, MSC Conscious motor processing, Scale, TUG Timed Up and Go test.

| **Predictor variable** | ***B*** | **S.E** | **Sig.** |
|---|---|---|---|
| **Age** | **-1.84** | **0.12** | **0.01** |
| **WOMAC pain** | **-1.03** | **0.299** | **0.03** |
| WOMAC stiffness | 2.01 | 0.589 | 0.14 |
| **WOMAC function** | **-1.67** | **0.099** | **0.02** |
| OKS | 1.97 | 1.294 | 0.23 |
| **CMP** | **-2.56** | **0.203** | **0.02** |
| MSC | 1.51 | 1.28 | 0.15 |
| **TUG** | **-4.45** | **0.161** | **0.01** |

# CHAPTER THREE

# AFTER TOTAL KNEE REPLACEMENT YOUNGER PATIENTS DEMONSTRATE SUPERIOR BALANCE CONTROL COMPARED TO OLDER PATIENTS WHEN RECOVERING FROM A FORWARD FALL

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## Preface

Total knee replacement (TKR) patients have been shown to be at an elevated risk of falling compared to healthy controls. Published data examining balance recovery from experimentally controlled forward falls have clearly shown several age-related differences between younger and older healthy adults. Over the past few decades there has been a substantial growth in younger knee osteoarthritic patients (<55 years old) undergoing TKR and it is projected that patients less than 65 years of age will become the majority having TKR surgery within the next two decades. Very little is known of this younger TKR population and age-related deficits observed in healthy adults may also distinguish younger TKR patients from the typical, older TKR patients (>65years old), which would have important implications to the surgical and rehabilitation practice. Therefore, the purpose of this study was to compare: 1) the stepping characteristics and, 2) centre of mass (COM) control after a forward fall between younger and older TKR patients, and their healthy age-matched controls. A convenience sample of 59 participants, including 29 unilateral primary knee replacement patients six months post-surgery, consisting of four groups: 1) Younger patient (n=15 (11 F), age: 54.3 ± 7.9 years), 2) Younger control (n=15 (13 F), age: 55.2 ± 4.0 years), 3) Older patient (n=14 (12 F), age: 76.9 ± 4.7 years), and 4) Older control (n= 15 (11 F), age: 77.7 ± 4.1 years). Using a tether-release method to replicate a forward fall, each participant completed the following four conditions: 1) eyes-open, stepping with right limb, 2) eyes-open stepping with left limb, 3) eyes-closed stepping with left limb, and 4) eyes-closed stepping with left limb. For all patients the surgical limb was defined as the right limb and the non-surgical as the left limb. Younger TKR patients recovered from a forward fall with a significantly smaller COM displacement to that of older TKR patients, but were similar to the healthy participants, across conditions. It was observed that the younger TKR patients employed stepping characteristics and joint kinematics that more effectively arrested the forward translation of their COM compared to the older TKR patients, as the quicker step and larger moment arm associated with the longer step, created a larger restorative torque. These stepping characteristics and joint kinematics seemed to have aided in attenuating the forward momentum of the forward fall, and may explain why the older TKR patients were much more likely to require additional steps to recover their balance. These findings suggest that the younger TKR patient is at a reduced risk of falling when recovering from a forward fall compared to the older TKR patient.

## 1. Introduction

Patients suffering from knee osteoarthritis experience impaired mobility and limited function in their daily activities (Bennell et al., 2008). Total knee replacement (TKR) surgery is the most effective intervention for patients with moderate and severe knee osteoarthritis (Zhang et al., 2008); as significant improvement in the symptoms of knee osteoarthritis such as knee pain and stiffness have been reported compared to pre-surgical observations (Hawker et al., 1998; Cushnaghan et al., 2009). However, although improved, significant deficits in function and mobility remain when compared to healthy controls (Viton et al., 2002; Wada et al., 2002; Gage et al., 2008; Swinkels et al., 2009). Viton et al. (2002) and Wada et al. (2002) reported persistent proprioceptive deficits after TKR, leading to limitations in lower limb mobility and postural control. The authors argued that this had an indirect contribution to a reduced performance in balance control. Further, Mauer et al. (2005) found that after TKR there was a reduction in obstacle avoidance success rate, compared to healthy controls, suggesting that after TKR there is an increased propensity to trip on an obstacle and consequentially an elevated risk of falling in this population. Moreover, among those TKR patients who fell prior to surgery, approximately 45% of them fell again in the year following surgery (Swinkels et al., 2009). The consequences of these falls could have significant and meaningful negative health outcomes for TKR patients.

Slips and stumbles are the most common balance disturbing stimuli and account for the majority of injury-producing falls in older individuals (Roudsari et al., 2005). Importantly, the majority of these falls have been reported to occur after a loss of stability in the forward direction, such as tripping while walking (Blake et al., 1988). In an effort to identify possible intrinsic factors that may contribute to a forward fall, researchers have developed surrogate balance recovery tasks to mimic the biomechanical requisites similar to those employed when recovering from a natural fall. A common approach is the tether-release method, where participants lean forward whilst suspended from a horizontal cable attached to their trunk. The cable is released and the participant experiences a forward loss of balance and to prevent the occurrence of a fall employ a rapid forward step (Wojcik et al., 1999, 2001; Madigan & Lloyd, 2005; Madigan, 2006; Arampatzis et al., 2008; Karamanidis et al., 2008; Carty et al., 2011; Barrett et al., 2012; Carty et al., 2012a; Carty et al., 2012b).

In experiments that have employed the tether-release approach there have been several performance-related differences observed between younger and older healthy adults. Older participants have been shown to employ shorter steps (Thelen et al., 1997; Luchies et al., 1994), slower step speeds (Wojcik et al., 1999), and more delayed stepping latencies (Thelen et al., 1997; Wojcik et al., 1999) compared to younger participants. It has also been observed that older individuals are more likely to require multiple steps to recover their balance (Luchies et al., 1994). Importantly, the reliance on multiple steps when recovering from a forward fall has been shown to predict future falls (Maki et al., 2001). Several studies have also suggested that the deterioration of the musculoskeletal function (e.g., proprioception), that has been observed with ageing (Erni & Dietz, 2001; Marigold & Patla, 2002), may play a key role in the reported age-related deficits observed between younger and older healthy individuals when maintaining balance (Pijnappels et al., 2005; Mackey & Robinovitch, 2006). Therefore, these age-related differences may contribute not only to the reduced ability of healthy older adults to recover their balance, but may also contribute to the reduced balance ability of older adults with lower limb osteoarthritis or after joint replacement.

It has been reported in the Canadian Joint Replacement Registry 2008–2009 annual registry (CJRR, 2009) that compared to the 1996–1997 reported knee replacement procedures, the largest relative percent increase over the last decade was in the 45-to-54 age group for both males and females (271% and 337% increase, respectively). It is anticipated that the average age at surgery will continue to decrease (Wells et al., 2002; Dixon et al., 2004) and it is projected that younger adults (<65 years old) will become the majority undergoing TKR surgery within the next two decades in the United States (Kurtz et al., 2009). Although this younger patient group is rapidly growing, the vast majority of the literature investigating the functional outcome after TKR has been based on the older ‘typical’ TKR patient (>65 years old). Recently, Street et al. (2013) reported that the largest improvement in perceived knee joint function (Oxford knee score) after TKR was observed to occur in the youngest patient group studied (50-59 years old). The Oxford knee score has been shown to not differ significantly from actual function scores (Khanna et al., 2011; Hamilton et al. 2012). Therefore, the younger TKR patient may also be experiencing elevated function after surgery compared to the typical, older patient. Further, the age-related deficits observed in healthy adults during a forward fall may also distinguish younger and older TKR patients from each other, which would have important implications to the surgical and rehabilitation practice.

Therefore, the purpose of this study was to investigate and compare: 1) the stepping characteristics and 2) centre of mass control after a forward fall between younger and older TKR patients, and their healthy age-matched controls. It was hypothesized that the younger TKR patients would employ stepping characteristics that would more effectively control the centre of mass when recovering from a forward fall compared to the older TKR patients, which is in agreement with previous findings demonstrating a longer and quicker recovery step for younger compared to older healthy adults recoving from a forward fall (Thelen et al., 1997; Wojcik et al., 1999).

## 2. Methodology

### 2.1 Participants

The participants from this study are part of a larger project investigating TKR and the affect of age on functional and psychosocial measures. Participant inclusion and exclusion criteria has been reported in chapter 2 (pg. 63) of this thesis.

### 2.2 Participant set-up and collection equipment

Upon arrival to the laboratory, participants were provided with the following: study/participant information sheet (Appendix A) and informed consent form (Appendix B). Upon obtaining informed consent, participants were asked to remove their shoes and socks and infrared reflective markers were applied. A total of 36 reflective markers (according to the Plug-in-Gait model, Nexus, Vicon, Colorado, USA) were attached to each participant on the following landmarks: front and back (left and right) head markers, C7, T10, clavicle, sternum, right scapula, and bilaterally on the acromioclavicular joint, upper arm, lateral epicondyle of the elbow, forearm, wrist (both on the ulnar and radial styli), anterior and posterior superior iliac spine, thigh, lateral femoral condyles, shank, lateral malleoli, calcaneus, and 2nd metatarsal head (Appendix C). This marker placement model has been used previously used when investigating forward falls and falls when crossing an obstacle (Curtze et al., 2010; Curtze et al., 2012; Gill & Hung, 2014). Movement was recorded using a seven-camera motion capture system (MX40, Vicon, Colorado, USA). Marker position was sampled at a frequency of 100Hz. Four force plates (OR6-7, AMTI, Massachusetts, USA) were arranged in a T-shaped configuration and sampled at 1000Hz. The dependent measures were calculated from the kinematic and kinetic data using commercial software (Plug-in-Gait model, Nexus, Vicon, Colorado, USA). Marker positions, angles and COM positions were exported and stored for further analysis.

### 2.3 Experimental Procedure

Following marker placement, a horizontal tether-release cable was attached to the back of a padded pelvic belt which was then placed on the participant. The tether-release cable was then attached to the release device, controlled by an electrical magnet (Visml 600 LED, VSIONIS) and mounted to a stable wooden structure (Appendix D). The boundaries of the feet on each force plate were marked using tape for subsequent trial reference. In order to determine the lean angle required to invoke a stepping recovery response, lean angle calibration trials were conducted; the absolute lean angle with respect to vertical was increased until a stepping response occurred with tether release in three consecutive trials. To aid in maintaining consistent lean angles between trials, once the release angle was established, the tether length remained unchanged across trials and consistent foot placement was assured using the taped marks on the force plates. The change in the lean angle was achieved by increasing the length of the tether holding the participant. The step invoking lean angle was participant specific and was kept constant across trials. Older healthy adult participants were previously found to be able to recover from a forward fall with a stepping response and without falling from a lower body lean angle of $15^{o}$ (Grabiner et al., 2005).

The experiment consisted of four conditions and five trials in each of the conditions, for a total of 20 experimental trials. The four conditions included: 1) eyes-open stepping with right limb, 2) eyes-open stepping with left limb, 3) eyes-closed stepping with right limb, and 4) eyes-closed stepping with left limb. For the patient groups, the surgical limb was assigned as the right limb and the non-surgical limb was assigned as the left limb. Before analysis, it was shown that limb-dominance in the control group had no effect on COM displacement ($F_{1,29} = 0.28$, $p = 0.603$). The participant leaned forward, maintaining their heels in contact with the ground, equally distributing their weight across both feet. Participants were instructed to keep their head, trunk and extremities aligned forward and muscles relaxed while leaning, this was visually inspected in real time by the investigator to ensure that participants maintained the established posture prior to tether release.

The order of trials for each participant was randomly assigned as to not produce an order affect. The release time for each of the experimental trials was also randomly generated between three and ten seconds after the experimental posture was adopted. Release of the magnet caused the participant to suddenly fall forward. The participant regained their balance using a stepping response. Temporal data of the release trigger was recorded and synced with the camera and force plate data.

In the event of an unsuccessful recovery, a fall to the ground was prevented using a full-torso harness tethered to a ceiling-mounted support track with a fall-prevention lanyard. The length of the lanyard was adjusted so that when the participant reached for the ground, there was approximately two inches between their fingertips and the ground. This prevented any part of the participant’s body, except their feet, from touching the ground.

## 2.4 Data Analysis

### 2.4.1 Stepping Characteristics

Stepping characteristics were evaluated by determining recovery step length, peak step velocity, step latency and number of steps. The lateral malleolus marker was used to indicate foot position during stepping. Step length was calculated as the anteroposterior difference between the average position of the lateral malleolus marker over the 0.5s prior to perturbation and the final position of the lateral malleolus position following the initial perturbation recovery step. Stepping velocity was derived using the 3-point finite difference in the position of the lateral malleolus marker of the stepping foot, and peak velocity was recorded for each trial. Step latency was calculated as the temporal difference between the release of the magnet and the initiation of movement of the lateral malleolus marker on the stepping foot. Movement initiation for the lateral malleolus marker was determine as an increase in the anteroposterior marker velocity three standard deviation above the average velocity observed during the 0.5 sec prior to the release of the magnet, this was also confirmed visually. In the event that the participant performed multiple steps during recovery, only the initial recovery step was used for analysis. The number of recovery steps was calculated using force plate data; each foot contact, defined as a force in excess of 20 N, was identified as a step and was visually confirmed and recorded in real time for each trial.

### 2.4.2 Pre-perturbation distance between the vertical projection of the centre of mass and the ankle marker

Pre-perturbation distance between the vertical projection of the centre of mass and the ankle marker was calculated by using the average position over the 0.5 sec prior to the release of the magnet for the lateral malleolus marker and the vertical projection of the centre of mass in the sagittal plane.

### 2.4.3 Centre of Mass

Estimation of the centre of mass (COM) position was calculated using a commonly used model (Plug-in-Gait, Nexus, Vicon, Colorado, USA). The peak anteroposterior centre of mass displacement and acceleration was analyzed. COM displacement position was calculated by averaging the COM position over the 0.5 sec prior to the release of the magnet in each of the trials (anteroposterior direction), and subtracting it from the peak COM position achieved during the perturbation in the same trial. The peak anteroposterior COM accelerations during falling (positive; prior to stepping foot contact) and recovery (negative; following stepping foot contact) were calculated from the COM position data, using the 3-point finite difference and the double-differentiation method.

### 2.5 Statistical Analysis

To address the purpose of this study, to investigate and compare the stepping characteristics and centre of mass control after a forward fall between younger and older TKR patients, and their healthy age-matched controls, the following analysis was conducted: four-factor repeated measures ANOVAs (*age* [younger/older] x *group* [patient/control] x *eye* [open/closed] x *limb* [left/right]) with participant nested in both *age* and *group* was used. Bonferroni adjusted tests were then used to assess the differences when a significant interaction effect was observed. A logistic regression analysis was conducted to predict if more than one step was required to arrest falling forward using participant's *age* and *group* (control or patient) as predictors.  All statistical analyses were conducted using JMP (v11.1.1, The SAS Institute, North Carolina, USA), and a *p*-value less than 0.05 was considered statistically significant.

## 3. Results

Participant characteristics and statistical analysis are shown in chapter 2 (pg. 69 and in Table 1, pg. 98) of this thesis.

### 3.1 Recovery step length

Recovery step length analysis for the four groups across the eyes-open and eyes-closed conditions (Figure 1) showed that the younger patient group had a significantly longer recovery step compared to the older patient group ($p < 0.001$), as did the two control groups ($p < 0.001$) across conditions ($F_{1,\,165} = 15.85$, $p = 0.001$). The younger participants and older control group did not differ significantly in recovery step length. The older TKR group showed a significant differences between the eyes-open and eyes-closed conditions; step length was significantly longer ($p < 0.03$) for the eyes-open compared to the eyes-closed condition ($F_{1,\,165} = 12.23$, $p = 0.002$), neither of the other groups showed this effect. The patient participants showed a 7.6% shorter right limb step length (Figure 2) compared to the healthy participants ($F_{1,\,165} = 16.80$, $p < 0.001$). All interactions and main effects for recovery step length are presented in Table 1.

### 3.2 Peak recovery step velocity

Peak recovery step velocity analysis for the four groups (Figure 3) showed that the recovery step peak velocity was not different between the younger control, younerg patient, and older control groups, but all three ($p < 0.001$, $p = 0.003$ and $p = 0.01$, respectively) had a greater recovery step peak velocity than for the older patient group ($F_{1,\,55} = 13.28$, $p = 0.001$). All interactions and main effects for peak recovery step velocity are presented in Table 2. Representative time series data of a healthy younger control for the ankle marker position and velocity during the balance recovery response is shown in Figure 4.

### 3.3 Recovery step latency

Recovery step latency analysis for the four groups across the eyes-open and eyes-closed conditions (Figure 5) showed that the younger patient group had a significantly shorter recovery step latency compared to the older patient group for the eyes-closed ($p < 0.01$) and eyes-open ($p < 0.03$) conditions ($F_{1,\,165} = 10.08$, $p = 0.002$), but was not significantly different to the two control groups. The two control groups had a significantly shorter recovery step latency delay compared to the older patient group ($p < 0.03$), but did not differ from each other. The TKR patients showed a 9.3% greater stepping latency in left limb and a 10.1% greater stepping latency in right limb (Figure 7) compared to the healthy participants ($F_{1,\,165} = 17.22$, $p < 0.001$). All interactions and main effects for recovery step latency are presented in Table 3.

### 3.4 Number of recovery steps

A logistic regression analysis was conducted to predict if greater than a single step was required to arrest falling forward using participant's age and group membership (control or patient) as predictors. A test of the full model against a constant only model was statistically significant, indicating that the predictors as a set could reliably distinguish between those who only required one step and those who required more than one step (chi-square = 23.586, $p < 0.001$ with df = 2). Prediction success overall was 84.7% (90.9% for only requiring one step and 66.7% for requiring greater than one step). The Wald criterion demonstrated that both age (Wald = 10.262; $p = 0.001$) and group (Wald = 8.139; $p = 0.004$) made a significant contribution to prediction. EXP(B) value indicates that when age is raised by one unit (one year) and the participant is a TKR patient the odds of requiring more than a single step when recovering balance increased by a factor of 1.134 and 11.392, respectively.

### 3.5 Peak knee joint angular displacement

Peak knee joint angular displacement for the four groups (Figure 7) showed that the two younger groups had a significantly higher peak knee joint angular displacement compared to the older patient group ($p < 0.01$). Also, the younger control group had a peak knee joint angular displacement that was significantly higher ($p < 0.02$) compared to the older control group ($F_{1, 165} = 9.08$, $p = 0.003$). The younger patient group did not differ significantly from the healthy participants. All interactions and main effects for peak knee joint angular displacement are presented in Table 4.

### 3.6 Pre-perturbation distance between the vertical projection of the centre of mass and the ankle marker

Analysis of the pre-perturbation distance between the vertical projection of the COM and the ankle marker for the four groups are shown in Figure 8. No significant interaction effects or main effects for pre-perturbation distance between the vertical projection of the centre of mass and the ankle marker were observed.

### 3.7 Centre of mass displacement

The anteroposterior centre of mass displacement for the four groups across limbs (Figure 9) showed that the younger patient ($p < 0.02$), olerd control ($p < 0.03$) and younger control groups ($p < 0.001$) had a significantly smaller COM displacement compared to the older patient group for both the right and left limbs ($F_{1, 165} = 6.16$, $p = 0.013$). The younger control, younger patient and older control groups had COM displacement that did not differ significantly from each other regardless of limb. All interactions and main effects for COM displacement are presented in Table 5.

### 3.8 Peak centre of mass falling acceleration

Peak anteroposterior COM falling (positive) acceleration for the four groups are shown in Figure 10. No significant interaction effects or main effects for peak COM falling acceleration were observed.

### 3.9 Peak centre of mass recovery acceleration

Peak anteroposterior COM recovery (negative) acceleration for the four groups across limbs (Figure 11) showed that the two younger groups had a significantly higher peak COM recovery acceleration across limbs compared to the older patient group ($p < 0.001$) and the older control group had a significantly higher peak COM recovery acceleration compared to the older patient group for the right limb ($p < 0.02$), but not for the left limb ($F_{1, 165} = 12.25$, $p = 0.002$). The younger control, younger patient and older control groups showed no significant difference in peak COM recovery acceleration regardless of limbs. All interactions and main effects peak COM recovery (negative) acceleration are presented in Table 6. Representative time series data of a healthy younger control for the COM displacement and acceleration during the balance recovery response are shown in Figure 12.

## 4. Discussion

A tether-release paradigm was used as a surrogate balance recovery task to identify possible performance-related differences between younger and older TKR patients and their healthy age-matched controls. Importantly, the younger TKR group recovered from a forward fall with a significantly smaller COM displacement to that of older TKR group, but was similar to that of the healthy groups. It was observed that the younger TKR group employed advantageous stepping characteristics and joint kinematics that more effectively arrested the forward translation of the COM compared to the older TKR group. It was also observed that increased age and being a TKR patient were predictors of increased likelihood to require greater than a single step to arrest forward momentum from a forward fall. These findings suggest that the younger TKR group would be at a reduced risk of falling when recovering from a forward fall compared to the older TKR group. Further, these results may also suggest that younger TKR patients load their prosthetic knee similar to younger healthy individuals, which might expose the knee implant to a greater risk of failure, compared to older patients.

