View metadata, citation and similar papers at core.ac.uk
brought to you by CORE
provided by Queensland University of Technology ePrints Archive

FUNCTIONAL ADAPTATION AND REHABILITATION FOLLOWING TOTAL KNEE REPLACEMENT

Yuanbiao Liu

Bachelor of Medicine
Master of Medicine

Submitted in fulfilment of the requirements for the degree of

Doctor of Philosophy

Institute of Health and Biomedical Innovation
Faculty of Health
Queensland University of Technology

December 2014

Keywords

Total knee replacement, proprioception, walking, turning, stair ascent and descent, muscle co-activation, surface EMG, anticipated postural adjustment, continuous relative phase, functional activity, coordination.

Abstract

Total knee replacement (TKR) has been shown to be a successful procedure in the relief of severe pain and restoration of alignment of the lower limb. Advances in surgical techniques and improvements in prosthesis design, have achieved more accurate alignment of the lower limb and positioning of the prosthesis and although limited at this stage, there is evidence to indicate potential improvement in functional outcomes following surgery. A major goal of this study was to extend knowledge of the biomechanical and neuromuscular factors associated with recovery following TKR and their influence on the performance of activities of daily living. This involves the identification of reliable measurement protocols for TKR patients through analysis and evaluation of functional locomotor performance and associated neuromuscular and biomechanical factors.

The aims of the thesis were to:

1. Determine the reliability of different proprioception measurement protocols when used in the examination of changes in knee proprioception following TKR;
2. Investigate the kinematic, biomechanical and neuromuscular adaptations during locomotion at 12 months following TKR; and
3. Examine changes in proprioception and the kinematic, biomechanical and neuromuscular adaptations during performance of simulated activities of daily living at 6 months following TKR.
4. Investigate the relationship between objective functional performance outcomes and outcomes derived from validated self -report clinical surveys.

Three interrelated studies involving TKR patients and age-matched control subjects were conducted to address these aims. The first study was designed to determine differences in knee proprioception following TKR and to identify the more reliable protocols for measurement of knee proprioception.

Although inconclusive, there is research evidence indicating changes in proprioception following TKR which is a potentially a key factor in the adaptation of neuromuscular mechanisms during the recovery period. The inconsistency in findings may reflect the reliability of protocols used, the diversity of the population and differences in the outcome measures. Accordingly, the initial phase of the study was designed to compare the inter-reliability of passive angular reproduction (PAR) and

dynamic joint position sense (DJPS) protocols in the measurement of proprioception at the knee using an isokinetic dynamometer. The study involved 14 TKR subjects at an average of 11.5 months post-operatively, and 15 age-matched controls.

The findings showed that constant error (CE) and absolute error (AE) showed good inter-session reliability. However, only AE using the dynamic protocol was more reliable when used to discriminate between proprioception of the contralateral knee and that of controls.

Using the same participants as in Study 1, the second study examined the gait characteristics of TKR subjects involving measurement of proprioception and anthropometric, kinematic and neuromuscular parameters during treadmill walking. Testing was also conducted at an average of 11.5 months post-operatively and outcomes were compared with age and gender matched control subjects.

Although TKR subjects were able to walk at similar velocities to controls this was achieved by compensatory kinematic and loading adaptations. These modifications were accompanied by changes in the patterns and variability of inter-joint coordination and increased co-activation of knee flexors and extensors. Proprioception measured by DJPS was shown to be significantly related to inter-joint coordination between knee and ankle during level walking.

The final study used similar measurement protocols and strategies to evaluate performance of TKR subjects in simulated tasks of daily living such as stair ascent and descent and when responding to signals indicating abrupt stopping or turning in a particular direction when walking. Subjects included 14 TKR patients at 6 months post-operatively and 9 age-matched control subjects.

Performance of stair ascent and descent and responding to turning signals following TKR was also accompanied by increased execution time and reaction time. As in walking, performance in these activities involved increased and decreased double and single support periods respectively and differences in kinematics and inter-joint coordination between TKR and age-matched controls.

Examination of the relationship between functional outcomes obtained from clinical survey tools and the more objective measures used in the 3 interrelated studies, showed a significant relationship with muscle strength, knee joint proprioception and inter joint coordination during stair climbing.

This thesis provides important evidence to improve understanding of the functional recovery of TKR patients. Importantly, the study examined the neuromuscular adaptations following TKR using more objective measures of daily living which are activities known to present major challenges to patients who are predominantly in the older age population. The study also identified relationships between these more objective measures of adaptation following TKR with outcomes of functional status from commonly used clinical self-report measures. These findings may assist in further establishing the validity of these tools which are easier to use in the broader clinical context.

Table of Contents

Keywords i

Abstract ii

Table of Contents v

List of Figures viii

List of Tables x

List of Abbreviations xii

Statement of Original Authorship xiv

Acknowledgements xv

CHAPTER 1: INTRODUCTION 1

1.1 Study 1 4

1.2 Study 2 4

1.3 Study 3 4

CHAPTER 2: LITERATURE REVIEW 1

2.1 Outcome measurements for TKR patients 3
- 2.1.1 Survey tools for TKR 5
- 2.1.2 Performance based evaluation 7

2.2 Impairments following total knee replacement 10
- 2.2.1 Muscle weakness 10
- 2.2.2 Decreased range of motion 14
- 2.2.3 Changes in proprioception 16
- 2.2.4 Locomotion after TKR 19

2.3 Adaptation of locomotor abnormalities following TKR 23

2.4 Conventional surgical technique vs computer assisted surgery 26
- 2.4.1 Prosthesis alignment 28
- 2.4.2 Functional outcomes 33

2.5 Summary 35
- 2.5.1 Outcomes from objective analyses 35
- 2.5.2 Surgical technique 36

CHAPTER 3: KNEE JOINT PROPRIOCEPTION AND MEASUREMENT RELIABILITY 39

3.1 Introduction 39

3.2 Methods 41
- 3.2.1 Subjects 41
- 3.2.2 Experimental protocol 43
- 3.2.3 Data analysis 46
- 3.2.4 Statistical analysis 47

3.3 Results 48
- 3.3.1 Group age and anthropometric profiles 48
- 3.3.2 Subjective assessment of knee function 49
- 3.3.3 Performance in joint position sense measurement 50
- 3.3.4 Reliability of proprioception measurement 58
- 3.3.5 Relationship between proprioception and functional performance 61
- 3.3.6 Discussion 61

3.3.7 Reliability of joint position sense measurement 62
3.3.8 Passive joint position sense 65
3.3.9 Dynamic joint position sense 68
3.3.10 Functional outcome measures 70

3.4 Conclusions 72

CHAPTER 4: INTER-JOINT COORDINATION OF LOWER LIMBS DURING LEVEL WALKING IN PATIENTS FOLLOWING UNILATERAL TKR 73

4.1 Introduction 73

4.2 Methods 75
4.2.1 Subjects 75
4.2.2 Experiment protocols 75
4.2.3 Data analysis 80
4.2.4 Statistical analysis 82

4.3 Results 83
4.3.1 Functional outcome measurement 83
4.3.2 Muscle strength 83
4.3.3 Temporal and spatial parameters 85
4.3.4 Joint kinematics during gait cycle 86
4.3.5 Continuous relative phase (CRP) 93
4.3.6 Muscle co-activation 95
4.3.7 Relationships between objective measurements and self-reported functional outcomes 102

4.4 Discussion 103
4.4.1 Muscle strength 104
4.4.2 Gait performance 106
4.4.3 Muscle activity 110
4.4.4 Relationships between self-reported outcomes and objective measures of functional performance 113

4.5 Conclusions 115

CHAPTER 5: FUNCTIONAL PERFORMANCE AND NEUROMUSCULAR ADAPTATIONS IN SIMULATED ACTIVITIES OF DAILY LIVING IN PATIENTS FOLLOWING UNILATERAL TKR 117

5.1 Introduction 117
5.1.1 Hypotheses 121

5.2 Methods 122
5.2.1 Subjects 122
5.2.2 Instruments 122
5.2.3 Experimental protocol 125
5.2.4 Subjective assessment of knee functionality 125
5.2.5 Analysis of functional performance 126
5.2.6 Data processing 128
5.2.7 Statistical analysis 131

5.3 Results 132
5.3.1 Anthropometric profiles 132
5.3.2 Muscle strength and proprioception characteristics 132
5.3.3 Qualitative self-reported functional outcomes 133
5.3.4 Functional outcomes of daily activity simulations 135
5.3.5 Neuromuscular mechanisms 143
5.3.6 Relationships between objective measurements and self-reported functional outcomes 157

5.4 Discussion 160

5.4.1 Muscle strength, proprioception and self-reported outcomes 161
5.4.2 Performance during functional activity simulations...164
5.4.3 Neuromuscular adaptations during functional activity simulations.....................168
5.4.4 Relationships between objective measurement and self-reported functional performance..171

5.5 Conclusion...173
5.5.1 Characteristics of first step of gait initiation...173
5.5.2 Stair ascent and descent 174
5.5.3 Self report outcomes 175

CHAPTER 6: SUMMARY AND CONCLUSIONS 177
Responses to simulated activities...180
During stair ascent and descent 180
Self report outcomes...181

6.1 Strengths of the study...182

6.2 Limitations of the study...182

6.3 Recommendations for future research..183

BIBLIOGRAPHY…………………………………………………………………………………..185

List of Figures

Figure 3.1. Subject positioning for measurement of proprioception in passive and dynamic modes. 44

Figure 3.2. Demonstration of the dynamic joint position sense testing.......... 45

Figure 3.3. Results of Oxford Knee Score for control and TKR groups.......... 50

Figure 3.4. Angular Error in passive angular reproduction during two sessions. 51

Figure 3.5. Absolute Error (AE) of DJPS at 4 velocities: Session 1.......... 54

Figure 3.6. Absolute Error (AE) of DJPS at 4 velocities: Session 2.......... 55

Figure 3.7. Absolute Error (AE) of knees tested at 4 different velocities. 56

Figure 3.8. Constant Error (CE) of knees tested at 4 different velocities. 57

Figure 3.9. Variable Error (VE) of knees tested at 4 different velocities. 57

Figure 4.1. Absolute symmetry index (ASI %) of muscle strength for knee extensors and flexors for TKR and control groups.......... 84

Figure 4.2. Angular displacement of hip joint for TKR and control groups. 88

Figure 4.3. Hip flexion at foot strike for TKR and control groups. 88

Figure 4.4. Maximum range of hip joint excursion during stance phase for TKR and control groups. 88

Figure 4.5. Angular displacement of knee joint for TKR and control groups. 89

Figure 4.6. Knee angle at initial contact for TKR and control groups. 90

Figure 4.7. Angular displacement of ankle joint for TKR and control groups. 91

Figure 4.8. Ankle dorsi-flexion at initial heel contact for TKR and control groups. 92

Figure 4.9. Relative phase between hip and knee joint for both the TKR and control groups during the stance phase. 93

Figure 4.10. Relative phase between knee and ankle joints for both the TKR and control groups during the stance phase. 94

Figure 4.11. Magnitude of peak muscle activity during the gait cycle for vastus medialis (VM), vastus lateralis (VL), rectus femoris (RF), medial hamstrings (MH) and biceps femoris (BF). 96

Figure 4.12. Muscle co-activation for TKR and control groups during the gait cycle. 97

Figure 4.13. Muscle co-activation for TKR and control groups during the stance phase. 98

Figure 4.14. Muscle co-activation for TKR and control groups during the loading response phase. 99

Figure 4.15. Relative EMG activation for TKR and control groups during mid stance.......... 100

Figure 5.1. Diagrammatic and pictorial representation of staircase and adjacent walkway. 123

Figure 5.2. Visual signals displayed on the second monitor for activity induction. 124

Figure 5.3. Schematic of inter connection of different units used for data collection. 124

Figure 5.4. Example of sEMG (a) and visual signal (b) recorded during gait initiation. 125

Figure 5.5. Schematic of foot displacement during testing of stair ascent/descent. 127

Figure 5.6. Example of path of the COP during APA of gait initiation led by the right leg. 129

Figure 5.7. Diagrammatic representations of the footprints for left turning: (A) Two-steps ipsilateral limb support turning; (B) One-step ipsilateral limb support turning (pivot turning); and(C) Contralateral limb support turning. 134
Figure 5.8. Joint angles during stair ascent. 140
Figure 5.9. Joint angles during stair descent. 141
Figure 5.10. Reaction times during gait initiation in response to visual signal. 144
Figure 5.11. Antero-posterior displacement of COP during S1 period. 146
Figure 5.12. Antero-posterior velocity of COP during S1 period. 146
Figure 5.13. Medio-lateral displacement of COP during S1 period. 147
Figure 5.14. Medio-lateral velocity of COP displacement during S1 period. 147
Figure 5.15. Antero-posterior displacement of COP during S2 period. 147
Figure 5.16. Antero-posterior velocity of COP during S2 period. 147
Figure 5.17. Medio-lateral displacement of COP during S2 period. 149
Figure 5.18. Medio-lateral velocity of COP during S2 period. 149
Figure 5.19. Antero-posterior displacement of COP in S3 period. 151
Figure 5.20. Antero-posterior velocity of COP in S3 period. 151
Figure 5.21. Medio-lateral displacement of COP in S3 period. 151
Figure 5.22. Medio-lateral velocity of COP in S3 period. 151

List of Tables

Table 3.1 Selection criteria for the TKR and control subjects 42

Table 3.2 Age and anthropometric profiles for TKR and control subjects (Mean ± SD) 48

Table 3.3 R-WOMAC score results for TKR and control groups (Mean ± SD) 49

Table 3.4 IKS knee score and function score results for TKR and control groups (Mean ± SD) 49

Table 3.5 Proprioceptive performance during PAR in Session 1 (Mean ± SD) 51

Table 3.6 Proprioceptive performance during PAR in Session 2 (Mean ± SD) 52

Table 3.7 Proprioceptive performance during DJPS in Session 1 (Mean ± SD) 54

Table 3.8 Proprioceptive performance during DJPS in Session 2 (Mean ± SD) 55

Table 3.9 Differences in the passive angular reproduction testing between Session 1 and Session 2: Mean (95% CI) 58

Table 3.10 Test-retest reliability ($ICC_{2,1}$ 95% CI) in the passive angular reproduction testing 58

Table 3.11 Differences in the dynamic joint position sense testing between Session 1 and Session 2: Mean (95% CI) 59

Table 3.12 Test-retest reliability of constant error at different velocities ($ICC_{2,1}$, 95% CI) in the dynamic joint position sense testing 60

Table 3.13 Test-retest reliability of absolute error at different velocities ($ICC_{2,1}$, 95% CI) in the dynamic joint position sense testing 60

Table 3.14 Test-retest reliability of variable error at different velocities ($ICC_{2,1}$, 95% CI) in the dynamic joint position sense testing 60

Table 3.15 Relationship between dynamic joint position sense and functional performance measures 61

Table 4.1 Anthropometric parameters and description of procedures (Modified from Davis, 1991) 76

Table 4.2 Marker positioning 76

Table 4.3 sEMG electrodes placement 78

Table 4.4 Results of self-reported and physician administered questionnaires for TKR and control groups (Mean ± SD) 83

Table 4.5 Average muscle strength (Nm) of knee extensor and flexors for women and men in TRK and control groups (Mean ± SD) 83

Table 4.6 Muscle strength (MVC and normalised MVC) for TKR and control subjects (Mean ± SD) 84

Table 4.7 Distance parameters for TKR and control groups (Mean ± SD) 85

Table 4.8 Temporal parameters of gait for TKR and control groups (Mean +SD) 86

Table 4.9 Relative temporal parameters of gait for TKR and control groups 86

Table 4.10 Knee kinematic characteristics during stance phase (Mean ± SD) 90

Table 4.11 Ankle kinematic characteristics at different stages of the gait cycle (Mean ± SD) 92

Table 4.12 Differences in coordination and variability of lower limb joints (Mean ± SD) 95

Table 4.13 Correlations of muscle strength and self-reported functional performance 100

Table 4.14 Correlations of relative phase dynamics and dynamic joint position sense..........100
Table 4.15 Correlations of relative phase dynamics and self-report function 102
Table 5.1 Age and anthropometric characteristics for TKR (n=14) and control subjects (n=9) (Mean ± SD)..........132
Table 5.2 Muscle strength (Nm) for TKR and control groups (Mean ± SD)..........132
Table 5.3 Absolute error of DJPS testing for TKR and control groups (Mean ± SD)..........133
Table 5.4 IKS score for TKR (pre- and post-operative) and control groups (Mean ± SD)......133
Table 5.5 Oxford Knee Score and R-WOMAC Scores for TKR and control groups (Mean ± SD)..........134
Table 5.6 Numbers of trials using different strategies for turning (ISLT/CSLT)..........136
Table 5.7 Characteristics of first step after gait initiation (Mean ± SD)..........136
Table 5.8 Average temporal parameters of stair ascent/descent for TKR and control groups (Mean ± SD)..........138
Table 5.9 Lower limb angles at special time points during stance phase of stair ascent/descent (Mean ± SD)..........142
Table 5.10 Reaction time and turning time for TKR and control groups (Mean ± SD)..........143
Table 5.11 Correlations between the first step of gait initiation and COP patterns during anticipatory postural adjustment..........152
Table 5.12 Muscle co-activation (%) during the period of reaction time of gait initiation (Mean ± SD)..........153
Table 5.13 Muscle co-activation (%) during stair ascent/descent (Mean ± SD)..........153
Table 5.14 Differences in coordination measures of operated and contralateral limb of TKR subjects and non-dominant limb of control subjects (Mean ± SD)..........156
Table 5.15 Correlations of muscle strength normalised for body weight and self-reported measures of functional performance..........157
Table 5.16 Correlations between self-report functional performance and temporal-spatial parameters during simulated activities of daily living..........158
Table 5.17 Correlations of relative phase dynamics during stair ascent/descent and self-reported function..........159
Table 5.18 Correlations of relative phase dynamics and dynamic joint position sense..........160

List of Abbreviations

6MWT	Six-Minute Walking Test
ACL	Anterior Cruciate Ligament
AE	Absolute Error
ADL	Activities of Daily Living
ANOVA	Analysis of Variance
AOA	Australian Orthopaedic Association
AP	Antero-Posterior
APA	Anticipatory Postural Adjustment
ASI	Absolute Symmetry Index
ASIS	Anterior Superior Iliac Spine
BF	Biceps Femoris
BMI	Body Mass Index
CE	Constant Error
CI	Confidence Interval
CLST	Contralateral Limb during Step Turn
COG	Centre of Gravity
COM	Centre of Mass
COP	Centre of Pressure
CRP	Continuous Relative Phase
CT	Computed Tomography
CV	Coefficient of Variance
DAS	Customised Data Log System
DJPS	Dynamic Joint Position Sense
EMG	Electromyography
Fx	Antero-Posterior Axis
GRF	Ground Reaction Force
H/Q	Hamstrings/Quadriceps strength ratio
HSS	Hospital for Special Surgery Knee Rating Score
ICC	Intra-Class Coefficient
IHBI	Institute of Health and Biomedical Innovation
IKS	International Knee Society
ILST	Ipsilateral Limb during Spin Turn
JPS	Joint Position Sense

MH	Medial Hamstrings
MRP	Mean Relative Phase
MVC	Maximum Voluntary Contractions
Nm	Newton-metres
NMES	Neuromuscular Electrical Stimulation
OA	Osteoarthritis
OKS	Oxford Knee Score
PAR	Passive Angular Reproduction
PCL	Posterior Cruciate Ligament
PSIS	Posterior Superior Iliac Spine
QUT	Queensland University of Technology
RF	Rectus Femoris
ROM	Range of Motion
R-WOMAC	Reduced Version of WOMAC
sEMG	Surface Electromyography
SF-36	Short-Form Health Survey
SPSS	Statistical Package for Social Science
SRP	Variability of the Relative Phase
TDPM	Threshold for the Detection of Passive Motion
TKR	Total Knee Replacement
TUG	Timed Up and Go
UHREC	University Human Research Ethics Committee
VAS	Visual Analogue Scale
VE	Variable Error
VL	Vastus Lateralis
VM	Vastus Medialis
VMA	Voluntary Muscle Activation
WOMAC	Western Ontario and McMaster University Osteoarthritis Index
W/T	Walking and Turning

Statement of Original Authorship

The work contained in this thesis has not been previously submitted to meet requirements for an award at this or any other higher education institution. To the best of my knowledge and belief, the thesis contains no material previously published or written by another person except where due reference is made.

Signature: QUT Verified Signature

Date: December 2014

Acknowledgements

Professor Tony Parker, my principal supervisor, for his supervision, support, feedback and patience during the whole PhD journey. His continuing encouragement and support was most valuable in providing me with the energy to move forward to completion.

My associate supervisors, Professor Graham Kerr for his guidance and support and Professor Ross Crawford for his important help in recruiting patients.

Mr Alan Barlow, technical officer of the School of Human Movement Studies, Queensland University of Technology, for assistance in developing new devices for the project and Dr Michael McDonald for advice in some biomechanical procedures when required.

Dr Bill Donnelly, Dr Hugh English and their colleagues from the Department of Orthopaedics at the Prince Charles Hospital.

Most significantly, all the volunteer participants and their family members, without whose participation and contribution this research would not have been possible.

My dear wife Liying, for her unconditional and enduring support, understanding and love, particularly during the 3 and half years when I was studying in Australia. Her own achievements in her work were also a source of inspiration and motivation for me to work harder to complete this project. My lovely daughter, Lezhou who just wanted her father to return home immediately when studying in Australia. This would have enabled me to drive her to school in the morning on weekdays and to the dancing studio on weekends.

My parents and parent-in-law, for their tolerance and encouragement, and for their time and sacrifice in babysitting.

Finally, I would also like to extend my appreciation to all of my friends and current colleagues. Most of them were involved in this long journey in some way: Professor Jianan Li, Professor Wei Lin, Dr David Parker, Mrs Carole Parker, Mr Adam Parker, Yaohui, Tiesong and Chaoren.

Chapter 1: Introduction

The knee joint is one of the most complex joints in the human body comprising 2 anatomically distinct articulations within a single joint capsule and supported by a complex array of ligamentous and muscular attachments. Functionally, the joint is designed for both stability and mobility roles during static posture and dynamic movement, in conjunction with the hip and ankle joints. Along with these 2 joints, the knee joint serves to lengthen and shorten the lower limb to facilitate locomotor and other fundamental activities of daily living.

Variability and limitations in knee function occur as a function of age and accompanying changes in the status of knee structure. For example, osteoarthritis (OA) is one of the most prevalent age-related musculoskeletal diseases which impacts on functional ability and is a significant burden on the health care system. Consistent with the ageing of the population, the prevalence of OA is increasing and the Framingham cohort study (Felson et al., 1995) indicated the number of patients with symptomatic radiographic knee OA is increasing at rates of 1% and 0.7% per year for women and men respectively, with a mean age of 71 years. By 2030, the number of persons with medically diagnosed arthritis is projected to increase by 40% over current levels to nearly 76 million, or 25% of the adult population (AAOS, 2008). This condition is exacerbated by increasing levels of obesity (Messier et al., 2005) and inactivity (Szoeke, Cicuttini, Guthrie, Clark, & Dennerstein, 2006; Verweij, van Schoor, Deeg, Dekker, & Visser, 2009), which may also be indicative of the increasing appearance of OA in younger age groups.

The most common site for the development of OA is the knee joint (Felson et al., 2000) and the condition is characterised by pain during weight-bearing activities, stiffness, swelling, osteophyte formation, joint space narrowing, and subcondral bone sclerosis. Each of these changes has a bearing on functional changes such as decreased range of motion and muscle weakness (Felson et al., 2000). At the early stage of OA, a range of conservative treatments are commonly implemented to control the symptoms of pain including medication, physical therapy, weight loss and avoidance of activities likely to aggravate the problem.

In some cases, while providing temporary relief, the conservative options are unable to control the progression of the condition and surgical intervention becomes the necessary option (Felson et al., 2000). TKR is an elective surgical procedure which is increasingly used for patients with moderate to severe OA (AOA, 2009). It is the major reason for this procedure in Australia (AOA, 2013) and it is predicted that the use of the procedure will increase to nearly half a million surgeries performed annually in the United States by 2030 (Kurtz, Ong, Lau, Mowat, & Halpern, 2007).

The increase in TKR surgery has been accompanied by significant improvements in surgical techniques and the design of prostheses. The latter reflects improved understanding of the complexities of the knee joint, improved knowledge of neuromuscular mechanisms associated with the joint and factors which extend the durability and longevity of the prosthesis. Correct alignment and positioning of the compartments of the knee prosthesis is also recognised as a critical factor in the restoration of normal biomechanical functioning of the knee joint and the survival of the replaced knee joint. More recently, computer assisted alignment devices and navigation systems have been developed to improve the accuracy of bony resections, implant positioning and alignment and to contribute to optimal balancing of soft tissue structures. Promising results with respect to the improvement of the alignment and compartment positioning have been reported using the novel techniques (Rodriguez, Bhende, & Ranawat, 2001; Stindel et al., 2002; Laskin, 2003; Bathis et al., 2004a; Van Damme et al., 2005). For example, in a prospective study (Bathis et al., 2004b), malalignment of the mechanical axis was found in 5% of patients following computer-assisted navigated surgery compared to approximately 26% of patients using conventional surgical procedures. However, no significant differences were found in functional outcomes of the 2 procedures using the more qualitative self-reported or physician administered outcome tools which may reflect the limitations in this type of measurement. After successful reconstruction and alignment of the lower limb, restoration of knee function and the ability to perform activities of daily living is a key goal or outcome of the TKR procedure. Although the goal is relevant for all TKR patients, it is particularly important for older subjects for whom independent living is dependent on locomotor function. This requirement for optimal functional outcomes will become increasingly significant as the proportion of patients under 65 years of age undertaking the procedure increases (AOA, 2009; AOA, 2013).

In addition to the routine clinical examination of alignment using X-rays and other imaging procedures, functional outcomes using clinical survey tools have shown improvement during the early post-operative period, stabilising around 6 months post-operatively, followed by gradual improvement over the next 1 to 2 years. Beyond this time frame, age-related decrements in functional outcomes may occur. However, relative to values for age-matched norms, functional limitations are apparent and persistent in approximately 15%~30% of patients after the surgery (Jones, Voaklander, Johnston, & Suarez-Almazor, 2000). This is particularly evident when performing physically demanding activities such as stair climbing and descent.

Although more limited with respect to TKR, information derived from more objective outcome measures indicates the need for a longer post-operative recovery and rehabilitation period, to allow optimal recovery in areas such as muscle weakness, reduced range of motion and locomotor function.

As indicated previously, the mobility and stability of the knee joint is dependent on the accurate and precise control of soft tissue structures around the joint and the essential role played by muscles in the control of dynamic stability. Proprioception provides sensory information associated with movement and joint position and as such is important in ensuring smoothness of motion and coordination between body segments. However, there is no consensus with respect to the impact of TKR surgery on joint proprioception with limited research evidence concerning the relationship between proprioception of the knee joint and inter-joint coordination of the lower limbs and efficient locomotor performance. This may in part reflect the lack of standardised procedures to measure proprioception and determination of the sensitivity and reliability of this parameter in this population. Although there are also significant ageing effects impacting movement ability of the elderly, such as increased reaction time and difficulties in dynamic postural control there is a lack of information regarding whether or not these neuromuscular mechanisms are further influenced by the TKR procedure.

Use of more objective measures of recovery and functional capacity from a biomechanical or physiological perspective is more limited. This may be indicative of the costs associated with these procedures, and limited translation of research in some of these areas to the clinical setting. In addition, objective functional measures derived from research in this domain are often inconsistent and in some cases unreliable. Development of more objective and sensitive outcome measures requires further research and validation of their utility, to better discriminate the potential advantages associated with new surgical techniques and prosthesis and the efficacy of post-operative rehabilitation interventions.

The project involved the conduct of 3 interrelated studies involving comparisons of functional outcomes between TKR subjects and age-matched controls. The potential for significant proprioceptive changes following joint replacement was considered an important area of investigation relative to the likely impact on functional recovery and lower limb stability.

The inconsistency in the measurement of proprioception found in previous studies, was addressed in Study 1, with analysis of different measurement protocols and the aim of identifying the most reliable protocol for use in the measurement of changes in proprioception following TKR. This protocol was then used in Studies 2 and 3 to determine the impact of proprioception and other biomechanical and neuromuscular factors on locomotion and simulated activities of daily living at 6 and 12 months post-operatively. The influence of biomechanical and neuromuscular adaptations on performance and the association between more objective functional outcomes and those derived from validated clinical survey tools was also evaluated in the 3 studies.

In summary, the aims of the 3 studies were:

1.1 STUDY 1

Investigation of knee joint proprioception at 11.5 months following TKR and examination of the reliability of different measurement protocols;

1.2 STUDY 2

Investigation of the gait characteristics of TKR patients during walking on a level surface and the examination of changes in kinematic, biomechanical and neuromuscular responses at 11.5 months post TKR surgery; and

1.3 STUDY 3

Examination of biomechanical and neuromuscular responses to simulated activities of daily living such as stair climbing and directional change during walking at 6 months post-operatively.