### 4.1 After total knee replacement younger patients employ stepping characteristics that differ from the typical, older patients when recovering from a forward fall

After a sudden perturbation the central nervous system is challenged to execute a set of coordinated postural corrections to maintain dynamic stability and ultimately avoid a fall. There are three main mechanisms by which stability may be maintained after a postural perturbation: 1) by increasing the base of support in relation to the changing COM (e.g., taking a step), 2) by counter-rotating segments around the COM or 3) by applying an external force (other than the ground reaction force), such as grasping for a nearby object (Hof et al., 2007). In the tether-release paradigm a stepping strategy was employed to regain stability. Differences in the stepping characteristics between the groups were observed. The length of the recovery step was shown to be significantly longer for the younger patient group compared to the older patient group, but was similar to the healthy participants. Age-related differences in stepping length have been previously reported (Thelen et al., 1997; Wojcik et al., 1999), where younger healthy adults restored stability after a forward fall using a longer step than older healthy adults. Reduced recovery step length employed by the older patients in particular, may be explained by a strategy to minimize joint forces at the knee (Hsiao & Robinovitch, 1999). King et al. (2005) reported that anterioposterior force impulse in the stepping leg was positively associated with step length when recovering from a forward fall, showing that when step length was reduced there was also a reduction in the anterioposterior force impulse after landing. The authors suggested that shorter steps were employed to reduce the biomechanical demands of the stepping limb. Therefore, the older TKR group may be reducing their step length as a way to attenuate the effects of residual pain and functional limitations, whether perceived or actual. The younger TKR patients did not seem to adopt this short-step strategy, suggesting a greater confidence in their knee joint stability. In the current study the younger patient group also had an elevated peak recovery step velocity and a shorter delay in recovery step latency compared to the older patient group, but again, did not differ from the healthy participants. Age-related differences in stepping velocity and stepping latency have been reported in previous studies (Thelen et al., 1997; Wojcik et al., 1999). Wojcik et al. (1999) reported that step velocity and the maximum lean angle a participant could recover from with only a single step without falling were strongly correlated with age and sex. The authors argued that the critical factor in a single-step balance recovery response is the speed with which the stepping limb motion can be executed. The implications of the work reported previously with the observations from this current study argue that the younger TKR patient would be at a reduced risk of falling when there is a sudden perturbation in their balance compared to the older TKR patient. Fall risk is also reflected in differences in the control of COM displacement, in which the younger and older TKR patients also differed. Future work should to look to see if these stepping characteristics also apply when TKR patients are recovering their balance from a lateral perturbation or when crossing an obstacle.

### 4.2 After total knee replacement younger patients display superior centre of mass control compared to the typical, older patients when recovering from a forward fall

Peak anteroposterior COM displacement was significantly smaller in the younger TKR group compared to the older TKR group, but was similar to the healthy participants. Importantly, biomechanical and functional observations between the different groups seem to play a role in the diminished COM control of the older TKR group. No difference was observed in the COM falling (positive) acceleration between groups, but the younger TKR group did have a significantly higher recovery (negative) COM acceleration compared to the older TKR group. This higher COM acceleration during the recovery phase seems to be partly explained by the stepping characteristics of the younger TKR group; as the faster initiation of their lower limb movement and a longer recovery step would enable a more efficient control of the forward translation of their COM than the older TKR group. These stepping characteristics would be advantageous for COM control; maintaining the COM further behind the anterior boundary of the base of support at landing (Karamanidis et al., 2008; Carty et al., 2012c; Carty et al., 2012b; Madigan, 2006; Thelen et al., 1997; van Dieen et al., 2005). Also, having a quicker step, with a greater moment arm (longer step) would allow for an earlier and greater restorative torque to be created to control the COM movement. To overcome this, the older TKR group employed a strategy of additional recovery steps; logistic regression analysis revealed that for every year older and when a TKR patient the odds of requiring more than a single step when recovering balance increased by a factor of 1.134 and 11.392, respectively. The need for additional steps is probably indicative of the older patient’s inability to arrest forward momentum because of the altered stepping characteristics and resultant lower COM recovery acceleration. Among older healthy adults, a larger first step and a more rapid movement of the stepping limb decreases the likelihood that multiple steps will be needed to regain balance (Carty et al., 2012c). Further, one of the most consistent findings in the literature is that older adults are much more likely to take multiple steps when their balance is perturbed compared to younger adults (Luchies et al., 1994;

McIlroy & Maki, 1996; Maki et al., 2000). Importantly, the reliance on multiple steps to recover from a forward loss of balance is predictive of a future fall (Maki et al., 2001).

An important determinant for employing additional recovery steps after a forward fall is lower extremity muscle strength (Carty et al., 2012a; Grabiner et al., 2005; Pijnappels et al., 2008a, b). Model predictions (Wu et al., 2007) have shown that lower limb strength can affect the minimal step length required to regain balance when falling forward (the lower the muscle strength, the greater the minimal step length required). Further, numerous studies examining lower limb strength in the elderly have shown significant losses in strength with ageing (Suominen et al., 1977; Larssonet al., 1979; Aniansson et al., 1986; Prudham et al., 1986; Whipple et al., 1987). Also, previous studies have reported decreased quadriceps strength of the surgical limb after TKR compared to healthy controls (Walsh et al., 1998; Berth et al., 2002; Silva et al., 2003; Gapeyeva et al., 2007; Yoshida et al. 2008). Moreover, a slowing of muscle contraction velocity is also observed with ageing (Larsson et al., 1979; Hortobagyi et al., 1995) and deficits in knee strength for TKR patients are more distinct during high velocity motion (Handel et al. 2005). These changes may have affected the rate of force generated at the lower limbs of the older TKR patients during the sudden perturbation forward and, hence, the ability to successfully regain stability. However, in whatever manner statistically different measures of muscle strength has been demonstrated previously and its contribution to TKR patient’s function, or loss thereof, muscle strength may not have a clinically relevant effect on actual functional measures for TKR patients (Yoshida et al. 2008). Other components important to balance response (e.g., sensory information), that are affected by knee OA and TKR may play a larger role in balance performance for TKR patients; future work should look to elucidate the contribution of each and how they affect function post-TKR.

### 4.3 The effect of sensory input and limb after total knee replacement when recovering from a forward fall

The older TKR group had a shorter step length for the eyes-closed compared to the eyes-open condition, and this effect was not observed in any of the other groups. This finding suggests that older TKR patients may elevate the weighting of visual information compared to other sensory information when recovering from a forward fall (Paulus et al., 1987). Proprioceptive and vestibular systems decline with age (Rosenhall & Rubin, 1975; Petrella et al., 1997) and diminished joint sensation is recognized as a factor contributing to balance deficits among knee osteoarthritis patients (Wegener et al., 1997) and among TKR patients (Barrack et al., 1983, 1991). It has been suggested that a decline in sensory input from the lower limbs with age imparts more dependence on other sensory inputs, such as vision, to maintain stability (Pyykko et al., 1990; Anacker & Di Fabio, 1992). Colledge et al. (1994) studied the relative contributions of vision, proprioception, and the vestibular system with increasing age to postural sway. In four different age groups (20-40, 40-60, 60-70 and over 70 years) it was found that the relative contribution of each sensory input was the same, with proprioception being the most predominant throughout each age group. However, when reliable proprioception information was removed (standing on a 10cm thick foam surface), they found that the dependence on vision was significantly increased, although the relative contributions of the sensory systems to balance did not alter with advancing age. The evidence suggests that proprioception may greatly influence postural stability, but a decline in proprioception with ageing may be further exacerbated with degeneration of the knee joint (e.g., osteoarthritis) and after TKR, and as such, could increase the older TKR patient's reliance on vision. When visual information was removed (eyes-closed conditions) the older TKR patients employed a different stepping response (e.g., shorter step and a longer stepping delay) than that observed for the eyes-open condition, which may increase the propensity for falls, especially when visual information is reduced (e.g., low light conditions). The younger TKR group was not similarly affected by the removal of the visual information and was able to recover from the forward fall much like the healthy participants, suggesting that proprioceptive loss reported by Barrack et al. (1983, 1991) for TKR patients may not affect or may be more efficiently adapted to in the younger TKR patient.

An important observation in stepping characteristics and COM control was that there was a significant difference between left (non-surgical) and right (surgical) limbs across the groups, but in particular for the patient groups. It was observed that the surgical limb was far less effective at controlling the COM compared to the non-surgical for the patient groups, healthy participants did not show this affect. Asymmetry in the balance response may be adopted in response to unilateral TKR and the associated pre-surgical pain and dysfunction and a residual uncertainty of the surgical limb's function. Gage et al. (2008) demonstrated bilateral changes in lower limb muscle activity following TKR in response to frontal plane rotational perturbations. The authors argued that a 'minimalist' strategy was adopted to reduce the computational burden on the CNS, whereby both limbs have a single motor response. The previous study investigated a feet-in-place recovery response, in this current study the balance recovery paradigm required a stepping response and thereby a much more demanding response and may help to explain why a limb specific rather than a centrally mediated bilateral limb response was observed. This finding has important ramifications on falls and the risk of falling when the typical, older TKR patient is confronted with a situation in which they are required to rely on their surgical limb to respond to a perturbation; as constraints for any response to a perturbation would be under the limited capacity of the surgical limb and thereby elevating the propensity of falling. The younger TKR patient also adopts this bilateral response, however, it seems that both limbs of the younger TKR patient performs much more like a healthy limb, thereby the possible negative consequences and increased fall risk may not affect this younger population. Future work should look to investigate if this same limb specific response is also apparent in joint loading, and if so, this could have significant consequences on prosthesis wear and failure.

## 5. Conclusion

The younger TKR patient demonstrated superior COM control in response to a forward fall compared to the typical, older patient. The cause of this superior COM control seems to be based, in part, on stepping characteristics which facilitated a quicker step and larger moment arm associated with the longer step, which helped create a larger restorative torque. Further, the stepping characteristics of the younger TKR patient compared to the older TKR group seemed to manifest in the adoption by the older TKR patient of a strategy of taking multiple steps to regain stability. The superior COM control of the younger TKR patients suggests that they are at a reduced risk of falling compared to the typical, older patient.

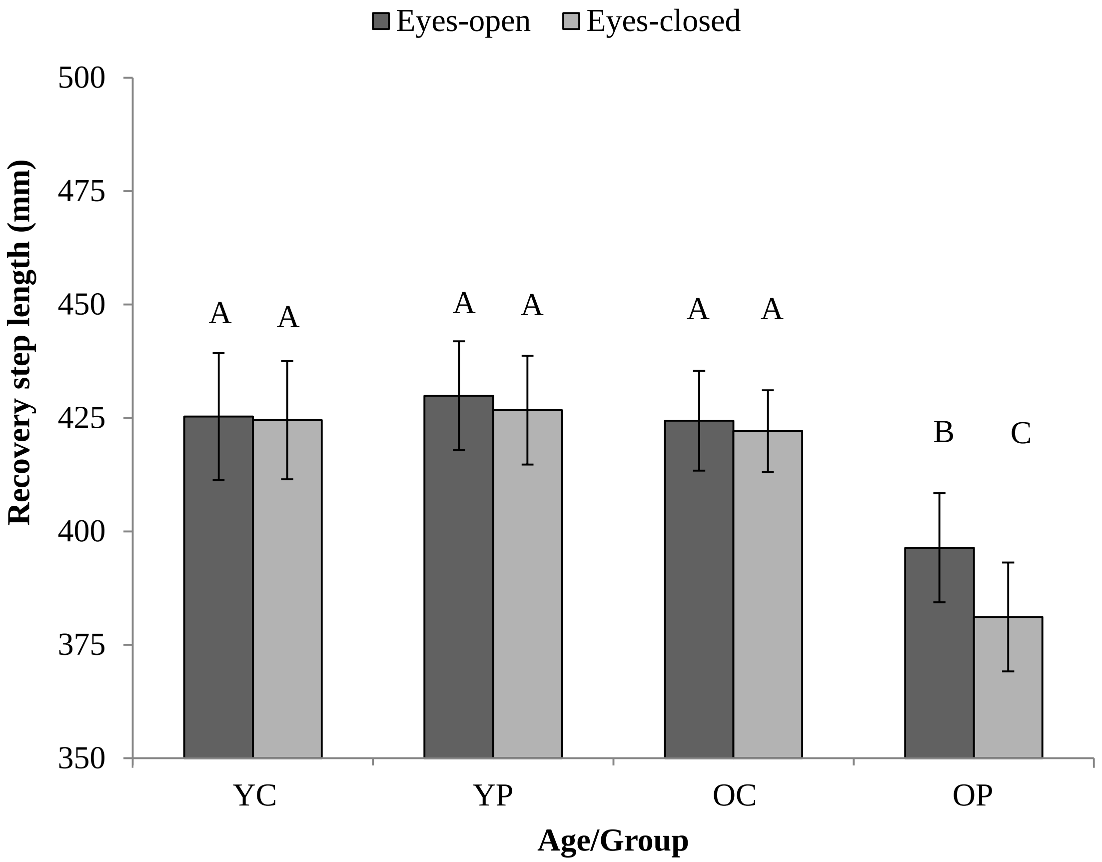

**Figure 1.** Step length for the stepping limb during the balance recovery response across the eyes-open and eyes-closed conditions. Mean (SD). YP = Younger patient, YC = Younger control, OP = Older patient, OC = Older control.

A different letter represents a significantly different step length ($p < 0.03$).

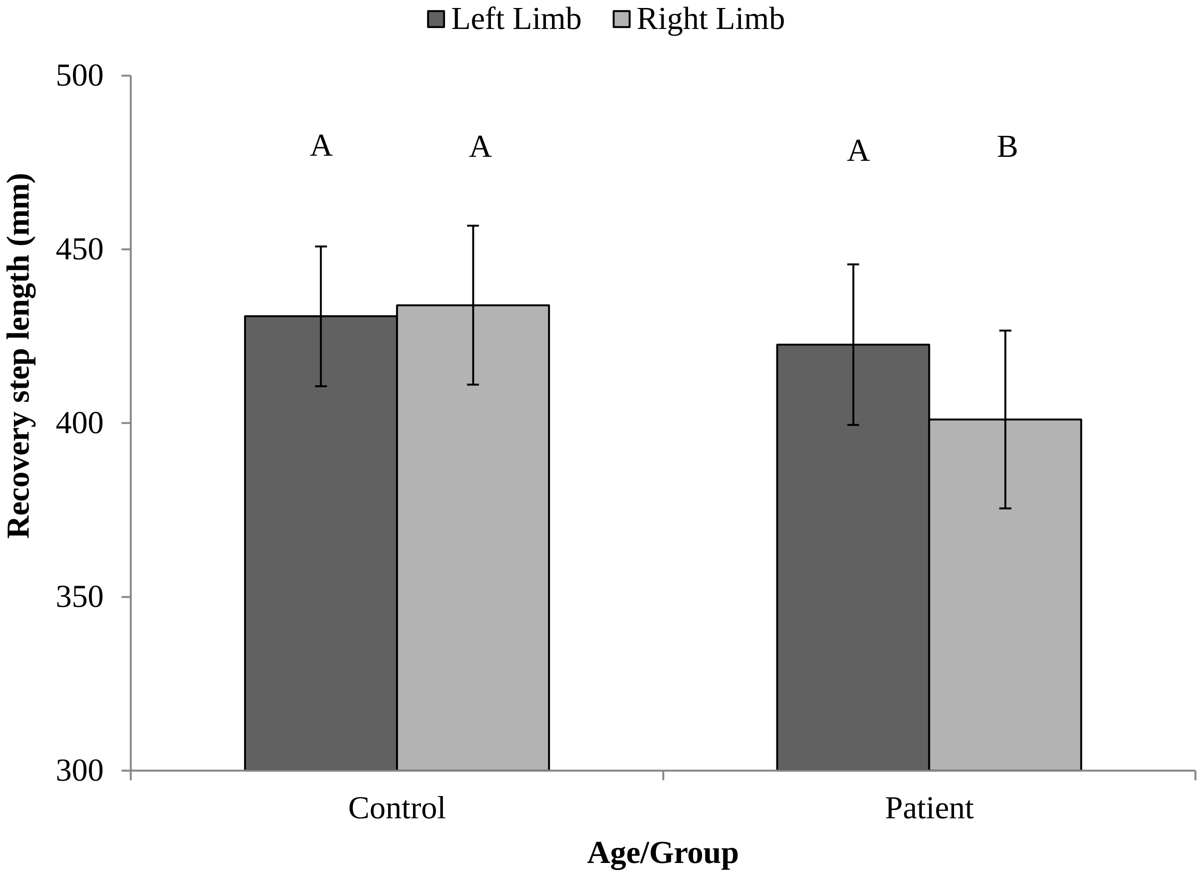

**Figure 2.** Step length for the stepping limb during the balance recovery response across limbs. Mean (SD).

A different uppercase letter demonstrated that the patient participants showed a 7.6% shorter right limb step length compared to the healthy participants ($F_{1, 165} = 16.80$, $p < 0.001$).

**Table 1**. Summary of 2x2x2x2 repeated measures ANOVA (outcome variable: recovery step length). When bold, ANOVA results indicated a significant interaction or main effect.

| Factor | ANOVA Result |
|---|---|
| **Age** | **$F_{1, 55} = 13.63$, $p = 0.005$** |
| **Group** | **$F_{1, 55} = 10.41$, $p = 0.002$** |
| **Age*Group** | **$F_{1, 55} = 9.98$, $p = 0.003$** |
| Limb | $F_{1, 165} = 1.47$, $p = 0.227$ |
| Age*Limb | $F_{1, 165} = 0.003$, $p = 0.955$ |
| **Group*Limb** | **$F_{1, 165} = 16.80$, $p < 0.001$** |
| Age*Group*Limb | $F_{1, 165} = 0.04$, $p = 0.841$ |
| **Eye** | **$F_{1, 165} = 23.22$, $p < 0.001$** |
| **Age*Eye** | **$F_{1, 165} = 12.23$, $p = 0.002$** |
| Group*Eye | $F_{1, 165} = 2.27$, $p = 0.134$ |
| **Age*Group*Eye** | **$F_{1, 165} = 15.85$, $p = 0.001$** |
| Limb*Eye | $F_{1, 165} = 2.44$, $p = 0.120$ |
| Age*Limb*Eye | $F_{1, 165} = 0.56$, $p = 0.456$ |
| Group*Limb*Eye | $F_{1, 165} = 0.36$, $p = 0.547$ |
| Age*Group*Limb*Eye | $F_{1, 165} = 0.17$, $p = 0.684$ |

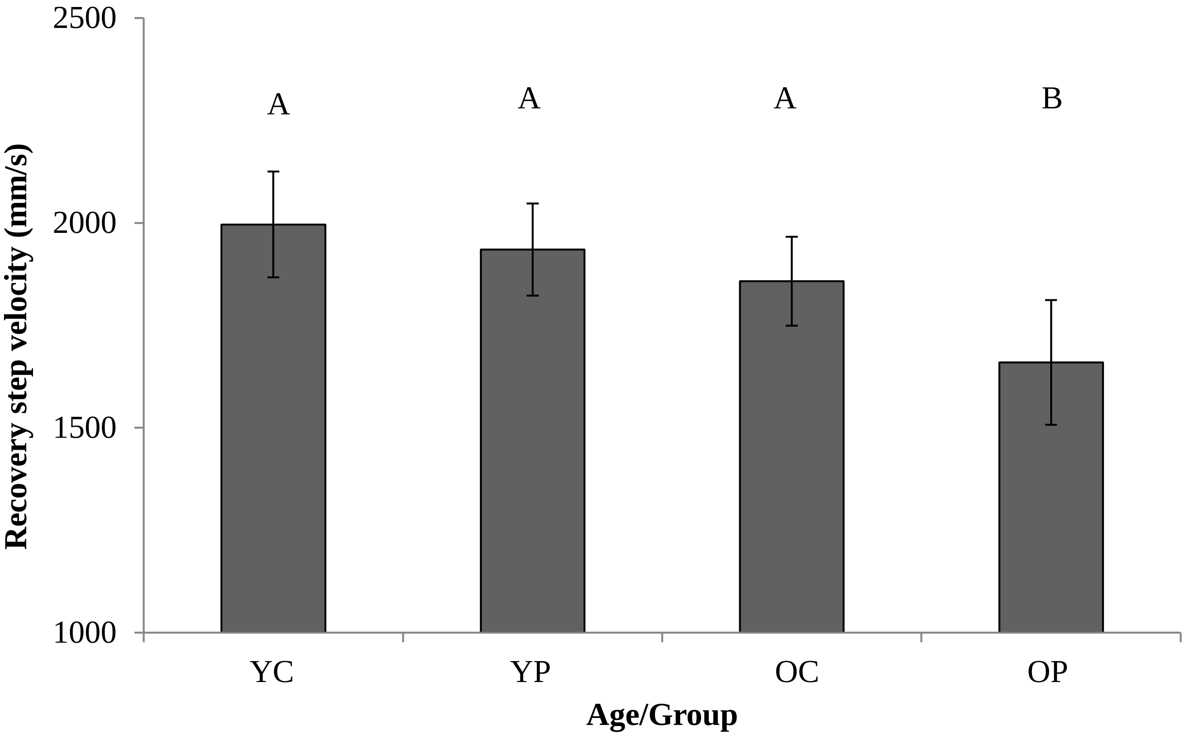

**Figure 3.** Stepping foot peak velocity during the balance recovery response. Mean (SD). YP = Younger patient, YC = Younger control, OP = Older patient, OC = Older control.

A different uppercase letter represents a significantly faster peak stepping foot velocity across conditions ($p < 0.01$).

**Table 2**. Summary of 2x2x2x2 repeated measures ANOVA (outcome variable: Stepping foot peak velocity during the balance recovery response). When bold, ANOVA results indicated a significant interaction or main effect.

| **Factor** | **ANOVA Result** |
|---|---|
| **Age** | **$F_{1, 55} = 38.22, p < 0.001$** |
| **Group** | **$F_{1, 55} = 23.67, p < 0.001$** |
| **Age*Group** | **$F_{1, 55} = 13.28, p = 0.001$** |
| Limb | $F_{1, 165} = 0.50, p = 0.479$ |
| Age*Limb | $F_{1, 165} = 2.24, p = 0.137$ |
| Group*Limb | $F_{1, 165} = 1.22, p = 0.271$ |
| Age*Group*Limb | $F_{1, 165} = 0.01, p = 0.991$ |
| **Eye** | **$F_{1, 165} = 6.10, p = 0.016$** |
| Age*Eye | $F_{1, 165} = 0.13, p = 0.722$ |
| Group*Eye | $F_{1, 165} = 0.15, p = 0.696$ |
| Age*Group*Eye | $F_{1, 165} = 3.00, p = 0.085$ |
| Limb*Eye | $F_{1, 165} = 0.31, p = 0.579$ |
| Age*Limb*Eye | $F_{1, 165} = 0.002, p = 0.980$ |
| Group*Limb*Eye | $F_{1, 165} = 0.005, p = 0.976$ |
| Age*Group*Limb*Eye | $F_{1, 165} = 0.31, p = 0.579$ |

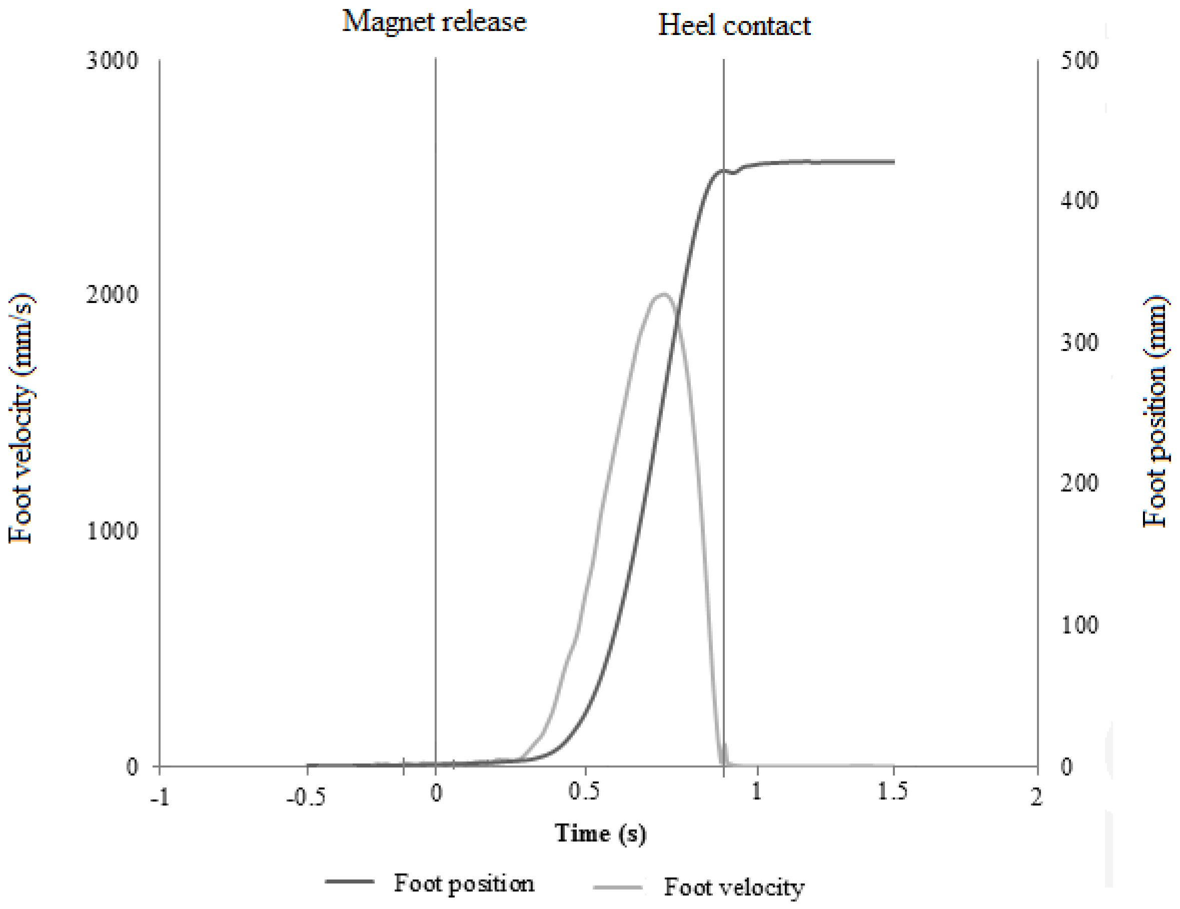

**Figure 4.** Representative time series data for foot position and foot velocity for a healthy younger paticipant. The lateral malleolus marker was used for calculations. Foot position and foot velocity are shown 0.5 sec prior to, till 1.5 sec after magnet release.

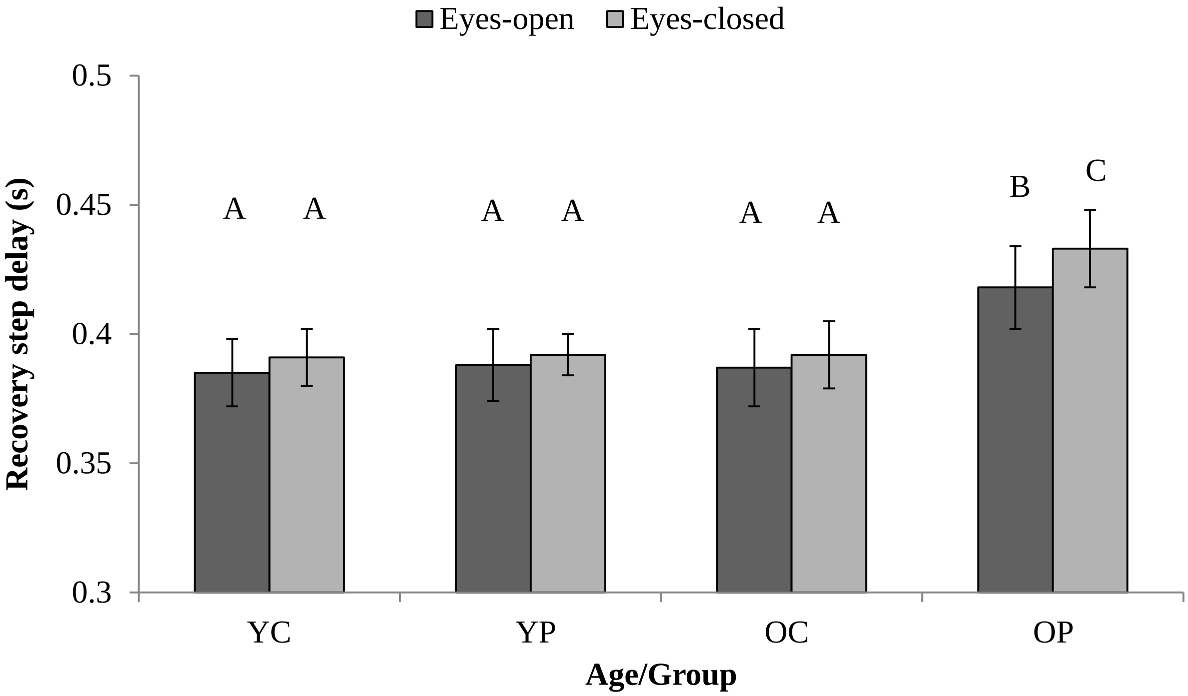

**Figure 5.** Step delay latency in the stepping limb during the balance recovery response across eyes open and eyes-closed conditions. Mean (SD). YP = Younger patient, YC = Younger control, OP = Older patient, OC = Older control.

A different letter represents a significantly different step length ($p < 0.03$).

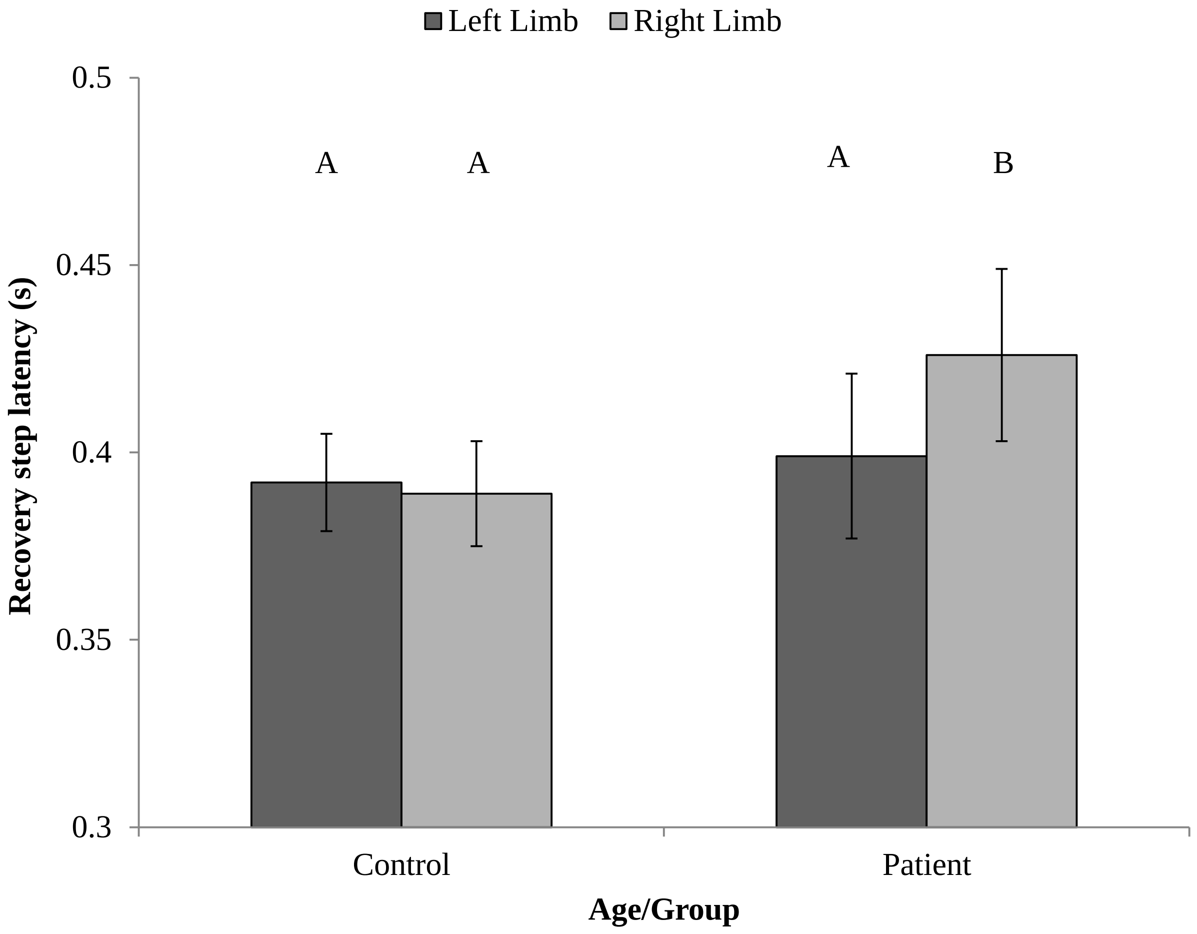

**Figure 6.** Step delay latency in the stepping limb during the balance recovery response across limbs between groups. Mean (SD).

A different uppercase letter demonstrates that the patient participants showed an 8.7% greater stepping latency in right limb compared to the control participants ($F_{1,\ 165} = 17.22$, $p < 0.001$)

**Table 3.** Summary of 2x2x2x2 repeated measures ANOVA (outcome variable: recovery step latency). When bold, ANOVA results indicated a significant interaction or main effect.

| Factor | ANOVA Result |
|---|---|
| **Age** | **$F_{1, 55}$ = 22.13, $p < 0.001$** |
| **Group** | **$F_{1, 55}$ = 10.68, $p = 0.002$** |
| **Age*Group** | **$F_{1, 55}$ = 11.36, $p = 0.002$** |
| Limb | $F_{1, 165}$ = 1.12, $p = 0.408$ |
| Age*Limb | $F_{1, 165}$ = 0.98, $p = 0.521$ |
| **Group*Limb** | **$F_{1, 165}$ = 17.22, $p < 0.001$** |
| Age*Group*Limb | $F_{1, 165}$ = 0.33, $p = 0.603$ |
| **Eye** | **$F_{1, 165}$ = 7.60, $p < 0.001$** |
| **Age*Eye** | **$F_{1, 165}$ = 10.21, $p = 0.002$** |
| **Group*Eye** | **$F_{1, 165}$ = 8.66, $p = 0.004$** |
| **Age*Group*Eye** | **$F_{1, 165}$ = 10.08, $p = 0.002$** |
| Limb*Eye | $F_{1, 165}$ = 2.44, $p = 0.120$ |
| Age*Limb*Eye | $F_{1, 165}$ = 0.56, $p = 0.456$ |
| Group*Limb*Eye | $F_{1, 165}$ = 0.36, $p = 0.547$ |
| Age*Group*Limb*Eye | $F_{1, 165}$ = 0.17, $p = 0.684$ |

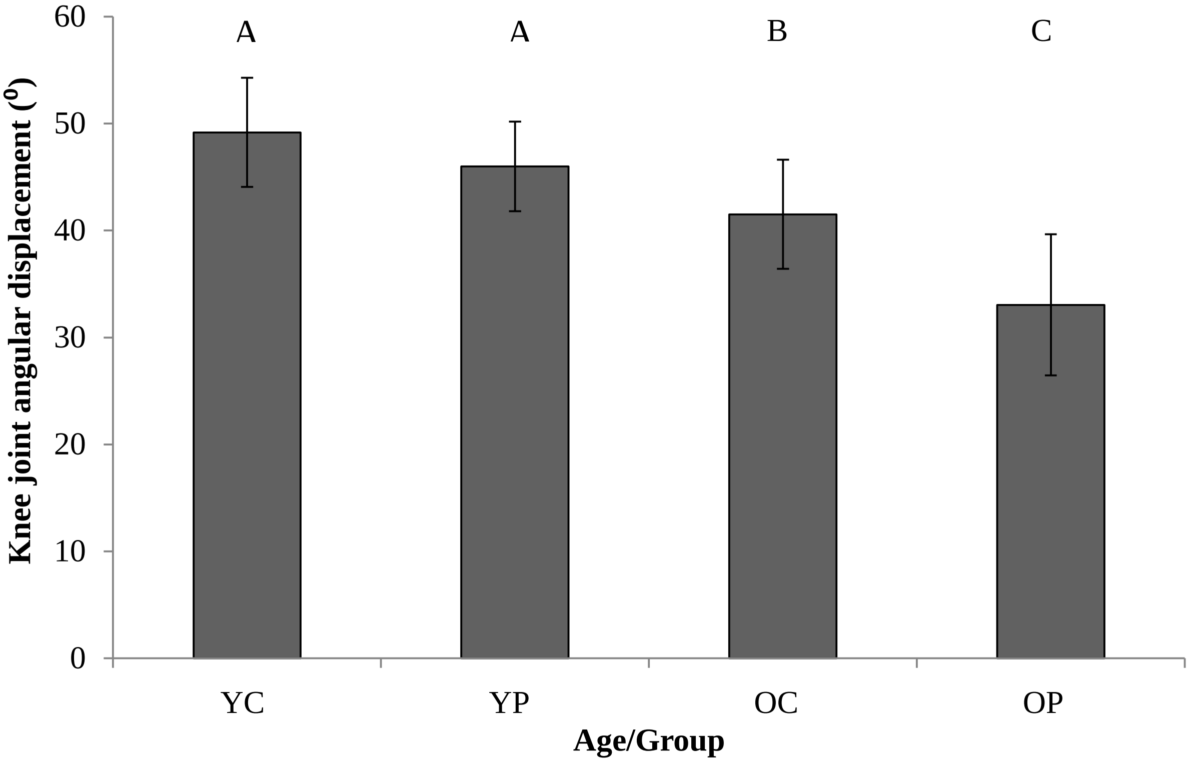

**Figure 7.** Peak knee joint angular displacement of the stepping limb during the balance recovery response. Mean (SD). YP = Younger patient, YC = Younger control, OP = Older patient, OC = Older control.

A different uppercase letter represents a significantly represents a significantly larger peak knee joint angular displacement ($p < 0.02$).

**Table 4**. Summary of 2x2x2x2 repeated measures ANOVA (outcome variable: peak knee joint angular displacement). When bold, ANOVA results indicated a significant interaction or main effect.

| **Factor** | **ANOVA Result** |
|---|---|
| **Age** | **$F_{1, 55} = 24.26, p < 0.001$** |
| **Group** | **$F_{1, 55} = 10.68, p = 0.002$** |
| **Age*Group** | **$F_{1, 55} = 9.08, p = 0.003$** |
| Limb | $F_{1, 165} = 2.68, p = 0.103$ |
| Age*Limb | $F_{1, 165} = 0.43, p = 0.511$ |
| Group*Limb | $F_{1, 165} = 0.16, p = 0.687$ |
| Age*Group*Limb | $F_{1, 165} = 1.96, p = 0.164$ |
| **Eye** | **$F_{1, 165} = 6.91, p = 0.009$** |
| Age*Eye | $F_{1, 165} = 0.04, p = 0.841$ |
| Group*Eye | $F_{1, 165} = 0.28, p = 0.601$ |
| Age*Group*Eye | $F_{1, 165} = 2.03, p = 0.156$ |
| Limb*Eye | $F_{1, 165} = 0.10, p = 0.749$ |
| Age*Limb*Eye | $F_{1, 165} = 3.87, p = 0.080$ |
| Group*Limb*Eye | $F_{1, 165} = 1.01, p = 0.316$ |
| Age*Group*Limb*Eye | $F_{1, 165} = 1.14, p = 0.286$ |

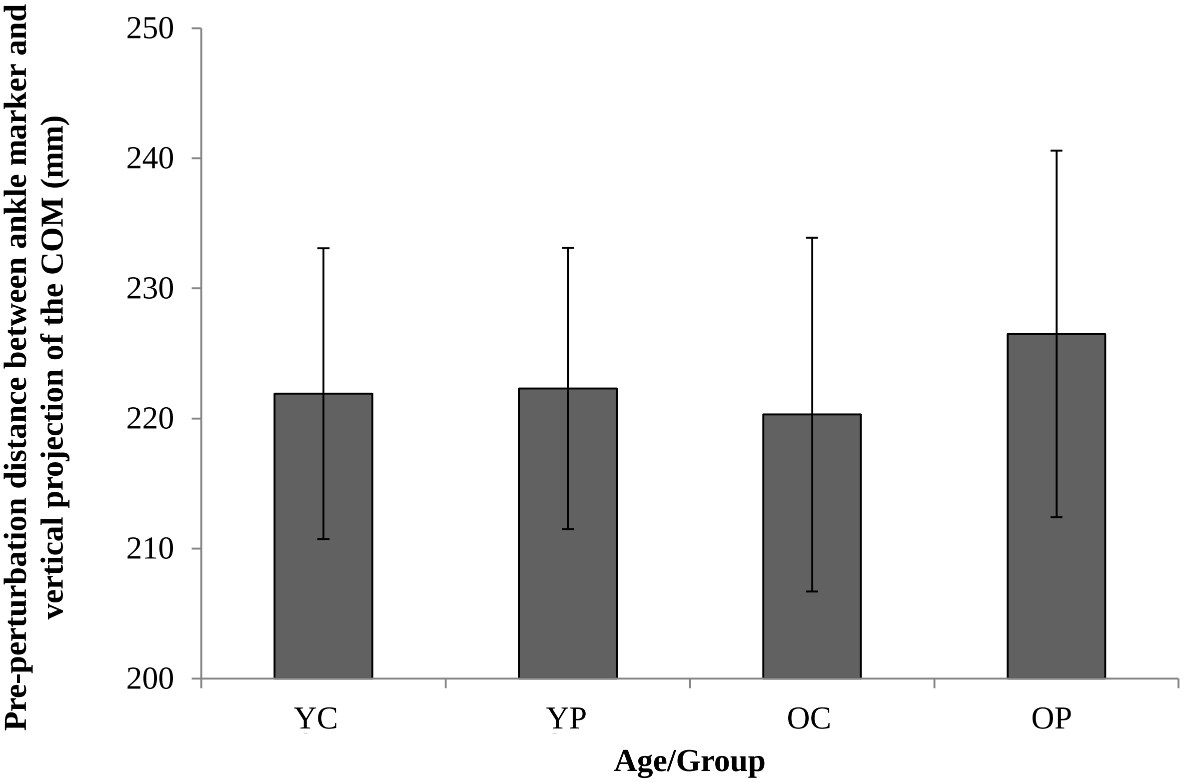

**Figure 8.** Pre-perturbation distance between the vertical projection of the centre of mass and the ankle marker. Mean (SD). YP = Younger patient, YC = Younger control, OP = Older patient, OC = Older control.