Chapter 2: Literature review

TKR is becoming one of the most common orthopaedic surgeries performed in the world. The annual number of operations tripled from 129,000 to 381,000 between 1990 and 2002 in the USA and more than 800,000 are carried out every year worldwide (Kurtz et al., 2005). In the financial year ending June 2002, there were 20,289 TKRs performed in Australia, which increased to 40,407 in 2011(AOA, 2012).

Osteoarthritis is a progressive and irreversible rheumatic disease affecting joint articular cartilage and subchondral bone. It is the most common disabling condition in Western countries and the main clinical indication for primary knee joint replacement (Mehrotra, Remington, Naimi, Washington, & Miller, 2005; AOA, 2013). The prevalence of OA increases with age and the ageing of the population will continue to increase the importance of TKR surgery and the need for effective rehabilitation. The proportion of patients aged less than 65 years undertaking primary TKR increased from 29.5% in 2003 to 35.6% in 2011 (AOA, 2012). This increase in the number of younger patients undergoing surgery has also been shown to a major factor related to the need for revision surgery (AOA, 2012).

TKR has been shown to be an effective procedure in reducing knee pain and symptoms of OA and improving quality of life, but evidence of comparable improvements in functional performance is incomplete (Boonstra, De Waal Malefijt, & Verdonschot, 2008; van der Linden, Rowe, Myles, Burnett, & Nutton, 2007). TKR patients have been shown to experience substantial functional deficits compared with their age- and gender-matched counterparts, particularly when performing biomechanically demanding activities such as stair negotiation (Noble et al., 2005). A recent review of outcome measures following TKR provided evidence that most patients show progressive improvement in pain relief and function during the first 6 months following surgery, but a substantial number do not meet expected outcomes at the 12-month period (Dowsey & Choong, 2013).

In contrast, a prospective study which followed-up the functional recovery of 325 TKR patients for 5 years post-operatively showed that self-reported improvements in function were sustained over the 5-year period (Cushnaghan et al., 2009).

Many factors impact on optimal outcomes including surgical expertise and techniques and prostheses used, together with multidisciplinary input from appropriate allied health professionals pre- and post-operatively. Such input is guided by improved knowledge of any continuing impairments and associated mechanisms derived from objective outcome measures, to better inform surgical procedure and longer term rehabilitation and functional improvement. These issues become increasingly important considering the increasing number of younger patients undertaking TKR surgery and their risk of revision surgery.

In the early period following the use of TKR surgery, the emphasis when considering outcome measures was placed on clinical results that were important to physicians or surgeons (Liang, Fossel, & Larson, 1990). Measures of success were defined by survival rate and radiographic findings rather than functional outcomes (Anderson, Wixson, Tsai, Stulberg, & Chang, 1996). More recently, increasing attention has been placed on the patient's perception of pain, functional performance and health-related quality of life, using a variety of questionnaires or surveys (Escobar et al., 2006; Liebs et al., 2013). While Stratford and Kennedy (2006) found that change in self-reported physical function was mainly influenced by the change in pain, it was suggested that performance based evaluation of physical function should be included to obtain a more complete picture of functional outcomes (Rossi et al., 2013; Stratford & Kennedy, 2006). A consensus of research experts in OA also identified physical function as one of the most important dimensions to be measured when evaluating the efficacy of a variety of intervention strategies (Bellamy et al., 1997; Muramoto et al., 2012).

Previous studies have suggested that overall functional outcome following TKR could be determined using a multi-factorial approach, including the patient's physical characteristics such as body weight (Foran, Mont, Etienne, Jones, & Hungerford, 2004), pre-operative functional capacity (Ackerman & Bennell, 2004), coexisting conditions (Ayers, Franklin, Ploutz-Snyder, & Boisvert, 2005), self-efficacy (van den Akker-Scheek, Stevens, Groothoff, Bulstra, & Zijlstra, 2007), and patient expectation, all of which may vary according to age, diagnosis and lifestyle (Clifford & Mallon, 2005; Fitzpatrick, Clary, & Rullkoetter, 2012). The type of surgical procedures, either using computer-assisted navigation systems, or conventional techniques and differences in the prosthesis design, are also important factors in determining functional outcomes (Ensini, Catani, Leardini, Romagnoli, & Giannini, 2007; Luring et al., 2006). Peri-articular soft tissue and cruciate ligament management and patellar resurfacing should also be considered in the outcome evaluation following TKR (Berti, Benedetti, Ensini, Catani, & Giannini, 2006; Fehring, 2006; Joglekar, Gioe, Yoon, & Schwartz, 2012).

Post-surgical management is also an important factor associated with functional outcomes (Walsh, Woodhouse, Thomas, & Finch, 1998; Worland, Arredondo, Angles, Lopez-Jimenez, & Jessup, 1998) and a broad range of post-operative rehabilitation programs have been employed by health professionals for this particular population (Wilk-Franczuk, Tomaszewski, Zemla, Noga, & Czamara, 2011). In some cases the efficacy and evidence base underpinning these programs may be limited (NIH, 2004) and clinical outcome measures generally rely on validated self-report tools rather than more objective functional measures. As such, more complete understanding of the existing impairments in patients following TKR matched with targeted and individualised protocols are required. Impairments such as muscle weakness (Rossi, Brown, & Whitehurst, 2006; Stevens, Mizner, & Snyder-Mackler, 2003), proprioceptive deficiency (Wada, Kawahara, Shimada, Miyazaki, & Baba, 2002), limited range of motion (Dennis, Komistek, Stiehl, Walker, & Dennis, 1998) and altered locomotor patterns (Noble et al., 2005) following TKR have been consistently documented. A range of measurement tools have been used to identify these impairments, however their relative validity and reliability and relationship with more qualitative outcome measures requires additional investigation.

2.1 OUTCOME MEASUREMENTS FOR TKR PATIENTS

Outcome measurements are important to evaluate the efficacy of a particular intervention. As indicated earlier, a major goal of TKR is to relieve pain and improve the functional capacity of patients suffering this degenerative articular disease. Consequently, measurements of outcome following TKR generally include the patients' perception of pain and ability to perform activities of daily living. Functional outcomes are evaluated using objective measures at different levels of functional complexity, ranging from evaluation of specific joint function, to overall body function such as locomotion (Stucki, Ewert, & Cieza, 2002). Some surgeons and patients may be focused more on pain reduction than the improvement of knee function. However, the fact that the number of younger patients undergoing surgery is increasing means that sustainable functional outcomes are assuming increasing importance.

Prostheses longevity and the need for revision surgery are also key factors in assessing outcomes and revision rates are related to surgeons experience and type of prosthesis used (AOA, 2013). An important determinant of prosthesis longevity is also related to the intrinsic stability of the knee, which is determined by neuromuscular support mechanisms and prosthesis alignment.

Revision rates in Australia are comparable with most other countries with patients 55 years or younger having a 13.6% chance of revision at 12 years post-operatively (AOA, 2013). In contrast, revision rates decline in older patients with those over 75 years having a 3.1% chance of additional surgery. Prosthesis longevity is influenced by a range of factors including the type of prosthesis used and the experience and skills of the surgeon.

Forster, Kothari, & Howard (2002) and Worland et al. (2002) reported prosthesis survival rates of 94.5% and 97% at 5 and 14 years respectively. The survival or failure rate varies according to the definition of failure of the procedure. When defined as the need for either femoral or tibial component revision, the rate was 94% at 18 years post-operatively (Diduch, Insall, Scott, Scuderi, & Font-Rodriguez, 1997). More recent research has shown an average survival rate of 82% at an average follow-up period of 22.4 years involving 163 total replaced knees in 130 patients (Sabouret, Lavoie, & Cloutier, 2013). A cumulative percentage of 6.1% for revision of TKR at an 11-year follow-up period was reported by the Australian Orthopaedic Association (AOA, 2012)

Correct alignment and positioning of implanted components is another important indicator of successful surgery, and restoration of the mechanical limb axis and accurate component orientation are 2 major factors affecting the longevity of the prosthesis (Bathis et al., 2004a). Malalignment and malpositioning may be associated with early failure because of the associated prosthesis loosening, accelerated wear and functional deficiency (Delp, Stulberg, Davies, Picard, & Leitner, 1998). Radiographic evaluation is the common procedure for alignment assessment. For example, the distance of Maquet's line, (passing from the centre of the femoral head to the centre of the body of the talus), to the centre of the knee, using a long-leg standing radiograph, provides the most accurate measure of coronal alignment (Jeffery, Morris, & Denham, 1991). Standard short-leg radiographs can also be used to measure the component angles in the coronal plane and to help identify the position and alignment error (Mahaluxmivala, Bankes, Nicolai, Aldam, & Allen, 2001).

A large number of outcome scoring scales have been developed to evaluate clinical outcomes of TKR subjects using self-reported questionnaires or physician administered surveys and their validity and reliability have been well documented (Hawker, Melfi, Paul, Green, & Bombardier, 1995; Lingard, Katz, Wright, Wright, & Sledge, 2001; Stratford, Kennedy, Woodhouse, & Spadoni, 2006). Integration of one generic and a disease specific questionnaire is recommended for measurement of clinical outcomes as these 2 distinct types of scales measure and provide different, but complementary aspects of patient outcomes (Bombardier et al., 1995; Guyatt, Feeny, & Patrick, 1993; Hawker et al., 1995).

2.1.1 Survey tools for TKR

Pain is the most common symptom experienced by TKR candidates, the severity of which is measured using a simple visual analogue scale (VAS) or other scales such as the Lewis score. The latter was designed to assess knee pain before and after TKR on both sides, by scoring the severity of pain with a scale of 0 to 3 after performing 10 standardised movements of the knee (4 active and 6 passive) (Fuchs, Skwara, & Rosenbaum, 2005; Fuchs et al., 2004). The total score is referred to as the Pain Index of the Knee, which is regarded as a valid and reliable tool for assessing the severity of knee pain in OA (Berth, Urbach, Neumann, & Awiszus, 2007; Lewis, Bellomo, Lewis, & Cumming, 1995). Additionally, pain has also been identified as an important component of several structured scales which will be discussed later.

Standardised questionnaires have been developed to assess the severity of symptoms and to evaluate the outcome of interventions. Disease-specific questionnaires such as the Western Ontario and McMaster University Osteoarthritis Index (WOMAC) (Bellamy, Buchanan, Goldsmith, Campbell, & Stitt, 1988), the IKS Knee Score and Function Score (Insall, Dorr, Scott, & Scott, 1989; Lingard et al., 2001) and the Hospital for Special Surgery knee rating score (HSS) (Ghazavi, Stockley, Yee, Davis, & Gross, 1997; Insall et al., 1989) are the most commonly used instruments used for functional evaluation. The WOMAC is completed by patients, while the HSS and IKS are designed to be completed by the physician or allied health professional.

The WOMAC is a disease-specific, self-administered questionnaire developed to study the patient's quality of life when diagnosed with OA of the hip or knee. The index comprises 24 items in 3 categories: pain (5 items), function (17 items) and stiffness (2 items) (Bellamy et al., 1988). The original questionnaire has been shown to be reliable, valid, and sensitive to the changes in the health status of patients with hip or knee OA (Bellamy et al., 1988). It is the most commonly cited questionnaire in the literature, when combined with the Medical Outcomes Survey, a 36-item Short-Form Health Survey (SF-36) (Ethgen, Bruyere, Richy, Dardennes, & Reginster, 2004). In patients over the age of 75 years, the correlation coefficient between the level of patient satisfaction and pain score derived from the WOMAC questionnaire was found to be greater than that of the HSS, which suggests higher reliability of the WOMAC (Anderson et al., 1996). A shorter version of the WOMAC was developed and validated (Whitehouse, Lingard, Katz and Learmonth, 2003) and has been shown to be a reliable and sensitive alternative to the complete version, especially when evaluating outcomes following TKR.

The IKS knee score and function score (Insall et al., 1989; Kreibich et al., 1996; Lingard et al., 2001) are widely used and are composed of 2 parts including clinical and functional outcome measures. The first is the Knee Score, which evaluates pain, stability, and range of motion, with deductions for flexion contractures, extension lag and malalignment. A maximum of 100 points is given for a well-aligned knee with no pain, 125° of motion, and negligible antero-posterior and medio-lateral instability. The second part is the Function Score, which uses walking distance and stair climbing as the main parameters, with deduction of points for the use of any walking aid. The maximum Function Score of 100 is awarded to a patient who demonstrates the ability to walk an unlimited distance and who can ascend and descend stairs normally (Liow, Walker, Wajid, Bedi, & Lennox, 2003).

In addition to subjective factors (pain, instability, use of walking aids, distance walked), several objective factors such as extension dysfunction, degree of flexion contracture and the presence of effusion are included in the HSS knee rating score (Bach et al., 2002; Insall, Ranawat, Aglietti, & Shine, 1976). In general, the HSS is easy to use and quick to record and good overall inter-observer correlation coefficients and fair-to-good reproducibility has also been reported (Bach et al., 2002).

The Oxford Knee Score (OKS) has also been adopted by previous studies which have investigated TKR outcomes (Chiu, Ng, Tang, & Lam, 2001; Gleeson, Evans, Ackroyd, Webb, & Newman, 2004; Spencer, Chauhan, Sloan, Taylor, & Beaver, 2007). This questionnaire was developed specifically for knee replacement procedures (Dawson, Fitzpatrick, Murray, & Carr, 1998) and is a self-administered and subjective measure (Liow et al., 2003) which provides a simple and brief scale for the assessment of outcomes after TKR. The scores are quick and easy to calculate and analyse, particularly with assistance from a clinician (Whitehouse, Blom, Taylor, Pattison, & Bannister, 2005).

The SF-36 is a generic health related instrument for measuring quality of life and is widely used in the TKR population (Escobar et al., 2006; Ware & Sherbourne, 1992). It comprises 36 items, covering 8 domains (physical functioning, physical role, bodily pain, general health, vitality, social functioning, and emotional role and mental health) and also incorporating physical and mental summary scales. When used 6 months following TKR, the SF-36 showed improvements of 28.3 and 2.79 points in physical capacity and general health, respectively (Escobar et al., 2006).

A comparison of the validity of the WOMAC and SF-36 to discriminate knee problems was made based on the responses of 1193 patients with respect to the common items used in both instruments, such as pain, physical functioning, and overall score (Hawker et al., 1995). The results showed that the WOMAC discriminates better among individuals with knee problems, while the SF-36 discriminates better among individuals with varying levels of self-reported general health status and co-morbidities. These findings provide evidence to support inclusion of both a generic and a disease specific measure in the study of patients following TKR.

Although these questionnaires have been widely used in clinical assessment and in some cases with performance based evaluations included, they are highly subjective and may be biased, with respect to language problems, evaluator desirability and other issues, such as pain. A study on the validity of the subscales of WOMAC, indicated that the physical function subscale may be unsuccessful in detecting functional changes, due to the overlap between the pain and function subscales (Stratford & Kennedy, 2004). Accordingly, other performance based evaluations such as the ‘timed-up and go’ (TUG) test (Cattaneo, Regola, & Meotti, 2006; Schoppen et al., 1999), a 6-minute walking test (6MWT) (Bonutti, Dethmers, McGrath, Ulrich, & Mont, 2008; Curb et al., 2006; Moffet et al., 2004; Ouellet & Moffet, 2002), stair negotiation (Kreibich et al., 1996; Ouellet & Moffet, 2002) and range of motion (ROM) evaluations (Anouchi, McShane, Kelly, Elting, & Stiehl, 1996) have been developed and adopted.

2.1.2 Performance based evaluation

The TUG test (Cattaneo et al., 2006; Schoppen et al., 1999) is a tool which was initially developed for dynamic balance evaluation. The validity and reliability of this test when used to evaluate patients with OA has been established. In performing the test, the subject is required to stand up from a chair, walk 3 metres, then turn around and return to the seated position. Time between the moment the pelvis leaves the chair and the pelvic contact on return to the seated position is recorded.

The 6MWT (Curb et al., 2006; Moffet et al., 2004; Ouellet & Moffet, 2002) measures the distance covered by a subject walking forwards and backwards along a level surface of a certain length (e.g. 30 or 50 metres) at a free and comfortable speed for a 6-minute period. Validity and reliability of this test has been reported (Guyatt et al., 1985) and its use has shown that before and 2 months after knee replacement surgery, the 6MWT represents 72% and 58% of control values respectively (Ouellet & Moffet, 2002).

Walking and stair ascent/descent are two of the most important activities of daily living and as such the safety and efficacy of performance of these activities is essential in the functional assessment domain during the rehabilitation process. Evaluation of locomotor ability is of high relevance as a majority of patients with OA report difficulties in walking and stair ascent/descent and these 2 activities may reflect changes in physical function (Barr et al., 1994). A 30-second stair climbing test (Bolton, Hornung, & Olsen, 1994), measures the number of steps up and down in a 12-step flight a subject can perform over a 30-second period. When performing this test, TKR patients have demonstrated a significant improvement when comparing the results at 3 months and 6 months post-operatively (Bolton et al., 1994). However, in a later study (Rossi, Hasson, Kohia, Pineda, & Bryan, 2006) when evaluated at 17 months post-operatively all of the 11 patients involved reported at least moderate difficulty with descending stairs, whereas 9 of 11 individuals reported at least moderate difficulty with ascending stairs at approximately 17 months post-operatively (Rossi, Hasson et al., 2006).

2.1.2.1 Biomechanical assessment

Biomechanical assessment may be regarded as a performance based evaluation using specific instruments, which provide objective measures during functional activities such as locomotion and stair negotiation. These measures generally involve a motion capture and analysis system used in conjunction with sEMG and force plates to provide kinematic and kinetic data during specific locomotor activities. With continuing technique development, many of the movements and forces acting on and around the knee can be measured accurately, enabling the clinician to evaluate the movement and forces through the structures within or around the knee joint (Minns, 2005).

A large number of gait studies have shown significant improvement following TKR in terms of gait speed and stride length (Byrne, Gage, & Prentice, 2002; Fantozzi et al., 2003; Ornetti et al., 2010; Saari, Tranberg, Zugner, Uvehammer, & Karrholm, 2004). Motion analysis showed that 2 months after TKR, patients tended to adopt an adaptive pattern of walking and stair ascent which was characterised by reduced knee motion associated with increased hip flexion and reduced ankle plantar flexion (Ouellet & Moffet, 2002).

Temporal parameters such as walking speed and number of gait trials collected for analysis have varied substantially across different studies. However, the effect of walking speed on biomechanical parameters during gait is well recognised and inconsistency in reporting, or controlling for walking speed, makes comparison between studies difficult. For example, subjects may be instructed to walk at a constant speed (Fuchs, Floren, Skwara, & Tibesku, 2002), or at a comfortable or self-selected speed (Benedetti et al., 2003; Bolanos et al., 1998; Wilson et al., 1996). Additionally, the selection of the number of gait cycles used for data analysis may differ (Benedetti et al., 2003; Saari, Tranberg, Zugner, Uvehammer, & Karrholm, 2005) and the results of gait parameters may be averaged (Wilson et al., 1996) or presented as maximum values for each parameter (Saari et al., 2005). The influence of these discrepancies on results has not been clearly determined.

Surface electromyography has also been used to record phasic muscle activity following TKR, but there has been considerable variance in the muscles investigated in the different studies. In general knee stabilising muscles for instance the rectus femoris, vastus medialis, vastus lateralis, semitendinosus/medial hamstrings, and long head of the biceps femoris, tibialis anterior and medial gastrocnemius have been included in a majority of the studies reviewed (Bolanos et al., 1998; Fuchs, Rolauffs, Plaumann, Tibesku, & Rosenbaum, 2005; Fuchs, Skwara et al., 2005). Muscle activity associated with trunk stabilisation has also been evaluated using the ipsilateral and contralateral longissimus dorsi, and gluteus medius, in order to identify the potential compensatory strategies employed (Benedetti et al., 1999).

Performance based measurements provide a measure of the overall functional capacity of subjects following TKR, in terms of speed and the time needed to complete a specific locomotor task. These tests such as TUG and 6MWT have been shown to be reliable and sensitive to changes over time. However, it is also important from a rehabilitation perspective, to recognise how the movement is performed and the potential for modification and/or improvement. With this more specialised evaluation, individualised strategies to improve function can be derived and employed and improvement can be monitored during the rehabilitation process. Therefore, further investigation which aims to identify the adaptive strategies used and the underlying mechanisms should be developed in order to improve the effectiveness of rehabilitation interventions and measurement of their outcomes.

2.2 IMPAIRMENTS FOLLOWING TOTAL KNEE REPLACEMENT

2.2.1 Muscle weakness

Patients with severe knee OA scheduled for TKR have shown a decrease of approximately 25% in the strength of muscles of the affected knee compared with that of their contralateral muscles (Anchuela, Gomez-Pellico, Ferrer-Blanco, Slocker, & Rodriguez, 2001; Berman, Bosacco, & Israelite, 1991; Fuchs, Tibesku, Floren, & Thorwesten, 2000; Lorentzen, Petersen, Brot, & Madsen, 1999; Walsh et al., 1998). Pain is the most common symptom of knee OA and has been proposed as a potential confounding factor in the measurement of muscle strength. However, the relationship between pain and muscle strength has not been clearly evaluated. Muscle weakness is one of the major impairments which may persist for months or years after surgery (Berman et al., 1991; Bolanos et al., 1998; Walsh et al., 1998). Knee extensor weakness is exacerbated during the first month post-operatively and strength may continue to decrease from 28% to 62% when compared with similar measures for the contralateral limb (Berman et al., 1991; Judd, Eckhoff, & Stevens-Lapsley, 2012; Rossi et al., 2002; Rossi & Hasson, 2004; Stevens et al., 2003). Comparison with age- and gender-matched controls also indicates an average decrease of 64% in force production of the quadriceps in the involved lower extremity of TKR patients at 3 to 4 weeks after surgery (Mizner, Stevens, & Snyder-Mackler, 2003).

As rehabilitation progresses in the first year post-operatively, there is a gradual recovery in muscle strength (Anchuela et al., 2001; Berman et al., 1991; Lorentzen et al., 1999; Unver, Karatosun, & Bakirhan, 2005), the degree to which may reflect resumption of daily activities and different rehabilitation protocols. At 12 months post-operatively, the results of 3 studies (Anchuela et al., 2001; Berman et al., 1991; Rossi, Brown, & Whitehurst, 2006) showed that the strength of the knee extensors of the involved lower limb was approximately 18% to 35% weaker than that of the contralateral limb. When compared with the muscle strength measured pre-operatively, there was a 20~40% improvement in both the isokinetic flexion and extension peak torque in 3 of the 4 studies at 12 months post-operatively (Berman et al., 1991; Kim et al., 2011; Rossi, Brown, & Whitehurst, 2006). In contrast, the third study found a 15~20% decrease of both flexor and extensor torque during the same period (Anchuela et al., 2001). All subjects in this study were female and no details of post-operative rehabilitation were provided, which may have had a bearing on the contradictory results.

Few studies have followed patients beyond the 12-month period. A study of isokinetic muscle strength in 44 TKR subjects at 2 years post-operatively indicated that the peak quadriceps extension torque of the operated limb was only 83% that of the contralateral limb (Berman et al., 1991). Similarly, a study of 32 TKR patients showed an average 30.7% decrease in peak isometric strength of the knee extensors at 2 years post-operatively when compared to the values of age-matched controls (Silva et al., 2003).

Even at 13 years post-surgery, the strength of the quadriceps of the operated limb was found to be lower than that of the contralateral limb and age-matched subjects (Huang, Cheng, Lee, & Lee, 1996). Isometric strength of the quadriceps was only about 70% that of the controls when tested at 30º or 60º of knee flexion. Isokinetic muscle strength was also shown to be only approximately 60% of that of control subjects, at testing velocities of 120º/sec and 180º/sec.

2.2.1.1 Muscle balance: hamstrings/quadriceps ratio

Strength imbalance between knee extensors and flexors is a factor that may alter joint stability (Portes, Portes, Botelho, & Souza Pinto, 2007) and influence muscular control of knee movement (Aagaard et al., 1997). The imbalance is represented by the hamstrings/quadriceps strength ratio (H/Q), which is calculated by dividing the maximum force values for flexion by those values for extension of the knee joint, determined at a particular angular position, velocity and contraction mode (Aagaard, Simonsen, Magnusson, Larsson, & Dyhre-Poulsen, 1998). The H/Q ratio is significantly influenced by a number of factors, such as the testing velocity, gravity correction and testing angle. In general, H/Q ratio increases as testing speed increases during isokinetic assessment and also increases with higher degrees of knee extension during isometric evaluation. Gravitational torque results in larger errors at higher extension angles, but gravity corrected H/Q ratios do not increase with increasing test speeds (Kannus, 1994). An increase in the H/Q ratio from 0.50 to 0.61 as velocities increased from 30°/sec and 180°/sec was found in a group of young athletes when performing isokinetic testing (Aagaard et al., 1998). A similar range of 0.58~0.62 for H/Q ratio was shown following testing of the isometric muscle strength of 156 asymptomatic adults, with an average age of 64.4 years and measured at 90° of knee flexion (Andrews, Thomas, & Bohannon, 1996). Significant increases in the H/Q ratio from 0.46 to 2.18 was also found from isometric testing with the knee extended from 90° of flexion to full extension. Both the decrease in extension torque and increase in flexion torque contributed to the increased H/Q ratio (Silva et al., 2003).

Differences in the methods used to determine the H/Q ratio makes comparison between studies difficult. For example, using percentage difference in the H/Q ratio between groups or between pre- and post-surgical conditions might be a means of eliminating the influence of assessment variability on the absolute values of the H/Q ratio. The H/Q ratio for TKR subjects is higher than for normal controls at 1 year (Anchuela et al., 2001), or 13 years after surgery (Huang et al., 1996). At 13 years post-operatively, the H/Q ratio was approximately 20% higher than that of controls when measured either isometrically or isokinetically (Huang et al., 1996). In contrast, comparison of TKR patients and controls 2 years after surgery indicated that the H/Q ratio was 9.5% lower in the patient group when using average isometric torque (Silva et al., 2003). Differences in the duration of follow-up between these 2 studies may also contribute to the inconsistency in these findings as the H/Q ratio may be altered in responding to the gradual process of recovery in muscle strength following surgery. This hypothesis has been demonstrated by a study which showed a H/Q ratio of 0.88 pre-operatively decreased to a value within normal limits at 2 years post surgery (Silva et al., 2003).

Biomechanically, the knee is one of the most complex joints in the human body and is dependent on the muscles around the knee providing enough support to the joint when carrying out dynamic activities. The significant asymmetry in quadriceps strength between operated and non-involved lower limbs and the altered H/Q ratio of the muscles of the operated leg following TKR have a substantial impact on the movement patterns and performance of the knee during functionally important tasks (Lorentzen et al., 1999; Mizner & Snyder-Mackler, 2005). Strength deficit of the quadriceps femoris muscle has been identified as a key risk factor for falls in the elderly (Lord, Rogers, Howland, & Fitzpatrick, 1999), impaired postural transfer (Moxley Scarborough, Krebs, & Harris, 1999) and impairment in other daily activities (Walsh et al., 1998). Patients tend to rely more on the uninvolved limb during walking and sit-to-stand transfer. This may lead to long-term consequences, such as an increased risk of accelerated progression of OA in the uninvolved lower extremity (Mizner & Snyder-Mackler, 2005). Consequently, it is important to identify the underlying mechanisms associated with muscle weakness following TKR, to develop appropriate strategies to prevent the long-term adverse effects of muscle asymmetry (Rossi, Brown, & Whitehurst, 2006), especially during the first few months post-operatively. Without effective intervention, adaptation strategies or behaviours may be developed to compensate for the weak muscle, such as the quadriceps avoidance gait, which may in turn lead to long-term disuse atrophy of related muscles (Benedetti et al., 1999).

2.2.1.2 *Muscle activation failure*

Although the previously mentioned studies provide valuable information concerning the longer-term muscle weakness following TKR, there is limited information related to the cause of the persistent muscle weakness. Synthesis of the available information from 8 studies suggests an apparent failure of voluntary muscle activation (VMA) may occur following TKR. In these studies, the VMA was mainly measured by the burst-superimposition technique (Mizner, Petterson, & Snyder-Mackler, 2005; Mizner et al., 2003; Stevens et al., 2003). This involves superimposing a supra-maximal electrical stimulus on a maximum voluntary isometric contraction, during which the peak volitional and electrically elicited forces are recorded. The VMA is calculated by dividing the maximum voluntary force by the electrically elicited force (Stevens et al., 2003). Results of studies which have evaluated the role of VMA in muscle weakness have shown that the average VMA of the involved quadriceps was decreased by 17% and 22% compared with the pre-operative (Mizner, Petterson, Stevens, Vandenborne, & Snyder-Mackler, 2005; Stevens et al., 2003) and control values respectively. The decrease in VMA accounted for a 65% decrease in muscle strength, while the combined effect of the decrease in VMA and the cross-sectional area contributed 85% of the strength loss in the quadriceps (Mizner, Petterson, Stevens et al., 2005). An investigation of VMA of the quadriceps indicated that the difference in VMA between the involved and contralateral limb was reduced from 20% pre-operatively to approximately 10% at 33 months post-operatively (Berth, Urbach & Awiszus, 2002).