No difference was observed for Pre-perturbation distance between the vertical projection of the centre of mass and the ankle marker between groups across the conditions.

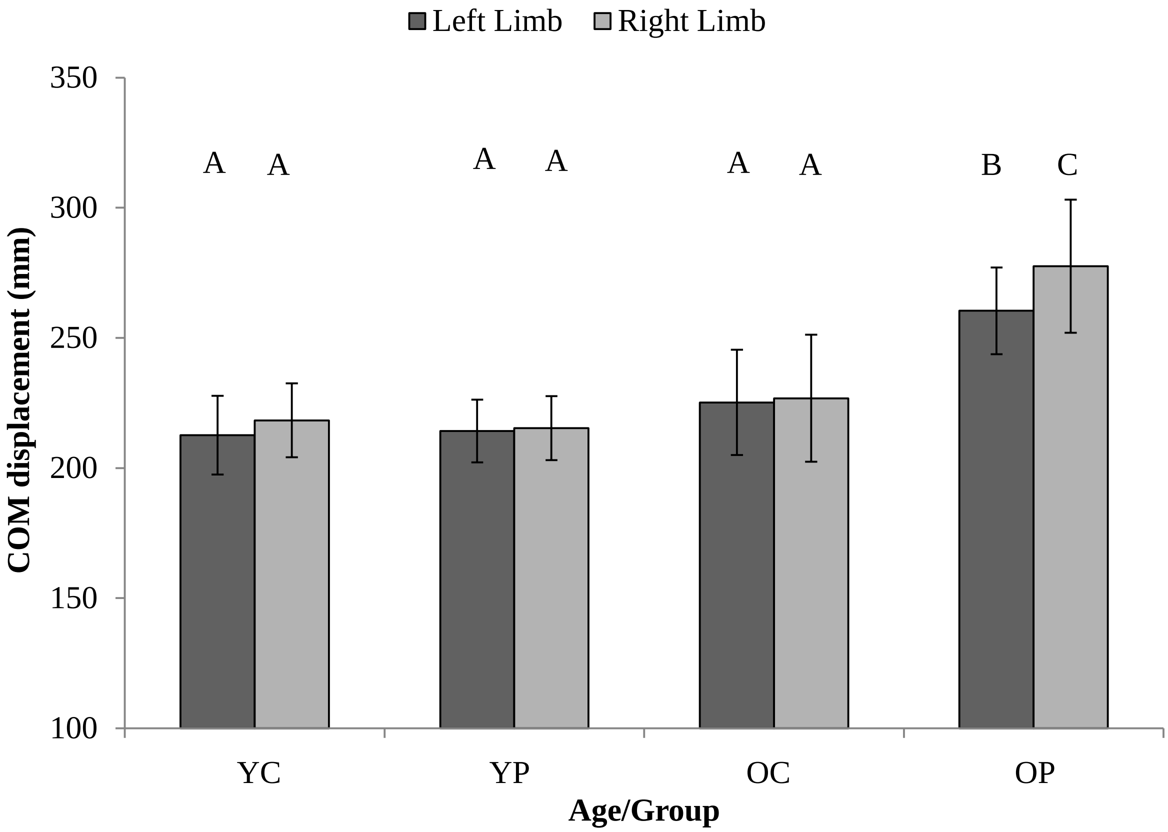

**Figure 9.** Centre of mass displacement during the balance recovery response. Mean (SD). Anteroposterior centre of mass displacement was reported. YP = Younger patient, YC = Younger control, OP = Older patient, OC = Older control

A different letter represents a significantly different peak centre of mass displacement ($p < 0.03$).

**Table 5.** Summary of 2x2x2x2 repeated measures ANOVA (outcome variable: COM displacement). When bold, ANOVA results indicated a significant interaction or main effect.

| **Factor** | **ANOVA Result** |
|---|---|
| **Age** | **$F_{1, 55} = 15.42, p < 0.001$** |
| **Group** | **$F_{1, 55} = 13.01, p < 0.001$** |
| Age*Group | $F_{1, 55} = 3.20, p = 0.079$ |
| **Limb** | **$F_{1, 165} = 3.98, p = 0.047$** |
| **Age*Limb** | **$F_{1, 165} = 6.16, p = 0.013$** |
| **Group*Limb** | **$F_{1, 165} = 4.11, p = 0.044$** |
| Age*Group*Limb | $F_{1, 165} = 0.98, p = 0.324$ |
| **Eye** | **$F_{1, 165} = 23.98, p < 0.001$** |
| Age*Eye | $F_{1, 165} = 0.02, p = 0.888$ |
| Group*Eye | $F_{1, 165} = 0.84, p = 0.361$ |
| Age*Group*Eye | $F_{1, 165} = 2.73, p = 0.100$ |
| Limb*Eye | $F_{1, 165} = 0.87, p = 0.352$ |
| Age*Limb*Eye | $F_{1, 165} = 0.02, p = 0.901$ |
| Group*Limb*Eye | $F_{1, 165} = 2.11, p = 0.148$ |
| Age*Group*Limb*Eye | $F_{1, 165} = 1.63, p = 0.204$ |

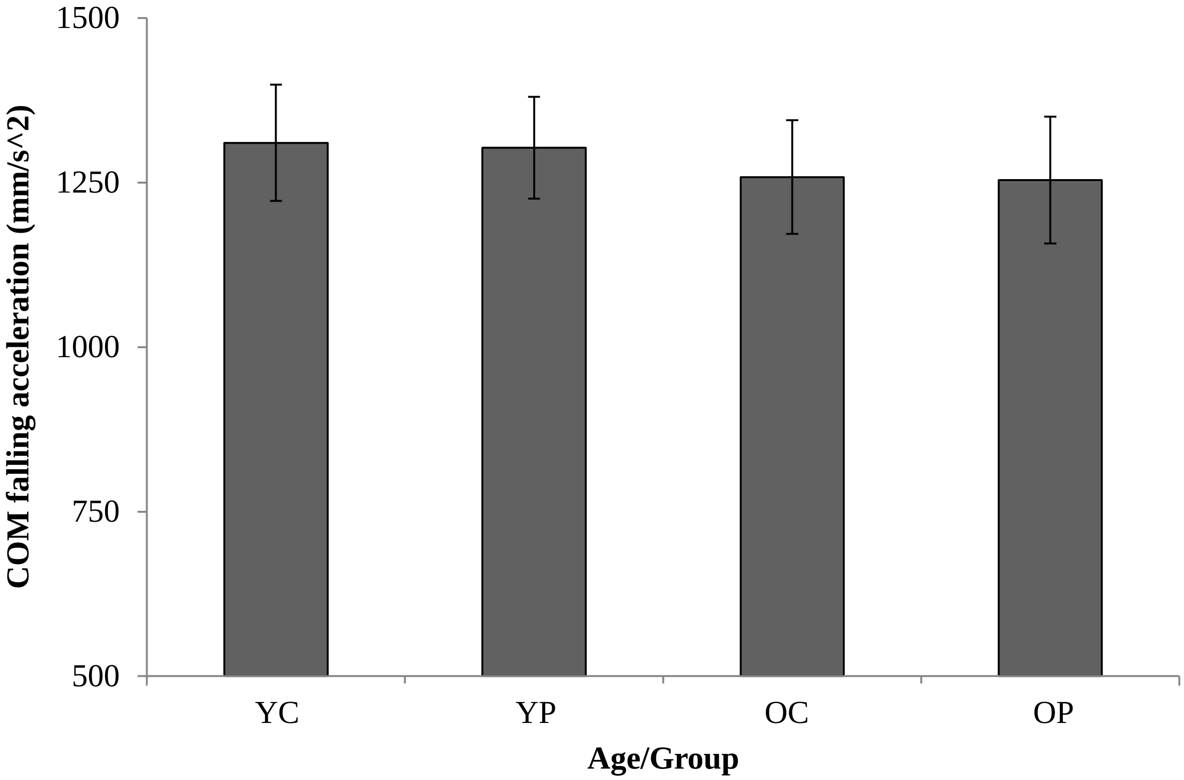

**Figure 10.** Peak positive centre of mass falling acceleration during the balance recovery response. Mean (SD). Anteroposterior centre of mass acceleration was reported. YP = Younger patient, YC = Younger control, OP = Older patient, OC = Older control.

No difference was observed for peak positive centre of mass falling acceleration between groups across the conditions.

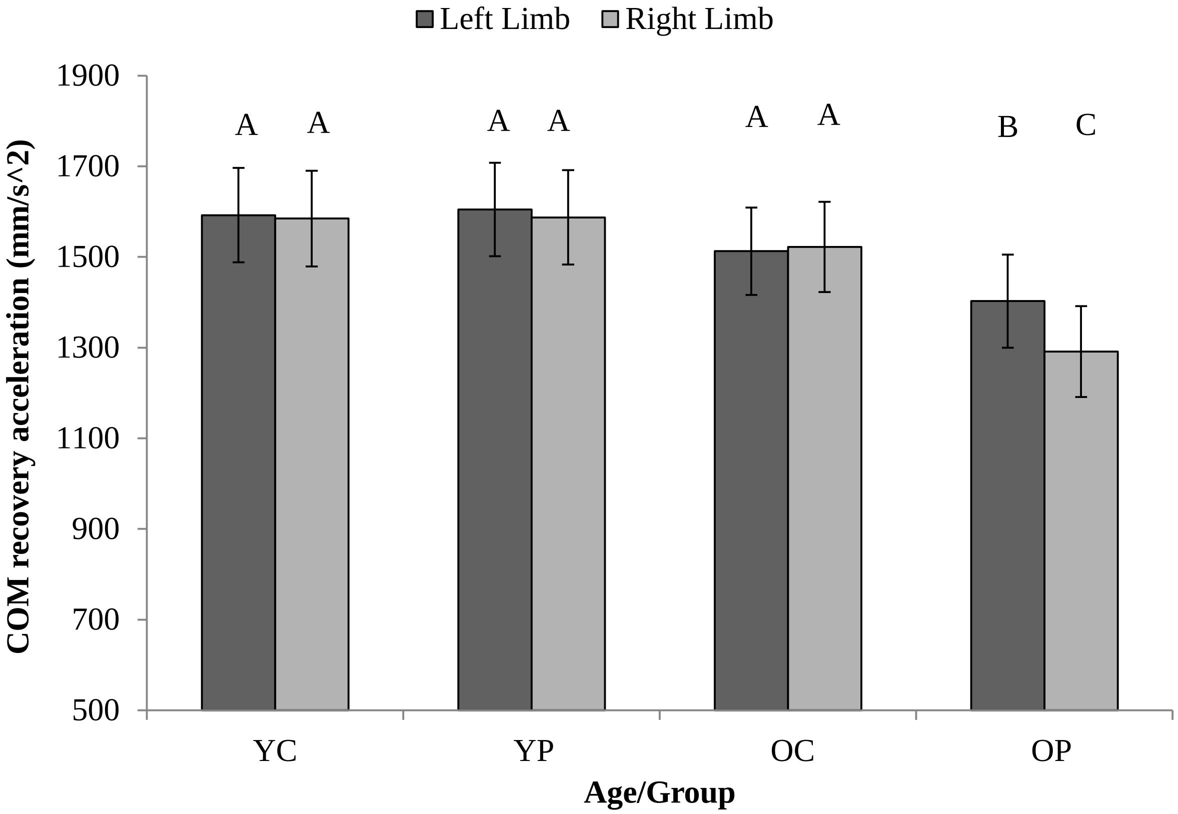

**Figure 11.** Peak negative centre of mass acceleration during the balance recovery response. Mean (SD). Anteroposterior centre of mass acceleration was reported. YP = Younger patient, YC = Younger control, OP = Older patient, OC = Older control.

A different letter represents a significantly different peak centre of mass recovery acceleration ($p < 0.02$).

**Table 6**. Summary of 2x2x2x2 repeated measures ANOVA (outcome variable: Peak negative centre of mass acceleration). When bold, ANOVA results indicated a significant interaction or main effect.

| **Factor** | **ANOVA Result** |
|---|---|
| **Age** | **$F_{1, 55} = 65.31, p < 0.001$** |
| **Group** | **$F_{1, 55} = 18.24, p < 0.001$** |
| **Age*Group** | **$F_{1, 55} = 12.34, p < 0.001$** |
| **Limb** | **$F_{1, 165} = 24.35, p < 0.001$** |
| **Age*Limb** | **$F_{1, 165} = 27.89, p < 0.001$** |
| **Group*Limb** | **$F_{1, 165} = 13.61, p < 0.001$** |
| **Age*Group*Limb** | **$F_{1, 165} = 12.25, p < 0.001$** |
| **Eye** | **$F_{1, 165} = 33.42, p < 0.001$** |
| Age*Eye | $F_{1, 165} = 0.13, p = 0.722$ |
| Group*Eye | $F_{1, 165} = 0.15, p = 0.696$ |
| Age*Group*Eye | $F_{1, 165} = 1.78, p = 0.185$ |
| Limb*Eye | $F_{1, 165} = 0.01, p = 0.910$ |
| Age*Limb*Eye | $F_{1, 165} = 1.81, p = 0.181$ |
| Group*Limb*Eye | $F_{1, 165} = 0.77, p = 0.355$ |
| Age*Group*Limb*Eye | $F_{1, 165} = 0.69, p = 0.423$ |

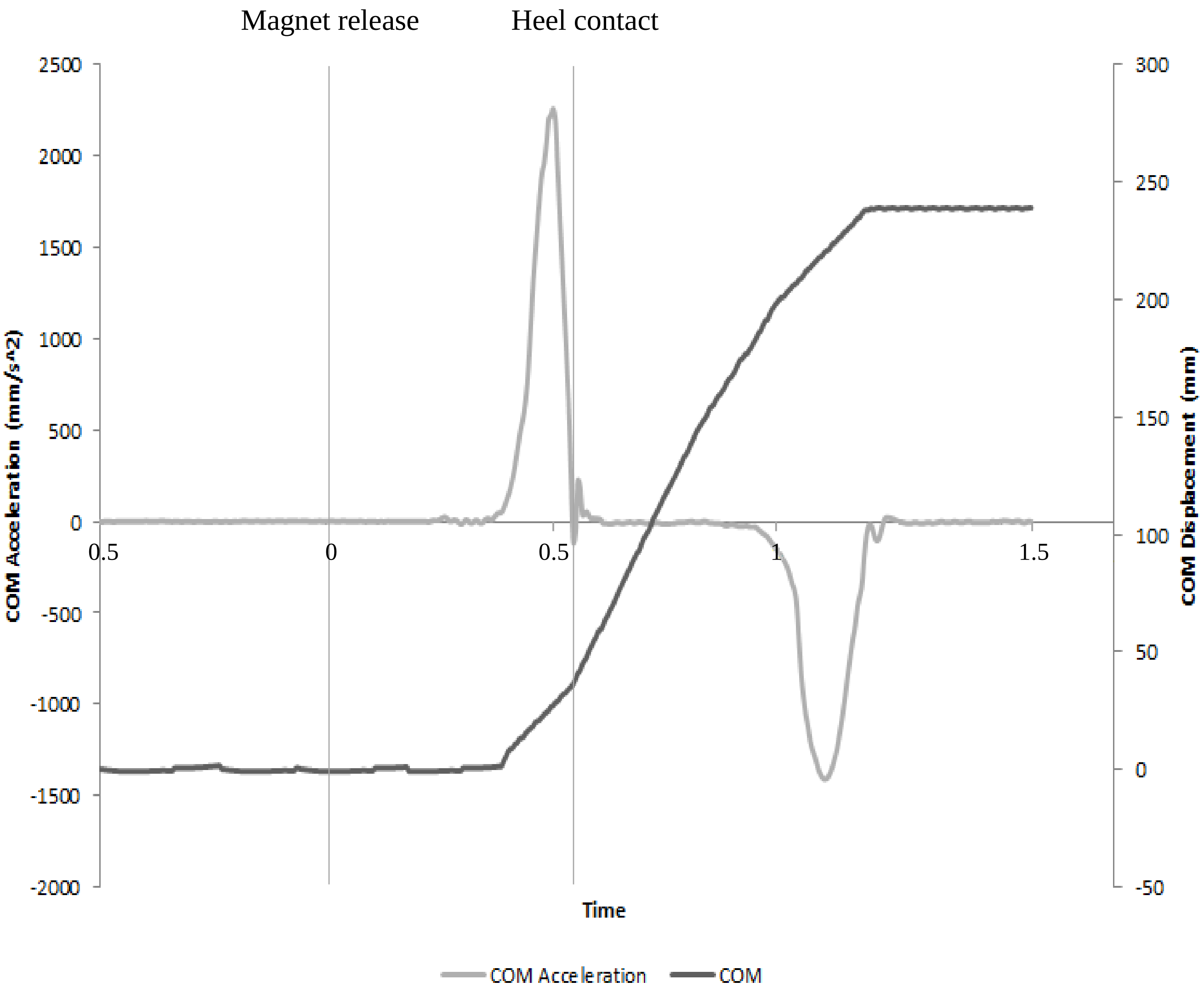

**Figure 12.** Representative time series data for centre of mass displacement and acceleration for a healthy younger participant. COM displacement and acceleration are shown 0.5 sec prior to, till 1.5 sec after magnet release.

# CHAPTER FOUR

# YOUNGER TOTAL KNEE REPLACEMENT PATIENTS DO NOT DEMONSTRATE ASYMMETRICAL HEEL STRIKE TRANSIENT AND KNEE JOINT MOMENTS DURING LEVEL WALKING

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Manuscript to be submitted in: Gait and Posture

## Preface

There is evidence to suggest that after total knee replacement (TKR) there is a predictable pattern of deterioration in other joints of the lower extremities, such as the contralateral knee. Abnormal gait patterns that can create excessive levels of impact forces in the lower extremities may precede the development and affect the progression of knee osteoarthritis (OA). TKR patients often retain abnormal gait patterns, such as asymmetry between limbs, post-TKR that were adopted before surgery, which may cause greater loading in the contralateral limb. The use of TKR has increased substantially during the past two decades, particularly among younger patients. Although the frequency of younger TKR patients (<55 years old) is rapidly growing, very little is yet known regarding their functional outcome post-TKR. It is not yet known if these younger patients assume the asymmetrical gait pattern observed in the typical, older TKR patient (>65years old) and the findings could have significant clinical implications. Therefore, the purpose of this study was to investigate and compare the heel strike transient, kinematics and joint moments of the knee during level walking in both the surgical and non-surgical limbs between younger and older TKR patients six months following unilateral knee replacement, and their healthy age-matched controls. A convenience sample of 59 participants, including 29 primary knee replacement patients six months after surgery, consisting of four groups: 1) Younger patient (n=15 (11 F), age: 54.3 ± 7.9 years), 2) Younger control (n=15 (13 F), age: 55.2 ± 4.0 years), 3) Older patient (n=14 (12 F), age: 76.9 ± 4.7 years), and 4) Older control (n= 15 (11 F), age: 77.7 ± 4.1 years) volunteered to participate in this study. The older TKR group demonstrated an asymmetrical heel strike transient and knee adduction moment magnitude between their surgical and non-surgical limbs, no other group showed this same pattern. These asymmetrical loading and moments across the surgical and non-surgical limbs of the older TKR patient could create or further progress osteoarthritic degeneration in the non-surgical limb.

These asymmetrical loading and moments was not observed in the younger TKR patient. The asymmetrical gait patterns observed in the older TKR patient may be due to a learned gait pattern which does not resolve despite treatment of the affected joint or to compensate for residual pain and functional impairment. The current findings may be clinically relevant in patients undergoing unilateral knee replacement, as delaying surgery could lead to the adoption of gait patterns that may negatively affect the contralateral limb and lead to greater activity avoidance and sendentarism, potentially leading to further health deterioration. Further, rehabilitation protocols may be required if patients are to learn to protect the contralateral joints appropriately following an otherwise successful TKR surgery.

## 1. Introduction

Knee osteoarthritis (OA) is a common degenerative condition resulting in joint pain and altered movement patterns. Excessive levels of impact forces have been suggested to contribute to degenerative changes in knee joint cartilage and there is evidence to suggest that an abnormal gait pattern may precede the development (Lynn et al., 2007) and affect the progression of knee OA (Radin et al., 1972; Simon & Radin, 1972; Radin et al., 1978; Collins et al., 1989). It has been reported that the ability to attenuate these impact forces is also reduced in knee osteoarthritic patients (Voloshin & Woak, 1982). Total knee replacement (TKR) is the most common surgical intervention for moderate to severe knee osteoarthritis, reducing pain and improving functional ability and activity limitations (Finch et al. 1998; Heck et al., 1998; König et al., 2000; Ranawat et al., 2003; Farquhar et al., 2008). However, although improved from pre-surgical levels, persistent deficits in long-term functional ability of TKR patients remain compared to their age-matched healthy counterparts (Finch et al. 1998). Importantly, a reduced ability to attenuate impact forces also persists post-TKR (Chu et al., 1986). And there is evidence to suggest that abnormal gait patterns observed before TKR are retained after surgery (Smith et al., 2004: Smith et al., 2006). Smith et al. (2004) found that around 70% of patients who had abnormal flexor or extensor gait patterns post-TKR showed those same patterns before surgery. Further, gait alterations including gait asymmetry have been observed in patients following knee replacement surgery (Webster et al., 2003; Mizner & Snyder-Mackler, 2005; McClelland et al., 2007; Stacoff et al., 2007) and it has been argued that the asymmetrical gait pattern may be a compensatory strategy to reduce the forces and loading in the surgical limb (Yoshida et al., 2008).

Epidemiological evidence suggests that after primary TKR there is a predictable pattern of deterioration in other major joints of the lower limb, such as the contralateral knee (Shakoor et al., 2002). Greater external peak knee adduction and extension moments as well as elevated medial compartment loading were found in the contralateral knee compared to the ipsilateral for those suffering from hip osteoarthritis (Shakoor et al., 2003). It has been argued that after unilateral TKR asymmetrical gait patterns play a contributory factor in the progression of OA in the contralateral knee joint (Shakoor et al., 2002). In a recent analysis of a 12 year cohort study, 80% of patients with unilateral knee OA were found to develop osteoarthritic changes in their contralateral limb (Metcalfe et al., 2012). Shakoor et al. (2002) reported that among patients undergoing an initial TKR, about one third went on to have a second joint replacement and that 92% of those replaced joints were the contralateral knee. Further, McMahon & Block, (2003) reported that after primary unilateral TKR there is an overall 10-year risk of contralateral TKR of 37.2%.

Currently more than 40,000 TKR procedures are performed in Canada each year (CJRR, 2009). Recently, demographic changes have been observed in national joint replacement registries. In the Canadian Joint Replacement Registry 2008–2009 annual report, the largest relative percent increase in knee replacement procedures over the last decade was in the 45-to-54 age group for both males and females (271% and 337% increase, respectively). Other joint replacement registries have also shown a similar trend; during the past 10 years, knee surgery for OA in patients less than 55 years of age has doubled in Sweden (Swedish Knee Arthroplasty Register, 2013) and in Australia, the proportion of patients less than 65 years of age at the time of surgery has reached 32% (Australian Orthopaedic Association National Joint Replacement Registry, 2008). Moreover, it is anticipated that the average age at surgery will continue to decrease (Wells et al., 2002; Dixon et al., 2004) and patients less than 65 years of age will become the majority undergoing TKR surgery during the next two decades in the United States (Kurtz et al., 2009).

The development of bilateral joint degeneration is a cause of significant disability and pain, and yet its aetiology is very poorly understood (White et al., 2010). Adopted asymmetrical gait patterns of TKR patients have been observed and have been argued to play a significant role in contralateral joint degeneration. Although the frequency of younger TKR patients is rapidly growing, there is very little yet known regarding their functional outcome post-TKR. It is not yet known if these younger patients assume this same asymmetrical gait pattern observed in the typical, older TKR patient and the findings could have significant clinical implications given greater duration and opportunity for younger patients to develop degenerative changes on the contralateral side. Therefore, the purpose of this study was to investigate and compare the heel strike transient vertical force, kinematics and joint moments of the knee during level walking in both the surgical and non-surgical limb between younger and older TKR patients six months following unilateral knee replacement, and their healthy age-matched controls. It was hypothesized that the older TKR patients would demonstrate larger knee adduction moments in the non-surgical limb, which has previously been observed after unilateral hip and knee replacement (Shakoor et al., 2002; Shakoor et al., 2003). However, it was also hypothesized that the younger TKR patient would not demontstate an asymmetrical pattern between limbs, as elevated muscle strength and sensory input observed in younger compared to older healthy adults (Rosenhall & Rubin, 1975; Whipple et al., 1987; Petrella et al., 1997) would also differentiate younger and older TKR patienst, aiding to normalize the gait pattern of younger TKR patients after surgery.

## 2. Methodology

### 2.1 Participants

The participants from this study are part of a larger project investigating TKR and the affect of age on functional and psychosocial measures. Participant inclusion and exclusion criteria has been reported in chapter 2 (pg. 63) of this thesis.

### 2.2 Participant set-up and collection equipment

Upon arrival to the laboratory, participants were provided with the following: study/participant information sheet (Appendix A) and informed consent form (Appendix B). Upon obtaining informed consent, participants were asked to remove their shoes and socks and infrared reflective markers were applied. A total of 36 reflective markers were attached to each participant on the following bony landmarks, according to the Plug-in-Gait model (Nexus, Vicon, Colorado, USA): front and back (left and right) head markers, C7, T10, clavicle, sternum, right scapula, and bilaterally on the acromioclavicular joint, upper arm, lateral epicondyle of the elbow, forearm, wrist (both on the ulnar and radial styli), anterior and posterior superior iliac spine, upper thigh, lateral femoral condyles, shank, lateral malleoli, calcaneus, 2nd metatarsal heads (Appendix C). This marker placement model has been used previously when investigating the gait of knee OA and TKR patients (Wang et al., 2009; Metcalfe et al., 2013; Urwin et al., 2014). Movement was recorded using a seven-camera motion capture system (MX40, Vicon, Colorado, USA). Marker position was sampled at a frequency of 100Hz. Four force plates (OR6-7, AMTI, Massachusetts, USA) were arranged in a T-shaped configuration and used to determine kinetic data and sampled at 1000Hz.

## 2.3 Experimental Procedure

### 2.3.1 Gait Analysis

A standing calibration was performed prior to walking trials to identify joint centers with respect to the coordinate system of each segment. Following the standing calibration, the participants were given the opportunity to carry out familiarization walking trials along the experimental walkway. During this period participants were asked to become familiar with walking over the force plates, without targeting. When participants reported that they felt familiar with the experimental walkway, a total of 10 successful walking trials were recorded along the 5-m walkway. Walking was performed at the individual’s self-selected pace. A successful trial was defined as a trial in which the participants contacted opposing force platforms with each foot. Participants performed a minimum of three complete gait cycles prior to entering the motion capture volume, and continued walking for at least two complete strides beyond the force plates, to ensure steady-state gait within the data capture volume.

Gait speed, step length, step width, single and double support time were analyzed as the spatiotemporal parameters. Gait speed was determined by calculating the distance traveled (within the motion capture space) by the sternum marker divided by the time taken to walk the measured distance. Step length was calculated from the distance between the ankle joint centres in the anteroposterior direction at heel contact of the lead limb (both when the right and left limb was lead limb during double support time). Step width was calculated from the distance between the ankle joint centres in the mediolateral direction. Single and double support time was calculated using force plate data, where the time in which both feet and a single foot was in contact with the force plate was extracted. To assess kinematic and kinetic gait parameters during the stance phase, the following peak angles and external moments were also analyzed for the knee: sagittal plane (flexion/extension), frontal plane (adduction/abduction) and coronal plane (internal/external rotation). Joint moments were normalized to bodyweight and height (%BW*H). The heel strike transient was determined using the vertical ground reaction force (GRF) and was defined as the heel strike vertical peak between 10 and 20 ms following heel strike (Levinger et al., 2008). The vertical GRF for the heel strike magnitude was normalized to the participant bodyweight (%BW). The dependent measures were analyzed for the patient groups by assigning the surgical limb as the right limb and the non-surgical limb was assigned as the left limb. Before performing statistical analyses it was shown that limb-dominance had no effect on the heel strike transient for the control groups ($F_{1,29} = 1.80$, $p = 0.330$). The dependent measures were calculated using commercial software (Plug-in-Gait model, Nexus, Vicon, Colorado, USA). Spatiotemporal parameters, knee angles, forces and joint moments were exported and stored for further analysis.

### 2.4 Statistical Analysis

To address the purpose of this study, to investigate and compare knee kinematic and kinetic variables during level walking of younger and older TKR patients, and their healthy age-matched controls, the following analysis was conducted: three-factor ANOVAs (*age* [younger/older] x *group* [patient/control] x *limb* [surgical/non-surgical]) with participant nested in factors *age* and *group*. Bonferroni adjusted T-tests were then used to assess the differences when a significant interaction effect was observed. All statistical analyses were conducted using JMP (v11.1.1, The SAS Institute, North Carolina, USA), and a p-value less than 0.05 was considered statistically significant.

## 3. Results

Participant characteristics and statistical analysis are shown in chapter 2 (pg. 69 and in Table 1, pg. 98) of this thesis.

### 3.1 Gait Analysis

#### 3.1.1 Spatiotemporal measures

The mean and standard deviation for the spatiotemporal measures for the four groups are shown in Table 1. Gait speed analysis (Table 2) revealed that there was a significant interaction effect of *age* x *group* ($F_{1, 55} = 8.13$, $p = 0.01$), showing that the older TKR group had a significantly ($p < 0.01$) slower gait speed compared to the two younger groups, however, the younger participants and the older healthy participants did not differ significantly for gait speed. There was also a main effect of *age* ($F_{1, 55} = 6.50$, $p = 0.02$), showing that younger participants walked at a gait speed that was 19.8% faster than the older participants. Step length analysis (Table 3) revealed that there was a significant interaction effect of *age* x *group* ($F_{1, 55} = 7.09$, $p = 0.01$), showing that the older TKR group had a significantly ($p < 0.01$) shorter step compared to the younger control, younger patient and older control groups, but the younger participants and older healthy participants did not differ significantly for step length. There was a main effect of *age* ($F_{1, 55} = 21.26$, $p < 0.001$) showing that younger participants' step length was 8.9% longer compared with the older participants. There was also a main effect of *group* ($F_{1, 55} = 18.01$, $p < 0.001$), as the healthy participants had an 8.2% longer step than the TKR patients. Step width analysis (Table 4) revealed that there was a main effect of *age* ($F_{1, 55} = 6.99$, $p = 0.01$) showing that the younger participants had a 7.6% smaller step width compared to the older participants. Single support (Table 5) and double support (Table 6) time analysis revealed that there was a main effect of *age* ($F_{1, 55} = 5.25$, $p = 0.03$; $F_{1, 55} = 6.12$, $p = 0.02$, respectively) showing the younger participants spent 9.0% longer period of time in single support and 9.2% less time in double support time compared to the older participants.

### 3.1.2 Knee kinematic measures

The mean and standard deviation for the knee kinematic measures for the four groups are shown in Table 7. Peak flexion angle analysis revealed there to be no significant interactions or main effects (Table 8). Peak extension angle analysis (Table 9) revealed that there was a significant interaction effect of *age* x *group* ($F_{1, 55} = 8.21$, $p = 0.007$) showing that the older TKR group had a significantly ($p < 0.02$) larger peak extension angle (less extended knee) compared to the younger control, younger patient and older control groups, but the younger control, younger patients and older healthy participants did not differ significantly for peak extension angle. There was a main effect of *age* ($F_{1, 55} = 5.55$, $p = 0.03$) showing that the younger participants had a 36.2% smaller peak extension angle than the older participants. There was also a main effect of *group* ($F_{1, 55} = 5.67$, $p = 0.02$) showing that the healthy participants had a 37.9% smaller peak extension angle than the TKR patients. Peak adduction angle analysis (Table 10) revealed that there was a main effect of *age* ($F_{1, 55} = 8.36$, $p = 0.007$) showing that the younger participants had a 24.2% smaller peak adduction angle than the older participants. There was also a main effect of *group* ($F_{1, 55} = 9.03$, $p = 0.005$) showing that the healthy participants had a 28.5% smaller peak adduction angle than the TKR patients. Peak abduction angle analysis revealed that there were no interactions or main effects (Table 11). Peak internal rotation angle analysis revealed that no interactions or main effects were observed (Table 12). Peak external rotation angle analysis (Table 13) revealed that there was a main effect of *age* ($F_{1, 55} = 6.06$, $p = 0.02$)

showing that the younger participants had 10.9% smaller peak external angle than the older participants.

### 3.1.3 Heel strike transient and knee kinetic measures

The mean and standard deviation for the heel strike transient and knee kinetic measures for the four groups are shown in Table 14. Peak flexion moment analysis (Table 15) revealed that there was a main effect of *age* ($F_{1,\,55}$ = 7.12, p = 0.01) showing that the younger participants had a 21.2% larger peak flexion moment than the older participants. Peak extension moment revealed (Table 16) that there was a significant interaction effect of *age* x *group* ($F_{1,\,55}$ = 7.09, p = 0.01) showing that the older TKR group had a significantly ($p < 0.039$) smaller peak extension moment compared to the younger control, younger patient and older control groups, but the younger participants and the older healthy participants did not differ significantly for peak extension moment. There was a main effect of *age* ($F_{1,\,55}$ = 8.36, p = 0.007) showing that the younger participants had a 33.9% larger peak extension moment than the older participants. There was also a main effect of *group* ($F_{1,\,55}$ = 6.56, p = 0.02) showing that the healthy participants had a 15.0% larger peak extension moment than the TKR patients ($F_{1,\,55}$ = 6.56, p = 0.02). A representative % stance phase knee flexion/extension moment data of the surgical and non-surgical limb for an older TKR patient is presented in Figure 1. Peak adduction moments analysis revealed (Table 17) that there was a significant interaction effect of *age* x *group x limb* ($F_{1,\,55}$ = 8.42, p = 0.007) showing that the older TKR group had a significantly (p = 0.01) larger adduction moment for the left limb compared to the right limb; no other group showed this difference between limbs. There was a significant interaction effect of *age* x *group* ($F_{1,\,55}$ = 10.09, p = 0.003) showing that the older TKR group had a significantly ($p < 0.031$) larger peak adduction moment to the three other groups, but the younger participants and the older healthy participants did not differ significantly for peak adduction moment. There was a main effect of *age* ($F_{1, 55}$ = 7.26, p = 0.01) showing that the younger participants had a 17.6% smaller peak adduction moment than the older participants. There was also a main effect of *group* ($F_{1, 55}$ = 8.08, p = 0.008) showing that the healthy participants had a 23.2% smaller peak adduction moment than the TKR patients ($F_{1, 55}$ = 8.08, p = 0.008). A representative % stance phase external knee adduction moment data of the surgical and non-surgical limb for an older TKR patient is presented in Figure 2. Peak abduction moment (Table 18), peak internal rotation moment (Table 19) and peak external rotation moment (Table 20) analysis revealed that there were no interactions or main effects. Heel strike transient analysis revealed (Table 21) that there was a significant interaction effects of *age* x *group x limb* ($F_{1, 55}$ = 7.41, p = 0.01) showing that the older TKR group had a significantly (p = 0.029) larger heel strike transient in the left limb compared to the right limb, but that no other group showed this difference between limbs. The older TKR group also had a significantly smaller heel strike transient in the right limb compared to the right limbs of the other three groups (p < 0.007). A representative vertical ground reaction force of the surgical and non-surgical limb for an older TKR patient, demonstrating the heel strike transient is presented in Figure 3.

## 4. Discussion

Greater than 50% of people with lower limb OA suffer with bilateral degeneration (Dawson et al., 2004; Peat et al., 2006). Gait analysis has shown that, in part, there may be a biomechanical basis to this occurrence. Shakoor et al. (2003) reported that peak external knee adduction moment and peak medial compartment loading were significantly higher in the contralateral knee of hip osteoarthritic patients and that this asymmetry persisted up to 23 months after hip replacement surgery. Gait alterations including gait asymmetry have also been observed in patients following knee replacement surgery (Webster et al., 2003; Mizner & Snyder-Mackler, 2005; McClelland et al., 2007; Stacoff et al., 2007) and the asymmetric gait pattern may play a role in the degenerative changes in the contralateral knee through an increase in joint loading. Asymmetry for the heel strike transient has also been observed in unilateral TKR patients (Levinger et al., 2008) and has been correlated with the aetiology and progression of osteoarthritis (Radin et al., 1975) and has been implicated in early prosthetic damage after TKR (Chu et al., 1986). The use of TKR has increased substantially during the past two decades, particularly among younger patients (Amstutz et al., 1984; Bellamy et al., 1988; Bozic et al., 2013). Currently there is very little known about the post-TKR function of this younger population. Therefore, this study investigated and compared the heel strike transient and the knee kinematics and joint moments during level walking in both the surgical and non-surgical limb for a group of younger and older TKR patients six months following unilateral knee replacement, and their healthy age-matched controls. The current findings indicate that the observed asymmetry in vertical impact force at heel strike and knee joint moments of the typical, older patient is not adopted in the younger TKR patient, which may have clinical importance to the initiation and progression of OA in the contralateral limb.

In this study participants walked at self-selected speed, which, for the patients groups, may have been influenced by functional limitations and perhaps pain. Gait speed was not controlled in this study as we wished to examine each participants typical gait pattern, which is more representative of real life than asking them to comply with a set speed. A reduction in walking speed is one part of the gait pathology associated with chronic osteoarthritis and which persist after joint replacement. TKR patients have been reported to demonstrate a self-selected gait speed of between 0.8–1.1 m/s (see review: McClelland et al., 2007), which is very similar to pre-surgical values reported (see review: Stubbs et al., 2014). It was observed that the older TKR group walked at a significantly slower speed compared to the younger participants. Interestingly, the younger TKR group did not differ significantly from either of the healthy control groups for gait speed. Also, the older TKR group had a significantly shorter step length than the three other groups. These observations in spatiotemporal measures for gait are similar to that reported for TKR patients when compared to their respective control groups (Fuchs et al., 2003; Saari et al., 2005). Age-related differences were also observed in single and double support time, but no effect of group or limb was observed. The aggregate of these observations – shorter step, slower walking speed, increased double limb support time – suggests that the older TKR group used a more cautious gait strategy compared to the younger TKR group. The more cautious gait pattern may have served to decrease joint contact forces and pain, but also possibly over a concern to prevent perturbations caused by internal or external sources when walking (Marigold & Patla, 2002; Pijnappels et al., 2005).

There is epidemiological evidence from Shakoor et al. (2002) of a predictable progression of osteoarthritis in the contralateral knee after joint replacement surgery. In a recent analysis of a 12-year cohort study, 24 of the 30 (80%) patients with unilateral OA at baseline developed bilateral OA (Metcalfe et al., 2012). Cross-sectional motion analysis has demonstrated differences between the surgical and non-surgical limbs after TKR (Jevsevar et al., 1993; Su et al., 1998; Mizner & Snyder-Mackler, 2005). Specifically, it has been reported that the non-surgical knee was shown to bear a larger load, demonstrating higher extensor moments and ground reaction forces when walking (Jevsevar et al., 1993; Mizner & Snyder-Mackler, 2005) and when rising from a chair (Su et al., 1998). This could be an adopted compensation pattern in an effort to avoid pain in the surgical limb, but this strategy produces altered loading patterns that place additional stresses on the non-surgical limb (Mizner & Snyder-Mackler, 2005). This compensation pattern seems to be a possible cause for the asymmetrical loading which was observed in the older TKR group. Importantly, these altered gait patterns may have long-term consequences of advancing OA in the contralateral limb (Ritter et al., 1994; Shakoor et al., 2002).

The peak knee joint angles did not differ between limbs, although, the older TKR group did not achieve the same peak extension angles as the other groups. There is some evidence that hamstrings activity during stance is prolonged in TKR patients, which may prevent full knee extension from being achieved. Additionally, impaired quadriceps or gluteal function may limit the amount of knee and hip extension achieved under resistance from bodyweight (McClelland et al., 2011). There was no difference in the peak angles in the transverse plane observed between groups or limbs; these findings support the work of Saari et al. (2005), who also reported no differences between TKR patients and controls in the peak knee angles during walking at a self-selected speed.

Increased loading at the knee joint has been suggested to play a role in degenerative changes in joint cartilage and the aetiology and progression of OA (Radin et al., 1978; Collins & Whittle, 1989). It has also been reported that the ability to attenuate these forces is reduced in the osteoarthritic knee (Voloshin & Woak, 1982) and in patient’s post-TKR (Chu et al., 1986). After TKR patients may be shifting their body weight over to the non-surgical limb in order to reduce the ground impact force and thus pain in the surgical limb at heel strike. Since altered gait, developed over the course of the degenerative process of OA, has been shown to persist in patients after undergoing knee replacement, asymmetric knee loading may be employed at heel strike to attenuate pain in the surgical limb. The older TKR group showed heel strike transient values that were asymmetrical between limbs (higher in the non-surgical limb), which were not observed in any of the other groups. However, the magnitude of the heel strike transient of the surgical limb for older TKR patient was within the reported range of asymptomatic individuals (Levinger & Gilleard, 2005; Levinger et al., 2008). The asymmetric heel strike transient between the limbs may be a compensation strategy to reduce the loading in the surgical limb by shifting the body weight over to the non-surgical limb. The older TKR group may not fully trust their surgical limb, or may have altered their habitual gait pattern as a function of years of pain and dysfunction associated with moderate to severe osteoarthritis, and as a consequence may walk more cautiously when loading the surgical limb. The younger TKR group does not adopt this same loading pattern at heel strike and therefore may be at a reduced risk of developing OA in the contralateral limb.