Physiotherapists have paid attention to the impairment of muscle weakness following TKR and resistance exercises are included in most of the routine rehabilitation protocols which aim to improve muscle strength (Anchuela et al., 2001; Rossi & Hasson, 2004; Shakespeare & Kinzel, 2005). However, conventional exercise prescription using resistance protocols appears insufficient to restore muscle function completely, particularly when a substantial VMA deficit is present. The need for comprehensive rehabilitation programs, including protocols to improve the VMA, such as neuromuscular electrical stimulation (NMES) and possibly to facilitate muscle strength is evident. To support this proposition, a study (Stevens, Mizner, & Snyder-Mackler, 2004) of the efficacy of high-intensity NMES demonstrated that 6 weeks of treatment increased muscle strength in the treated limb compared with the contralateral limb and the effect was still evident 6 months later. In contrast, this difference was not demonstrated following a more traditional voluntary exercise intervention. Similarly, the average percentage increase in VMA for the involved leg was 52% compared with 13% in the contralateral leg. However, these findings need to be confirmed by further investigation, with longer-term follow-up and studies involving larger sample size.

In summary, although not evaluated, the relative inactivity of the older TKR subjects during the longer follow-up period may have accelerated the normal age related decrease in muscle strength. Consequently, more appropriate age sensitive and effective rehabilitation intervention protocols are required to slow down, or compensate for the trend towards a decline in functional capacity. Such protocols may involve investigation of the effect of combining more formalised exercise programs with activities of daily living. This may serve to improve the compliance of the subjects, and lead to improved functional outcomes from this costly, but essential surgical procedure.

2.2.2 Decreased range of motion

Post-operative ROM is an important determinant of patient satisfaction after the TKR procedure and is an important outcome measure (Boese, Gallo, & Plantikow, 2011; Miner, Lingard, Wright, Sledge, & Katz, 2003; Naylor et al., 2012). Obtaining full knee extension and sufficient knee flexion post-operatively is critical in relation to daily functional requirements. For example, daily activities which involve deep knee bending require knee flexion of 110° or more.

The TKR procedure has been shown to substantially improve knee passive ROM and a majority of the 9 studies reviewed which measured the post-operative ROM, reported a value of greater than 100° (Becker, Insall, & Faris, 1991; Dennis et al., 1998; Ishii et al., 2008; Kotani, Yonekura, & Bourne, 2005; Stiehl, Voorhorst, Keblish, & Sorrells, 1997; Unver et al., 2005). This represents an acceptable functional ROM for accomplishing most activities of daily living. However, evidence of the effects of different prostheses and the management of the posterior cruciate ligament (PCL) (i.e., retention, removal or substitution) on ROM is inconclusive and remains a source of controversy. An evaluation of patients undergoing bilateral-paired PCL-retaining and PCL-sacrificing TKR, found no difference in post-operative motion, with an average 100° and 105° of flexion for the PCL-retaining and PCL-sacrificing groups respectively (Ishii et al., 2008). Dorr, Ochsner, Gronley, & Perry, (1998) evaluated functional outcomes in bilateral-paired PCL-retaining and cruciate-sacrificing TKR and found a similar ROM during both gait and passive flexion. Stiehl et al. (1997) conducted a non-randomised, multi-centre study with 782 TKR subjects implanted with the same prosthesis, to evaluate factors affecting the ROM at 24 months post-operatively. In contrast to the previous study, the results showed that although post-operative ROM improved from the pre-operative levels for both the PCL-retaining and PCL-sacrificing groups, the post-operative ROM was greater in the PCL-retaining group. However, the pre-operative ROM of the PCL-retaining group was greater than that of the PCL-sacrificing group, which directly influenced the validity of the results, making comparison between the studies difficult.

A randomised control study, which compared the benefit of PCL-retention or PCL-substitution on passive non-weight-bearing ROM at 1 year post-operatively, showed no significant difference between the 2 groups (Dennis et al., 1998). In contrast, another randomised control study (Straw, Kulkarni, Attfield, & Wilton, 2003), found a significant difference in ROM, in favour of PCL-substitution when evaluated at 3.5 years post-operatively. The mean ROM of the PCL-substitution group and PCL-retaining group was 110° and 100°, respectively. This finding was consistent with the results of a prospective, randomised control study with a mean follow-up of 31 months (Maruyama, Yoshiya, Matsui, Kuroda, & Kurosaka, 2004). The results indicated that the range of motion was greater in the PCL-substitution group, with an average ROM of 129.6° compared to 122.2° in the PCL-retaining group. Both PCL-substitution and PCL-retaining groups had a similar pre-operative ROM of 112°. The PCL-substitution knee showed consistent execution of posterior femoral rollback during knee flexion, while the PCL-retention knee exhibited a paradoxical anterior femoral translation. It was also shown, that the forward sliding during flexion of the PCL-retention knee, was associated with impingement of the posterior aspect of the tibial insert against the shaft of the femur (Bellemans, Vandenneucker, & Vanlauwe, 2005).

In addition to prosthesis design and management of the PCL, there is also evidence to suggest that pre-operative ROM has a significant influence on the post-operative results and is the most important determinant of post-operative ROM (Skinner, 1993). A multi-centre, non-randomised study of 782 TKR participants, found that patients with a pre-operative ROM of less than 90° showed a gain of 28° during the 24-month follow-up period (Stiehl et al., 1997). The same study found that those with a pre-operative ROM between 90° to 105° improved by 15°, in contrast to patients with a ROM of more than 105° prior to surgery, who lost 1° of movement after the surgery. These results suggest that those scheduled for surgery with a low ROM, will benefit most from the surgery and those with a relatively normal ROM pre-operatively will retain this range. Therefore, the magnitude of the change in ROM between pre- and post-operative values should also be considered when evaluating the efficacy of the surgery, or comparing the efficacy of different surgical techniques.

Findings from studies on ROM may also be influenced by the measurement protocols used. For example, a significant decline in ROM in both PCL-substitution (127° to 113°) and PCL-retaining subgroups (123° to 103°), has been shown under weight-bearing, compared to the ROM measured under non-weight bearing conditions (Dennis et al., 1998). This decline in the weight-bearing condition may result from the complex interaction of dynamic muscle forces, soft tissue constraints, posterior soft tissue impingement and articular congruity. In contrast under passive non-weight bearing conditions, the knee seeks the course of least resistance and may not reflect normal weight bearing articulated motion. Further investigations are needed to explore the influence of these potential mechanisms on ROM and their influence on measurement outcomes.

2.2.3 Changes in proprioception

Proprioception is a sensory modality that involves the perception of movement or kinesthesia (movement sense) and JPS based on other than visual or auditory information (Lephart, Pincivero, & Rozzi, 1998). It is now generally accepted that proprioceptive input plays an important role in the coordination of limb movements. This input is affected by signals from mechanoreceptors in the muscles, tendons, joint capsules, ligaments, and skin, which provides the nervous system with information with respect to body position and movement. In turn, this contributes to the formation of a conscious perception of joint position, motion and force. Proprioceptive functions are essential in ensuring a smoothness of motion and development of the velocity and force required for accurate movement from one position to another (Cordo, Carlton, Bevan, Carlton, & Kerr, 1994; Cordo, Gurfinkel, & Levik, 2000).

The complexity of the underlying sources and neural pathways involved in proprioception has stimulated the adoption of various protocols for its assessment. These include measurement of error in the reproduction of movement during active or passive angular movement of the ipsilateral leg (Wada et al., 2002), or by determination of the threshold for the detection of passive motion (TDPM) (Swanik, Lephart, & Rubash, 2004) and the magnitude of body sway during single leg stance (Fuchs, Tibesku, Genkinger, Laass, & Rosenbaum, 2003).

Five studies which have evaluated JPS, found consistent results for patients with severe knee OA. Proprioception of the affected knee had deteriorated and angular reproduction acuity of patients was significantly lower than that of age-matched controls (Barrett, Cobb, & Bentley, 1991; Hurley, Scott, Rees, & Newham, 1997; Marks, 1996; Swanik et al., 2004; Wada et al., 2002). For example, Wada et al. (2002) found that pre-operatively, the mean absolute angular error in JPS of 4.4º for OA patients was significantly greater than that for the control group (2.4º).

The evidence is inconclusive in relation to the changes in proprioception following TKR. For example, no significant improvement in joint reproduction was found following TKR, with the mean absolute angular error being 4.4º and 3.6º pre- and post-operatively respectively (Wada et al., 2002). Other studies have demonstrated small improvements in proprioception following TKR (Attfield, Wilton, Pratt, & Sambatakakis, 1996; Swanik et al., 2004; Warren, Olanlokun, Cobb, & Bentley, 1993). Swanik et al. (2004) found that subjects reproduced joint position more accurately after surgery, with a mean angular reproduction error of 1.7º post-operatively, compared with 3.2º pre-operatively. Meanwhile, the mean TDPM of 3º after surgery was less than the pre-operative value of 2.0º by the same study. This finding was attributed to the retention of capsulo-ligamentous structures, the enhanced positional feedback emanating from these structures and reduced pain and inflammation. Differences in the age and assessment methods used in these studies make direct comparison of the outcomes difficult, as ageing adversely affects proprioceptive performance (Barrett et al., 1991; Skinner, 1993).

The significance of ligamentous retention in the TKR procedure is supported by knowledge of the proprioceptive properties of the PCL. Earlier research (Schultz, Miller, Kerr, & Micheli, 1984) demonstrated histologically, the existence of mechanoreceptors in human cruciate ligaments and suggested that they provide proprioceptive information and contribute to reflex inhibition in response to injurious movements of the knee. It is now well recognised that the normal PCL is extensively innervated by mechanoreceptors such as Ruffini endings, Ruffini corpuscles of the Golgi tendon organ type and Pacinian corpuscles. These receptors have important afferent functions which provide the central nervous system with information on the movement and position of the joint (Franchi, Zaccherotti, & Aglietti, 1995; Krogsgaard, Dyhre-Poulsen, & Fischer-Rasmussen, 2002). Since afferents originating from the ligaments are involved in the control of muscle stiffness and co-ordination, other researchers (Johansson, Sjolander, & Sojka, 1991) have concluded that ligaments contribute to functional joint stability by a combination of their mechanical and sensory characteristics.

As the PCL is considered important in knee proprioception, knowledge of the effects of removing this source of afferent nerve receptors on the sense of joint position and movement is important. Although there is increased focus by orthopaedic surgeons on proprioceptive performance in arthritis and following various types of TKR, the results are inconclusive and evidence to support the advantage of whether to sacrifice, retain or substitute the PCL from a proprioceptive perspective is limited.

Five studies were found which compared the effect of retention or sacrifice of the intra-articular ligaments on proprioception after TKR, however, no consensus can be derived from the findings. Fuchs et al. (2003) used body sway during single leg stance on a force plate as a measure of proprioceptive performance and showed that proprioceptive outcomes in patients with both anterior cruciate ligament (ACL) and PCL retained were comparable with healthy age-matched subjects. However, body sway testing might be confounded by other information resources, such as those associated with vestibular and visual systems. In a study of knee implantation with a PCL-retaining prosthesis, a more accurate JPS was found by comparison with those using the PCL-sacrificing alternative at 1 year post-operatively (Warren et al., 1993). Proprioception was measured as the accuracy of reproduction of the perceived knee angle, using a hand-held leg model, when the knee was passively moved to one of the pre-determined angles between 0º and 60º of flexion. In contrast, no significant differences between the PCL-retention and PCL-sacrificing groups were found when proprioception was measured with TDPM at a velocity of 0.5 º/sec (Cash, Gonzalez, Garst, Barmada, & Stern, 1996; Swanik et al., 2004), or using the accuracy of actively reproducing a predetermined position with the ipsilateral leg (Wada et al., 2002).

An alternative to only sacrificing the PCL is to excise the ligament and replace it with a posterior stabilised tibial insert. This serves to facilitate the correction of any fixed deformities and is consistent with an anticipated improvement in biomechanical functioning. However, no difference was found in proprioception between this alternative design and the PCL-retention design, using the average angular deflection at TDPM at a velocity of 0.5°/s (Cash et al., 1996). This study was cross-sectional in design and the results may have been further confounded by the use of 2 different prostheses in the PCL-retaining group. Using the same prostheses with different management of the PCL, Ishii, Terajima, Terashima, Bechtold, & Laskin (1997) compared the influence on proprioception of PCL-retention and substitution, at an average of 2 years post-operatively in 55 knees. No significant differences were found between the PCL-retention and substitution groups as measured by the absolute angular errors during knee angle reproduction under weight-bearing conditions (Ishii et al., 1997).

In other studies, the validity of the findings was confounded by differences in the grouping of subjects in relation to variance in, for example, age categories and comparison or lack of comparison with normal controls. These grouping strategies may lead to bias as a function of inter-subject variability and age-related decline (Knoop et al., 2011; Skinner, 1993). Interpretation of the findings from these studies is further exacerbated by differences in proprioceptive measurement protocols. Accordingly, further research is required to identify the most sensitive and reliable proprioceptive test as an objective functional outcome measure for patients following TKR. This will permit comparison of proprioception pre- and post-operatively within the same group and assist in eliminating inter-subject variability.

2.2.4 Locomotion after TKR

Locomotion is the self-powered, patterned motion of the limbs, or other anatomical parts by which an individual customarily moves from place to place. Among them, walking and stair climbing are the most common locomotion forms for daily living. The results of a relatively large number of studies have shown alterations in the walking patterns of patients following TKR, with an average follow-up period ranging from 3 months to 10 years and when compared to those of age-matched healthy subjects (Alnahdi, Zeni, & Snyder-Mackler, 2011; Apostolopoulos et al., 2011; Bejek, Paroczai, Szendroi, & Kiss, 2011; Benedetti et al., 1999; Benedetti et al., 2003; Bolanos et al., 1998; Fantozzi et al., 2003; Lee, Tsuchida, Kitahara, & Moriya, 1999; Mizner & Snyder-Mackler, 2005; Wilson et al., 1996). Additionally, approximately 75% of 243 patients following unilateral TKR, reported difficulty in stair negotiation 1 year following TKR surgery (Noble et al., 2005).

Total knee replacement patients tend to walk at slower speeds with shortened stride length (Alnahdi et al., 2011) and longer gait cycle duration, when compared with age-matched healthy controls. For example, at 6 months post-operatively, the speed of progression (106.7cm/sec) and cycle duration (1.3s) of TKR patients was 82 and 125% that of the controls respectively. The ratio of stride length to height was 0.645, representing 80% of the ratio for controls (Ouellet & Moffet, 2002). Other researchers (Benedetti et al., 2003; Fantozzi et al., 2003; Saari et al., 2005), consistently found that TKR patients walked with a shortened single support phase and prolonged double support phase. On average, the single support phase decreased from 34.7% to 30.7% of the gait cycle, while the percentage of double support phase increased from 31.8% to 37.3% (Benedetti et al., 2003; Fantozzi et al., 2003; Ouellet & Moffet, 2002; Saari et al., 2005).

Gait analysis has also shown that patients commonly walk with a 'stiff knee' gait pattern, which is indicative of limited knee flexion during the loading response and mid-stance phases, as well as inadequate knee extension during terminal stance (Lee et al., 1999). As a consequence, total knee excursion in the sagittal plane has been shown to decrease. This has been shown to occur irrespective of the post-operative time, ranging from 48.9º at 6 months, 12 months (49.7º) and 48.8º at 24 months, in comparison to 57.1º for age-matched controls (Benedetti et al., 2003).

In contrast to the constantly reduced excursion of knee flexion during level walking, some other gait parameters have been shown to improve slightly during the recovery period after surgery. For example, stride length may recover to a value similar to that of age-matched healthy subjects at approximately 2 years after surgery (Benedetti et al., 1999). It was also found (Lee et al., 1999) that free gait velocity increased at 6 months after the operation when compare to the pre-operative value, but no further change was found at 1 year. A longitudinal study that followed-up 2 years after the surgery, confirmed the persistence of an abnormal kinematic characteristics during walking (Benedetti et al., 2003), which was characterised by significantly reduced knee flexion during mid-stance and swing phase.

Findings from these studies suggest that the temporo-spatial parameters of level walking may not be adequate enough for longer-term monitoring of functional recovery. Although the temporo-spatial parameters may recover to a level comparable to that of age-matched controls, significantly altered characteristics of the knee joint may still persist at the same time point following the surgery. Therefore, the value of some outcome measures commonly used, such as walking speed, distance covered in a particular time as required in the 6MWT may have more limited value when monitoring functional recovery over an extended post-operative period.

In addition to level walking, other potentially more challenging activities such as stair climbing have been evaluated following TKR surgery. Results of 3 studies which examined stair climbing showed patients tend to ascend at a slower rate, with a smaller total range of knee flexion when compared to that of age-matched controls (Byrne et al., 2002; Fantozzi et al., 2003; Saari et al., 2004). During side-stepping, the patients tended to spend more time in postural preparation and during the landing phase, irrespective of whether or not the supporting leg had been operated on (Viton et al., 2002).

Investigations of the kinetics associated with level walking showed that the peak knee extension moment of force and the knee joint power in the sagittal plane were consistently smaller than that for the age-matched controls during the 2 years follow-up period (Benedetti et al., 1999; Benedetti et al., 2003). In addition to level walking, mobility and alterations in gait patterns when stair climbing, side-stepping and sit-to-stand transfer have also been investigated (Viton et al., 2002, Mizner & Snyder-Mackler, 2005). When tested at an average of 15 months post-operatively, 50% of a group of 10 TKR patients were unable to step onto a 20cm high step (Byrne et al., 2002). The same study compared the kinetic characteristics of TKR patients with 7 age-matched individuals during a 12.5cm high stepping task. The findings indicated that the moment of force of the operated knee was always less than that of the contralateral limb and controls. This finding was consistent with other studies (Benedetti et al., 1999; Benedetti et al., 2003), which found that TKR patients increase the work of the hip muscles of the operated limb by 45%. It has been suggested that this increased muscular activity is required to compensate for a 46% decrease in the work of the knee muscles identified in another study of stair climbing (Byrne et al., 2002). In this study, this decrease was demonstrated when the operated knee was in a leading position, as the TKR patients were stepping onto a 12.5cm high platform in a step-by-step pattern.

The gait pattern is multi-factorial and the type of implant may play an important role in the formation and deterioration of normal gait (Fantozzi et al., 2003; Saari et al., 2005). Comparison of gait parameters during level walking among patients implanted with geometrically different tibial inserts, indicated that patients with a concave tibial insert, demonstrated greater hip flexion than those with a flat insert, but less extension at the hip and knee during walking. A similar comparison of gait parameters between patients with a mobile bearing prosthesis and posterior stabilised prosthesis, showed a slower velocity in the mobile bearing group, which was accompanied by reduced knee excursion during walking (Fantozzi et al., 2003).

Three-dimensional fluoroscopic analysis has also been used to quantitatively analyse in-vivo functional performance of different TKR prosthesis designs during locomotion. Udomkiat, Meng, Dorr, & Wan, (2000) compared 38 matched pairs of patients with knee OA who underwent primary TKR, involving cruciate retention and posterior stabilised designs involving PCL-retention or PCL-substitution. The 2 types of prosthesis were designed with identical articular surfaces. At a minimum 2-year follow-up period, these 2 groups showed similar functional outcomes measured by the IKS knee score and distance of level walking covered during a predetermined time period. Fluoroscopic kinematics showed that those with the PCL-substitution procedure experienced antero-posterior, femoro-tibial translation, which was more consistent with that of the normal knee during gait and deep knee bending. This finding may result from the greater conformity of the articular surfaces and control from the post/cam mechanism. The anterior translation of the femur over the tibia during knee extension observed in this study, confirms earlier research findings (Dennis, Komistek, & Mahfouz, 2003; Fantozzi et al., 2003; Stiehl, Komistek, & Dennis, 2001), which indicate that the posterior stabilisation designed implants have posterior femoral rollback more consistent with normal knees.

In contrast to the normal in-vivo osteo-kinematics in knees implanted with PCL-substitution and posterior stabilisation design mentioned previously, knees implanted with PCL-retaining prostheses have paradoxically posterior translation of the condyles during extension (Fantozzi et al., 2003; Stiehl, Dennis, Komistek, & Crane, 1999). This paradoxical posterior translation of the condyles decreases the lever arms of the extensor muscles. This in turn may increase the quadriceps force required during knee extension to achieve muscle work comparable with that of knee extensor muscles with normal lever arms. However, as indicated earlier, there is strong evidence that the strength of the quadriceps decreases in patients following TKR (Judd et al., 2012; Rossi, Brown, & Whitehurst, 2006; Stevens et al., 2003). Theoretically, particular coordination of the muscles around the knee joint may be developed to compensate for the reduced lever arms and muscle weakness. The strategies developed to compensate for the paradoxical translation of the femoral condyles in patients with PCL-retaining prostheses and the muscle weakness needs further investigation, as well as the long-term impact of these compensations.

Information from these studies has identified significant alterations in gait and performance of some types of daily activities, such as stair ascent/descent or sit-to-stand transfer. However, there are few studies which have explored the relationship between gait abnormality and the apparent impairments, in particular, the relationship between muscle weakness, proprioception and range of motion. One study explored the correlation between the discrepancy of vertical ground reaction force (GRF) for the involved and non-involved limbs and quadriceps strength (Mizner & Snyder-Mackler, 2005). For patients following unilateral TKR, the average peak vertical GRF of the involved limb was 14% lower than that of the contralateral limb. Results of this study further indicated that the discrepancy in GRF between the involved and non-involved limbs was correlated with the quadriceps index. This index is the ratio of involved to non-involved quadriceps torque as represented by the muscle strength imbalance between the 2 limbs (Mizner & Snyder-Mackler, 2005). Further studies with respect to the kinetic characteristics, particularly the muscle activation patterns during these activities, are required to provide a more complete understanding of the mechanisms underlying the alterations in kinematic and neuromuscular control parameters for this population. Findings from these studies are also important in the design and evaluation of intervention strategies to improve the overall function of patients following TKR.

2.3 ADAPTATION OF LOCOMOTOR ABNORMALITIES FOLLOWING TKR

Previous research has shown changes in the locomotor parameters of patients with OA measured pre- or post-operatively, such as decreased walking speed, stride length and double support time. However the reasons for these changes are not well understood. It has been suggested (Winter, Patla, Frank, & Walt, 1990) that there are 2 potential mechanisms to explain these changes; self-selection of a slower gait to execute a safer and more dynamically stable gait, and secondly physiological and neuromuscular adaptations.

Recent studies have supported the proposition that there is a physiological basis for locomotor adaptations following TKR (Alnahdi et al., 2011; Fantozzi et al., 2003; Saari et al., 2004). The lower extremity joints are intimately related and function as a unit. Therefore, intuitively, changes in loading and structure occurring at one joint, or sub-unit of the lower extremity, could result in the use of adaptation or compensatory strategies at the other ipsilateral lower limb joints (Byrne et al., 2002; Itokazu, Uemura, Aoki, & Takatsu, 1998; Mizner & Snyder-Mackler, 2005; Ouellet & Moffet, 2002; Saari et al., 2005), joints of the contralateral limb (Alnahdi et al., 2011; Byrne et al., 2002; Mizner & Snyder-Mackler, 2005) and sometimes involving the trunk (Fantozzi et al., 2003; Itokazu et al., 1998; Li et al., 2013; Ouellet & Moffet, 2002).

The presence of knee joint arthritis may lead to reduced knee extension, which may be the one of the most common abnormal gait patterns acquired pre-operatively (Ishii et al., 1998). As mentioned previously, following TKR, subjects tended to decrease their knee extension which was accompanied by reduced hip extension and/or increased hip flexion when compared with healthy controls during level walking (Ouellet & Moffet, 2002; Saari et al., 2005) or stair ascent (Ouellet & Moffet, 2002). The results indicated that patients may actively flex the hip to maintain balance (Saari et al., 2005) and the extensor moment of the hip was larger than that of controls during single leg support. This was confirmed by the magnitude of the EMG activity of the medial hamstrings (Ouellet & Moffet, 2002). In contrast, during other phases of the gait cycle, the moments of hip extensor and flexor were significantly decreased (Ouellet & Moffet, 2002). This may be an active adaptation, aimed at eliminating the abnormal antero-posterior displacement of the distal femur, which can be reduced by avoidance of full knee extension and limitation of knee flexion.

At 2 months post-operatively, it was found that the ipsilateral ankle exhibited an abnormal kinematic and kinetic profile (Ouellet & Moffet, 2002). The plantarflexion angle was significantly decreased when compared to that of control subjects during the double support and swing phases. Meanwhile, the plantarflexor moments of the ankle were decreased significantly during the swing phase of stair ascent and support phase of level walking (Ouellet & Moffet, 2002). Another study investigated the kinetic characteristics of lower limb joints while performing sit-to-stand transfer at 3 months post-operatively (Mizner & Snyder-Mackler, 2005). Results showed that the peak hip and knee moments of force of the operated limb were significantly lower than for the contralateral limb. Peak ankle moments of the operated and the contralateral limbs were not statistically different. Another study analysed the kinetic characteristics in the frontal plane of 2 groups of patients at 6 months and 12 months post-surgery and compared their values with a group of age-matched 20 control subjects (Alnahdi et al., 2011). Higher adduction angle, dynamic loading, knee adduction moment and impulse were found in the non-operated knee when compared to those of the operated knee.

The results of these studies provide support to the assumption that the lower limb joints may play different roles when performing various motor tasks, to ensure that the lower limb functions as an integrated unit. From the kinematic perspective, the lower limb joints of hip, knee and ankle need to be effectively coordinated with involvement of the neuromuscular system under control of the central nervous system. Further evaluation of neuromuscular coordination during performance of other motor tasks of daily living, such as posture transfer, stair ascent/descent and compensatory mechanisms adopted by other body parts, other than lower limb joints, is required.

When carrying out functional activities involving transfer of load between supporting limbs, it can be assumed that following unilateral TKR patients will be more reliant on the contralateral limb for support. This assumption was confirmed during a sit-to-stand transfer activity, when the vertical ground reaction force of the involved limb was found to be 14% less than that of the contralateral limb (Mizner & Snyder-Mackler, 2005).

A study of load distribution on the feet of the operated and contralateral limbs as measured by static and dynamic baropodometry, showed a significant increase in the percentage of loading on the treated side while in a static position. This increase was not observed when evaluated in the dynamic activity, during which an increased proportion of the load was associated with the non-operative limb (Bergami, Gildone, Zanoli, Massari, & Traina, 2005). These findings lend further support to the proposition that the compensation strategies adopted by TKR patients may be task dependent, with different strategies adopted to suit variance in task demands.

Compensatory functions during different tasks may also involve other joints and with transfer across other body regions such as the trunk (Fantozzi et al., 2003; Itokazu et al., 1998; Ouellet & Moffet, 2002; Viton et al., 2002). Using goniometry, force plates and switch sensors on the chair surface, Itokazu et al. (1998) studied the biomechanical characteristics of patients after TKR during a sit-to-stand transfer. Patients with a knee flexion angle of less than 100º, required a higher angular velocity at the hip and excessive velocity of trunk swing, to lift themselves upwards when compared to those with a knee flexion of more than 100º. In the single support phase during walking, the trunk has also been shown to flex more in TKR patients than controls as a compensatory mechanism to maintain the centre of gravity (COG) anterior to the knee joint axis (Ouellet & Moffet, 2002).

A study which investigated postural control strategies used by TKR patients, found a persistent asymmetrical behaviour in trunk movements during the side-step. This was determined from analysis of the displacement of markers placed on the acromion and anterior iliac crest on the supporting side (Viton et al., 2002). Following TKR, patients tended to move both markers towards the supporting leg and then towards the moving leg. In contrast, the healthy controls tended to move the anterior iliac crest marker directly toward the moving side. Another study which explored the relationship between reduction in the knee adduction moment and lateral trunk tilt, found that patients tended to tilt the trunk in the coronal plane toward the treated knee. This in turn produced a reduction in the adduction moment (Fantozzi et al., 2003).

Recent studies using fluoroscopic analysis, demonstrated unpredictable intrinsic knee kinematics when examining both fixed and mobile implants. For example, in many patients following TKR, it has been shown that an abnormal and paradoxical pattern of anterior translation of the femur occurs during knee flexion (Catani et al., 2009; Dennis et al., 2003; Stiehl et al., 2001). The potential negative effects of this pattern of anterior translation, muscle weakness and instability, may be compensated by a strategy which involves prolonged and increased muscle co-

contraction around the involved knee during the stance phase (Benedetti et al., 1999; McClelland, Webster, & Feller, 2007; Ouellet & Moffet, 2002).

Another hypothesis suggests that modification of locomotor parameters and abnormal patterns of locomotion occur as a result of a habitual behaviour related to pain and functional impairments developed before surgery. Fisher, White, Yack, Smolinski, & Pendergast (1997) found that the gait pattern of knee arthritic patients was very similar to that of TKR and ACL deficit patients. This remained unchanged following involvement in a quantitative, progressive exercise rehabilitation protocol aimed at restoring muscular strength, endurance and contraction speed. The authors concluded that the patients would have developed a strategy of "functional adaptation", acquired over time and which became habitual. It was initiated with the goal of reducing pain in the knee, thus making the knee movements unresponsive to the rehabilitation protocol. It was also suggested that additional gait retraining may be necessary to "re-program" the locomotor pattern together with the quantitative progressive exercise rehabilitation protocol. The energy cost of these "habitual abnormal gait patterns" and their potential for modification with effective rehabilitation requires further investigation.

A majority of these studies consistently support the conclusion that the gait patterns of patients after TKR are significantly different from those of able-bodied subjects. However, these studies did not effectively evaluate postural control and movement coordination during different phases of the gait cycle, such as the alterations which may have occurred during the initiation of gait. The findings of these studies suggest that there may be different neuromuscular adaptations which underlie the altered kinematic and kinetic patterns of the lower extremities during locomotion following TKR. How these adaptations relate to the impairments following TKR and the role they play in the formation of compensatory strategies warrants further investigation.

2.4 CONVENTIONAL SURGICAL TECHNIQUE VS COMPUTER ASSISTED SURGERY

TKR is conventionally performed using an extra-medullary or intra-medullary mechanical alignment guidance system. Despite the use of contemporary mechanical alignment systems, significant errors in post-operative alignment of the mechanical axis of greater than a range of ±3° are estimated to occur in approximately 20~30% of knees following surgery (Bathis et al., 2004b; Mahaluxmivala et al., 2001; Tolk, Koot, & Janssen, 2012; Zhang, Chen, Chai, Liu, &

Wang, 2011). The fundamental limitations of these systems is that evaluation of the degrees of freedom in most mechanical alignment systems is dependent on visual inspection and most importantly, the guide systems are designed based on standardised bone geometry. The latter obviates the possibility of customised positioning of the implant relative to the physical characteristics of individual patients (Delp et al., 1998; Tolk et al., 2012).

Computer-assisted alignment devices have been developed to improve the accuracy of bony resections, implant positioning and alignment and to help with soft tissue balancing. They may also provide an additional benefit by reducing the risk of fat and marrow embolisation seen with intramedullary instruments (Laskin & Beksac, 2006). Different types of computer navigation systems have been developed (Stiehl, 2007) and are generally designed to compare landmarks obtained during surgery, with reference to landmarks of the patient's leg made pre-operatively or intra-operatively (Laskin & Beksac, 2006). Pre-operative anatomical references are usually obtained using computed tomography (CT) scans (Laskin, 2003). Intra-operatively, imaging systems, such as fluoroscopy, are used to obtain anatomical references, to assist in calculation of axes by the computer (Rodriguez et al., 2001; Van Damme et al., 2005). The third approach, which is currently in wide use, is an image-free navigation system. This system collects the individual information through direct measurement during surgery, by identification of bony landmarks of the leg, or through kinematic algorithms used to calculate the joint centres and define mechanical alignment. Essentially, the computer system guides the surgeon in cutting the bones and positioning the prosthesis during surgery (Stindel et al., 2002).

Developments in computer technology and improved surgical instruments have stimulated greater use of computer-assisted navigation systems by orthopaedic surgeons over the last decade and an increase in research designed to evaluate the efficacy and advantages of this technique. Results analysed over this period included in the AOA National Joint Replacement Registry, showed no differences in the rate of revisions between computer navigation involving 42,584 TKR's and non-computer assisted procedures (AOA, 2013).

However, there are now many studies showing improved prosthesis alignment and accuracy with navigation and some studies showing improved function and survival. Consequently, the primary objective of this phase of the review is to explore whether computer-assisted navigation TKR results in improved prostheses alignment compared with the conventional technique. Evidence of improvement in functional outcomes relative to use of the 2 procedures will also be discussed.

2.4.1 Prosthesis alignment

Accurate restoration of the anatomical alignment of the femoral and tibial components of the knee is a major objective of the TKR procedure (Halder et al., 2012). Malalignment affects the integrity of the implanted prosthesis and surrounding structures and results in decreased longevity of the prosthesis, impaired functional outcomes and increased risk of revision surgery. For example, a 24% increase in the mechanical loosening rate occurred at a median period of 8 years when deviation of the mechanical axis was greater than 3°. This rate was approximately 8 times greater than in patients with normally aligned knees (Jeffery et al., 1991). Rand and Conventry (1998) found a prosthesis survival rate of 90% after 10 years when the mechanical axis was within 0~4° valgus. This rate decreased significantly to less than 73% when the axis deviation was greater than 4°.

Although the relationship between the sagittal alignment and long-term outcomes is unknown, hyperextension between the femoral and tibial components has been reported to increase the risk of osteolysis and anterior tibial post impingement with posterior-stabilised prostheses.

In addition to alignment of the mechanical axis in the frontal and sagittal plane, rotation of the femoral and tibial components is also particularly critical to a pain-free functional knee after surgery. Abnormal component rotation is associated with patellar mal-tracking and post-operative anterior knee pain (Barrack, Schrader, Bertot, Wolfe, & Myers, 2001). Therefore, the accuracy of positioning and alignment of the femoral and tibial components should be evaluated in the frontal, sagittal, and axial planes.

2.4.1.1 Definitions of alignment

As indicated earlier, the fundamental limitation of the conventional mechanical guidance system is the difficulty in determining appropriate alignment to allow appropriate degrees of freedom of movement as an alternative beyond reliance on visual inspection by the surgeon. In recognition of this issue, detailed definitions of the correct alignment of the prosthesis in 3 planes have been included in previous studies when comparing the advantages of computer-assisted navigation surgery over the more conventional surgical procedures.

All studies included in this review provided a detailed definition of the alignment of the prosthesis. For instance, overall lower limb alignment was mainly evaluated based on plain radiographs taken during standing and representing full-length (hip to ankle) weight-bearing antero-posterior (AP) aspects. The centres of the femoral head, knee and ankle joints were first identified. The angle between the line connecting the centres of the hip and knee and the line joining the centres of the knee and ankle joint was determined and used to represent the overall mechanical axis of the lower extremity in the frontal/coronal plane (Chang & Yang, 2006; Haaker et al., 2005; Mullaji & Shetty, 2009).

The coronal tibial component angle, is defined as the angle between the anatomical axis of the tibia and the horizontal axis of the tibial tray. The coronal femoral component angle, is the medial angle between the mechanical load axis of the femur and the horizontal axis of the 2 prosthetic condyles (Haaker et al., 2005).

In addition, the mechanical axis in the sagittal plane is defined as the line drawn from the centre of the femoral head, as detected by a concentric circle template, to the centre of the ankle joint (Minoda, Kobayashi, Iwaki, Ohashi, & Takaoka, 2009). Few studies have been conducted to determine the accuracy of overall limb alignment in this plane. This may reflect the difficulty in obtaining a lateral view of the femoral head, particularly in obese patients (Minoda et al., 2009). In contrast, measurements of the lateral femoral and tibial component angles in the sagittal plane have been well investigated. These measures are mainly derived from standard lateral radiographic views of the knee joint, as proposed by the IKS total knee arthroplasty roentgenographic evaluation and scoring system (Ensini et al., 2007).

Considering the reality of the 3-dimensional movement characteristics of the knee joint, appropriate restoration of the alignment in the transverse plane may be valuable to facilitate optimal function and restore knee joint function. Even small deviations have a considerable impact on patellar-femoral tracking, stability and the overall biomechanical characteristics of the knee joint. Several reference axes have been proposed to establish proper rotational alignment of the femoral components. Among these axes, the trans-epicondylar axis has been shown to approximate the flexion-extension axis of the knee. In assessing component rotation, the rotational deviation of the femoral component from the referenced axis was determined by the angle between the line connecting the femoral fixation pins and the surgical epicondylar axis. The rotational error of the tibial component was defined as the angle between the angle bisecting the line of the tibial component fins and the line between the medial third of the tibial tuberosity and the geometric COG of the tibia (Lutzner, Krummenauer, Wolf, Gunther, & Kirschner, 2008; Matziolis, Krocker, Weiss, Tohtz, & Perka, 2007).

2.4.1.2 Optimal alignment

Whether a conventional mechanical alignment system, or computer-assisted navigation surgical technique is used, the goal of optimal alignment intra-operatively is to completely restore anatomical alignment. In order to fully restore the overall mechanical axis of the lower limb, femoral alignment is positioned at 90º to the mechanical axis in the frontal and sagittal planes and parallel to the transepicondylar axis for rotation. For the tibia, the aim is alignment at 90º to the mechanical axis in the frontal plane and along a line from the lateral border of the medial third of the tibial tubercle to the centre of the tibial plateau for rotation (Lutzner et al., 2008).

To restore optimal alignment in the sagittal plane, the posterior slope of the tibial component is usually recommended by the manufacturer, or determined by lateral pre-operative radiographs of the tibial plateau (Ensini et al., 2007). For example, a posterior slope of 3º is recommended for the press-fit condylar Sigma mobile-bearing knee prosthesis (PFC Sigma, Depuy, Warsaw, Indiana) (Kim, Kim, & Yoon, 2007). A posterior slope of 5° in the sagittal plane is suggested when a Scorpio PCS prosthesis is used. This prosthesis is a cemented, unconstrained, cruciate retaining implant incorporating a rotating platform (Stryker Orthopaedics) (Lutzner et al., 2008).

The exact degree of malalignment below which good clinical and functional outcomes can be expected, is unknown with respect to post-operative radiographic evaluation. In the absence of this information, most studies have accepted the placement of components within a deviation of less than 3º of the mechanical axis (Bathis et al., 2004b; Jenny & Boeri, 2001; Kim et al., 2007; Matziolis et al., 2007; Mullaji, Kanna, Marawar, Kohli, & Sharma, 2007; Seon & Song, 2005; Sparmann, Wolke, Czupalla, Banzer, & Zink, 2003; Tingart et al., 2008). Accordingly, those with a deviation of greater than 3º are recognised as outliers. Other studies have adopted stricter criteria with respect to the mechanical axis and have used a femoral component angle of 2º (Confalonieri, Manzotti, Pullen, & Ragone, 2005; Manzotti, Pullen, & Confalonieri, 2008).

2.4.1.3 Advantages of computer-assisted navigation surgery in alignment improvement

Improved accuracy in prosthetic alignment provides the rationale for the continued development of computer-assisted navigation systems. Such improvement is confirmed by a majority of studies which have shown fewer malalignment cases when computer-assisted navigation surgery was performed, in comparison with conventional surgical groups (Bathis et al., 2004b; Chauhan, Scott, Breidahl, & Beaver, 2004; Chin, Yang, Yeo, & Lo, 2005; Confalonieri et al., 2005;

Decking, Markmann, Fuchs, Puhl, & Scharf, 2005; Ensini et al., 2007; Haaker et al., 2005; Lutzner et al., 2008; Matziolis et al., 2007; Mullaji et al., 2007; Rosenberger et al., 2008; Seon & Song, 2005; Seon et al., 2007; Sparmann et al., 2003; Stockl et al., 2004; Tingart et al., 2008). More precise restoration of the mechanical axis in the frontal plane has also been demonstrated in either prospective, randomised control studies (Chauhan, Scott et al., 2004; Chin et al., 2005; Decking et al., 2005; Ensini et al., 2007; Luring et al., 2008; Spencer et al., 2007), retrospective studies (Confalonieri et al., 2005; Haaker et al., 2005; Kamat et al., 2008; Rosenberger et al., 2008; Stulberg & Zadzilka, 2006), or by purely routine clinical service observations. The latter studies had no particular inclusion and exclusion criteria other than the indication and contra-indication of the TKR procedure (Bathis et al., 2004b; Tingart et al., 2008).

The results of the studies reviewed, showed malalignment of the mechanical axis greater than 3º in approximately 10% of patients (range: 1.7% to 35%) undergoing computer-assisted navigation surgery. In contrast, approximately 31% of patients in the conventional TKR group demonstrated malalignment ranging from 13% to 72%. For example, in a prospective study (Bathis et al., 2004b), significantly better restoration of the mechanical axis of the lower limb was found in computer-assisted TKR patients compared with those undergoing conventional surgical techniques. Ninety-six percent of patients in the computer-assisted group had a deviation of the mechanical axis of less than 3º varus/valgus, while in the conventional group, only 78% of patients were within this range. Similarly, a varus/valgus alignment less than 3º in 95% of the patients in the computer-assisted group was found in another prospective study with 500 patients in each group. In contrast, only 74% of patients in the conventional group had a frontal alignment of less than ± 3º (Tingart et al., 2008). Importantly, there was no particular inclusion/exclusion criteria employed in the study, which represents a clinical routine and demonstrates the advantages of computer-assisted techniques over conventional operations in a more realistic perspective (Tingart et al., 2008). In contrast, others have shown no significant differences in radiographic alignment between the 2 techniques (Kim et al., 2007; Stulberg & Zadzilka, 2006). This may reflect other variables and possible reasons such as inexperience with the navigation system, or improper patient recruitment for the selective use of the navigation technique (Kim et al., 2007). Furthermore, the different types of prosthesis and interface/platform of the navigation system adopted in these studies, may contribute to the inconclusive outcomes.

Significantly better frontal (Confalonieri et al., 2005; Matziolis et al., 2007) and sagittal (Jenny & Boeri, 2001) alignment of the femoral component of the prosthesis has been demonstrated in patients undergoing computer-assisted surgery when compared with conventional procedures (Chauhan et al., 2004; Ensini et al., 2007; Luring et al., 2008; Rosenberger et al., 2008; Sparmann et al., 2003; Tingart et al., 2008). In a clinical observational study involving a cohort of 1000 patients, without particular manipulations on the potential confounding factors as indicated earlier (Tingart et al., 2008), the mean deviation of the femoral component in the frontal plane was 1.2º in the computer-assisted group compared with that of 2.4º in the conventional surgery group. The percentage of outliers with a deviation of greater than 3º, was 4% in the computer-assisted group, versus 32% in the conventional group. Lutzner et al. (2008) also failed to show any statistically significant differences between the 2 techniques in terms of deviation of the femoral component in either the frontal or sagittal planes. Outcomes with respect to accuracy of alignment of the tibial component, showed that more patients who received the computer-assisted navigation procedure recovered optimal alignment, with an average outlier (> ± 3º) rate of 4% in the frontal plane, compared to those in the conventional surgery group. Failure rates of 11% have been found in a number of studies for those receiving conventional alignment procedures. The average deviation in tibial alignment for the computer-assisted procedure group, was also significantly less than that of the conventional group, with ranges from 0.01~3.78º and 0.67~7º across the studies reviewed, respectively (Bathis et al., 2004b; Chauhan, Scott et al., 2004; Ensini et al., 2007; Haaker et al., 2005; Lutzner et al., 2008; Matziolis et al., 2007; Rosenberger et al., 2008; Sparmann et al., 2003; Tingart et al., 2008). Although no significant differences were found in terms of the deviation of the tibial slope across a number of studies (Bathis et al., 2004b; Haaker et al., 2005; Lutzner et al., 2008; Matziolis et al., 2007; Rosenberger et al., 2008; Stockl et al., 2004; Tingart et al., 2008), significantly more consistent component positioning and reduced rate of malalignment was found in patients undergoing computer-assisted surgery (Chauhan, Scott et al., 2004; Matziolis et al., 2007; Rosenberger et al., 2008; Sparmann et al., 2003).

Limited evidence was found with respect to the accuracy of rotational alignment of components in the transverse plane as a function of computer-assisted navigation techniques. Three studies showed a significant improvement in rotational alignment of the femoral component using computer-assisted navigation compared with conventional procedures (Chauhan, Scott et al., 2004; Lutzner et al., 2008;

Stockl et al., 2004). No significant differences in femoral and tibial rotation were found between computer assisted or conventional surgical techniques, with a mean femoral rotation of 0.3 and 0.12, respectively (Matziolis et al., 2007). Different landmarks used in the evaluation of femoral rotation by the 2 surgical groups may contribute to the inconsistency and make direct comparison and synthesis of the information difficult. There is limited agreement with respect to the most suitable landmarks used to determine anatomically tibial rotation during surgery. This may lead to greater variations in rotational alignment of the tibial component with a significantly greater degree of deviation (7.5º) and variability (6.0º) compared with values of 0.3º and 1.4º for the femoral component, respectively (Matziolis et al., 2007). The inconsistency in the rotational alignment of the tibial component has also been verified by other studies (Lutzner et al., 2008; Stockl et al., 2004).

A majority of studies support the hypothesis that computer-assisted navigation systems improve the accuracy of component positioning and provide a significant advantage in restoration of the overall mechanical axis of the lower limb and the femoral and tibial axis, in both the frontal and sagittal planes. Previous studies have also provided evidence of the benefits of computer-assisted navigation surgery in improving rotational alignment of the femoral component. However, the diversity of the reference points used by different navigation systems contributes to the inconclusive evidence at this time, which may influence measurement outcomes and partly explain differences between the 2 procedures (Minoda et al., 2009). In addition to restoration of the optimal alignment of the lower limb, the TKR procedure also facilitates improved functional performance as a result of effective re-alignment with a pain free implanted knee joint. This outcome is particularly important, considering the significant increase in the number of people under 65 years of age undertaking TKR surgery (AOA, 2009; AOA, 2012), with recognition of the need to include relevant functional performance measures in the evaluation of the clinical and surgical outcomes.

2.4.2 Functional outcomes

Recovery of overall functional performance in a pain free environment is an aim of TKR surgery and subsequent rehabilitation programs. Results of 6 studies which investigated functional outcomes following 2 different surgical techniques showed that all outcome measures significantly improved after surgery regardless of the surgical techniques (Decking, Markmann, Mattes, Puhl, & Scharf, 2007; Ensini et al., 2007; Kim et al., 2007; Seon & Song, 2005; Seon et al., 2007; Spencer et al., 2007). For example, the HSS score improved from about 65 (60~68.5) before surgery to approximately 90 (89~93.3) at 1 year post-operatively for both surgical techniques at these 2 time points (Kim et al., 2007; Seon et al., 2007). Other clinical scales such as the IKS (Decking et al., 2007; Kim et al., 2007; Lutzner et al., 2008), WOMAC (Decking et al., 2007; Kim et al., 2007; Spencer et al., 2007; Stulberg, Yaffe, & Koo, 2006) and OKS (Ensini et al., 2007) showed similar results. Furthermore, no significant differences were identified between the two surgical techniques in almost all of the aforementioned previous studies using these self-reported, or physician administered questionnaires. Seon et al. (2007) investigated the durability of early post-operative improvement, by evaluating clinical outcomes pre-operatively and at 3, 6 and 9 months and 1 year post-operatively. The study involved 45 patients admitted for bilateral TKR, who had undertaken to have one knee operated on using computer-assisted navigation TKR and the other using conventional TKR. The computer-assisted navigation group showed better results in terms of the HSS and WOMAC scores until 6 months after surgery. The authors suggested that navigation assisted surgery resulted in better knee functional scores than conventional surgery up to 6 or 9 months post-operatively. However, no significant advantages were found between the 2 techniques at 1 year post-operatively (Seon et al., 2007).

To evaluate the effectiveness of computer-assisted navigation systems in patients with significant extra-articular deformity, a series of 34 patients representing a total of 40 knees involving TKR were reviewed retrospectively using qualitative survey measures (Mullaji & Shetty, 2009). The results indicated significant improvement in outcome scores and effectiveness associated with computer-assisted navigation surgery in restoration of alignment of the mechanical axis in the frontal plane. The IKS score improved from 49.7 pre-operatively, to 90.4 post-operatively and the IKS function score improved from 47.3 to 84.9 (Mullaji & Shetty, 2009). The relatively small sample size and lack of a control group, limited the findings of this study. These results and those from a relatively limited number of studies provide insufficient evidence to confirm the benefits of the 2 procedures on functional outcomes. This may reflect the lack of sensitivity of the commonly used qualitative tools to detect, for example, differences in alignment, suggesting the need for more objective outcome measures.

Although the advantages of using a computer-assisted navigation TKR system has been shown in previous studies, no significant advantages of the latest technique have been shown in the functional outcomes when evaluated with the self-reported or physician administered questionnaires. This finding may be attributed to the inadequate sensitivity of the survey tools used in the previous studies, suggesting the need for more objective and sensitive measurements when making comparisons between the latest developed surgical technique and the conventional surgery.

In 5 of 6 studies which used range of movement measures, no differences were found in ROM between the 2 surgical procedures. (Decking et al., 2007; Kim et al., 2007; Matziolis et al., 2007; Seon et al., 2007; Stulberg et al., 2006). Two studies comparing the outcomes associated with computer navigated and conventional surgery showed a comparable range of motion for both knees, regardless of the evaluation time pre-operatively and at 3-month intervals following surgery (Kim et al., 2007; Seon et al., 2007). In contrast, Seon and Song (2005) found that the mean flexion ROM of the navigation-assisted group was 131.9° at 1 year post-operatively, which was greater than that of the conventional group (125.4°).

Several objective measures, such as gait analysis and other biomechanical evaluations have been employed in this expanding area and have attempted to discriminate the subtle advantages and improvements associated with different surgical techniques and prosthesis designs. More investigations involving more sensitive, accurate and valid objective measures are needed to fully confirm the efficacy of surgical and rehabilitation procedures and prosthesis design.

2.5 SUMMARY

The research provides evidence to support a range of positive outcomes following TKR including pain relief, restoration of biomechanical alignment of the lower limb and improvement in some functional characteristics. However, when considered against values for age-matched peers, some functional outcomes appear less than optimal.

2.5.1 Outcomes from objective analyses

For example functional characteristics such as range of movement, strength, and proprioception have shown decrements when compared to the contralateral limb and results of control subjects. Such differences have been identified at different times post-operatively, ranging from 6 months to 2 years following surgery.

Compared to the relatively greater number of studies of muscle strength and range of motion, less information concerning changes in proprioception was found and there is a lack of consensus with respect to proprioceptive performance following TKR. This may reflect the complexity of the neural mechanisms underlying proprioception and the fact that a variety of different protocols with questionable reliability have been used to measure proprioception in studies of TKR outcomes.

The current evidence indicates significant alterations in the gait characteristics of TKR patients. Altered kinematic characteristics of the knee joint and related alterations in the hip and knee joint and joints of the contralateral limb have been shown in previous studies using the technique of gait analysis. Considering the potential decrements in proprioception and changes in muscular alignment and neuromuscular control, adaptations in muscle activity around the knee joint and inter-joint coordination between lower limb joints is anticipated. Additional research is required to confirm these hypotheses and is a focus of investigation in this study.

Although improvements in functional outcomes using survey based tools such as WOMAC, OKS, HSS and IKS have been shown, the relationship between these self-reported measures and more objective measures has not been clearly demonstrated.

2.5.2 Surgical technique

Optimal mechanical alignment of the knee joint components and lower limb is a major aim of TKR surgery. This is critical for the longevity of the prosthesis and optimisation of the biomechanical characteristics of the knee joint. New computer-assisted navigation systems have been developed to improve the accuracy of prosthesis alignment and some of the advantages of this technique over more conventional procedures have been shown. However at this time, inconsistency in the evidence and the lack of more objective outcome data does not allow confirmation of the benefits. This may reflect the lack of adequate sensitivity of the evaluation tools used in the previous studies. A number of self-reported or physician administered questionnaires have been developed and adopted in the evaluation of functional outcomes for TKR subjects. However, the validity and reliability of these questionnaires has been challenged recently as the weight or disproportionate influence of pain in the overall score of these questionnaires and may confound the influence of other functional performance criteria.

The increasing numbers in the community undergoing TKR surgery emphasises the need for continued research to evaluate and continue to improve the efficacy of the surgical and rehabilitation procedures involved. Surgical improvement is progressing with respect to computer assisted procedures designed to improve alignment of the components involved. The outcome of these procedures is evaluated from biomechanical and functional perspectives, the latter involving both qualitative and objective measurement procedures. However the current literature identifies the need for closer examination of existing measures and the potential design and evaluation of more reliable and objective measures of functional outcomes following TKR. Ideally, the more objective measures should simulate as closely as possible, fundamental activities of daily living. Improved understanding of the relationships between the outcome measures derived from qualitative and more objective outcome measures is also required.

The ultimate objective of the TKR procedure is to restore knee function and assist in maintaining independent living and an active lifestyle. As such, a major goal of this thesis was to evaluate changes in the biomechanical and neuromuscular patterns during the first 12-month recovery period following TKR during the performance of key activities of daily living. The goal was achieved through the design and conduct of 3 interrelated studies with the following aims:

Accordingly the aims of this study were to:

Study 1. Determine the reliability of different proprioception measurement protocols when used in the examination of changes in knee proprioception following TKR;

Study 2. Investigate the kinematic, biomechanical and neuromuscular adaptations and relationships during locomotion at 12 months following TKR; and

Study 3. Examine changes in proprioception and the kinematic, biomechanical and neuromuscular adaptations during performance of simulated activities of daily living at 6 months following TKR.

Chapter 3: Knee joint proprioception and measurement reliability

3.1 INTRODUCTION

Sensory feedback from mechanoreceptors in the skin, muscles, tendons, menisci, capsule and ligaments, in and around the knee joint, provides information to the motor control system on segmental movement and position. This information is integrated by the central nervous system to differentiate and regulate whole body and segmental posture and joint stability (Riemann & Lephart, 2002a). Proprioception is believed to modulate muscle function (Hurley, 2003) and initiate reflex stabilisation of the joints and protection of the knee joint (Fremerey et al., 2000), especially under dynamic conditions (Riemann & Lephart, 2002b). Theoretically, knee joint proprioception is critical for accurate modulation and activation of muscles around the joint, thus providing adequate neuromuscular control of knee joint position and movement, maintaining proper inter-joint coordination and the performance of physical tasks (van der Esch et al., 2007).

Joint injury or disease may lead to changes in proprioceptive processing and inaccurate proprioception has been identified as a major factor in the development of knee OA. It is also associated with functional limitations in patients with knee OA and other conditions such as ACL rupture. In patients with severe knee OA, proprioception is deteriorated as demonstrated by a significant reduction in acuity when reproducing knee joint angle compared to that of age-matched controls (Barrett et al., 1991; Swanik et al., 2004; Wada et al., 2002; van der Esch et al., 2007).

Although several studies have investigated proprioceptive capacity in patients following TKR, the results are inconsistent with respect to the influence of different factors associated with knee replacement on proprioception (Attfield et al., 1996; Swanik et al., 2004; Wada et al., 2002; Isaac et al., 2007). Potential factors which may be associated with the variability of results include differences in the age of participants (Barrett et al., 1991; McChesney & Woollacott, 2000; Skinner, 1993), variations in surgical management of the cruciate ligament (Cash et al., 1996; Fuchs et al., 2003; Swanik et al., 2004; Wada et al., 2002; Warren et al., 1993) and differences in the geometric profile of the implanted prosthesis (Cash et al., 1996). To further confound the situation, different protocols have been used to measure proprioception making comparison between studies/results difficult. These have included the TDPM (Cash et al., 1996; Swanik et al., 2004), reliability and accuracy of angular reproduction by the ipsilateral leg (Wada et al., 2002) and reproduction of a predetermined knee angle using a hand-held leg (Warren et al., 1993).

The reality that proprioception can only be measured indirectly, makes it difficult to guarantee reliability without increased risk of uncertainty and inaccuracy of the measurement. Several modalities have been adopted in the assessment of proprioceptive of TKR patients; however, reliability of the measurement protocols in this particular population has not been well documented. Although a range of factors may contribute to the inconclusive results with respect to the proprioceptive changes in subjects following TKR, differences in the mode of assessment tool/method may be a key factor.

It has been suggested that proprioception is involved in the control of limb posture, the specification of movement direction and the extent and magnitude of the movement. (Cordo et al., 1994; Riemann & Lephart, 2002a, 2002b). The central nervous system is able to use proprioceptive information from one active joint to coordinate subsequent rotations at other joints of the same limb. This is influenced by movement velocity and position of the body segment (Cordo et al., 1995). In a study designed to examine the role of joint velocity and position information in the coordination of arm and hand movement, a DJPS protocol was found to be of value in identifying proprioceptive information related to both the velocity and the angular position of the joint to trigger coordinated movement (Cordo et al., 1994). In contrast to the protocols mentioned earlier, which mainly rely on angular position as the main source of information, DJPS may be more sensitive when used to discriminate proprioceptive function of the knee joint following TKR. To the authors' knowledge, no previous studies have used this protocol in this clinical context.

Consequently, this study was designed to investigate:

1. The reliability of passive and dynamic protocols in the measurement of proprioception following TKR surgery;
2. Differences in proprioception of the knee joint between TKR patients and age-matched control subjects; and
3. Examination of the relationship between measures of proprioception and other functional outcome measures.

The hypotheses for the study were as follows:

1. Measurement of JPS is more sensitive and reliable when measured dynamically at different velocities rather than passively;
2. Proprioception of the replaced knee is limited by comparison with the contralateral knee and that of the age-matched control subjects; and
3. Self-reported functional outcome measures are related to measures of proprioception.

3.2 METHODS

3.2.1 Subjects

Subjects were recruited following primary TKR conducted by a single orthopaedic surgeon specialising in knee joint surgery. In the recruitment process, files of all TKR patients who visited the orthopaedic outpatient clinic for their 12-month post-operative consultation were reviewed by the surgeon and identified as potential volunteers for the study. The aims and requirements of the study were discussed by the surgeon with those patients who satisfied the inclusion criteria. An information document, outlining the project and the requirements for participation, was then given to those patients who expressed interest in being involved. Age and gender matched control subjects were recruited from the community, according to the selection criteria, by means of personal communication, or by introduction through other participants and friends (Table 3.1).

Following initial contact and review by the surgeon, each potential subject who had indicated willingness to participate in the study was referred to the investigator who contacted the patient by telephone, or face-to-face, to provide further information if necessary. After agreeing to be involved, the patient was invited to attend a preliminary session at the Queensland University of Technology (QUT) Institute of Health and Biomedical Innovation (IHBI) where further information was provided and additional subject screening undertaken to confirm fulfilment of the inclusion criteria.