Analysis of the joint moments revealed significant differences in peak knee moments between groups and limbs. The older participants employed smaller peak flexion and extension moments compared to the younger participants. Also, the older TKR group had a significantly smaller peak extension moment compared to the other three groups. Different external flexion-extension joint moment patterns have been described previously in TKR patients (Dorr et al., 1988; Andriacchi, 1993). The asymmetrical characteristics of flexion-extension moments found during gait were thought to be associated to abnormal phasing of the quadriceps and hamstrings (Andriacchi, 1993). Dorr et al. (1988) found that TKR patients adopted a ‘‘stiff knee’’ during stance that was associated with sagittal plane moments.  This gait pattern may have been utilized as a strategy to avoid shear forces at the knee (and pain) or a functional adaptation in response to factors such as instability or reduced muscle strength associated with the knee (Hurwitz et al., 1999). Many previous studies have found increased peak adduction moment in knees with medial OA (Weidenhielm et al., 1994; Baliunas et al., 2002; Miyazaki et al., 2002). The adduction moment during stance phase relates to the medial offset of the body's center of mass with the resultant ground reaction force passing medial to the center of the knee (Johnson et al., 1980). This tends to cause greater compressive loads on the medial compartment of the knee (Schipplein & Andriacchi, 1991; Andriacchi, 1994). Consequently, as much as 60% to 80% of the total load across the knee passes through the medial compartment (Andriacchi, 1994). Higher loads in the medial compartment may explain a rate of degeneration in the medial compartment. The older TKR group had a significantly larger peak adduction moment compared to the control groups, but also that the increased adduction moment was restricted to the non-surgical limb, which was 19.2% greater compared to the surgical limb. No other group demonstrated this asymmetric adduction moment. Similar asymmetry between limbs in knee adduction kinetics has been reported previously (Milner & O'Bryan, 2008; Metcalfe et al., 2013). Importantly, greater knee adduction moments have been linked to OA progression (Astephen & Deluzio, 2005; Mündermann et al., 2005; Hunt et al., 2006). This asymmetry in knee adduction moments observed in the older TKR patient suggests that their non-surgical knee is at higher risk for the development and progression of OA than the younger TKR patient, particularly in the medial compartment.

The asymmetrical gait pattern observed post-TKR is often present before surgery and the pain and dysfunction associated with end-stage knee OA is thought to be at the root of these gait changes. There is increasing evidence that supports the concept that chronic pain could create peripheral and central neuronal reorganization (Woolf & Salter, 2000; May, 2008, 2009; Apkarian et al., 2009). Rodriguez-Raecke et al. (2013) monitored structural changes in the brain for 20 patients with chronic pain due to unilateral hip OA, before hip joint replacement surgery and up to 1-year after surgery and compared them to 20 healthy controls that were matched for sex and age. The hip OA patients had significantly less gray matter in the premotor cortex and the supplementary motor areas in the brain compared to controls. The authors concluded that abnormalities in gray matter were secondary to the degeneration of the joint and are at least in part due to changes in motor function and bodily integration. Recently, Shanahan et al. (2014) reported functional magnetic resonance imaging data on a small group of knee OA patients during functional tasks at the knee, hand and ankle. It was reported that during the knee task (but not for the hand or ankle tasks), knee OA patients showed reduced activation in the basal ganglia, cerebellum and premotor cortex when compared to healthy controls. The authors suggested that these results provide evidence of reorganization of sensorimotor processing in the brain for patients with knee OA that specifically affected motor tasks that involved the knee. The very progressive nature of OA could then create changes and reorganization in the brain and could explain, in part, why abnormal gait patterns persist for knee OA patients even after TKR has improved pain and function. The younger TKR patient does not demonstrate asymmetry between limbs, the reason for this is unknown, but this may be partly explained by a more acute progression of OA degeneration for the younger TKR patient and thereby the time required to enact these changes in the brain might not have existed. Rodriguez-Raecke et al. (2013) found that when the patients were pain free after recovery from hip replacement there was an increase in observed gray matter in the same areas that were diminished before surgery. Therefore, another possible reason the younger patients did not display the asymmetrical gait pattern at six month post-TKR is that the beneficial effects of surgery (reduced pain and improved function) created similarly beneficial changes in the brain that occurred sooner in the younger patient compared to the that of the older patient. There is evidence to show that there are observed age-related plasticity deficits (Burke & Barnes, 2006), but whether this had an effect here is only speculative. Much more research is needed to elucidate if in fact TKR patients show persistent changes in the brain, in which areas, if these changes are associated with functional impairment and if these changes were also present before surgery.

The current findings indicate that asymmetrical vertical impact force at heel strike and peak knee moments observed for the older TKR group may place higher forces on their contralateral limb. These patterns were not observed for younger TKR patients and therefore may have clinical importance for younger patients undergoing unilateral knee replacement. It is important to note, however, that the present study was a cross-sectional investigation, and hence a causal relationship between the development of OA and the observed higher loading and moments for the non-surgical limb cannot be determined.  There is evidence that gait adaptation and gait asymmetry, which occurs in response to knee pain and functional impairment, before surgery persists postoperatively. It is unknown if the asymmetric loading is a modification to avoid pain in the surgical limb or an inherent causative factor (Radin et al., 1991). These unknowns could potentially be addressed in a longitudinal study.

## 5. Conclusion

The older TKR group demonstrated an asymmetrical heel strike transient and peak knee adduction moment magnitude between the surgical and non-surgical limbs, and no other group, including the younger TKR patients, showed this same pattern. The observed asymmetrical loading across the surgical and non-surgical limbs could contribute to the initiation or further progression of osteoarthritic degeneration in the non-surgical limb. These changes may be due to a learned gait pattern and alteration in brain activation which does not resolve despite treatment of the affected joint. The current findings may be clinically relevant in patients undergoing unilateral knee replacement and further rehabilitation may be required if patients are to learn to protect the other joints appropriately following an otherwise successful TKR surgery. The results also seem to argue that undergoing TKR earlier in OA progression (when indicated) might result in less chance of OA progression and eventual knee replacement in the contralateral knee.

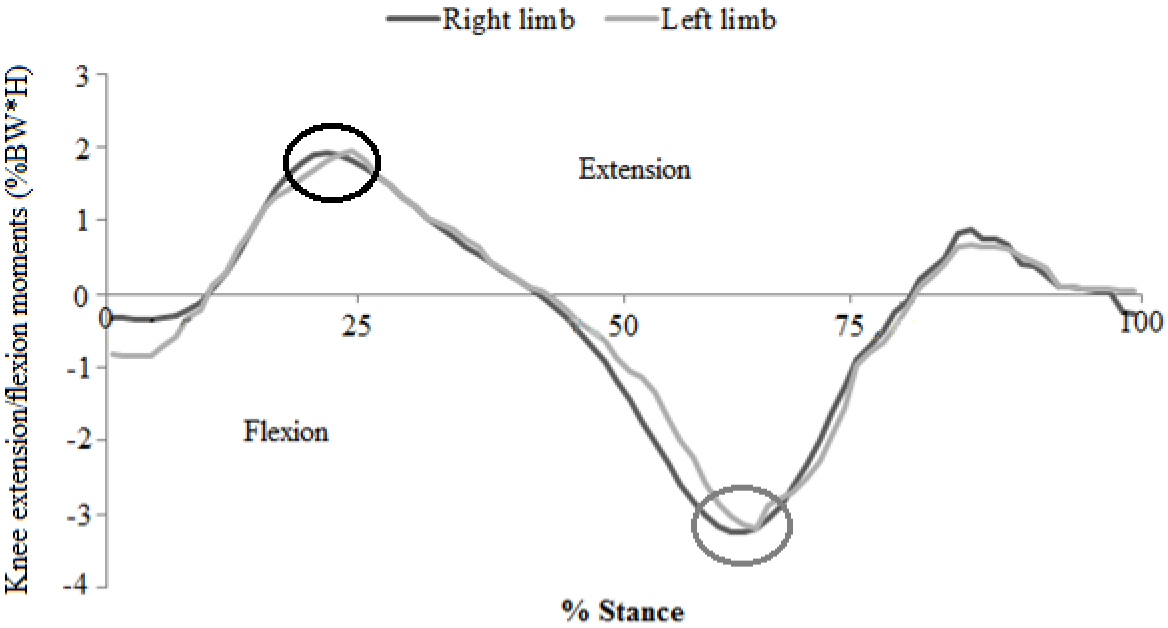

**Figure 1.** Representative knee extension moment data for the right (surgical) and left (non-surgical) limbs of an older TKR patient normalized to % stance. Before data was normalized to % stance the peak value was identified and confirmed graphically before analysis. Black circle indicates where the peak extension moment was calculated from. Grey circle indicates where the peak flexion moment was calculated from.

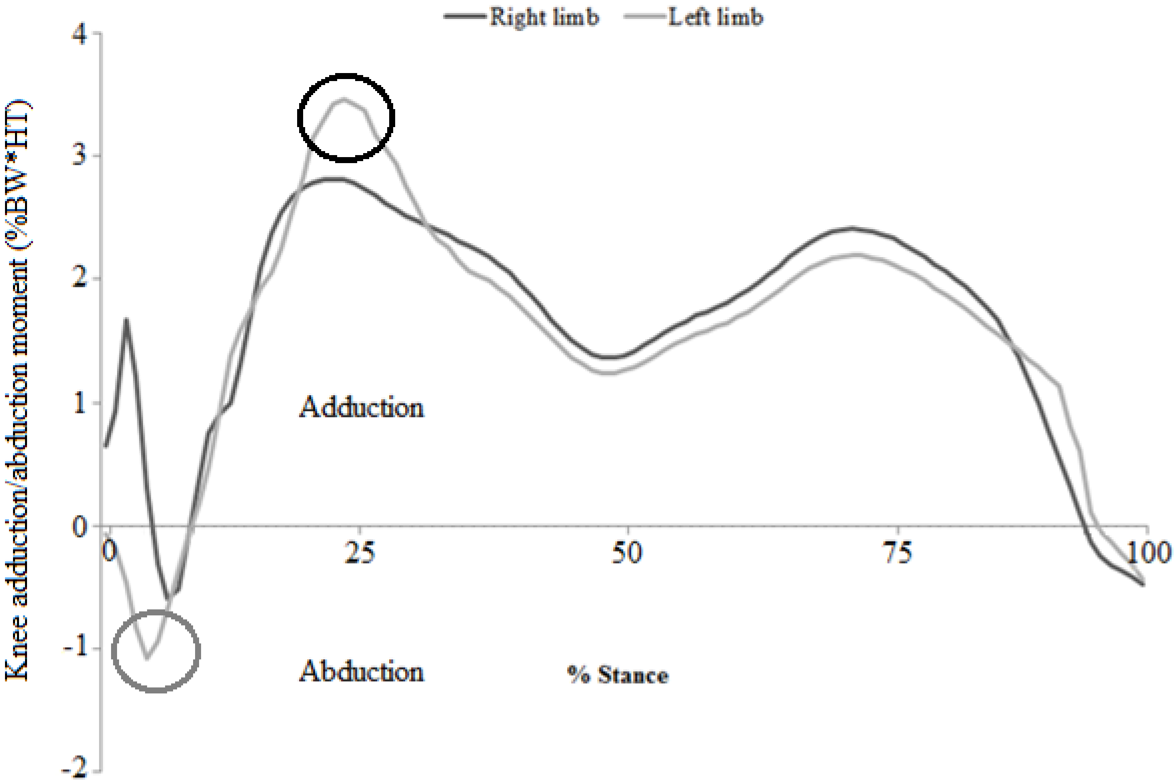

**Figure 2.** Representative external knee adduction moment data for the right (surgical) and left (non-surgical) limbs of an older TKR patient normalized to % stance. Before data was normalized to % stance the peak value was identified and confirmed graphically before analysis. Black circle indicates where the peak adduction moment was calculated from, this peak usually occurs soon after heel contact (Hunt et al., 2006; Street et al., 2013). Grey circle indicates where the peak abduction moment was calculated from.

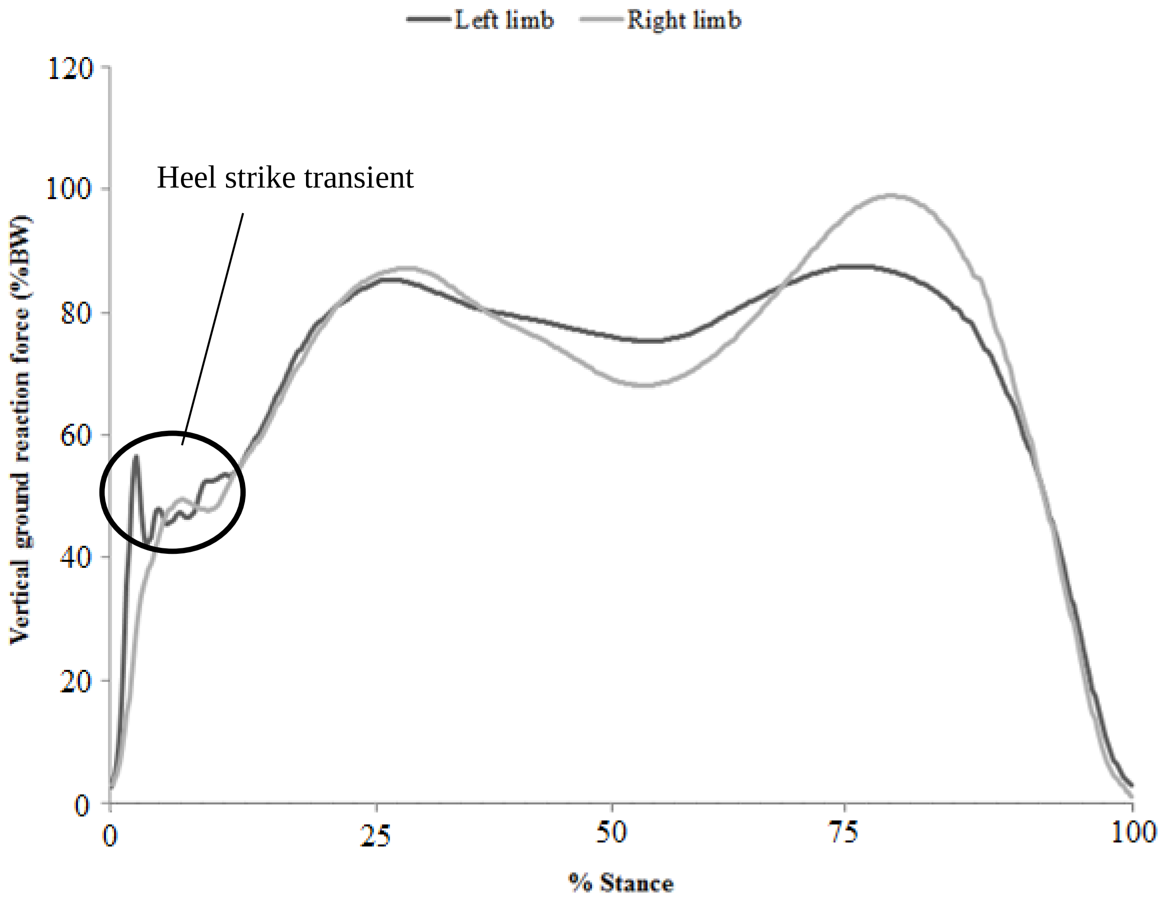

**Figure 3.** Representative vertical ground reaction force for the right (surgical) and left (non-surgical) limbs of an older TKR patient normalized to % stance. The heel strike transient is found early (<10% stance phase) in the stance phase at heel contact.

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**Table 1.** Spatiotemporal gait measures of the right and left limbs for the four groups. Mean (SD). YP = Younger patient, YC = Younger control, OP = Older patient, OC = Older control.

* Represents a significantly different value compared to the old TKR patient group ($p < 0.01$). When bold, a significant main effect of age was observed between the younger and older participants. ‡ Represents a significant main effect of group was observed between healthy controls and TKR patients for that measure.

| **Variable** | **Group** | | | |
|---|---|---|---|---|
| | **YC** | **YP** | **OC** | **OP** |
| **Gait speed, m/s** | **1.25(0.17)*** | **1.13(0.13)*** | 0.99(0.15) | 0.93(0.11) |
| **Step length‡, m** | | | | |
| Right limb | **0.68(0.1)*** | **0.67(0.1)*** | 0.65(0.1)* | 0.56(0.2) |
| Left limb | **0.68(0.2)*** | **0.66(0.1)*** | 0.66(0.2)* | 0.57(0.1) |
| **Step width, m** | | | | |
| Right limb | **0.12(0.02)** | **0.12(0.02)** | 0.13(0.02) | 0.14(0.03) |
| Left limb | **0.12(0.02)** | **0.13(0.01)** | 0.13(0.02) | 0.13(0.02) |
| **Single support time, s** | | | | |
| Right limb | **0.39(0.04)** | **0.39(0.07)** | 0.34(0.08) | 0.35(0.11) |
| Left limb | **0.39(0.05)** | **0.38(0.06)** | 0.36(0.07) | 0.36(0.09) |
| **Double support time, s** | | | | |
| Right limb | **0.24(0.05)** | **0.25(0.05)** | 0.27(0.07) | 0.29(0.11) |
| Left limb | **0.25(0.06)** | **0.26(0.06)** | 0.26(0.07) | 0.28(0.08) |

**Table 2**. Summary of 2x2x2 ANOVA (outcome variable: gait speed). When bold, ANOVA results indicated a significant interaction or main effect.

| Factor | ANOVA Result |
|---|---|
| **Age** | **$F_{1,\,55}$ = 6.50, p = 0.02** |
| Group | $F_{1,\,55}$ = 0.51, p = 0.478 |
| **Age*Group** | **$F_{1,\,55}$ = 8.13, p = 0.01** |
| Limb | $F_{1,\,55}$ = 0.22, p = 0.658 |
| Age*Limb | $F_{1,\,55}$ = 0.57, p = 0.468 |
| Group*Limb | $F_{1,\,55}$ = 0.44, p = 0.490 |
| Age*Group*Limb | $F_{1,\,55}$ = 0.18, p = 0.709 |

**Table 3**. Summary of 2x2x2 ANOVA (outcome variable: step length). When bold, ANOVA results indicated a significant interaction or main effect.

| Factor | ANOVA Result |
|---|---|
| **Age** | **$F_{1, 55} = 21.26, p < 0.001$** |
| **Group** | **$F_{1, 55} = 18.01, p < 0.001$** |
| **Age*Group** | **$F_{1, 55} = 7.09, p = 0.01$** |
| Limb | $F_{1, 55} = 0.14, p = 0.713$ |
| Age*Limb | $F_{1, 55} = 3.50, p = 0.067$ |
| Group*Limb | $F_{1, 55} = 1.22, p = 0.312$ |
| Age*Group*Limb | $F_{1, 55} = 0.10, p = 0.750$ |

**Table 4**. Summary of 2x2x2 ANOVA (outcome variable: step width). When bold, ANOVA results indicated a significant interaction or main effect.

| Factor | ANOVA Result |
|---|---|
| **Age** | **$F_{1, 55} = 6.99, p = 0.01$** |
| Group | $F_{1, 55} = 1.14, p = 0.339$ |
| Age*Group | $F_{1, 55} = 1.07, p = 0.342$ |
| Limb | $F_{1, 55} = 0.33, p = 0.512$ |
| Age*Limb | $F_{1, 55} = 2.59, p = 0.088$ |
| Group*Limb | $F_{1, 55} = 1.21, p = 0.313$ |
| Age*Group*Limb | $F_{1, 55} = 0.66, p = 0.448$ |

**Table 5**. Summary of 2x2x2 ANOVA (outcome variable: single support time). When bold, ANOVA results indicated a significant interaction or main effect.

| Factor | ANOVA Result |
|---|---|
| **Age** | **$F_{1, 55} = 5.25, p = 0.03$** |
| Group | $F_{1, 55} = 1.33, p = 0.293$ |
| Age*Group | $F_{1, 55} = 0.11, p = 0.745$ |
| Limb | $F_{1, 55} = 0.18, p = 0.709$ |
| Age*Limb | $F_{1, 55} = 1.52, p = 0.276$ |
| Group*Limb | $F_{1, 55} = 0.88, p = 0.437$ |
| Age*Group*Limb | $F_{1, 55} = 0.42, p = 0.495$ |

**Table 6**. Summary of 2x2x2 ANOVA (outcome variable: double support time). When bold, ANOVA results indicated a significant interaction or main effect.

| **Factor** | **ANOVA Result** |
|---|---|
| **Age** | **$F_{1,55} = 6.12$, $p = 0.02$** |
| Group | $F_{1,55} = 1.08$, $p = 0.341$ |
| Age*Group | $F_{1,55} = 0.26$, $p = 0.702$ |
| Limb | $F_{1,55} = 1.22$, $p = 0.312$ |
| Age*Limb | $F_{1,55} = 1.26$, $p = 0.305$ |
| Group*Limb | $F_{1,55} = 1.41$, $p = 0.288$ |
| Age*Group*Limb | $F_{1,55} = 1.24$, $p = 0.308$ |

**Table 7.** Kinematic measures for the right and left limbs of the four groups. Mean (SD). YP = Younger patient, YC = Younger control, OP = Older patient, OC = Older control.