A participant information package was given to subjects who fulfilled the inclusion criteria and agreed to participate in the study. The informed consent form and testing protocol was introduced to the participants before signing to participate in the study. Ethical clearance for the study was obtained from the University Human Research Ethics Committee (UHREC) at QUT and all testing was conducted in accordance with the National Statement on Ethical Conduct in Research Involving Humans (National Health and Medical Research Council, 2007).

Table 3.1
Selection criteria for the TKR and control subjects

Selection criteria
All subjects in both control and TKR groups were: • Age between 60~75 years; • No history of any other lower limb joint arthroplasty; • No general central nervous system dysfunction; • Absence of serious medical problems (congestive heart failure, severe asthma, un-controlled hypertension and cognitive problems which prevented understanding of the testing protocol; • No evidence of severe lower limb joint disease other than the operated knee joint in the TKR group; • Absence of peripheral neuropathy; and • Absence of severe lower limb vascular disease.
Additional criteria for TKR subjects: • Undertaking primary unilateral TKR due to severe knee OA; • Implanted with a prosthesis of the same design and operation performed by the same surgeon using identical surgical procedure; • No significant symptoms associated with the contralateral knee; • Undertaken the surgery approximately 12 months prior to the testing; • Ability to produce a range of motion of the knee joint greater than 90^0; and • Ability to walk independently on a level surface.

A total of 14 individuals (7 males and 7 females) who had undergone primary unilateral TKR, together with 15 participants (9 males and 6 females) without history of knee replacement surgery were recruited as subjects for the study. Six subjects were operated on the left knee joint and the remaining 8 subjects had their right knee replaced. Both groups were matched as closely as possible for age, with an average age of 66.3 and 68.9 years in the control and TKR groups respectively.

3.2.2 Experimental protocol

3.2.2.1 Subjective assessment of knee functionality

The knee function of subjects in both groups was assessed using the R-WOMAC score, IKS knee score and function score and the OKS.

Seven items selected from the original 17 items representing functional activity, together with additional questions associated with the perception of pain and stiffness are included in the R-WOMAC. This modified scale has previously been confirmed as a practical, valid, reliable and responsive alternative to the full functional scale, especially for subjects following TKR (Whitehouse et al., 2003).

The IKS score is composed of 2 sections including clinical and functional measures (Insall et al., 1989; Kreibich et al., 1996; Lingard et al., 2001). The first part is the Knee Score, which considers pain, stability, and range of motion as the main parameters, with deductions for flexion contractures, extension lag, and malalignment. The second part is the Function Score, which uses walking distance and stair climbing as the main parameters, with deduction for the use of a walking aid.

The OKS is a self-report, patient based outcome score consisting of 12 questions related to knee function. Each question is graded 1 (highest) to 5 (lowest) to produce a minimum score of 12 (normal function) and a maximum of 60 depicting poor function (Dawson et al., 1998; Spencer et al., 2007).

3.2.2.2 Measurement of knee joint position sense

The Biodex System 3 isokinetic dynamometer was adopted as the instrument for measurement of JPS. The Biodex system is a contemporary isokinetic dynamometer, with an electrically controlled servomechanism used both in the clinical and research setting. The system has been identified as a valid and reliable instrument for torque and position measurements (Dvir, 1995; Van Meeteren, Roebroeck, & Stam, 2002; Drouin, Valovich-McLeod, Schultz, Gansneder, & Perrin, 2004) and has been used previously for evaluation of knee joint proprioception (Callaghan, Selfe, McHenry, & Oldham, 2008; Thijs et al., 2007).

When tested, subjects were asked to wear shorts and to be barefooted in order to minimise the cutaneous sensory input from the leg. The subjects were instructed to sit upright on the chair of the dynamometer, with their back supported and the knee hanging over the edge of the apparatus. This position was set to a distance of 3cm between the proximal border of the popliteal fossa and the edge of the apparatus (Figure 3.1).

Figure 3.1. Subject positioning for measurement of proprioception in passive and dynamic modes.

To minimise contribution from cutaneous receptors and avoid direct skin contact of the lever arm, the tested lower leg was placed in an air splint and then secured to the attachment, with the fixation strap positioned 4cm proximal to the medial malleolus, in accordance with the manual of procedures for the dynamometer. The knee joint of the tested leg was aligned with the axis of the dynamometer and the thigh and the upper body were secured to the seat of the chair with fixation straps. Subjects were blindfolded and wore headphones during the testing to minimise the visual and auditory cues. Initially, the knee and hip joints were positioned at 90° and 85° of flexion respectively.

In measurement of JPS in the passive mode, the subject's knee was first moved passively by the investigator to 75° of flexion, which served as the starting position. The knee joint was then extended passively by the dynamometer at a constant velocity of 2°/sec to 45° of flexion (defined as the target position) and this position was maintained for 10 seconds for subjects to perceive and remember this target position. The leg was then passively moved back to a random trajectory between 70~80° of flexion followed by moving to 75° of flexion (starting position) for formal testing. Subsequently, the leg was extended towards 45° of flexion by the dynamometer after an interval of between 5 and 15 seconds, with a constant velocity of 2°/sec. This variable time interval was selected to minimise the possibility that subjects rely on timing to estimate the target position. During the extension phase, the subject was asked to press a hand-held stop button connected to the dynamometer at the point in time when they perceived the target angle had been achieved. Subjects were allowed to perform 3 trials prior to the formal testing protocol which involved testing of both knees for 6 repetitions (Selfe, Callaghan, McHenry, Richards, & Oldham, 2006). The non-operated knee of the TKR subjects and the dominant side of the control group were tested first.

In evaluation of JPS in the dynamic mode, the task involved passive rotation of the leg in the Biodex system (Figure 3.2) from a starting position of 90° of knee flexion (defined as starting position) to 30° of knee flexion (end position). This involved movement over a range of 60° of knee extension at different velocities (15, 30, 45 and 60 deg/sec). Subjects were required to press a hand-held button to record a signal when they believed they had moved through 45° of extension (target position). The test was repeated at different velocities (15, 30, 45 and 60 deg/sec), with 15 trials at each velocity. Velocity was randomised in blocks of the same velocity and an order of velocities of 15, 30, 60 and 45 deg/sec was used for all participants.

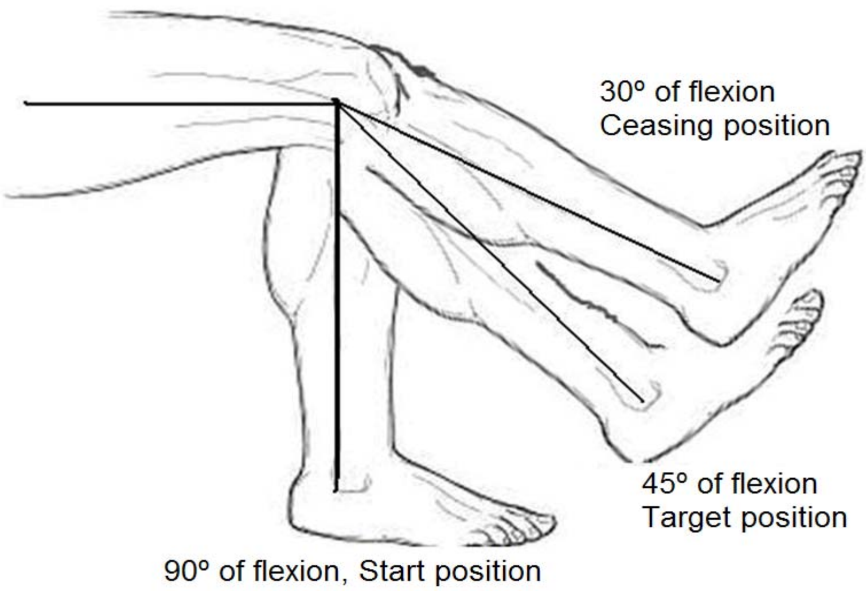


Figure 3.2. Demonstration of the dynamic joint position sense testing.

Prior to each formal test session, participants received 15 repetitions as practice trials at a consistent, slow velocity (5°/sec), to experience the target angle identified earlier in the test of proprioception (Cordo et al., 1994). The actual test session consisted of 60 trials, with 15 trials at each of the 4 extension velocities. During the practice and testing session, feedback of performance was provided verbally by indicating the magnitude and direction of deviation from the target position. To determine the test-retest reliability of the procedures, a second test using the same passive and dynamic protocols was conducted 1 week after the first test session.

3.2.3 Data analysis

3.2.3.1 Surveys

Scores for each component of the R-WOMAC, such as pain (0~20), joint stiffness (0~8) or physical function (0~28) were calculated. Summary scores for individual subjects were derived from the mean of all responses, multiplied by 25, and subtracted from 100 (Whitehouse et al., 2003). The raw R-WOMAC function score was evaluated against the 0 to 100 scale, with a score of 0 indicating extreme restriction in all activities and a score of 100 representing no restriction for any of the items evaluated.

The IKS and functional scores were calculated separately by reference to a scale which ranged from 0 to 100 points, with 100 points representing the highest score. Fifty of the 100 points in the IKS score represent the intensity of pain experienced by the subjects, with a value of 50 points indicating no pain. The other 50 points in the IKS score reflect the clinical assessment, including range of motion, stability, alignment and flexion contracture. For the function score, points are allocated for distance walked and stair-climbing ability and deductions are made for the use of any walking aids, where 100 represents unlimited walking distance and normal stair-climbing without the use of any aid (Lingard et al., 2001). The scores for Knee Score and Function Score were calculated separately.

A summary of the OKS based on the responses of the 12-item questionnaire was calculated for each subject (Spencer et al., 2007).

3.2.3.2 Proprioception measures

For proprioceptive testing, 3 dependent variables were calculated according to previously developed procedures (Cordo et al., 1994; Verschueren, Brumagne, Swinnen, & Cordo, 2002). These are constant error (CE) (accuracy), variable error (VE) (precision), and absolute error (AE) (combination of accuracy and precision).

CE was the arithmetic difference between the target angle and the perceived angle. CE represents accuracy with directional bias. A negative CE value represents an undershoot error, which means the perceived angle was in a more flexed position than the target position. A positive value represents an overshoot error.

VE was defined as the standard deviation of the angle errors between the target position and the position where subjects perceived and pressed the hand-held button. VE represents the consistency of angle deviations and was calculated separately for position sense when measured using the passive protocol and for each velocity of the dynamic model.

AE was defined as the absolute value of the deviation between the subjects' responses and the target, irrespective of direction. This measure accounted for bias and variability.

3.2.4 Statistical analysis

The methods of statistical analysis for the different data sets are presented separately below. All analyses were conducted using the Statistical Package for Social Science (SPSS, Version 15.0.0; Chicago, IL, USA) for Windows.

Descriptive statistics for age, weight, height, Body Mass Index (BMI) and time since surgery for the TKR group were calculated. After the normality distribution was confirmed using the Kolmogorov-Smirnv test, an independent-samples t-test was used to identify any differences in these measures between the control and TKR groups.

Descriptive statistics for each group were calculated for the individual components for pain, joint stiffness and function, together with the summary scores for the R-WOMAC, IKS and function scores and the OKS. After confirmation of normality and equal variance, an independent samples t-test was used to compare these parameters between the control and TKR groups.

To demonstrate the relative reliability of the 2 protocols of proprioceptive measurement, 2 test-retest statistical procedures were used including: 1) Mean difference and 95% confidence interval (CI); and 2) the two-way random effect model (absolute agreement definition), single measure Intra-class coefficient (ICC) and 95% CI (Hurkmans et al., 2007; Rankin & Stokes, 1998).

Differences in the measures of proprioception in the passive mode were compared between knees (operated knee, non-operated knee, dominant knee and non-dominant knee of the control subjects) using one-way analysis of variance

(ANOVA) (independent variable: knee). One-way ANOVA was also used to compare differences in measures of DJPS between knees for each velocity separately. LSD post-hoc test was used to determine the location of any significant differences.

The impact of movement velocity when testing proprioception dynamically on the magnitude of AE, VE and CE for the knees of TKR and control subjects, was further analysed for Session 1 and Session 2 separately using a two-way ANOVA (knees × velocity).

Pearson's correlation coefficient was adopted to demonstrate the relationship between the outcomes of the more qualitative and subjective functional evaluation instruments and the objective measurements of position sense determined passively and dynamically in the second testing session.

3.3 RESULTS

3.3.1 Group age and anthropometric profiles

Age and anthropometric profiles of the TKR and control subjects are presented in Table 3.2.

Table 3.2
Age and anthropometric profiles for TKR and control subjects (Mean ± SD)

Characteristics	TKR subjects	Control subjects	t-value	*p*-value
Age (yr)	68.9 ± 4.9	66.3 ± 5.1	1.389	0.176
Weight (kg)	84.7 ± 20.6	73.9 ± 12.8	1.698	0.101
Height (m)	1.68 ± 0.1	1.72 ± 0.1	1.121	0.272
BMI (kg/m^2)*	29.7 ± 4.7	25.0 ± 2.5	3.436	0.002*

*Significant difference ($p < 0.05$).

No significant differences were found between TKR and control groups with respect to age, body weight and height. The mean body mass index (BMI) of the TKR group was significantly ($p < 0.05$) higher than that for the control group.

The mean post-operative follow-up period for TKR subjects was 11.5 months (range: 7–15 months) at the time of commencement of testing. This variance reflected recruitment difficulties, the diversity of the patient population and the need to minimise the number of surgeons involved and any potential variations in surgical technique.

3.3.2 Subjective assessment of knee function

Analysis of the survey data indicated that pain, stiffness and functional limitation parameters for the control group were consistent with normal knee function. In contrast, similar measures for TKR patients were significantly ($p < 0.05$) higher on each of the 3 subscales leading to a lower total R-WOMAC score for TKR patients when compared to controls (As shown in

Table 3.4, significantly lower scores on both the IKS knee score and function score were found for TKR subjects when compared to that of the controls. TKR subjects had significantly lower IKS scores compared to those of the controls.

OKS results (Figure 3.3) were significantly ($p < 0.001$) higher in the TKR group, with an average value of 21.43 (SD ± 6.25) when compared to the score for the control group of 12.07 (SD ± 0.26).

Table 3.3).

As shown in

Table 3.4, significantly lower scores on both the IKS knee score and function score were found for TKR subjects when compared to that of the controls. TKR subjects had significantly lower IKS scores compared to those of the controls.

OKS results (Figure 3.3) were significantly ($p < 0.001$) higher in the TKR group, with an average value of 21.43 (SD ± 6.25) when compared to the score for the control group of 12.07 (SD ± 0.26).

Table 3.3
R-WOMAC score results for TKR and control groups (Mean ± SD)

Variables	TKR group	Control group	*p*-value
Pain *	2.22 ± 3.11	0 ± 0	< 0.05*
Stiffness *	1.56 ± 1.33	0 ± 0	< 0.001*
Function *	3.22 ± 3.63	0 ± 0	< 0.05*
Total score *	86.10 ± 11.19	100 ± 0	< 0.001*

*Significant difference ($p < 0.05$).

Table 3.4
IKS knee score and function score results for TKR and control groups (Mean ± SD)

IKS	TKR group	Control group	*p*-value
Knee Score	80.14 ± 8.42	99.67 ± 1.29	<0.001*
Function Score	74.29 ± 19.10	100 ± 0	<0.001*

*Significant difference ($p < 0.05$).

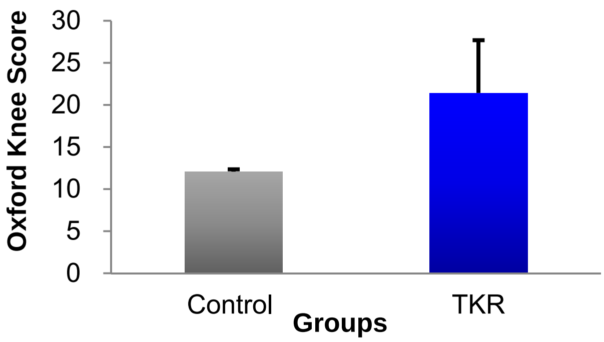


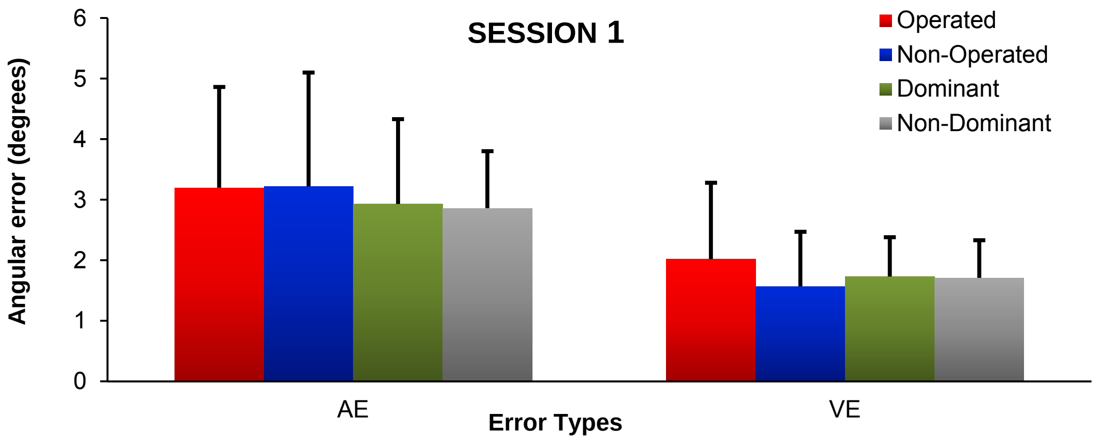
Figure 3.3. Results of Oxford Knee Score for control and TKR groups.

3.3.3 Performance in joint position sense measurement

An identical experimental and instrument configuration was used to evaluate test-retest reliability of the measures of proprioception obtained during the 2 test sessions which were conducted 1 week apart.

3.3.3.1 Passive angular reproduction performance

As shown in Table 3.5 and



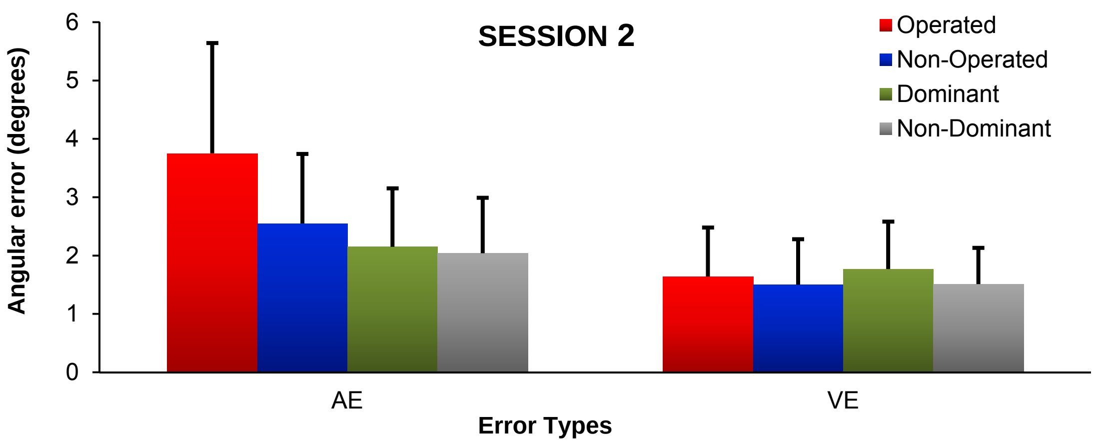


Figure 3.4 (Session 1), no significant differences were found between the TKR and control groups with respect to the 3 variables for proprioception (CE, AE and VE).

Table 3.5

Proprioceptive performance during PAR in Session 1 (Mean ± SD)

Error type	TKR group		Control group		
	Operated	**Non-Operated**	**Dominant**	**Non-Dominant**	***p*-value**
CE	-0.99 ± 3.20	-0.27 ± 3.61	-0.82 ± 2.66	-0.51 ± 2.06	0.917
AE	3.44 ± 1.64	3.23 ± 1.88	3.07 ± 1.45	3.02 ± 1.11	0.882
VE	1.84 ± 0.82	1.66 ± 1.21	1.91 ± 0.96	1.91 ± 0.99	0.895

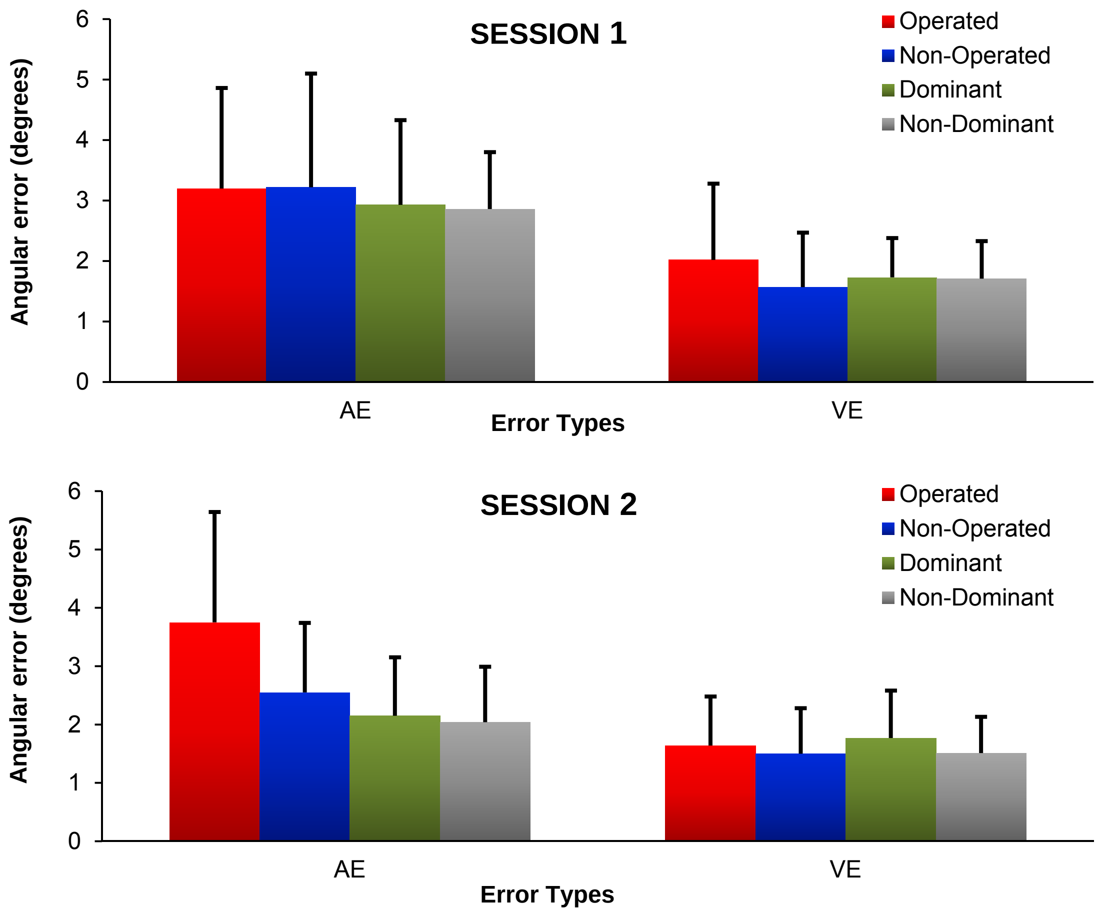


Figure 3.4. Angular Error in passive angular reproduction during two sessions.

As shown in Table 3.6, no significant differences were found between TKR and control groups with respect to the CE and VE during the second testing session. In contrast, the mean AE of the operated knee was significantly (p < 0.05) greater than that of their contralateral knees and those of the control subjects.

Table 3.6
Proprioceptive performance during PAR in Session 2 (Mean ± SD)

Error type	TKR group		Control group		*p*-value#
	Operated	**Non-Operated**	**Dominant**	**Non-Dominant**	
CE	-0.63 ± 2.92	-0.06 ± 3.32	-0.83 ± 2.82	-0.48 ± 2.19	0.901
AE	3.75 ±1.89	2.55 ± 1.19	2.50 ± 1.43	2.37 ± 1.56	0.048[*,a,b,c]
VE	1.64 ± 0.84	1.50 ± 0.78	1.95 ± 0.94	1.75 ± 1.19	0.634

p-values are reported for one-way ANOVA comparisons between the knees for both TKR group and control group.

* Significant ($p < 0.05$) main effect of groups.

[a] Significant difference ($p < 0.05$) between the operated and non-operated knees for TKR group.

[b] Significant difference ($p < 0.05$) between the operated knees and the dominant knees for control group.

[c] Significant difference ($p < 0.05$) between the operated knees and the non-dominant knees for control group.

3.3.3.2 Dynamic joint position sense of knee joint

As shown in on Table 3.7, no significant differences were found for CE and AE between the 2 groups, regardless of the velocity adopted during the measurement. However, ANOVA revealed statistically significant differences in AE at 4 testing velocities with a p-value of less than 0.05 at testing Session 1 (Figure 3.5). Post-hoc (LSD) analyses further demonstrated that the AE of the replaced knee was significantly greater than that of the contralateral or non-operated limb and both dominant and non-dominant knees of the control subjects.

Consistent with the results for test Session 1, no significant differences were found with respect to the CE and VE between groups at 4 movement velocities during testing Session 2 (Table 3.8). Also in agreement with the findings for Session 1, ANOVA analysis revealed that the AE was significantly different among groups (

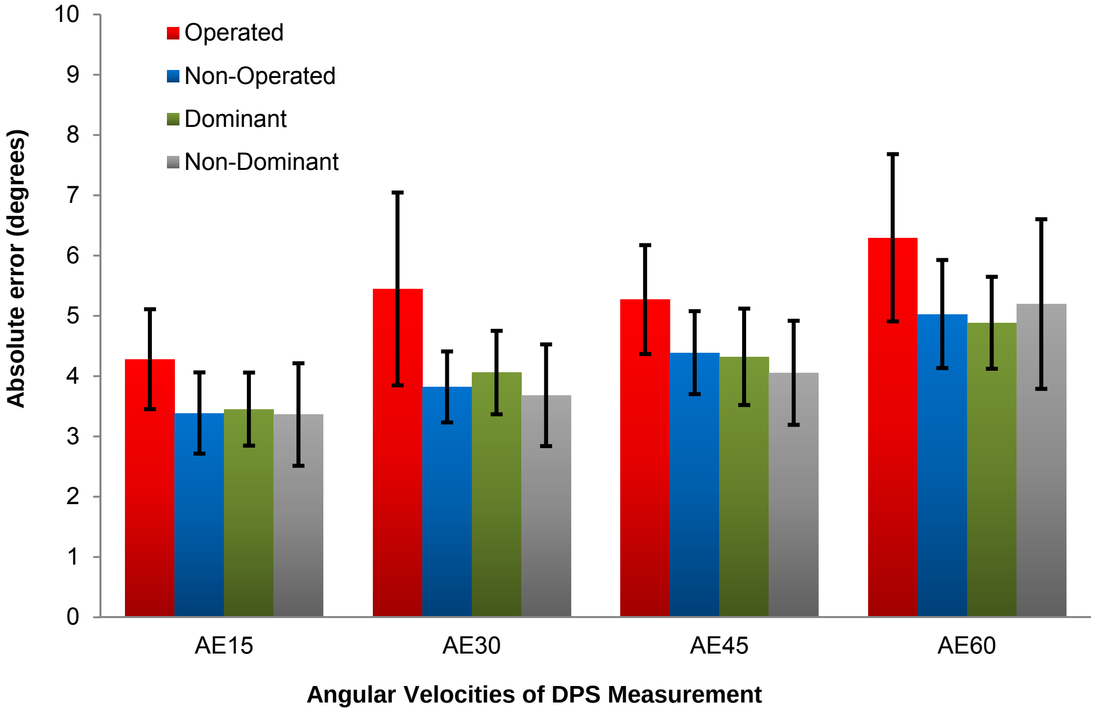


Figure *3.6*). Post-hoc (LSD) test again revealed that the magnitude of AE was significantly greater in the replaced knee than that of the contralateral knee and both the dominant and non-dominant knees of control subjects.

Table 3.7

Proprioceptive performance during DJPS in Session 1 (Mean ± SD)

Velocity		TKR group		Control group		F value	p-value
		Operated	Non-Operated	Dominant	Non-Dominant		
CE	15°/s	0.64 ± 3.78	1.79 ± 1.99	1.50 ± 2.10	0.39 ± 2.60	0.893	0.451
	30°/s	1.39 ± 4.76	1.80 ± 2.51	1.08 ± 2.45	0.31 ± 2.98	0.536	0.659
	45°/s	-0.33 ± 4.72	-0.23 ± 2.74	1.14 ± 3.25	1.12 ± 3.14	0.772	0.515
	60°/s	-0.86 ± 6.18	-1.34 ± 3.48	0.13 ± 3.45	0.22 ± 2.86	0.485	0.694
AE	15°/s	4.61 ± 1.30	3.50 ± 0.93	3.57 ± 0.68	3.42 ± 0.74	5.026	0.004
	30°/s	5.55 ± 1.84	4.16 ± 0.92	3.94 ± 0.81	4.01 ± 0.71	6.268	0.001
	45°/s	5.56 ± 1.95	4.30 ± 0.85	4.54 ± 0.69	4.57 ± 0.77	3.200	0.030
	60°/s	6.69 ± 2.36	5.46 ± 1.11	5.27 ± 0.76	5.40 ± 0.99	3.759	0.016
VE	15°/s	2.30 ± 0.74	2.04 ± 0.67	2.49 ± 0.87	2.37 ± 0.98	0.759	0.522
	30°/s	3.01 ± 1.25	2.62 ± 0.69	2.43 ± 0.69	2.33 ± 0.73	1.689	0.180
	45°/s	2.84 ± 1.22	2.36 ± 0.64	2.83 ± 0.89	2.59 ± 0.60	0.956	0.420
	60°/s	3.82 ± 1.51	3.41 ± 1.06	3.06 ± 0.88	3.27 ± 1.04	1.142	0.340

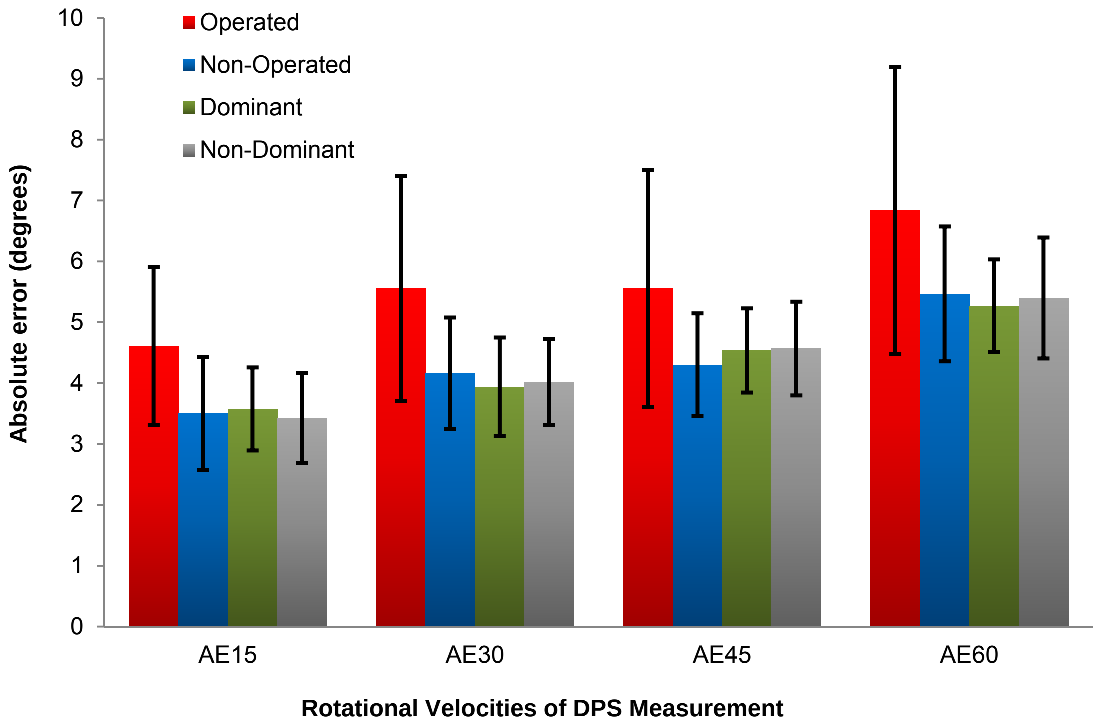


Figure 3.5. Absolute Error (AE) of DJPS at 4 velocities: Session 1.

Table 3.8

Proprioceptive performance during DJPS in Session 2 (Mean ± SD)

Velocity		TKR group		Control group		F value	*p*-value
		Operated	Non-Operated	Dominant	Non-Dominant		
CE	15°/s	0.97 ± 2.67	1.48 ± 1.19	0.65 ± 2.30	0.95 ± 2.07	0.371	0.774
	30°/s	1.85 ± 3.81	0.78 ± 1.72	1.10 ± 2.29	1.74 ± 2.13	0.563	0.642
	45°/s	0.81 ± 3.01	-0.50 ± 2.92	0.82 ± 2.50	0.47 ± 2.24	0.754	0.525
	60°/s	-0.47 ± 3.77	-1.29 ± 3.07	0.89 ± 2.52	0.64 ± 3.32	1.460	0.236
AE	15°/s	4.28 ± 0.83	3.39 ± 0.67	3.45 ± 0.61	3.36 ± 0.85	4.959	0.004
	30°/s	5.44 ± 1.60	3.82 ± 0.59	4.06 ± 0.69	3.88 ± 0.56	9.235	0.000
	45°/s	5.27 ± 0.90	4.39 ± 0.69	4.35 ± 0.83	4.15 ± 0.97	5.927	0.001
	60°/s	6.29 ± 1.39	5.17 ± 0.96	5.04 ± 0.65	5.06 ± 0.87	4.431	0.007
VE	15°/s	2.28 ± 0.68	1.82 ± 0.45	1.91 ± 0.49	2.02 ± 0.65	1.732	0.171
	30°/s	2.51 ± 1.13	1.98 ± 0.57	2.01 ± 0.70	2.04 ± 0.56	1.506	0.224
	45°/s	2.58 ± 0.82	2.34 ± 1.05	2.26 ± 0.50	2.14 ± 0.55	0.857	0.469
	60°/s	3.01 ± 1.02	2.89 ± 0.94	2.77 ± 0.64	2.89 ± 0.94	0.166	0.919

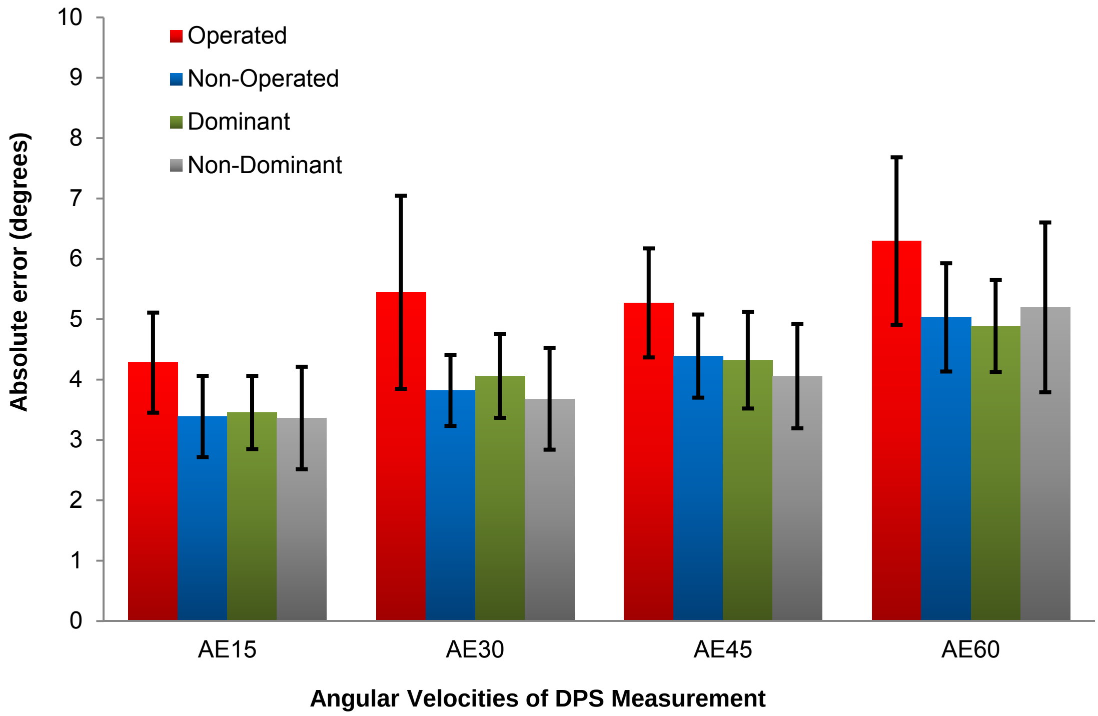


Figure 3.6. Absolute Error (AE) of DJPS at 4 velocities: Session 2.

No significant interaction effect was found between knees and movement velocities as indicated by Wilkis' Lambda values of 0.821 (p=0.306) for Session 1 and 0.754 for Session 2 (p = 0.089), respectively. Both TKR and control groups showed an increased magnitude of AE corresponding to the increases in movement velocity (Figure 3.7). The main effect of movement velocity comparing the operated and non-operated knees of the TKR group and dominant and non-dominant knees of the control group was statistically significant ($p < 0.05$) for both sessions. Post-hoc tests revealed significantly ($p < 0.05$) higher AE for the operated knee compared to that of the non-operated knee of the TKR group and both knees of the control group. This finding was consistent across the 4 testing velocities in both test sessions.

As shown in Figure 3.8, movement velocity did not significantly influence CE for TKR and control groups, although there was a trend towards subject overshoot at higher speeds, in contrast to a tendency to undershoot at a slower movement velocity.

Moderate but non-significant increases in VE when using the DJPS protocol were shown for both knees of the TKR and control group (Figure 3.9).

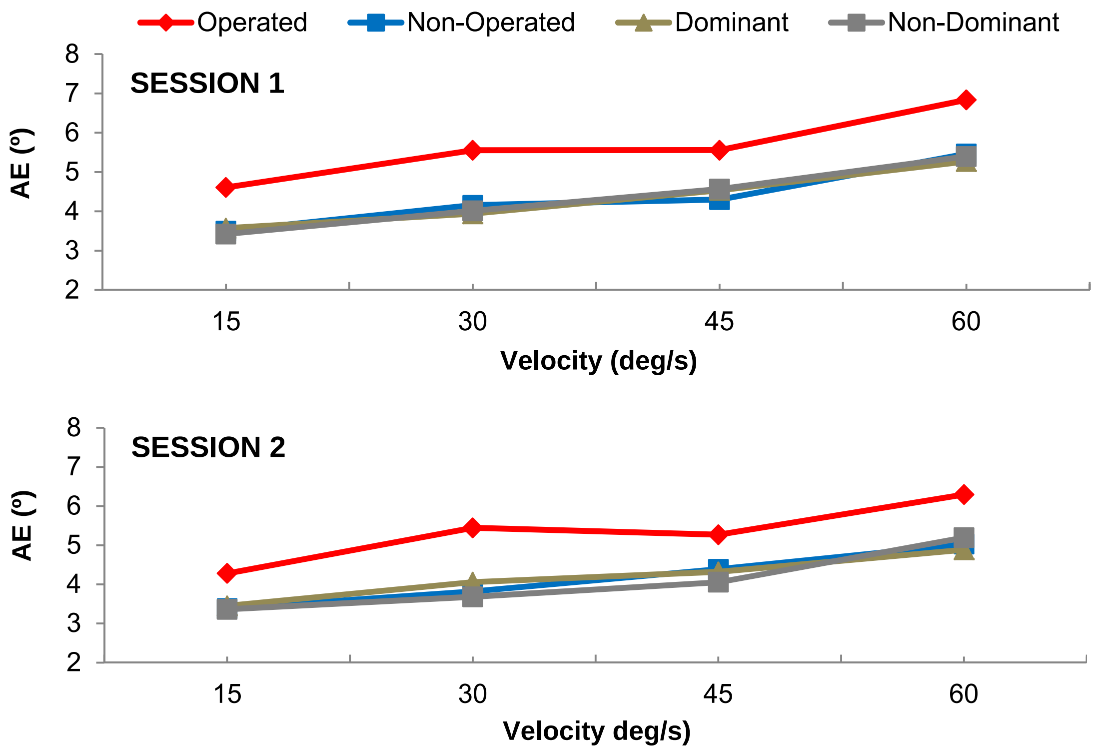


Figure 3.7. Absolute Error (AE) of knees tested at 4 different velocities.

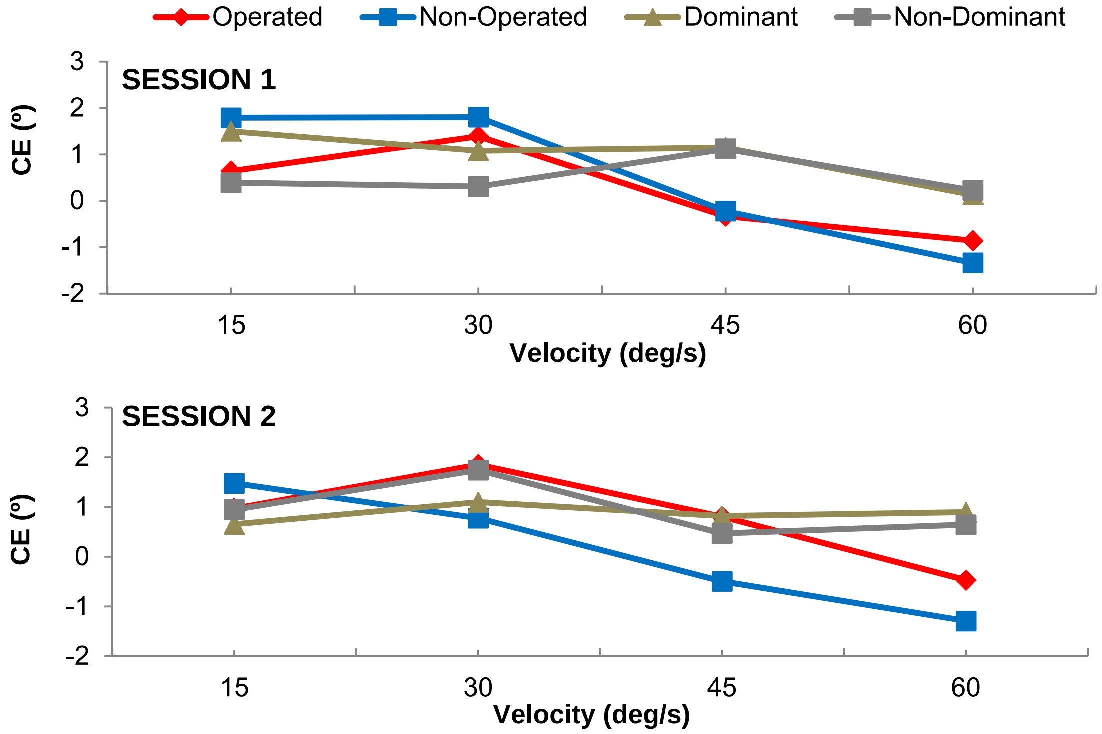


Figure 3.8. Constant Error (CE) of knees tested at 4 different velocities.

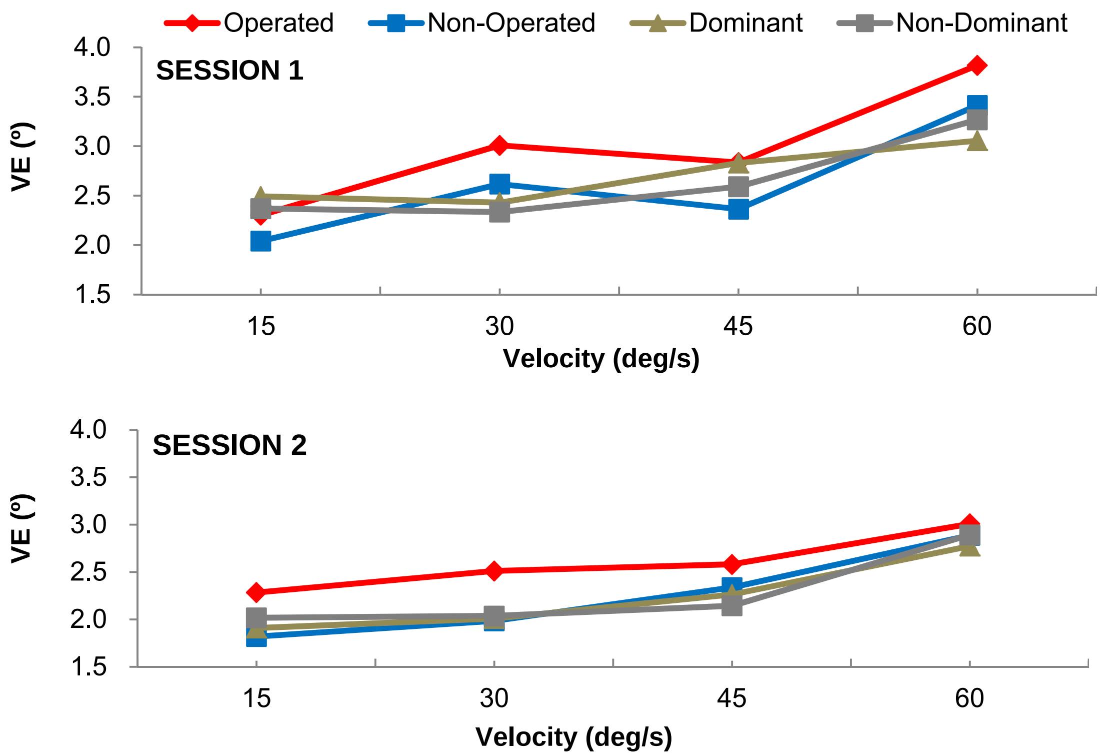


Figure 3.9. Variable Error (VE) of knees tested at 4 different velocities.

3.3.4 Reliability of proprioception measurement

3.3.4.1 Reliability of the passive angular reproduction measurement

No significant differences were found between testing Session 1 and Session 2 for all of the error variables in both the TKR and control groups (Table 3.9).

The ICC values were calculated separately for each of the 3 variables including CE, AE and VE during the PAR testing (Table 3.10). Results showed good to excellent reliability of CE and AE of PAR testing with values of ICC greater than 0.75, while VE showed fair to good reliability with an ICC value in the TKR group of less than 0.75.

Table 3.9
Differences in the passive angular reproduction testing between Session 1 and Session 2: Mean (95% CI)

Variables	TKR group		Control group	
	Operated	Non-Operated	Dominant	Non-Dominant
CE	0.37 (-0.14~0.88)	0.14 (-0.10~0.39)	-0.01 (-0.40~0.38)	0.03 (-0.40~0.46)
AE	0.31 (-0.60~1.21)	-0.68 (-1.49~0.14)	-0.57 (-1.13~0.00)	-0.66 (-1.37~0.05)
VE	-0.20 (-0.69~0.28)	-0.16 (-0.82~0.50)	0.04 (-0.40~0.48)	-0.17 (-0.61~0.28)

Table 3.10
Test-retest reliability ($ICC_{2,1}$ 95% CI) in the passive angular reproduction testing

Variables	TKR group		Control group	
	Operated	Non-Operated	Dominant	Non-Dominant
CE	0.99 (0.97~0.99)	0.99 (0.98~0.99)	0.98 (0.98~0.99)	0.97 (0.90~0.99)
AE	0.75 (0.23~0.92)	0.75 (0.62~0.92)	0.86 (0.57~0.95)	0.71 (0.55~0.90)
VE	0.66 (0.07~0.89)	0.54 (0.43~0.85)	0.78 (0.35~0.93)	0.85 (0.74~0.95)

3.3.4.2 Reliability of dynamic joint position sense measurements

No significant differences between Session 1 and Session 2 were found for both CE and AE, regardless of the velocity used during the testing (Table 3.11). However, significant (p < 0.05) decreases in VE were found in Session 2 when compared to Session 1 at different velocities. This included, the VE15, VE30 and VE45 for dominant side of the control subjects and VE45 for the non-dominant side of the control subjects. Meanwhile, VE30 of both operated and non-operated knees of the TKR subjects showed a significant improvement.

The ICC values together with 95% CI for CE, AE and VE during DJPS at 4 different velocities for both groups are shown in Table 3.12 to Table 3.14. The small ICC values of 0.31 for CE60 and 0.33 for VE60 were found for the non-dominant leg and dominant leg of the control group, indicated poor reliability for these 2 variables. More consistent ICC values of AE were found with only one value of AE measured at 45°/sec. This was shown to be below 0.75, indicating a fair to good reliability for this variable of AE at the different velocities used in this study.

Table 3.11

Differences in the dynamic joint position sense testing between Session 1 and Session 2: Mean (95% CI)

Variable	TKR group		Control group	
	Operated	**Non-Operated**	**Dominant**	**Non-Dominant**
CE15	0.33 (-1.56~2.22)	-0.31 (-1.00~0.37)	-0.84 (-1.85~0.16)	0.56 (-0.86~1.97)
CE30	0.46 (-0.99~1.92)	-1.02 (-2.19~0.14)	0.02 (-1.11~1.15)	1.44 (-0.15~3.02)
CE45	1.17 (-0.30~2.65)	-0.27 (-1.63~1.10)	-0.32 (-1.67~1.03)	-0.65 (-1.96~0.67)
CE60	-0.48 (-3.16~2.21)	-0.82 (-2.81~1.16)	0.78 (-0.88~2.44)	0.42 (-2.35~3.20)
AE15	-0.33 (-0.75~0.09)	-0.12 (-0.34~0.11)	-0.57 (-1.13~0.00)	-0.66 (-1.37~0.05)
AE30	-0.11 (-0.84~0.62)	-0.34 (-0.73~0.05)	0.12 (-0.30~0.54)	-0.13 (-0.29~0.02)
AE45	-0.29 (-0.78~0.51)	0.09 (-0.29~0.46)	-0.19 (-0.40~0.02)	-0.41 (-0.85~0.02)
AE60	-0.40 (-1.06~0.26)	-0.29 (-0.63~0.04)	-0.22 (-0.47~0.02)	-0.34 (-0.68~0.01)
VE15	-0.02 (-0.27~0.23)	-0.22 (-0.58~0.14)	-0.58 (-1.03~-0.14)	-0.35 (-0.87~0.17)
VE30	-0.50 (-0.88~-0.12)	-0.63 (-1.02~-0.24)	-0.42 (-0.79~-0.05)	-0.30 (-0.73~0.10)
VE45	-0.25 (-0.80~0.29)	-0.03 (-0.76~0.70)	-0.57 (-1.03~-0.11)	-0.45 (-0.79~-0.10)
VE60	-0.81 (-1.29~0.33)	-0.53 (-1.09~0.04)	-0.28 (-0.82~0.26)	-0.37 (-0.96 ~0.21)

Table 3.12

Test-retest reliability of constant error at different velocities ($ICC_{2,1}$, 95% CI) in the dynamic joint position sense testing

Variable	TKR group		Control group	
	Operated	Non-Operated	Dominant	Non-Dominant
CE15	0.66 (0.04~0.89)	0.85 (0.53~0.95)	0.80 (0.39~0.93)	0.58 (0.25~0.86)
CE30	0.91 (0.71~0.97)	0.72 (0.12~0.91)	0.77 (0.32~0.92)	0.56 (0.31~0.85)
CE45	0.89 (0.66~0.97)	0.79 (0.34~0.93)	0.79 (0.36~0.93)	0.77 (0.31~0.92)
CE60	0.77 (0.27~0.93)	0.96 (0.88~0.99)	0.67 (0.03~0.89)	0.31 (0.22~0.53)

Table 3.13

Test-retest reliability of absolute error at different velocities ($ICC_{2,1}$, 95% CI) in the dynamic joint position sense testing

Variable	TKR group		Control group	
	Operated	Non-Operated	Dominant	Non-Dominant
AE15	0.87 (0.61~0.96)	0.94 (0.81~0.98)	0.97 (0.90~0.99)	0.84 (0.51~0.95)
AE30	0.85 (0.52~0.95)	0.77 (0.27~0.93)	0.76 (0.49~0.88)	0.84 (0.52~0.95)
AE45	0.75 (0.50~0.89)	0.78 (0.32~0.93)	0.93 (0.80~0.98)	0.71 (0.55~0.90)
AE60	0.78 (0.62~0.93)	0.76 (0.25~0.92)	0.89 (0.66~0.96)	0.76 (0.59~0.85)

Table 3.14

Test-retest reliability of variable error at different velocities ($ICC_{2,1}$, 95% CI) in the dynamic joint position sense testing

Variable	TKR group		Control group	
	Operated	Non-Operated	Dominant	Non-Dominant
VE15	0.90 (0.69~0.97)	0.56 (0.36~0.86)	0.52 (0.42~0.84)	0.54 (0.37~0.85)
VE30	0.92 (0.74~0.97)	0.60 (0.24~0.87)	0.69 (0.09~0.89)	0.57 (0.39~0.85)
VE45	0.74 (0.58~0.92)	0.41 (0.35~0.64)	0.50 (0.33~0.83)	0.59 (0.42~0.86)
VE60	0.88 (0.63~0.96)	0.69 (0.04~0.90)	0.33 (0.20~0.78)	0.61 (0.44~0.87)

3.3.5 Relationship between proprioception and functional performance

Compromised proprioception measured by AE during testing of DJPS at the second session was associated with greater limitation in functional performance, as identified in the results of the qualitative questionnaires (Table 3.15). No significant relationships were found between the measures of proprioception as determined by PAR and outcomes of the self-reported questionnaires.

Table 3.15
Relationship between dynamic joint position sense and functional performance measures

	R-WOMAC		**Oxford-12 item**		**IKS-function score**	
	Pearson's coefficient	***p*-value**	**Pearson's coefficient**	***p*-value**	**Pearson's coefficient**	***p*-value**
AE30	-0.376	0.045	0.381	0.041	-0.384	0.046
AE45	-0.426	0.021	0.431	0.020	-0.489	0.007
AE60	-0.488	0.007	0.494	0.006	-0.463	0.012

3.3.6 Discussion

Anatomical studies have demonstrated that the proprioceptive input from mechanoreceptors in connective tissue structures such as muscles, tendons, joint capsules, ligaments, and skin is essential in providing the nervous system with information with respect to control of body position and movement (Hogervorst & Brand, 1998). The information contributes to formation of a conscious perception by the central nervous system of joint positioning (Hogervorst & Brand, 1998) and the planning, control and correction of motor commands (Ghez & Sainburg, 1995).

The effect of ageing and conditions such as knee OA on proprioception is well documented. However, due to the complexity of the underlying mechanisms and neural pathways involved in proprioception and different protocols used in its measurement, the reliability of these measurements has not been fully demonstrated. In addition to ageing factors and joint conditions, knowledge of the reliability of proprioceptive measurement following joint replacement is limited.

Consequently, a primary goal of this study was to evaluate the reproducibility and reliability of proprioception measurement at the knee following TKR using both PAR and DJPS. Identification of the most reliable measurement protocol was then used in the evaluation of differences in proprioceptive function between TKR patients and age-matched control subjects. Finally, the relationship between the proprioceptive measures and functional outcomes derived from the qualitative questionnaires following TKR was evaluated.

3.3.7 Reliability of joint position sense measurement

Reliability of a measurement such as proprioception is important when evaluating changes in proprioception following surgery and the efficacy of rehabilitation interventions. Improved reliability will reduce the risk of measurement error and provide more accurate interpretation of research findings. Such reliability is particularly important in prospective follow-up studies. Measurement errors comprise systematic bias and random error, the former usually resulting from the learning or fatigue effects during the test and re-test sessions. In contrast, random error is mainly due to the inherent variations of subjects or the instruments used (Rankin & Stokes, 1998).

In the present study, no differences were found between a majority of the test and re-test scores obtained from JPS testing, using either passive or dynamic protocols indicating good reliability. The ICC is the most widely used expression of test-retest reliability identified in the literature and an ICC > 0.75 is generally acknowledged as having excellent reliability and an acceptable criterion for clinical studies. In contrast, ICC levels of <0.40 and between 0.40 and 0.75 are referred to as representing poor reliability and poor to good reliability respectively (Lonn, Crenshaw, Djupsjobacka, & Johansson, 2000; Shrout & Fleiss, 1979). Reference to these criteria showed that the reliability of testing of PAR in this study was fair to good. The reliability of measurements derived from testing of JPS using a dynamic protocol indicated variations in reliability, with only fair to good for CE and VE. In contrast, the reliability for measures of AE was good to excellent. The relatively high reliability of AE compared with VE during proprioceptive assessment is consistent with the findings of earlier studies on the elbow joint of healthy subjects using similar protocols (Juul-Kristensen et al., 2008), with ICC values of 0.59 and 0.007, respectively. The reduced reliability of measurement may be attributed to the lower precision of VE (Juul-Kristensen et al., 2008).

The reliability of proprioceptive measurement has been previously evaluated in a limited number of studies which have focused on proprioceptive assessment of the hip (Benjaminse, Sell, Abt, House, & Lephart, 2009), ankle (Deshpande, Connelly, Culham, & Costigan, 2003; Lim & Tan, 2009; You, 2005) and elbow joints (Juul-Kristensen et al., 2008). Anatomical and physiological differences between joints and variations in the number of mechanoreceptors and muscle spindles make it essential to provide joint specific reliability measures for proprioception.

No directly comparable information was available with respect to the reliability of measurement of angle reproduction using passive and dynamic protocols at the knee joint. Although several studies have investigated the reliability of proprioceptive assessment of this joint in healthy subjects (Ageberg, Flenhagen, & Ljung, 2007; Hurkmans et al., 2007; Pincivero, Bachmeier, & Coelho, 2001) and patients with knee OA (Hurkmans et al., 2007; Marks & Quinney, 1993), the differences in the protocols used makes direct comparison with the results of this study difficult. The protocols used in previous studies for proprioceptive assessment of the knee joint in OA or TKR subjects were generally divided into 2 categories: detection of joint position (joint position sense), or joint movement sense. Three of the 4 studies mentioned previously (Ageberg et al., 2007; Hurkmans et al., 2007; Pincivero et al., 2001) used the protocol defined as the TDPM. It has been suggested that this protocol, provides a measurement of proprioception which differs from measures derived from passive and active protocols involving perceptions of joint position sense (Wada et al., 2002) as used in the present study.