* Represents a significantly different value compared to the old TKR patient group ($p < 0.02$). When bold, a significant main effect of age was observed between the younger and older participants. ‡ Represents a significant main effect of group was observed between healthy controls and TKR patients for that measure.

| **Knee Variable** | **Group** | | | |
|---|---|---|---|---|
| | **YC** | **YP** | **OC** | **OP** |
| **Peak angle ($^0$)** | | | | |
| **Flexion** | | | | |
| Right limb | 61.4(7.1) | 59.5(7.7) | 58.4(8.3) | 57.2(8.8) |
| Left limb | 60.6(6.3) | 58.6(7.6) | 59.2(7.5) | 57.6(7.3) |
| **Extension‡** | | | | |
| Right limb | **2.2(3.3)*** | **4.1(4.1)*** | 3.5(4.3)* | 6.8(5.2) |
| Left limb | **2.6(3.4)*** | **3.6(3.3)*** | 4.0(3.9)* | 5.3(4.1) |
| **Adduction‡** | | | | |
| Right limb | **2.3(4.0)** | **3.6(4.2)** | 3.1(3.7) | 5.2(5.8) |
| Left limb | **3.0(3.1)** | **3.3(3.9)** | 3.4(2.9) | 4.4(3.6) |
| **Abduction** | | | | |
| Right limb | 1.6(2.2) | 1.4(3.1) | 1.8(2.4) | 2.4(3.2) |
| Left limb | 1.3(2.9) | 2.1(3.0) | 1.5(2.9) | 1.8(3.0) |
| **Internal rotation** | | | | |
| Right limb | 3.1(1.9) | 2.1(1.6) | 1.8(1.1) | 2.5(2.9) |
| Left limb | 2.4(2.1) | 1.8(1.2) | 1.6(1.4) | 2.6(2.3) |
| **External rotation** | | | | |
| Right limb | **6.1(4.4)** | **6.1(3.2)** | 6.5(4.1) | 8.2(5.3) |
| Left limb | **7.0(4.2)** | **5.5(3.9)** | 6.3(4.3) | 6.6(4.9) |

**Table 8**. Summary of 2x2x2 ANOVA (outcome variable: peak knee flexion angle). When bold, ANOVA results indicated a significant interaction or main effect.

| **Factor** | **ANOVA Result** |
|---|---|
| Age | $F_{1, 55} = 0.44$, $p = 0.490$ |
| Group | $F_{1, 55} = 0.48$, $p = 0.481$ |
| Age*Group | $F_{1, 55} = 1.09$, $p = 0.340$ |
| Limb | $F_{1, 55} = 0.58$, $p = 0.466$ |
| Age*Limb | $F_{1, 55} = 0.50$, $p = 0.490$ |
| Group*Limb | $F_{1, 55} = 1.01$, $p = 0.337$ |
| Age*Group*Limb | $F_{1, 55} = 0.13$, $p = 0.712$ |

**Table 9**. Summary of 2x2x2 ANOVA (outcome variable: peak knee extension angle). When bold, ANOVA results indicated a significant interaction or main effect.

| Factor | ANOVA Result |
|---|---|
| **Age** | **$F_{1, 55}$ = 5.55, p = 0.03** |
| **Group** | **$F_{1, 55}$ = 5.67, p = 0.02** |
| **Age*Group** | **$F_{1, 55}$ = 8.21, p = 0.007** |
| Limb | $F_{1, 55}$ = 0.14, p = 0.713 |
| Age*Limb | $F_{1, 55}$ = 0.57, p = 0.468 |
| Group*Limb | $F_{1, 55}$ = 0.51, p = 0.478 |
| Age*Group*Limb | $F_{1, 55}$ = 0.73, p = 0.453 |

**Table 10**. Summary of 2x2x2 ANOVA (outcome variable: peak knee adduction angle). When bold, ANOVA results indicated a significant interaction or main effect.

| Factor | ANOVA Result |
|---|---|
| **Age** | **$F_{1, 55}$ = 8.36, p = 0.007** |
| **Group** | **$F_{1, 55}$ = 9.03, p = 0.005** |
| Age*Group | $F_{1, 55}$ = 1.09, p = 0.340 |
| Limb | $F_{1, 55}$ = 0.80, p = 0.443 |
| Age*Limb | $F_{1, 55}$ = 1.03, p = 0.339 |
| Group*Limb | $F_{1, 55}$ = 0.55, p = 0.470 |
| Age*Group*Limb | $F_{1, 55}$ = 1.13, p = 0.337 |

**Table 11**. Summary of 2x2x2 ANOVA (outcome variable: peak knee abduction angle). When bold, ANOVA results indicated a significant interaction or main effect.

| **Factor** | **ANOVA Result** |
|---|---|
| Age | $F_{1, 55} = 0.48$, $p = 0.481$ |
| Group | $F_{1, 55} = 1.52$, $p = 0.276$ |
| Age*Group | $F_{1, 55} = 1.28$, $p = 0.298$ |
| Limb | $F_{1, 55} = 1.14$, $p = 0.338$ |
| Age*Limb | $F_{1, 55} = 1.30$, $p = 0.296$ |
| Group*Limb | $F_{1, 55} = 0.61$, $p = 0.453$ |
| Age*Group*Limb | $F_{1, 55} = 0.12$, $p = 0.742$ |

**Table 12**. Summary of 2x2x2 ANOVA (outcome variable: peak knee internal rotation angle). When bold, ANOVA results indicated a significant interaction or main effect.

| **Factor** | **ANOVA Result** |
|---|---|
| Age | $F_{1, 55}$ = 1.23, p = 0.312 |
| Group | $F_{1, 55}$ = 1.26, p = 0.305 |
| Age*Group | $F_{1, 55}$ = 1.09, p = 0.340 |
| Limb | $F_{1, 55}$ = 1.15, p = 0.337 |
| Age*Limb | $F_{1, 55}$ = 0.61, p = 0.453 |
| Group*Limb | $F_{1, 55}$ = 0.11, p = 0.745 |
| Age*Group*Limb | $F_{1, 55}$ = 0.17, p = 0.688 |

**Table 13**. Summary of 2x2x2 ANOVA (outcome variable: peak knee external rotation angle). When bold, ANOVA results indicated a significant interaction or main effect.

| Factor | ANOVA Result |
|---|---|
| **Age** | **$F_{1, 55} = 6.06$, p = 0.02** |
| Group | $F_{1, 55} = 0.71$, p = 0.499 |
| Age*Group | $F_{1, 55} = 1.11$, p = 0.339 |
| Limb | $F_{1, 55} = 0.34$, p = 0.508 |
| Age*Limb | $F_{1, 55} = 1.01$, p = 0.337 |
| Group*Limb | $F_{1, 55} = 0.22$, p = 0.658 |
| Age*Group*Limb | $F_{1, 55} = 1.21$, p = 0.344 |

**Table 14.** Heel strike transient and kinetic knee measures for the right and left limbs of the four groups. Mean (SD). HST = Heel strike transient. YP = Younger patient, YC = Younger control, OP = Older patient, OC = Older control.
* Represents a significantly different value compared to the older TKR patient group ($p < 0.03$).
† Represents a significantly larger heel strike transient in the non-surgical limb compared to the surgical limb. When bold, a significant main effect of age was observed between the younger and older participants. ‡ Represents a significant main effect of group was observed between healthy controls and TKR patients for that measure.

| **Knee Variable** | **Group** | | | |
|---|---|---|---|---|
| | **YC** | **YP** | **OC** | **OP** |
| **Peak moment (%BW*H)** | | | | |
| **Flexion** | | | | |
| Right limb | **-2.32(0.7)** | **-2.30(0.6)** | -2.26(0.4) | -2.20(0.7) |
| Left limb | **-2.25(0.6)** | **-2.31(0.5)** | -2.24(0.4) | -2.23(0.5) |
| **Extension‡** | | | | |
| Right limb | **2.66(0.3)*** | **2.61(0.4)*** | 2.46(0.6)* | 2.34(0.8) |
| Left limb | **2.67(0.4)*** | **2.59(0.3)*** | 2.48(0.5)* | 2.39(0.6) |
| **Adduction‡** | | | | |
| Right limb | **2.29(0.1)** | **2.36(0.2)** | 2.33(0.2) | 2.32(0.2) |
| Left limb | **2.32(0.2)*** | **2.34(0.2)*** | 2.32(0.2)* | 2.92(0.2)† |
| **Abduction** | | | | |
| Right limb | -0.80(0.2) | -0.88(0.2) | -0.81(0.3) | -0.86(0.3) |
| Left limb | -0.81(0.2) | -0.84(0.3) | -0.82(0.3) | -0.83(0.3) |
| **Internal rotation** | | | | |
| Right limb | 0.93(0.2) | 0.91(0.1) | 0.91(0.2) | 0.94(0.3) |
| Left limb | 0.91(0.1) | 0.92(0.1) | 0.90(0.2) | 0.92(0.3) |
| **External rotation** | | | | |
| Right limb | -0.09(0.2) | -0.11(0.1) | -0.13(0.2) | -0.12(0.1) |
| Left limb | -0.11(0.2) | -0.13(0.1) | -0.12(0.2) | -0.11(0.2) |
| **HST (%BW)** | | | | |
| Right limb | 0.55(0.06)* | 0.52(0.08)* | 0.55(0.07)* | 0.49(0.11) |
| Left limb | 0.56(0.05) | 0.56(0.11) | 0.53(0.08) | 0.66(0.08)† |

**Table 15**. Summary of 2x2x2 ANOVA (outcome variable: peak knee flexion moment). When bold, ANOVA results indicated a significant interaction or main effect.

| Factor | ANOVA Result |
|---|---|
| **Age** | **$F_{1, 55} = 7.12$, $p = 0.01$** |
| Group | $F_{1, 55} = 0.52$, $p = 0.477$ |
| Age*Group | $F_{1, 55} = 1.28$, $p = 0.298$ |
| Limb | $F_{1, 55} = 0.18$, $p = 0.709$ |
| Age*Limb | $F_{1, 55} = 1.14$, $p = 0.339$ |
| Group*Limb | $F_{1, 55} = 0.17$, $p = 0.688$ |
| Age*Group*Limb | $F_{1, 55} = 1.21$, $p = 0.313$ |

**Table 16**. Summary of 2x2x2 ANOVA (outcome variable: peak knee extension moment). When bold, ANOVA results indicated a significant interaction or main effect.

| **Factor** | **ANOVA Result** |
|---|---|
| **Age** | **$F_{1, 55} = 8.36$, $p = 0.007$** |
| **Group** | **$F_{1, 55} = 6.56$, $p = 0.02$** |
| **Age*Group** | **$F_{1, 55} = 7.09$, $p = 0.010$** |
| Limb | $F_{1, 55} = 0.61$, $p = 0.453$ |
| Age*Limb | $F_{1, 55} = 1.02$, $p = 0.337$ |
| Group*Limb | $F_{1, 55} = 1.32$, $p = 0.291$ |
| Age*Group*Limb | $F_{1, 55} = 0.22$, $p = 0.658$ |

**Table 17**. Summary of 2x2x2 ANOVA (outcome variable: peak knee adduction moment). When bold, ANOVA results indicated a significant interaction or main effect.

| Factor | ANOVA Result |
|---|---|
| **Age** | **$F_{1, 55}$ = 7.26, p = 0.01** |
| **Group** | **$F_{1, 55}$ = 8.08, p = 0.008** |
| **Age*Group** | **$F_{1, 55}$ = 10.09, p = 0.003** |
| Limb | $F_{1, 55}$ = 1.07, p = 0.342 |
| Age*Limb | $F_{1, 55}$ = 0.44, p = 0.490 |
| Group*Limb | $F_{1, 55}$ = 1.30, p = 0.296 |
| **Age*Group*Limb** | **$F_{1, 55}$ = 8.42, p = 0.007** |

**Table 18**. Summary of 2x2x2 ANOVA (outcome variable: peak knee abduction moment). When bold, ANOVA results indicated a significant interaction or main effect.

| **Factor** | **ANOVA Result** |
|---|---|
| Age | $F_{1, 55} = 0.57$, $p = 0.468$ |
| Group | $F_{1, 55} = 1.52$, $p = 0.276$ |
| Age*Group | $F_{1, 55} = 0.42$, $p = 0.495$ |
| Limb | $F_{1, 55} = 1.21$, $p = 0.313$ |
| Age*Limb | $F_{1, 55} = 1.07$, $p = 0.342$ |
| Group*Limb | $F_{1, 55} = 0.61$, $p = 0.453$ |
| Age*Group*Limb | $F_{1, 55} = 0.22$, $p = 0.658$ |

**Table 19**. Summary of 2x2x2 ANOVA (outcome variable: peak knee internal rotation moment). When bold, ANOVA results indicated a significant interaction or main effect.

| **Factor** | **ANOVA Result** |
|---|---|
| Age | $F_{1, 55} = 0.86$, $p = 0.440$ |
| Group | $F_{1, 55} = 1.01$, $p = 0.337$ |
| Age*Group | $F_{1, 55} = 1.33$, $p = 0.290$ |
| Limb | $F_{1, 55} = 0.27$, $p = 0.502$ |
| Age*Limb | $F_{1, 55} = 1.12$, $p = 0.338$ |
| Group*Limb | $F_{1, 55} = 1.07$, $p = 0.342$ |
| Age*Group*Limb | $F_{1, 55} = 0.14$, $p = 0.713$ |

**Table 20**. Summary of 2x2x2 ANOVA (outcome variable: peak knee external rotation moment). When bold, ANOVA results indicated a significant interaction or main effect.

| **Factor** | **ANOVA Result** |
|---|---|
| Age | $F_{1, 55} = 1.23$, $p = 0.301$ |
| Group | $F_{1, 55} = 1.01$, $p = 0.401$ |
| Age*Group | $F_{1, 55} = 1.43$, $p = 0.286$ |
| Limb | $F_{1, 55} = 0.82$, $p = 0.442$ |
| Age*Limb | $F_{1, 55} = 0.65$, $p = 0.498$ |
| Group*Limb | $F_{1, 55} = 1.26$, $p = 0.305$ |
| Age*Group*Limb | $F_{1, 55} = 0.14$, $p = 0.713$ |

**Table 21**. Summary of 2x2x2 ANOVA (outcome variable: heel strike transient). When bold, ANOVA results indicated a significant interaction or main effect.

| **Factor** | **ANOVA Result** |
|---|---|
| Age | $F_{1, 55} = 1.03$, p = 0.339 |
| Group | $F_{1, 55} = 0.88$, p = 0.437 |
| Age*Group | $F_{1, 55} = 1.23$, p = 0.312 |
| Limb | $F_{1, 55} = 1.52$, p = 0.276 |
| Age*Limb | $F_{1, 55} = 0.86$, p = 0.440 |
| Group*Limb | $F_{1, 55} = 1.25$, p = 0.305 |
| **Age*Group*Limb** | **$F_{1, 55} = 7.41$, p = 0.01** |

# CHAPTER FIVE

# CONCLUSIONS, LIMITATIONS AND FUTURE WORK

## Conclusions

The purpose of this thesis was to investigate the rapidly growing younger TKR patient and compare their observations with that observed for the typical, older TKR patient and healthy age-matched controls. This main purpose was first investigated by examining how the TKR patient's age affected measures of balance confidence, functional mobility and movement reinvestment. Secondly, the stepping characteristics and centre of mass control after a forward fall was investigated to elucidate if different balance recovery strategies were adopted when falling forward between the younger and older TKR patients. Lastly, a comparison between the surgical and non-surgical limbs for the heel strike transient, kinematics and joint moments of the knee during level walking was conducted to identify if differences between the younger and older TKR patients existed.

Balance confidence and functional mobility have been linked to fall risk, overall well-being and the level of independence when completing tasks of daily living (Hatch et al., 2003; Medley & Thompson, 2014). The results from the first study indicated that the younger TKR patient reported lower levels of pain, joint stiffness, and movement reinvestment, and elevated levels of physical function, functional mobility and balance confidence compared to the typical TKR patient. The balance confidence and functional mobility scores observed for the younger TKR group were much more closely related to their age-matched healthy controls rather than the older TKR patient. Movement reinvestment is a process of shifting what is normally an automatic form of movement control to a conscious form of control (Masters, 1992; Masters et al., 1993). Movement reinvestment tends to occur in situations where: 1) individuals are highly motivated to make successful movements, 2) self-conscious about the method in which they move or 3) have difficulty in moving effectively. For example, stroke patients or those suffering from Parkinson's disease tend to score higher than age-matched controls (Masters et al., 2007; Orrell et al., 2009). However, movement reinvestment is a concept that has not previously been examined for TKR patients or if age could distinguish the degree in which movement reinvestment affected TKR patients. It was found that the younger TKR patients scored significantly lower than the older TKR patients on the MSRS as well as both the movement self-consciousness and the conscious motor processing components subscales. From a multiple regression analysis, pain, function, movement reinvestment and function mobility were significantly correlated with balance confidence scoring. Further, a patient's age was significantly correlated with balance confidence, showing that for every year the patient was older there was a 1.84% decrease in their balance confidence scoring. The summation of the findings from this first study suggest that the younger TKR patient would be at a reduced risk of falling and have less activity restrictions, and thereby ultimately the younger TKR patient may experience a better outcome six months post-surgery than the typical older TKR patient. The young TKR patient may therefore engage in more physical activity, possibly leading to long-term health benefits, but could also help explain the increase in revision rates that have been reported among younger TKR patients compared to the typical TKR patient.

Most falls occur after a loss of stability in a forward direction (Blake et al., 1988), for example, tripping over an obstacle while walking. As such, identifying the mechanisms by which stability deficits occur for TKR patients when falling forward is of importance, as the findings can be used to inform the development of effective rehabilitation exercise interventions for this population to improve fall prevention. In the second study A tether-release paradigm was employed as a surrogate balance recovery task to identify possible performance-related differences between younger and older TKR patients and their corresponding healthy age-matched controls. It was found that the younger TKR group recovered from a forward fall with a significantly smaller COM displacement to that of the older TKR group. It seems as though the stepping characteristics and joint kinematics employed by the younger TKR group were more effective at arresting the forward translation of the COM compared to the older TKR group. The ability of the younger TKR patient to use a longer step and to step more quickly would then create an earlier and greater torque (greater moment arm) to be created to control the forward momentum of the COM. Logistic regression analysis showed that increased age and being a TKR patient were predictors of increased likelihood to require greater than a single step to arrest forward momentum from a forward fall. These findings suggest that the younger TKR patient would be at a reduced risk of falling when recovering from a forward fall compared to the older TKR group. Additionally, these findings may also suggest that younger TKR patients load their prosthetic knee similar to younger healthy individuals, which might expose the knee implant to a greater risk of failure, compared to older patients.

Previous research has shown that there is a predictable pattern of deterioration in other joints of the lower extremities after TKR, such as the contralateral knee. There is evidence that there may be a biomechanical component to this occurrence; as abnormal gait patterns that can create excessive levels of impact forces in the lower extremities may precede the development and affect the progression of joint degeneration. Knee OA patients have been shown to adopt asymmetry between their affected and sound limbs in sagittal and frontal plane kinetics and these gait patterns are often retained after TKR, which may cause greater loading in the contralateral limb. The older TKR group demonstrated an asymmetrical heel strike transient and knee adduction moment magnitude between their surgical and non-surgical limbs, no other group showed this same pattern. These asymmetrical loading and moments across the surgical and non-surgical limbs could create or further progress osteoarthritic degeneration in the non-surgical limb. Many previous studies have found increased peak adduction moment in knees with medial OA compartment (Weidenhielm et al., 1994; Baliunas et al., 2002; Miyazaki et al., 2002). An increase in the knee adduction moment tends to cause greater compressive loads on the medial compartment of the knee (Schipplein & Andriacchi, 1991; Andriacchi, 1994), where as much as 60% to 80% of the total load across the knee passes through the medial compartment (Andriacchi, 1994). It was observed that the older TKR group had a significantly larger (19.2%) knee adduction moment at their non-surgical knee compared to the surgical knee, suggesting that their non-surgical knee is at higher risk for the development and progression of OA, particularly in the medial compartment. It was also observed that the older TKR group showed heel strike transient values that were asymmetrical between limbs (higher in the non-surgical limb), which were not observed in any of the other groups. The asymmetric heel strike transient between the limbs may be a compensation strategy to reduce the loading in the surgical limb by shifting the body weight over to the non-surgical limb. The older TKR group may not fully trust their surgical limb and as a consequence may walk more cautiously when loading the surgical limb. However, this then may create greater loading that can negatively affect osteoarthritic degeneration in the non-surgical limb.