In addition to subject variance, the reliability of the test-retest procedure is mainly influenced by factors that may cause inconsistencies in the testing procedures used in the 2 sessions. To reduce any variability, the testing procedure used in the present study was standardised with respect to the same tester conducting all tests, use of the same verbal instructions, and identical setting-up of the dynamometer chair and positioning of the subject. As recommended by previous studies (Fonseca et al., 2005; Hurkmans et al., 2007; MacDonald, Hedden, Pacin, & Sutherland, 1996), the same air splint was also used to reduce input of cutaneous information and vibration of the dynamometer motor. Measurement of proprioception can also be confounded by the environmental circumstances during the measurement. For example, the attention of the subjects may be influenced by the surrounding noise which may also stimulate subjects to use any sounds such as that emanating from the equipment as auditory cues to estimate the initiation of the movement (Koralewicz & Engh, 2000). To avoid these problems, headphones were worn during the course of the measurement procedures.

Six and 15 repetitions were used in this study in the measurement of passive and dynamic JPS respectively to reduce the potential influence of within-subject variability. In contrast, similar measures in previous studies have involved either 3 or 5 repetitions (Hopper et al., 2003; Hurkmans et al., 2007; Ishii et al., 1997; Khabie et al., 1998). Recommendations from these and other studies indicate that 5 and 6 repetitions respectively for assessment of active-active and passive-passive JPS provides a stable measure for minimising the standard deviation in absolute terms by less than 5% of the average recorded from at least 3 successive trials (Selfe et al., 2006). For dynamic testing of JPS, 10 to 20 repetitions were used in the study of ankle (Verschueren et al., 2002) and elbow joint proprioception (Cordo et al., 1995; Cordo et al., 1994) and constant results of the AE and VE were found in these previous studies.

Subjects in the present study were allowed to practice the protocol prior to testing to familiarise with the measurement procedure. Improvement in a number of the measures of VE was found when comparing the results of the 2 test sessions. However, no significant practice effect was found in the CE and AE during DJPS testing. The findings were in agreement with the results of a previous study, which found that the decreased VE was shown to relate to limited practice and familiarisation with the procedure when testing the elbow joint (Cordo et al., 1994). This earlier study also found that the significant decrease in VE was only found when tested at the fastest velocity. In contrast, no significant practice effect was found in the CE. Therefore, the influence of any learning effects on the AE can most likely be excluded and the reliability can mainly be attributed to within-subject variability of the measurement (Juul-Kristensen et al., 2008).

The time interval between the initial test and re-test sessions may also play a role in the potential learning effect inherent in these tests of proprioception. A period of one week between test sessions was adopted in the present study, in accordance with previous reliability studies of proprioceptive assessment in the hip joint of healthy subjects using the same device (Biodex System 3) (Ageberg et al., 2007). No significant alterations in the magnitude of both JPS and TDPM between test sessions were found using this time period. This finding was consistent with the results of a study of patients with knee OA and healthy control subjects using an interval of 14 days between test sessions (Hurkmans et al., 2007). In contrast, when the interval between test sessions was 24 hours, more accurate performance during repeated DJPS testing was reported in both elderly and young adults. A potential learning effect was identified as the main contributor to this improvement (Verschueren et al., 2002).

In summary, in TKR patients and control subjects, measurements of CE, AE and VE of JPS using a passive protocol showed fair to good reliability. Fair to good reliability was also found in the CE and VE when JPS was tested in the dynamic mode. The AE of DJPS showed good to excellent reliability.

3.3.8 Passive joint position sense

As described earlier, measurement of proprioception is generally divided into joint motion sense and position sense. Ipsilateral testing of joint angle reproduction is generally considered to be a measurement of JPS and is further categorised into either passive or active angle reproduction protocols used during the testing. The results of angle reproduction testing and accuracy of the measurement can be influenced by a number of task-related factors such as weight-bearing status and joint position at the end of the range of motion during the testing (Goble, Coxon, Wenderoth, Van Impe, & Swinnen, 2009).

Measurement of accuracy in angle reproduction in passive protocols, as used in this study, has been used for measurement of proprioception in previous studies involving elderly adults (Skinner, Barrack, & Cook, 1984; Tsang & Hui-Chan, 2003), ACL-deficient subjects (Fischer-Rasmussen & Jensen, 2000), patients following ACL-reconstruction (Bonfim, Jansen Paccola, & Barela, 2003; Reider et al., 2003) and knee OA patients (Hassan, Mockett, & Doherty, 2001; Swanik et al., 2004). Findings from these studies indicate that the acuity of PAR provides a valid measure which is able to distinguish potential proprioceptive changes in those with pathologic conditions. Results of these earlier studies consistently demonstrated that older people and those with different pathologic conditions showed decreased accuracy in angle reproduction when compared to their age-matched healthy subjects.

Findings from this study indicated that at an average of 11.5 months post-operatively the TKR patients demonstrated accuracy in reproducing the target angle for the operated knee. This was comparable with that found for the contralateral knee and similar measures of their age-matched control subjects during the first testing session. However, significant differences ($p < 0.048$) were found in the acuity of PAR, as indicated by AE in the second testing session, although no significant improvement was found in both groups as indicated earlier. This result was consistent with findings from a previous study of 38 TKR patients at an average of 18 months post-operatively using similar protocols for the measurement of proprioception (Wada et al., 2002). An average AE of 3.6° in the operated knee was found in the TKR group, which was significantly greater than that of the control group (2.4°) (Wada et al., 2002). The present study showed similar proprioceptive performance with an AE of 3.75° in the operated knee and 2.5° for the dominant side of the control subjects.

In addition to AE, no significant differences were found in other measures of PAR acuity such as CE and VE. These findings were consistent with earlier findings in which CE was unable to distinguish differences in proprioceptive accuracy in the knees of patients with torn knee menisci and their contralateral knee using a similar measurement protocol (Thijs et al., 2007). Results of the present study confirm the importance of AE as a reliable measure of PAR which has been used by a majority of previous studies of similar patient groups irrespective of whether the JPS was measured with a passive (Fuchs, Frisse, Tibesku, Laass, & Rosenbaum, 2002; Wada et al., 2002) or active protocol (Fuchs, Thorwesten, & Niewerth, 1999; Lattanzio, Chess, & MacDermid, 1998).

CE is a measure of the difference between the target and the perceived angle and is a measure of angular bias. The value of CE can be positive or negative when overshoot or undershoot occurs respectively. The overshoot and undershoot errors cancel each other out when calculating the average CE. This may lead to misleading results in some cases, with low CE in subjects demonstrating high variability during the proprioceptive testing. VE represents the variability of CE. AE is the absolute value of the deviation between the target angle and the subject's perceived angle, irrespective of direction, which accounts both for bias and variability and therefore it combines the characteristics of both CE and VE (Schmidt & Lee, 1999; Verschueren et al., 2002). Although the different values of these variables have been demonstrated in a study of DJPS (Verschueren et al., 2002), the present study is the first study to include all of these 3 variables and to demonstrate that AE is a more practical representation of proprioception than CE and VE in patients following TKR surgery.

A target angle of 45° of knee flexion in the middle of the joint range of motion and a movement of extension from 75° of knee flexion used in the present study, was in accordance with previous studies of proprioception using angle reproduction protocols (Birmingham et al., 2001; Hassan et al., 2001; Isaac et al., 2007; Lattanzio et al., 1998; Mohammadi, Taghizadeh, Ghaffarinejad, Khorrami, & Sobhani, 2008; Wada et al., 2002). It has been proposed that the joint position and direction of joint motion have a significant effect on proprioceptive acuity. In a study of 29 ACL-deficient athletes, higher proprioceptive acuity was found in movements towards extension starting from 15° compared to 45° of knee flexion. More accurate proprioceptive performance was also found when moving into extension rather than flexion at the starting angle of 15° of knee flexion (Borsa, Lephart, Irrgang, Safran, & Fu, 1997). The latter finding was confirmed by a more recent study of 20 TKR patients (Swanik et al., 2004). The results showed that the magnitude of error in PAR during extension from 15° of knee flexion was 2.06° compared to a value of 3.20° when flexed from the same starting angle. Improvement in proprioception towards the end of the joint range of motion may be associated with increased mechanoreceptor recruitment at the extreme or end position of the joint range, where additional extra-articular structures may be involved in providing feedback for knee positioning (Borsa et al., 1997). Therefore, a middle position within the knee joint range of motion was used in the present study to reduce the influence of extra-articular structures as proprioceptive feedback resources as much as possible. As such, testing of proprioception in the present study relied more on the intra-articular proprioception resources.

Previous research suggests that joint angle reproduction is more accurate when using active rather than PAR protocols (Pickard, Sullivan, Allison, & Singer, 2003; Selfe et al., 2006). This may be indicative of increased involvement of muscle receptors during active reproduction of the pre-determined joint angle. In this situation, more motor units are recruited and more muscle spindles are activated, which serves to improve and enhance joint position acuity (Madhavan & Shields, 2005; Proske, 2006). Proprioceptive performance can also be improved under weight-bearing compared to non-weight-bearing conditions (Baker, Bennell, Stillman, Cowan, & Crossley, 2002; Bullock-Saxton, Wong, & Hogan, 2001). The knee joint functions in conjunction with the hip and ankle joints to facilitate most fundamental functional activities of daily living under weight-bearing conditions. As such, it may be more functionally and clinically relevant to measure proprioceptive performance under weight-bearing conditions. However, considerably more knee extensor strength is required to control body weight when testing proprioception during weight-bearing (Kramer, Handfield, Kiefer, Forwell, & Birmingham, 1997). This makes such testing less appropriate for subjects with OA, muscle weakness or acute injury than non-weight-bearing protocols.

In summary, in the context of this study, AE during PAR has been identified as the most appropriate measure to discriminate the decreased proprioceptive acuity in the operated knee of TKR patients. However, more practice prior to the formal testing, or more repetitions may be required in the protocol, as the AE was unable to identify the differences in the first testing session. In addition, further investigation is needed to study proprioceptive deficiency in relation to other outcome measures of this population.

3.3.9 Dynamic joint position sense

Although the position and motion senses are the fundamental components of proprioception, it is essential to coordinate these sources of information when undertaking complex sensorimotor tasks (Goble et al., 2009). Dynamic JPS represents the ability to monitor position during motion. This has been thoroughly evaluated in healthy young individuals using a task involving opening the hand when the elbow joint rotates through a predetermined target position at a particular velocity (Cordo et al., 1995; Cordo et al., 1994).

Previous studies involving patients with knee OA who have undertaken the TKR procedure have shown a decline in both components of proprioceptive performance. The decline has been demonstrated by a decrease in position sense and motion sense which was evaluated using the threshold for detection of passive movement protocol (Hassan et al., 2001; Swanik et al., 2004). The present study aimed to explore the potential negative effect of knee replacement surgery on DJPS. The results confirmed that proprioceptive performance in relation to DJPS was impaired in the replaced knee. This was indicated by a significantly increased AE of the replaced knee of TKR patients at an average of 11.5 months post-operatively, compared to that of the non-operated contralateral knee and those of control subjects during the DJPS assessment. This finding occurred, regardless of the velocity at which the knee joint was rotated.

Although CE and VE were also included as measures of acuity of the DJPS in the present study, the results were consistent with the findings derived from PAR testing. As such, CE and VE were unable to distinguish differences in proprioceptive performance in the TKR knees and the AE was the only variable which discriminated the decreased proprioceptive accuracy of the replaced knee from that of the contralateral knee and control subjects. Moreover, statistically significant differences in the AE of PAR were only found in the second testing session. In contrast, AE of DJPS was found to be significantly different in both testing sessions.

No comparative studies were found which investigated the DJPS of the knee joint. A relatively small number of studies have investigated DJPS, and have mainly focused on the ankle and elbow joints with the aim of identifying age related changes and the potential mechanism of any changes (Cordo et al., 1995; Cordo et al., 1994; Madhavan & Shields, 2005; Verschueren et al., 2002). Significant decreases in proprioceptive acuity as evaluated by DJPS have been found with ageing in the ankle joint with a mean AE of 2.7° for older subjects aged between 55 to 75 years compared to 2.2° of younger adults (22 years) when the ankle joint was rotated at speeds ranging from 15°/s to 30°/s (Verschueren et al., 2002). The result was confirmed by a later study which indicated that elderly subjects showed significantly greater AE of proprioceptive performance when the elbow joint was rotated at 10~90°/s (Madhavan & Shields, 2005). There was no significant difference in the age of groups in this study which suggests that any ageing effects relate predominantly to within group variance. The results of the present study showed a trend towards an increase in the magnitude of AE with greater velocities of joint movement. The AE increased from approximately 3.3° at 15°/s to more than 5° at 60°/s in the knees of the control subjects and the non-operated knee of the TKR subjects. The values of AE in the operated knee increased from 4.3° to 6.3° simultaneously. These increases were consistent with the results of previous studies in which the effect of movement velocities on DJPS has been investigated (Madhavan & Shields, 2005; Verschueren et al., 2002). A significantly greater magnitude of AE of the DJPS in ankle joint was found as a function of increased movement velocities ranging from 15°/s to 30°/s (Verschueren et al., 2002) and 10~90°/s in both young and elderly individuals (Madhavan & Shields, 2005).

In addition to the impact of the velocity of rotation on the magnitude of AE, the inclusion of practice prior to the formal testing may also influence proprioceptive performance. As indicated in an earlier study, the AE of the DJPS in ankle joint showed a significant improvement in both young and elderly adults when the same proprioceptive measurement was repeated following a 24-hour time interval (Verschueren et al., 2002). Results of this study were consistent with an even earlier study which showed that proprioceptive performance improved with repetition, regardless of the age of the participants and suggested that familiarisation with the testing task via practice repetitions contributed to the improvement (Meeuwsen, Sawicki, & Stelmach, 1993). Therefore, a fixed number of 15 repetitions were given in the present study as practice trials, to ensure that both groups of subjects understood the DJPS testing task.

In summary, the findings indicated that the AE of DJPS is the most appropriate measure to be used in the measurement of proprioceptive performance to identify the reduced proprioceptive acuity in the replaced knee as long as sufficient practice repetitions are given. Furthermore, since DJPS integrates both velocity and position information during the sequential movement tasks and is recognised as more functionally relevant than the PAR, more investigation is warranted to explore the relationship between the proprioceptive deficiency as measured by DJPS and other functional outcome measures.

3.3.10 Functional outcome measures

Results of the present study showed that TKR patients at an average of 11.5 months post-operatively had lower functional outcomes using self-reported information when compared to age-matched control subjects, regardless of the questionnaire used. The overall scores of the R-WOMAC and its 3 sub-scales consistently showed less optimal functionality of TKR subjects when compared to control subjects. Both the knee score and function score of the IKS Score, together with the OKS, also showed that the self-reported functional performance of the TKR subjects was deficient relative to that of healthy controls.

Post-operative improvements have been shown by numerous studies which have compared self-reported functional performance in TKR patients pre- and post-operatively (Kane, Saleh, Wilt, & Bershadsky, 2005; Spencer et al., 2007). At approximately 1 year post-operatively, an average overall score of the R-WOMAC of 86 was found in the current study, which was in agreement with a previous study of 71 TKR patients of similar age (Spencer et al., 2007). This earlier study reported a mean value of 76 at 6 months post-operatively, which was improved from a pre-operative value of 45.7. Further improvement occurred during a 2-year follow-up period to reach an overall WOMAC score of 83.5 (Spencer et al., 2007). A meta-analysis from 7 studies involving 2925 patients showed that the overall score of WOMAC improved from a pre-operative value of 48.3 to 76.8 at 2 years post-operatively with an effect size of 1.62 (Kane et al., 2005). Only 7 items of the original 17 items of functional perspective of WOMAC were retained for the R-WOMAC, which include ascending stairs, rising from sitting, walking on the flat, getting in or out of a car, putting on socks, rising from bed, and sitting.

Improvements in knee function assessed by other self-report questionnaires such as the OKS and the physician administered questionnaire (IKS knee score and function score) have also been shown in previous studies (Jacobs, Anderson, Limbeek, & Wymenga, 2004; Kamat et al., 2008; Lim, Luscombe, Jones, & White, 2006; Spencer et al., 2007). An overall IKS score of 154 was shown in the present study, which was comparable to a score of 135 measured in a previous study at 1 year post-operatively (Kim et al., 2007). Results for the OKS survey were also consistent with those obtained from studies of TKR patients of similar age measured at 1 year (Kamat et al., 2008) and 2 years (Spencer et al., 2007) post-operatively. Another study showed that the OKS of 25.8 was maintained at 5 years following surgery (Kamat et al., 2008).

Compromised proprioception as measured by AE of DJPS was found to be associated with less optimal self-reported functional outcome measures in the present study. This finding was consistent with earlier findings from studies, which explored the relationship between functional performance and proprioception measures in patients with knee OA. Although direct comparison with other studies is potentially influenced by differences in the proprioception measurement protocols used, the results of the present were consistent with those of previous studies, indicating that reduced accuracy of proprioceptive performance was related to poor self-reported functional outcomes. Studies which have used the threshold for detection of passive movement as an index of proprioception, have consistently demonstrated a relationship between measures of proprioception and the WOMAC score (Pai, Rymer, Chang, & Sharma, 1997; van der Esch et al., 2007). In contrast when JPS was used conflicting results have been found (Barrack, Skinner, & Buckley, 1989; Bennell et al., 2003; Grob, Kuster, Higgins, Lloyd, & Yata, 2002; Hortobagyi, Garry, Holbert, & Devita, 2004; Hurley et al., 1997).

These findings suggest that establishment of the relationship between proprioception and functional performance may be further influenced by the measurement protocols of functional performance used. Poorer proprioception has been demonstrated in those subjects with greater disability as assessed by the WOMAC physical function score (Pai et al., 1997), stair climbing time (Barrack et al., 1989) and walking speed (Skinner, Barrack, Cook, & Haddad, 1984). A significant correlation with an R value of 0.95 has been revealed between measurements of stair-walking time and JPS (Marks, 1994). In contrast, little association has been found between proprioceptive performance and functional disability when measured by self-report questionnaires and objective measures such as balance and gait in a study of 220 knee OA patients (Bennell et al., 2003). Therefore, in addition to the measure of proprioception, the protocol of functional performance measurement may also play a critical role in establishing a relationship between proprioception and functional ability.

Proprioception in the present study was measured using both passive and dynamic protocols of varying velocity. Moreover, the proprioception, as measured by the DJPS protocol, was shown to be associated with the functional outcome scores measured by each of the survey tools. Evidence from previous research to substantiate this relationship was not found making comparison with findings from earlier studies which used different measurement protocols inappropriate. As such, further investigations are required to verify the findings of this study. More studies using objective functional outcome measurements are also required since DJPS integrates both the position and velocity information during movement and it is acknowledged as a more functional relevant measurement of proprioception.

Further knowledge of the relationship between qualitative and more objective measures of knee function is essential to assist in the identification of appropriate and sensitive measures which may be used to evaluate the efficacy of surgical and rehabilitation procedures. The outcomes of Study 1 will be used to examine the relationship between proprioception and more objective measures of functional outcomes following TKR surgery.

3.4 CONCLUSIONS

Recovery of functional performance of TKR patients at approximately 1 year post-operatively was lower than functional values of age- and gender-matched counterparts when measured by validated self-report clinical survey tools.

All 3 variables associated with the measurement of proprioception (CE, AE and VE) used in the present study, showed fair to good test-retest reliability during PAR testing. AE at all rotation velocities used during dynamic testing and the CE and VE at most of the rotation velocities showed good to excellent reliability with ICC values of greater than 0.70.

Proprioceptive deficits were apparent in the replaced knee, which was supported by the fact that the magnitude of AE of the replaced knee was significantly greater than that of the contralateral knee off the TKR patients and those of the control subjects. This finding was consistent, regardless of whether a passive or dynamic measurement protocol was used.

No significant correlations were found between the variables of PAR and functional ability as measured by self-report qualitative questionnaires. In contrast, AE during dynamic testing of JPS were found to be significantly related to functional outcomes obtained from the self-report questionnaires.

Chapter 4: Inter-joint coordination of lower limbs during level walking in patients following unilateral TKR

4.1 INTRODUCTION

Gait analysis has been recognised as a key tool for the more objective measurement of functional TKR outcomes. Gait analysis following TKR has shown significant improvement in terms of velocity of gait and stride length when compared to pre-operative conditions (Apostolopoulos et al., 2011; Byrne et al., 2002; Fantozzi et al., 2003; Saari et al., 2004). Modifications to normal gait patterns following TKR are characterised by reduced knee excursion associated with a more flexed hip and reduced ankle plantarflexion. These results indicate that not only excursion of the knee joint itself, but also movements of the other lower limb joints are altered during walking (Ouellet & Moffet, 2002). However, the influence of knee OA and TKR on inter-joint coordination has not been well investigated.

Inter-joint coordination during walking is an essential fundamental component of human mobility, which is controlled and organised by the central nervous system with involvement of the neuromuscular system. The segments or joints of the body must be coordinated to carry out a smooth, stable and effective pattern of locomotion. Dynamical systems theory proposes that movement patterns arise from the synergistic organisation of the neuromuscular system based on morphological, biomechanical and environmental factors and task constraints (Glazier & Davids, 2009). Previous studies have indicated the important contribution of the altered sensorimotor function in knee OA to the changed movement patterns during performance of activities of daily living (Hurley et al., 1997; Mouchnino et al., 2005).

Inter-joint coordination describes the relationship between the motions of 2 joints or segments, including both angular displacements and velocities which are associated with not only the efferent motor control from the central nervous system, but also informative feedback from afferent joint receptors (Burgess-Limerick, Abernethy, & Neal, 1993; Chiu & Chou, 2012). According to the principles of the dynamical systems theory, inter-joint coordination provides information on how the neuro-musculoskeletal system organises the redundant degrees of freedom of the joints and segments to achieve a smooth, efficient and accurate functional movement (Bernstein, 1967; Chiu & Chou, 2013; Kurz & Stergiou, 2002). Inter-joint coordination of 2 joints or segments during gait can be expressed through relative phase measures which are the deviations of phase angle of these 2 related joints or segments. The phase angle combines the information of joint angular positions and velocities (Kurz & Stergiou, 2002; Kurz, Stergiou, Buzzi, & Georgoulis, 2005). Identifying alteration of the patterns of inter-joint coordination can provide quantitative information on how the segments or joints are coordinated during gait. This may provide useful insight into the influence of the knee proprioceptive or afferent mechanisms on the control of the locomotor task.

Proprioception provides the segmental movement or position information related to the motor control system and which is integrated by the central nervous system to differentiate and regulate total posture and segmental posture (joint stability) (Riemann & Lephart, 2002a, 2002b). Knee joint proprioception is critical for accurate modulation and activation of muscles around the joint, thus providing adequate neuromuscular control of knee joint position and movement and maintenance of proper inter-joint coordination and performance of physical tasks (van der Esch et al., 2007). Impaired proprioceptive performance of the knee joint in patients with knee OA and TKR has been demonstrated as one of the deficiencies in sensorimotor function. However, no studies were identified which have investigated the effects of decreased proprioception on the inter-joint coordination and muscle co-activation in patients following TKR, when they are performing fundamental activities of daily living such as walking on a level surface at a comfortable and self-selected speed. Consequently, the purpose of this study was to:

1. Compare the inter-joint coordination and variability of walking between subjects following TKR with age and gender matched counterparts;
2. Compare the patterns of muscle co-contraction between knee extensors and flexors in patients following TKR and those of control subjects;
3. Explore the relationship between DJPS measures and inter-joint coordination; and
4. Explore the relationship between self-reported scores of functional outcomes and the coordination and variability of walking.

The hypotheses for the study are as follows:

1. Following TKR, patients walk with less than optimal coordination and with greater variability in coordination than age-matched control subjects
2. A higher level of muscle co-activation will be found in patients following TKR than for age-matched control subjects;
3. Dynamic JPS is positively related to inter-joint coordination during walking; and
4. Lower levels of coordination and greater variability during walking are negatively related to qualitative functional outcome measures.

4.2 METHODS

4.2.1 Subjects

The same TKR and age-matched control subjects involved in the previous investigation and described in Chapter 3 participated in this study. Because of the brief time-scale between the 2 studies, the demographic information for TKR and control subjects was unchanged and all subjects continued to fulfil the inclusion criteria as indicated in Chapter 3.

The TKR and control groups had an average age of 68.9 and 66.3 years, respectively and no significant differences were found in mean body weight and height between the groups.

4.2.2 Experiment protocols

4.2.2.1 Subjective assessment of knee functionality

Prior to the objective measures the subjects completed the functionality surveys described in Chapter 3.

4.2.2.2 Measurement of dynamic joint position sense of the knee joint

Findings as outlined in Chapter 3, indicate that the measurement of angular reproduction and position sense is reliable using either passive or dynamic protocols. However, only the dynamic protocol was shown to be significantly associated with self-reported functional outcomes and consequently this protocol was selected for use in this study.

Measures of proprioception reported in this chapter are consistent with those derived from the second session of the test-retest reliability study of the measurement of JPS reported in Chapter 3. The second session of proprioception measurement was conducted on the same day as the gait evaluation was conducted.

Table 4.1
Anthropometric parameters and description of procedures (Modified from Davis, 1991)

Measure	Description
Height (1)	Measured when barefoot, feet together and arms by the sides.
Body mass (1)	Measured with all clothes removed except underwear.
ASIS breadth (1)	Represents horizontal distance between anterior superior iliac spines.
Thigh length (2)	Measured as the vertical distance between the superior margin of the greater trochanter of the femur and superior margin of the lateral tibial condyle.
Mid thigh circumference (2)	Measured at a position midway between the trochanteric and tibial landmarks identified above with a tape perpendicular to the long axis of the leg.
Calf length (2)	Measured as the vertical distance between the superior margin of the lateral tibia and the lateral malleolus.
Calf circumference (2)	Represents the maximum circumference of the calf.
Knee diameter (2)	Measured as the maximum breadth of the knee across the femoral epicondyles.
Foot length (2)	Measured as the distance from the posterior margin of the heel to the tip of the longest toe.
Malleolus height (2)	Measured as the vertical distance from the standing surface to the lateral malleolus.
Malleolus diameter (2)	Measured as the maximum distance between the medial and lateral malleoli.
Foot breadth (2)	Measured as the breadth across the distal ends of metatarsals I and V.

(1): Single measure.

(2): Double measures for right and left side of body.

Table 4.2
Marker positioning

Position	Description
Sacrum	At level of 1st sacral vertebra.
ASIS (L/R)	Points where ASIS distance measured.
Femoral wand (L/R)	At level where circumference of thigh measured.
Femoral epicondyle (L/R)	Lateral femoral condyle.
Tibial wand (L/R)	At level where maximum circumference of calf measured.
Heel (L/R)	Posterior aspect of calcaneous.
Lateral Malleolus (L/R)	On the 33most distal point on the lateral malleolus.
Metatarsal head II (L/R)	On the head of second metatarsal bone.

4.2.2.3 Gait analysis

Gait analyses were conducted in the gait laboratory of IHBI at QUT. Kinematic data were recorded using a 6-camera motion analysis system (VICON MX 13, OMG, UK) at a sampling rate of 100Hz. Two force plates (OR-6-6, AMTI, USA) embedded in the middle of the walkway were used to collect GRF data at a sampling rate of 1000Hz. A 16-channel wireless sEMG system (ZeroWire, Aurion, Italy) was used to collect EMG signals from the muscles of interest and recorded at a sampling rate of 1000Hz. All kinematic data, GRF information and EMG signals were synchronised during the process of real time data collection and recorded using VICON Motus software (Version 9.2, VICON Motion Analysis Inc, OMG, UK) for further off-line analysis.

Retro-reflective markers were used to track the motion of body segments and marker positions were selected according to the Davis protocol (Davis, Õunpuu, Tyburski, & Gage, 1991; Peppe, Chiavalon, Pasqualetti, Crovato, & Caltagirone, 2007). This requires obtaining the subjects' anthropometric measures (Table 4.1) and placing retro-reflective markers on the pelvis and lower limb segments as shown in Table 4.2. Markers 14mm in diameter were attached directly on the defined landmarks with double sided tape according to the Davis protocol (Davis et al., 1991; Peppe et al., 2007). Another 4 markers were attached to the thigh and calf of both lower limbs approximately 10 cm away from the skin using plastic sticks or wands.

The subjects were allowed to take several walking practice trials to familiarise themselves with the walkway before data collection began. During the walking test, subjects walked at a self-selected speed along a straight trajectory on the 10-metre long walkway. The starting point was adjusted to ensure that optimal placement of the foot on the force plate at foot strike was followed by the contralateral foot on another force plate. The starting point was selected to allow subjects to take several steps before striking the force plate, to ensure they were walking at a constant velocity over the plates. Subjects were asked to walk repeatedly along the walkway until 10 satisfactory and consistent trials were recorded. Good walking trials were defined as those in which the subject stepped with one foot on the first force plate and the contralateral foot on the second force plate respectively, without disruption of a normal walking pattern.