The summation of this thesis demonstrates that the younger TKR patient differs from the typical, older TKR patient in which the majority of the literature is based. These findings provide an initial perspective on how age may affect the outcome after TKR. Younger knee replacement patients clearly demonstrated balance confidence, functional mobility and movement reinvestment values that would suggest a reduced risk of falling compared to the typical TKR patient. The stepping characteristics and superior centre of mass control observed for the younger TKR patient when recovering from a forward fall seems to further support a reduced fall risk. Further, the results lend support to providing TKR as an intervention option to younger patients presenting with severe knee OA who would otherwise be indicated for TKR, as delaying surgery could lead to the adoption of gait patterns that may negatively affect the contralateral limb and lead to greater activity avoidance and sendentarism, potentially leading to further health deterioration.

## Limitations and Future work

A number of limitations regarding the present study need to be acknowledged. The cross-sectional design of this study only provides a snapshot of the participants. Importantly, no cause and effect relationships can be determined. Having data before undergoing TKR, as well as after, would have been important to disseminate how age may have impacted the change from pre- to post-TKR. However, as this study is one of the first to specifically investigate and compare the psychosocial, balance recovery and gait measures observed between younger and older TKR patients, it is important to first identify if in fact any differences exist. Now that we now know there are differences, exploring a longitudinal design to possibly elucidate the influence TKR may have on the younger and older TKR patients is an important next step. For example, Yoshida et al. (2009) investigated and compared TKR patients and healthy age-matched controls for changes in quadriceps strength and function of both their surgical and non-surgical limbs up to 3-years after TKR surgery. The TKR patients demonstrated differences in quadriceps strength between limbs at 3-months and 1-year, but were not different at 3-years after TKR. The authors reported that the symmetry reported 3-years after TKR in quadriceps strength was primarily the result of a progressive weakness in the non-surgical limb. Also, there was significant improvement in self-reported function between 3-months and 1-year, but from 1-year to 3-years post-TKR there was a significant decline in the physical component score of the Medical Outcomes Study and in the 36-Item Short-Form Health Survey. It would be important to identify if the younger TKR patient also showed a similar decline after the 1-year mark and if the decline continued in the following years.

Another potential limitation of the current study is the lack of a detailed assessment of activity level for both patients and healthy controls. Currently, there are few published reports regarding patients' actual activity levels after TKR. To date, the majority of our understanding around joint replacement patients’ activity levels have been based on questionnaires (Dahm et al., 2008) and pedometer studies (Seedhom & Wallbridge, 1985; Schmalzried et al., 1998), possibly creating bias and erroneous conclusions. Furthermore, the data has demonstrated wide individual variability among similar demographics, thus, current activity assessments or conclusions for TKR patients cannot be based on sex or age. Several previous studies have examined the outcome in younger TKR patients (Ranawat et al., 1989; Diduch et al., 1997; Dahm et al., 2008). Dahm et al. (2008) reported that men and patients younger than 70 years had higher mean UCLA (University of California, Los Angeles) scores (a questionnaire that asked participants to identify the phrase that best describes their current activity level, ranging from “Wholly Inactive, dependent on others, and can not leave residence” to “Regularly participates in impact sports”) and Knee Society function scores, where 71 patients (38%) were engaged in heavy manual labour or high impact sports. Importantly, there is a growing consensus that argues that prosthetic wear is not simply a function of time in situ, but also a function of use

(Schmalzried et al., 1998, 2000) and activity levels have been correlated with wear and potential prosthesis failure (Lavernia et al., 2001; Kuster, 2002). The current therapeutic dilemma (Stulberg, 1995) for surgeons and a more cautious decision making process when contemplating whether to proceed with TKR in the younger patient over concerns of prosthesis wear and possible revision surgeries could be mitigated or confirmed knowing both the amount and intensity of activity the younger patient engages in and how it may affect prosthesis wear and surivorship. Documenting activity levels could be appropriately achieved through the use of triaxial accelerometers over a 5-7 day period.

The majority of the clinical outcome measures commonly used, including the OKS, were originally developed when TKR was performed largely on an older and possibly more sedentary population. Therefore, for the younger and possibly more functionally capable patients the implementation of additional functional assessment tools may be more accurate in discriminating outcome variability after surgery. For many of the outcome measures from this current study there was a ceiling effect for the younger TKR patient and therefore any variability that may have existed may not have been fully identified. Recently, the use of modified outcome measures such as the Knee Injury and Osteoarthritis Outcome Scores (Roos & Toksvig-Larsen, 2003) and the High Activity Arthroplasty Score (Talbot et al., 2010) have been implemented in an effort to overcome the increased function of the younger patient. Future research in which patient outcomes are investigated in the younger TKR patient may create more accurate conclusions using these modified tools. Data should be collected to examine if these tools better characterize the outcome for younger TKR patients.

This thesis has reported that TKR patients demonstrate superior stepping characteristics and COM control compared to the typical, older TKR patient when recovering from a forward fall. The majority of falls for older adults have been reported to occur after a loss of stability in the forward direction (Blake et al., 1988), however, falls in the lateral direction or when crossing an obstacle were not examined. Importantly, TKR patients demonstrate greater balance impairment in the frontal plane in comparison to the sagittal plane (Viton et al., 2002; Gage et al., 2008), and falls directed in this plane are more likely to result in injuries than falls occurring in the sagittal plane (Smeesters et al., 2007). Further, Mauer et al. (2005) found that after TKR there was a reduction in obstacle avoidance success rate, compared to healthy controls, suggesting that after TKR there is an increased propensity to trip on an obstacle and consequentially an elevated risk of falling in this population. Future work should investigate if the results from the current study are also observed when younger and older TKR patients are perturbed in a lateral direction or when crossing an obstacle.

This thesis has also identified altered gait patterns (e.g., asymmetry between the surgical and non-surgical limbs) in the older TKR patient that was not observed in the younger TKR patients The asymmetrical gait pattern observed post-TKR is often present before surgery and pain associated with end-stage knee OA is thought to be at the root of these gait changes. There is a growing amount of evidence demonstrating that chronic pain can create peripheral and central neuronal reorganization (Woolf & Salter, 2000; May, 2008, 2009; Apkarian et al., 2009). Recent reports have also shown that changes in the brain, specifically in the premotor cortex and the supplementary motor area, showing reduced activation in hip OA patients before hip joint replacement surgery and up to 1-year after surgery and when compared to healthy age-matched controls (Rodriguez-Raecke et al., 2013). Further, Shanahan et al. (2014) reported functional magnetic resonance imaging data on a small group of knee OA patients during functional tasks at the knee, hand and ankle. It was reported that during the knee task, but not during the hand or ankle tasks, knee OA patients showed reduced activation in the basal ganglia, cerebellum and premotor cortex when compared to healthy controls. The authors suggested this gave evidence of reorganization of sensorimotor processing in the brain with knee OA specifically affected motor tasks that involved the knee. These changes in the brain that occur with the progressive nature of OA may play a role in the abnormal gait patterns that persist for knee OA patients even after TKR has improved pain. The younger TKR patient did not demonstrate asymmetry between limbs, the reason for this is unknown. Future research should look to see if activation patterns in the brain differ between the younger and older TKR patient and if so, determine in which regions of the brain the differences appear.

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### Chapter One – Introduction and Literature Review

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## Chapter Three - After Total Knee Replacement Younger Patients Demonstrate Superior Balance Control Compared to Older Patients when Recovering from a Forward Fall

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## Chapter Four - Younger Total Knee Replacement Patients do not Demonstrate Asymmetrical Heel Strike Transient and Knee Joint Moments during Level Walking

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## Chapter Five - Conclusions, Limitations and Future Work

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# APPENDICES

## Appendix A: Research study information sheet

## RESEARCH STUDY INFORMATION FORM

**Title of project**:
A Comparison of the Gait, Balance Recovery and Fall Efficacy with Total Knee Replacement: Differences between Younger and Older Patients.

**Principle investigators**:
Brian D. Street, Ph.D(c)., York University
William H. Gage, Ph.D., York University

**Introduction:**
You are invited to take part in a research study. Before you agree to participate, it is important you read the information below regarding the study. It describes the purpose of the study, the risks and benefits to yourself and your right to withdraw at any time. Make sure that all of your questions have been answered before you consent to participate.

**Purpose of study**:
Knee joint replacement is an effective treatment option for individuals suffering from moderate to severe knee osteoarthritis; as substantial improvement in an individual's function and pain has been observed after knee joint replacement. Typical knee joint replacement recipients are in the later 60s or early 70s, as such this age demographic is where the majority of research has been derived from. However, recent reports in Canadian, Swedish and Australian knee joint replacement registries have reported that not only are more knee joint replacement surgeries taken place, but that recipients are getting younger. In the Canadian Joint Replacement Registry for 2009, it was reported that over a ten year period, the 45-54 age group saw a 300% increase over the past decade, whereas, over the same period, there was only a 90% increase in the traditional patient group (65-74 years old). How the younger demographic cohort will be affected with surgery is unknown. What we do know is that an individual's strength and the haste at which one can respond to a loss of balance declines as we get older, both of which are important contributors to an individual's overall quality of life. Therefore, the focus of this research is to investigate if there is a difference in function between younger and older individuals after knee joint replacement, in the way they walk, recover their balance or perceive their confidence not to fall and compare these findings to those of healthy age-matched individuals.

**Procedures involved in this study**:
You will be asked to visit the biomechanics laboratory at York University on one occasion. If you are part of the patient group that has undergone total knee joint replacement, your visit will occur six months post-surgery. If you are part of the healthy control group your visits will occur at your convenience. During your visit, you will be asked to be barefoot and wear your own shorts and tee shirt during data collections. If there are any highly reflective areas on your

clothing, we will temporarily cover these areas with black tape; the equipment we use to record your movements is very sensitive to reflections, which might disrupt the recordings. A total of twenty-seven highly reflective markers will be placed on your body at strategic points, so that our camera system can detect and record your movements. Double-sided adhesive tape will be used to adhere these markers to your clothing and skin. Electrical activity in your muscles will be recorded using small electrodes placed on the skin over four different muscles on your calves and thighs, on each leg. Prior to placing the electrodes on your skin, these areas we will lightly shave the skin to remove hair and dead skin, and then scrub the areas using an alcohol pad to clean the surface. The skin is cleaned in this way to reduce electrical resistance and improve the quality of the recording. This whole process will require approximately 30 minutes.

Once the markers and electrodes have been placed on your skin, you will be fitted with a safety harness that is attached to a rail system in the ceiling that will prevent you from falling, but will not provide any assistance in weight bearing. You will then be asked to perform ten walking trials, where you will walk down a 5-meter pathway at your own pace. During these walking trials we will record your movements with cameras and force plates, the activity of your muscles will also be recorded. Next you will be asked to complete two quiet standing trials (one with eyes open and one with eyes closed) for sixty seconds, where you will stand and maintain a comfortable position. At this stage you will then be asked to complete ten balance recovery trials, where you will be asked to stand comfortably on the force plates, connected to a moveable platform. This platform will move horizontally either from front-to-back or side-to-side, this movement will be no more than ten centimeters. Once the platform is in motion you will be asked to maintain your balance to the best of your ability, your movements will be recorded by the cameras and force plates, muscle activity will also be recorded. Finally, you will be asked to fill out two questionnaires that will be used to assess your confidence not to fall when completing activities encountered in a normal day.

**Time commitment**:
The maximum time commitment for this study is approximately 2 hours; 45 minutes will be devoted to the walking trials and 45 minutes will be devoted to the balance recovery trials. Lastly, 30 minutes will be devoted to the falls confidence questionnaires.

**Personal benefits of participation**:
There are no direct benefits to you as a participant in this research.

**Explanation of procedures and risks**:
The risks associated with your participation in this study include development of skin irritation or a slight rash associated with the use of double-sided tape to adhere the reflective markers and the recording electrodes. If you develop a rash or skin irritation, it will likely last no longer than 24 hours. If skin irritation or a rash persists beyond 24 hours, please consult your family doctor. Because you will be asked to walk during this study, there is a risk of falling. However, any risk of injury from falling will be mitigated by the harness system, which will prevent contact with the floor or any other surface. Also, you will be walking on level, uncluttered surfaces, and therefore your risk of falling is no greater than that throughout the rest of your day.

**Changing your mind about participation/stopping the session**:
Your participation in this research is entirely voluntary. Should you decline to participate or choose to withdraw from participation in this study, your current and future relationships with the researchers and York University, your physician and attending Hospital, or any other group involved in this research will not be jeopardized. You may withdraw from this study at any time without penalty. To do so, indicate this to the researcher or one of the research assistants by saying, "I no longer wish to participate in this study."

**Participant feedback:**
After the study is completed, you will be sent a letter that will describe the results of the study, and how the knowledge gained in the study will be used to continue improving healthcare for people who have experienced osteoarthritis leading to knee joint replacement.

**Confidentiality**:
Confidentiality will be provided to the fullest extent possible by law. To ensure the confidentiality of your data, each participant in this study will be identified by a unique identification code known only to the researchers. All of your information and records, electronic, written, video, or otherwise, will be kept in a secured filing cabinet in a locked room within York University for seven years, at which time the data will be destroyed. All electronic records will be computer password protected and accessible only to the researchers.

**Contact information**:
If you have any questions about the study at any time, please contact Brian D. Street at his office (416) 736-2100 ext. 22042 or via email bds209@yorku.ca. You may also contact Dr. Gage at his office, at (416) 736-2100 ext. 21479 or via email at whgage@yorku.ca.

**Concerns about your participation**:
This study has been reviewed and approved ethical clearance through the Research Ethics Board at York University. The final decision about participation is yours. All of the information supplied from your participation will be held in confidence unless you indicate your consent; your name will not be reported in any report or publication of the research. If you have any questions about the ethics review process, or about your rights as a participant in the study, please contact the Manager, Office of Research Ethics, York University, 309 York Lanes, phone 416-736-5914.

## Appendix B: Informed consent form

### Informed Consent Form

I agree to take part in a research study being conducted by Brian D. Street.

I have made this decision based on the information I have read in the Information Letter. All the procedures, any risks and benefits have been explained to me. I have had the opportunity to ask any questions and to receive any additional details I wanted about the study. I understand that this is a research study, and not a clinical evaluation.

If I have questions later about the study, I can contact Brian D. Street at his office (416) 736-2100 ext. 22042 or via email bds209@yorku.ca. You may also contact Dr. Gage at his office, at (416) 736-2100 ext. 21479 or via email at whgage@yorku.ca.

I understand that I may withdraw from the study at any time, without penalty, by telling the researcher.

This project has been reviewed by, and received ethics clearance through the Research Ethics Board at York University. If I have any comments or concerns resulting from my participation in this study, I may contact the Manager, Office of Research Ethics, York University, 309 York Lanes, phone 416-736-5914.

| | |
|---|---|
| ______________________________ | ______________________________ |
| Printed Name of Participant | Signature of Participant |
| ______________________________ | ______________________________ |
| Dated | Signature of person who obtained consent |

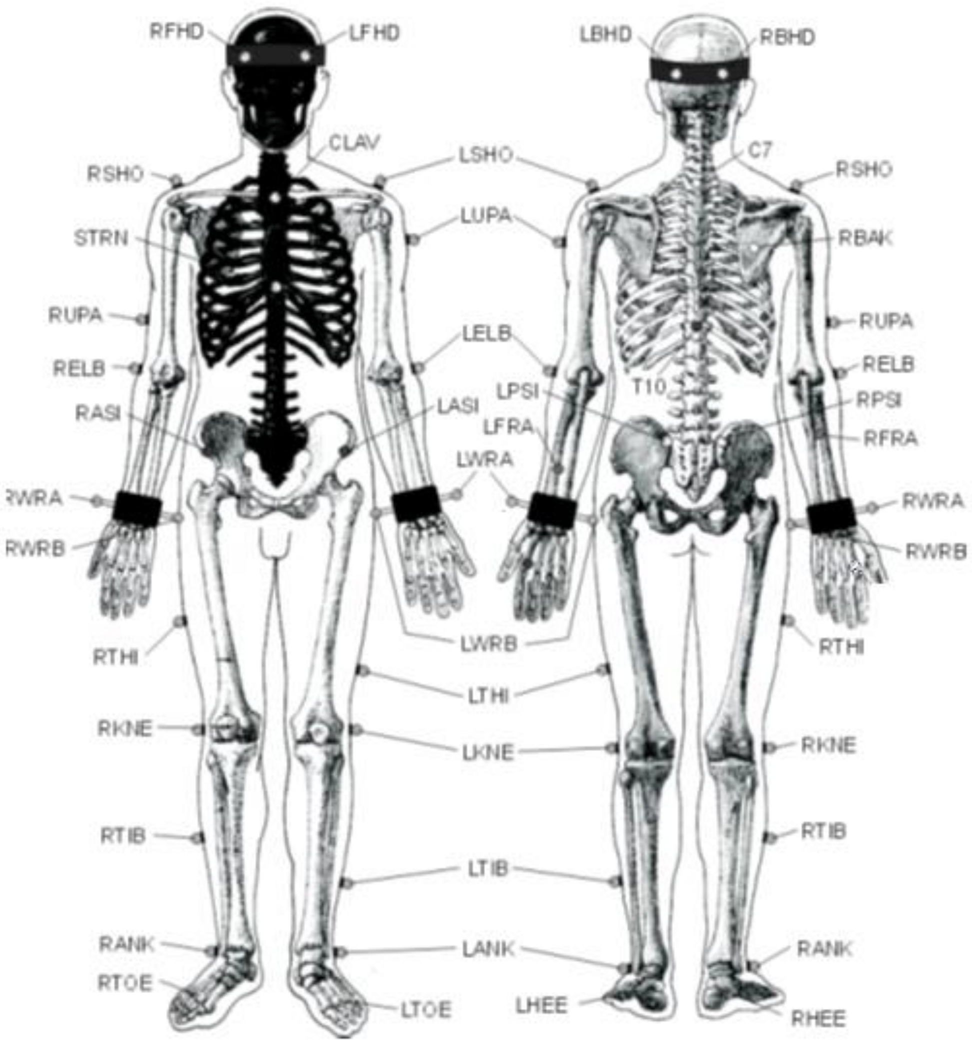
### Videotaping and Photography

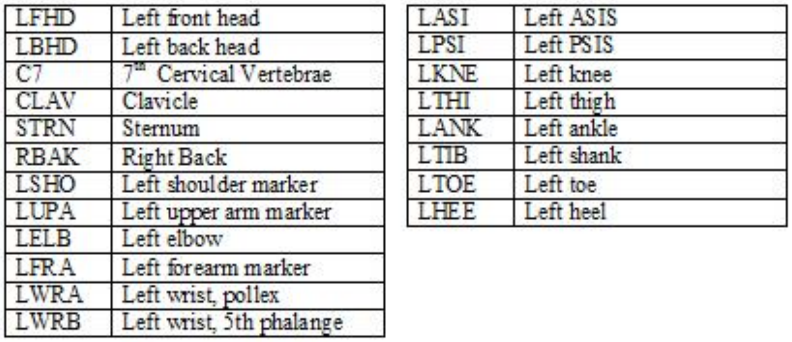
Typically, videotaping and/or photography is used to provide a visual record of each participant's performance during testing. In the event that elements of the participant's performance are unclear, this record is used to confirm the participant's performance. In addition, from time to time, these visual records are used to describe the tests used in the current research to other scientists and clinicians during presentations and conferences to share research findings.

By initialing on the lines below, I am indicating that I give the research team permission to (please initial all that apply):

_______videotape and/or photograph my participation in this study.
_______use videos and photos of me when they present this research in educational and professional venues, as long as I am *not* personally identifiable.

**Appendix C: Plug-in-Gait marker placement.** Where left side markers are listed there is an identical marker for the right side. Image and marker explanation can be viewed at: http://www.idmil.org/mocap/Plug-in-Gait+Marker+Placement.pdf





| | |
|---|---|
| LFHD | Left front head |
| LBHD | Left back head |
| C7 | 7th Cervical Vertebrae |
| CLAV | Clavicle |
| STRN | Sternum |
| RBAK | Right Back |
| LSHO | Left shoulder marker |
| LUPA | Left upper arm marker |
| LELB | Left elbow |
| LFRA | Left forearm marker |
| LWRA | Left wrist, pollex |
| LWRB | Left wrist, 5th phalange |

| | |
|---|---|
| LASI | Left ASIS |
| LPSI | Left PSIS |
| LKNE | Left knee |
| LTHI | Left thigh |
| LANK | Left ankle |
| LTIB | Left shank |
| LTOE | Left toe |
| LHEE | Left heel |

## Appendix D: Tether-release apparatus and electromagnet.

- Tether was attached to the participant and intern attached to the magnet. Magnet release was randmonly released and temporal synced with kinematic and kinetic data.

- Holding Force of magnet: Up to 600 lbs (272 kg)

- Magnet shown disengaged

- Magnet is shown engaged