4.2.2.4 Electromyographic recording

Surface EMG signals were collected from 5 muscles around both knees using a 16-channel wireless system (Zerowire, Aurion, Italy). Following skin preparation by shaving body hair, the skin was swabbed with alcohol wipes around the belly of each muscle. Two Ag/AgCl pre-gelled surface electrodes (Red Dot Multipurpose, 3M, USA) were then applied in line with the muscle fibres and positioned 2cm apart over the midline of the muscle belly (Table 4.3). The signal was collected by a single-differential, self-contained sensor and transmitted wirelessly (16-bit at 4 kb/s) from the sensor to the receiver/amplifier. Within the receiver/amplifier, the signals were band-passed (10−500 Hz) with a roll-off of 6 dB/octave using an analogue, resistor–capacitor (RC) filter. To reduce the cross-talk, subjects were asked to perform a movement to activate the target muscle and the sEMG response of this muscle and the antagonist observed to check for cross-talk.

Surface EMG signals were collected from the 5 muscles simultaneously on both ipsilateral and contralateral sides following procedures in accordance with 2 previous studies involving a similar population (Benedetti et al., 1999; Benedetti et al., 2003). Muscles involved included the rectus femoris (RF), vastus medialis (VM), vastus lateralis (VL), medial hamstrings (MH) and biceps femoris (BF).

Table 4.3
sEMG electrodes placement

Muscles	Anatomical Landmarks
Rectus femoris	Located on the centre of the anterior surface of the thigh, approximately half the distance between the knee and the iliac spine.
Vastus medialis	Placed at an oblique angle (55 degrees), 2 cm medially from the superior rim of the patella.
Vastus lateralis	Placed approximately 3 to 5 cm above the patella, on an oblique angle just lateral to midline.
Medial hamstrings	Placing the electrode on the medial aspect of the thigh, located approximately 3 cm from the lateral border of the thigh and approximately half the distance from the gluteal fold to the back of the knee.
Biceps femoris	Placed 2 cm apart, parallel to the muscle fibres on the lateral aspect of the thigh, two-thirds of the distance between the trochanter and the back of the knee.

4.2.2.5 Muscle strength measurement of knee extensors and flexors

Following completion of the gait analysis, all participants performed 3 repetitions of isometric maximum voluntary contractions (MVC) of the quadriceps and hamstrings muscles of both limbs. Measurements were obtained using a Biodex System 3 isokinetic dynamometer and sEMG data was recorded simultaneously during the strength evaluation. The sEMG data collected during MVC testing was used to normalise sEMG activation recorded during gait, which was expressed as a percentage of maximal voluntary contraction (%MVC) (Burden, Trew, & Baltzopoulos. 2003).

During strength testing, the subject was seated on the dynamometer with hips and knees flexed at 90°. The position of the seat was adjusted to ensure proper alignment between the axis of the knee joint and the rotational axis of the lever arm. The leg to be tested was then fixed to the lever arm of the dynamometer with restraining straps according to the Biodex manual of procedures. Restraining straps were also used to stabilise the thigh, pelvis and upper chest to minimise unwanted leg, pelvic and trunk movement.

Prior to the collection of MVC data, participants were informed of the procedures and allowed to practice sub-maximal voluntary contractions with visual feedback on the screen of the Biodex system. This allowed familiarisation with the testing procedure and warm-up of the muscles. The subject was asked to attempt to extend or flex the test leg, pushing or pulling as hard as possible against the leg constraint or strap, during which time extensor or flexor muscle strength was measured for 5 seconds. Verbal encouragement and real-time visual feedback of the force produced during the testing were used to motivate subjects to produce a maximal force. The procedure was performed 3 times with 60 seconds rest between each contraction. The highest value obtained was regarded as the MVC (Hassan et al., 2001). The non-operated limb of the TKR subjects or the non-dominant leg of the control subjects was tested first followed by the contralateral limb.

The raw MVC data measured by the dynamometer was expressed in Newton-metres (Nm) and was normalised according to body weight for comparison purposes. In addition, the asymmetry of knee muscle strength between operated and non-operated legs in TKR subjects and dominant and non-dominant legs of control subjects was determined. An absolute symmetry index (ASI) was calculated using the following equation developed by (Stacoff, Diezi, Luder, Stussi, & Kramers-de Quervain, 2005).

$$ASI\ (\%) = \left| \frac{MVC_{dominant} - MVC_{non-dominant}}{(MVC_{dominant} + MVC_{non-dominant})/2} \right| \times 100 \qquad (1)$$

4.2.3 Data analysis

Gait data was processed using the VICON Motus software as described earlier (4.2.2.3 Gait analysis, page 79). The Motus software is a batch file that sequentially executes a series of calculations from the synchronised motion, force plate, sEMG and anthropometric data. The raw kinematic data from the gait analysis was firstly interpolated to fill in any gaps where markers may have been blocked during data collection and then filtered with second order low pass Butterworth filter (cut-off frequency of 6Hz).

The gait cycle was determined from the kinematic data based on the moment of heel contact to the next heel contact of the same leg. Temporal parameters such as velocity (cm/s), cadence (steps/min), and gait cycle time (s) and stride length (cm) were also calculated. Other temporal parameters of gait such as stance, swing and double support times, were expressed both in absolute time values in seconds and as a percentage of the gait cycle time to facilitate comparison among gait cycles and between groups. Swing time was also expressed in relation to the stance period (swing/stance ratio) for both left and right legs respectively. Additionally, joint (hip, knee and ankle) angular displacement and angular velocity in the sagittal plane were calculated for further analysis.

Based on the angular displacement and velocity data, relative phase between hip-knee and knee-ankle was calculated as representative of inter-joint coordination, according to a protocol which uses a customised program developed using MATLAB (Boonstra et al., 2007). In this protocol, stance phase is normalised by dividing the time axis of stance phase into 100 increments. In order to allow comparison between strides and subjects, angular displacement and amplitude of angular velocity were normalised to 0 and 1 for every gait trial separately, using the following equations:

$$\alpha_{norm}(i) = \frac{\alpha(i)}{max\{|\alpha(i)|\}} \qquad (2)$$

Where α_{norm} is the normalised joint angular displacement, α is the joint angular displacement, α_{max} is the maximum of the joint angular displacement during the same gait trial and *i* is the time in increments.

$$\alpha'_{norm}(i) = \frac{\alpha'(i)}{max\{|\alpha'(i)|\}} \qquad (3)$$

Where α'_{norm} is the normalised joint angular velocity, α' is the joint angular velocity, α'_{max} is the maximum of the joint angular velocity during the gait trial, and *i* is the time in increments.

Phase angles (Φhip, Φknee and Φankle) were calculated for every gait trial separately using the following equation:

$$\Phi(i)j = arctan\frac{\alpha'_{norm}(i)}{\alpha_{norm}(i)} \qquad (4)$$

Where Φ stands for phase angle, *j* is the joint (hip, knee or ankle), α_{norm} is the normalised joint angular displacement, α'_{norm} is the normalised joint angular velocity and *i* is the time in 100 increments.

The relative phase for each walking trial was then calculated using the following formula:

$$\Phi HK = \Phi_{hip}(i) - \Phi_{knee}(i) \qquad (5)$$

$$\Phi KA = \Phi_{knee}(i) - \Phi_{ankle}(i) \qquad (6)$$

The relative phase was averaged over the 10 trials to obtain a mean relative phase (MRP) for hip-knee and knee-ankle separately for the ipsilateral and contralateral lower limbs of the TKR and control subjects.

Variability of the relative phase (SRP) was measured by the standard deviation between corresponding points of the relative phase across the 10 trials for each lower limb of the TKR and control subjects. The SRP is a measure of the variability of inter-joint coordination during level walking.

The individual MRP and SRP scores for the operated lower limb and the contralateral lower limb were compared to the same score of the control group using equations:

$$MARP_{diff}(i)k,h = |MRP(i)h - MRP_{control}(i)| \qquad (7)$$

$$SARP_{diff}(i)k,h = |SRP(i)h - SRP_{control}(i)| \qquad (8)$$

$MARP_{diff}$ is the absolute difference between the group average MRP plot of the dominant leg in the control group and individual MRP plots of both lower limbs in the TKR group and the contralateral lower limbs of control subjects (Kurz et al., 2005). $SARP_{diff}$ is the difference between the group average SRP plot of the dominant leg of the control group and individual SRP plots of both lower limbs of TKR subjects and the contralateral non-dominant lower limbs of control subjects. *h* represents the individual patients, *k* is the operated lower limb or contralateral lower limb, and *i* is the time in increments.

Surface EMG signals acquired simultaneously with the kinematic data were processed off-line. The amount of muscle co-activation (operationally defined as the simultaneous activation of 2 muscles) between muscles in the lower extremity was determined using the following formula: EMGS/EMGL × (EMGS+EMGL). EMGS is the level of activity in the less active muscle and EMGL is the level of activity in the more active muscle. This ratio was multiplied by the sum of the activity found in the 2 muscles. This method provides an estimation of the relative activation of the pair of muscles, as well as the magnitude of the co-activation (Rudolph, Axe, Buchanan, Scholz, & Snyder-Mackler, 2001).

4.2.4 Statistical analysis

All analyses were performed using SPSS with a confidence interval and a *p*-value < 0.05 regarded as statistically significant. The Student's t-test was used to assess differences in inter-joint coordination and variability in coordination of stance phase during level walking of the non-dominant of control group and that of the operated non-operated lower limbs of the TKR subjects.

These differences were recognised as significant if $MARP_{diff}$ and $SARP_{diff}$ were significantly different from 0.

One-way ANOVA was used to compare differences between TKR and control groups in muscle strength, temporal patterns of gait, and angular displacement at specific events in the gait cycle. Comparisons involved analysis of differences between operated and non-operated knees of the TKR patients and dominant and non-dominant knees of the control subjects. LSD post-hoc test was used to determine the location of significant differences where appropriate.

The relationships between the qualitative functional measures, DJPS, $MARP_{diff}$ and $SARP_{diff}$ and muscle co-activation were determined using the Pearson's correlation coefficient.

4.3 RESULTS

4.3.1 Functional outcome measurement

As shown in Table 4.4, with the exception of scores for the OKS questionnaire, which showed significantly ($p < 0.05$) higher scores for the TKR group, the results of the other surveys indicated significantly lower scores for this group when compared to the controls. As indicated earlier, a higher score using the OKS and lower scores resulting from the other questionnaires represented less positive and impaired functional outcomes.

Table 4.4
Results of self-reported and physician administered questionnaires for TKR and control groups (Mean ± SD)

	TKR group	Control group	*p*-value
R-WOMAC	86.10 ± 11.19	100.00 ± 0	<0.001*
IKS-Knee Score	80.14 ± 8.42	99.67 ± 1.29	<0.001*
IKS-Function Score	74.29 ± 19.10	100.00 ± 0	<0.001*
OKS	21.43 ± 6.25	12.07 ± 0.26	<0.001*

*Significant difference ($p < 0.05$).

4.3.2 Muscle strength

Differences in muscle strength of women and men were compared for the dominant side of control subjects and the operated side of the TKR subjects Table 4.5.

On average, female TKR subjects generated 52.2% lower extension muscle strength than male controls, while female control subjects generated 50.7% lower muscle strength of the knee extensors than for male TKR subjects. Female TKR and control subjects generated 48.6% and 53.3% less flexion muscle strength than male TKR and control subjects, respectively. No significant differences were found in the gender variance in TKR and control subjects.

Table 4.5
Average muscle strength (Nm) of knee extensor and flexors for women and men in TRK and control groups (Mean ± SD)

	TKR group			Control group		
	Women	Men	Difference	Women	Men	Difference
Extensors (Nm)	91.0 ± 32.1	138.5 ± 50.3	52.2%	124.8 ± 31.0	188.0 ± 45.7	50.7%
Flexors (Nm)	33.0 ± 9.7	49.0 ± 19.1	48.6%	53.9 ± 10.8	82.6 ± 25.4	53.3%

No significant differences were found between the TKR and control groups in the strength of knee extensors in contrast to the findings for knee flexor strength, which was significantly lower in the TKR group (20Nm) as shown in Table 4.6.

Table 4.6

Muscle strength (MVC and normalised MVC) for TKR and control subjects (Mean ± SD)

	TKR group		Control group		
	Operated	**Non-Operated**	**Dominant**	**Non-Dominant**	***p*-value**
Extensors (Nm)	118.2 ± 49.1	136.5 ± 43.5	160.7 ± 61.4	142.7 ± 48.9	0.179
Flexors (Nm)	42.1 ± 16.4[a]	53.3 ± 16.4[a]	72.2 ± 28.2	67.9 ± 28.0	0.004
N-Extensors[1]	1.41 ± 0.50[a]	1.63 ± 0.47[a]	2.15 ± 0.68	1.92 ± 0.54	0.004
N-Flexors[1]	0.50 ± 0.18[a]	0.63 ± 0.15[a]	0.97 ± 0.30	0.91 ± 0.28	<0.001
H/Q ratio	0.38 ± 0.09[a]	0.39 ± 0.06[a]	0.46 ± 0.10	0.48 ± 0.11	0.009

[1] N-Extensors and N-Flexors are the muscle strength normalised by body weight.

[a] Significant difference ($p < 0.05$) between the TKR and control groups.

When normalised by body weight, strength scores of the extensors and flexors of both limbs for TKR subjects were significantly lower than those of the control subjects. The H/Q ratio of the TKR subjects was also significantly smaller than that of the control subjects. However, no significant differences were found in the absolute and normalised values for muscle strength between operated and non-operated limbs of TKR subjects.

The ASI for both extensors and flexors in the TKR subjects was significantly greater than for control subjects as shown in Figure 4.1.

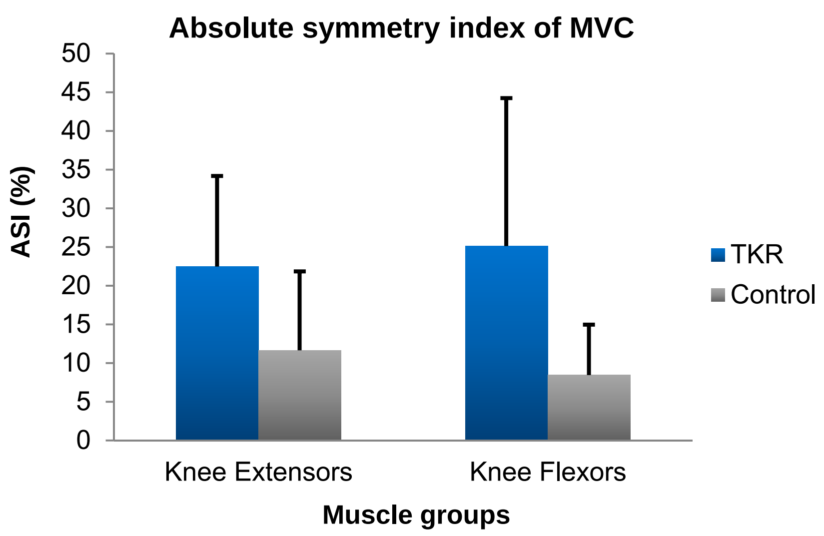


Figure 4.1. Absolute symmetry index (ASI %) of muscle strength for knee extensors and flexors for TKR and control groups.

4.3.3 Temporal and spatial parameters

As shown in Table 4.7, although the walking velocity of the control group was slightly higher than that for TKR subjects, this difference was not significant. No significant differences between groups were found for other distance or temporal parameters of gait including cadence, stride length, relative velocity and stride length.

Table 4.7
Distance parameters for TKR and control groups (Mean ± SD)

	TKR subjects	**Control subjects**	***t*-value**	***p*-value**
Cadence (steps/min)	110.4 ± 8.1	112.1 ± 9.4	0.514	0.612
Velocity (cm/s)	123.2 ± 27.8	133.4 ± 19.6	1.145	0.262
Stride length (cm)	133.2 ± 29.2	141.9 ± 15.0	0.999	0.330
Relative velocity (%BH)	73.2 ± 15	77.7 ± 10	0.957	0.348
Relative stride length (%BH)	79.1 ± 15	82.7 ± 7	0.836	0.414

The within group variability in velocity, stride length and relative values of these 2 parameters, as a function of body height, was higher for the TKR subjects when compared with control subjects. For example, the coefficients of variance (CV) for velocity of the TKR and control group were 22.6% and 14.7% respectively. Similarly, the CV for stride length of the 2 groups was 21.9% and 10.6% respectively.

Although no significant differences were found in stride and stance times, significant differences were identified in the duration of swing, and single and double support periods (Table 4.8). Post-hoc tests revealed significantly shorter swing phases for both operated and non-operated sides of the TKR group by comparison with those of the control group. Longer double support and shorter single support times in the TKR group were also demonstrated. However, no significant differences in these measures were found between the operated and non-operated leg of the TKR group.

Temporal parameters normalised as a function of stride time are presented in Table 4.9. Significantly prolonged stance and double support ratios were shown in TKR subjects compared to those of the controls, accompanied by significantly decreased swing and single support ratios.

Table 4.8

Temporal parameters of gait for TKR and control groups (Mean +SD)

Variables	TKR group		Control group		
	Operated	Non-Operated	Dominant	Non-Dominant	*p*-value
Stride time (s)	1.09 ± 0.09	1.09 ± 0.09	1.09 ± 0.09	1.09 ± 0.09	1.000
Stance time (s)	0.72 ± 0.09	0.71 ± 0.08	0.69 ± 0.08	0.68 ± 0.07	0.515
Swing time (s)	0.37 ± 0.02[a]	0.38 ± 0.02[b]	0.40 ± 0.03	0.41 ± 0.04	0.004
Double support time (s)	0.35 ± 0.09[a]	0.35 ± 0.09[a]	0.29 ± 0.06	0.29 ± 0.07	0.028
Single support time (s)	0.38 ± 0.02[a]	0.37 ± 0.02[a]	0.41 ± 0.04	0.40 ± 0.03	0.006

[a] Significant difference ($p < 0.05$) between TKR and control groups.

[b] Significant difference ($p < 0.05$) between non-operated side of TKR group and non-dominant side of the control group.

Table 4.9

Relative temporal parameters of gait for TKR and control groups

Variables	TKR group		Control Group		*p*-value
	Operated	Non-Operated	Dominant	Non-Dominant	
Stance ratio	65.87 ± 2.95[a]	65.05 ± 2.91[b]	63.18 ± 2.36	62.50 ± 2.55	0.004
Swing ratio	34.13 ± 2.95[a]	34.95 ± 2.91[b]	36.82 ± 2.36	37.50 ± 2.55	0.004
Single support ratio	34.85 ± 2.89[c]	34.22 ± 2.96[a]	37.52 ± 2.83	36.84 ± 2.30	0.005
Double support ratio	31.71 ± 5.04[a]	32.09 ± 6.31[a]	26.35 ± 4.05	26.86 ± 4.95	0.003

[a] Significant difference ($p < 0.05$) between TKR and control groups.

[b] Significant difference ($p < 0.05$)) between non-operated side of TKR group and non-dominant side of control group.

[c] Significant difference ($p < 0.05$) between operated side of TKR group and dominant side of control group.

4.3.4 Joint kinematics during gait cycle

4.3.4.1 Hip

Greater hip flexion was found for both limbs of the TKR subjects compared to that of the control subjects. The start and finish of this difference in angular displacement occurred at approximately 30% and 65% of the gait cycle respectively (Figure 4.2).

No significant differences were found between the 2 groups in the degree of hip flexion at foot strike (

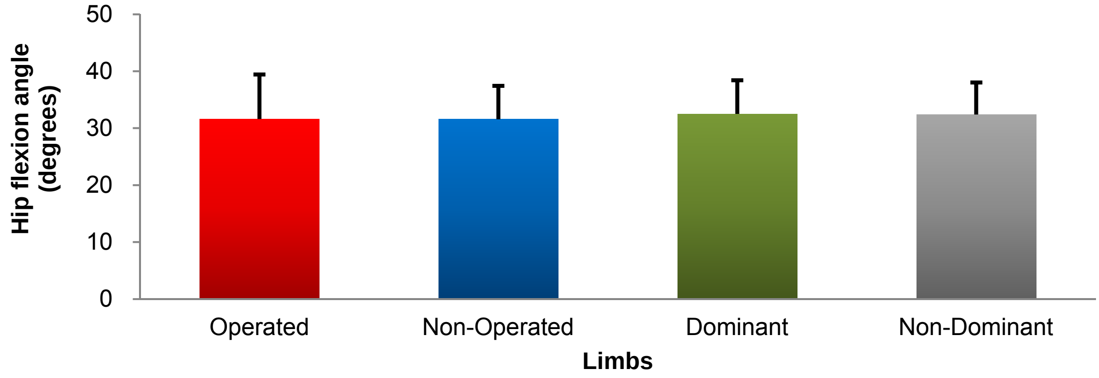


Figure *4.3*). Although the maximal degree of hip extension for the TKR subjects was smaller than that of the control groups (Figure 4.2), this difference was not significant. Consequently, the range of excursion of the hip joint during stance phase did not differ between the 2 groups (

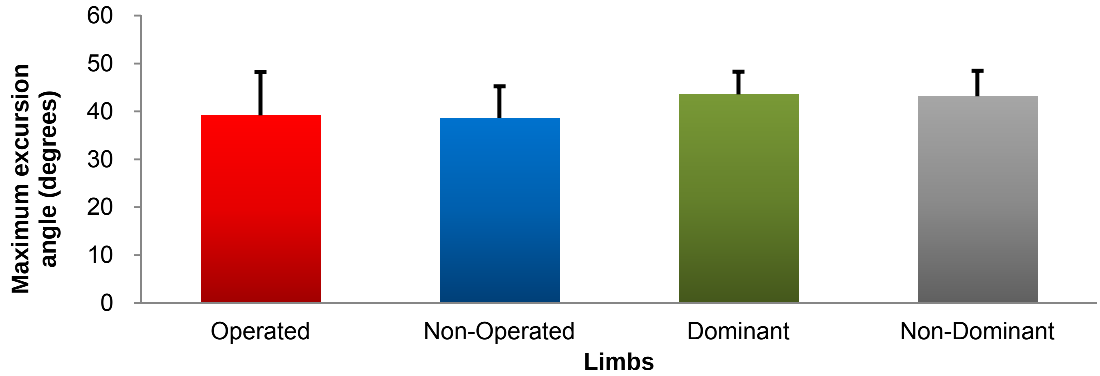


Figure *4.4*). The excursion range for the hip joint is defined as the angular difference between the maximum degree of hip flexion and the maximum extension angle before the swing phase begins.

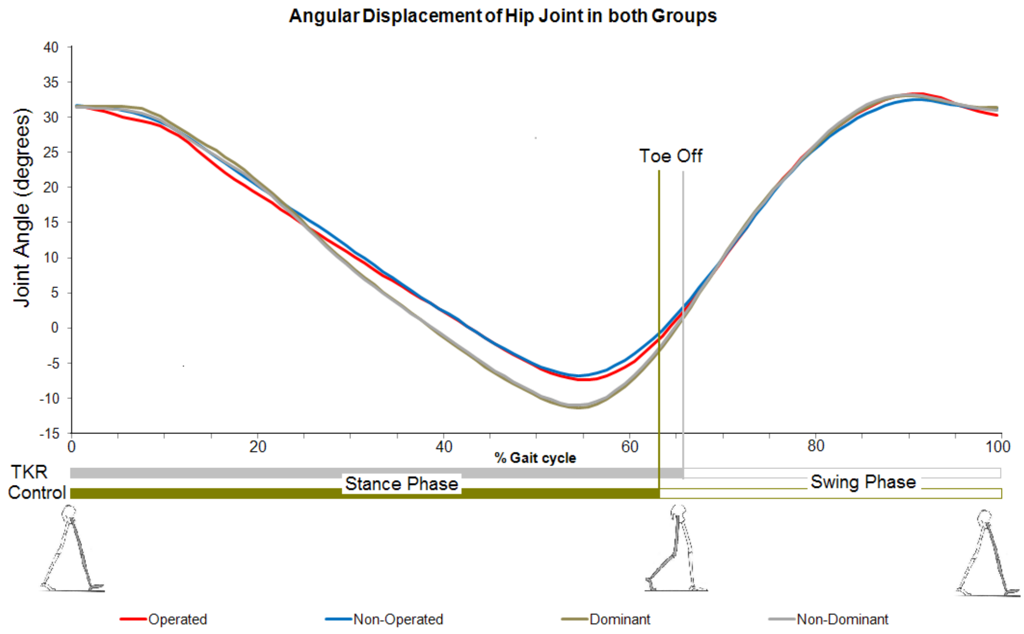


Figure 4.2. Angular displacement of hip joint for TKR and control groups.

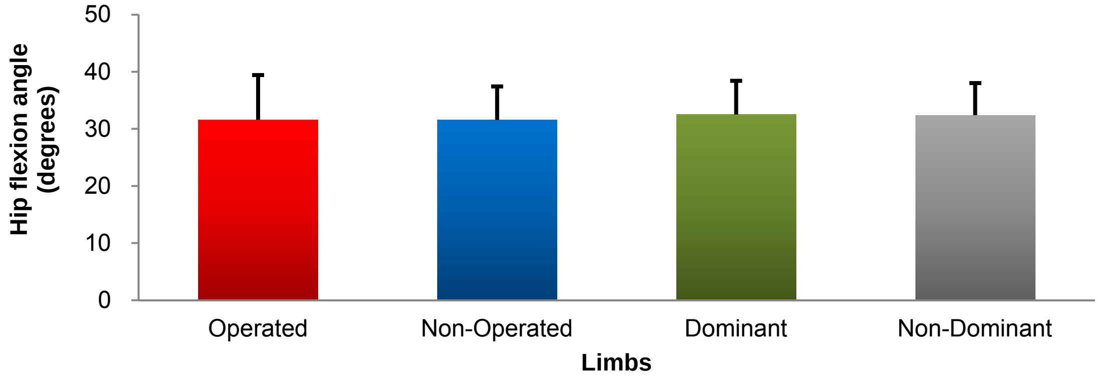


Figure 4.3. Hip flexion at foot strike for TKR and control groups.

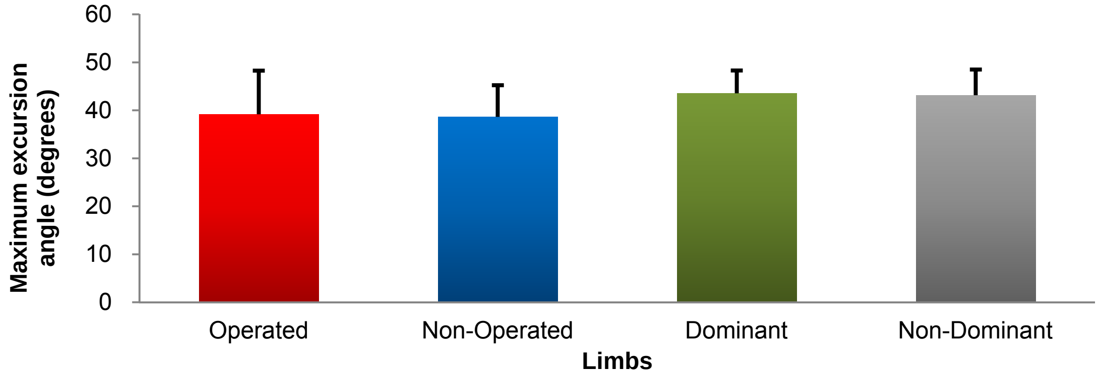


Figure 4.4. Maximum range of hip joint excursion during stance phase for TKR and control groups.

4.3.4.2 Knee

The average degree of flexion at the operated knee was greater than that of the knees of control subjects at initial contact (

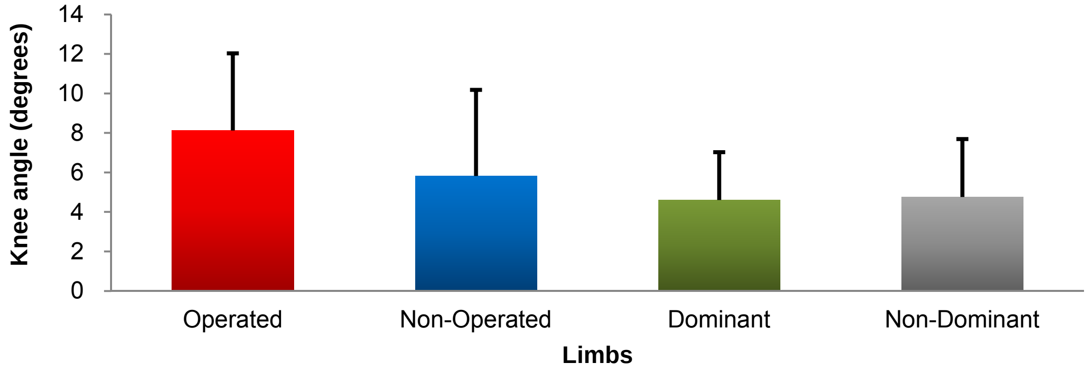


Figure *4.6*). Additionally, a significantly smaller magnitude of knee extension during the late stance phase for the operated limb was demonstrated at approximately 40% of the gait cycle by comparison with the contralateral limb and limbs of the control group. The movement towards the reduced extension began and ended at 28% and 53% of the cycle respectively (Figure 4.5).

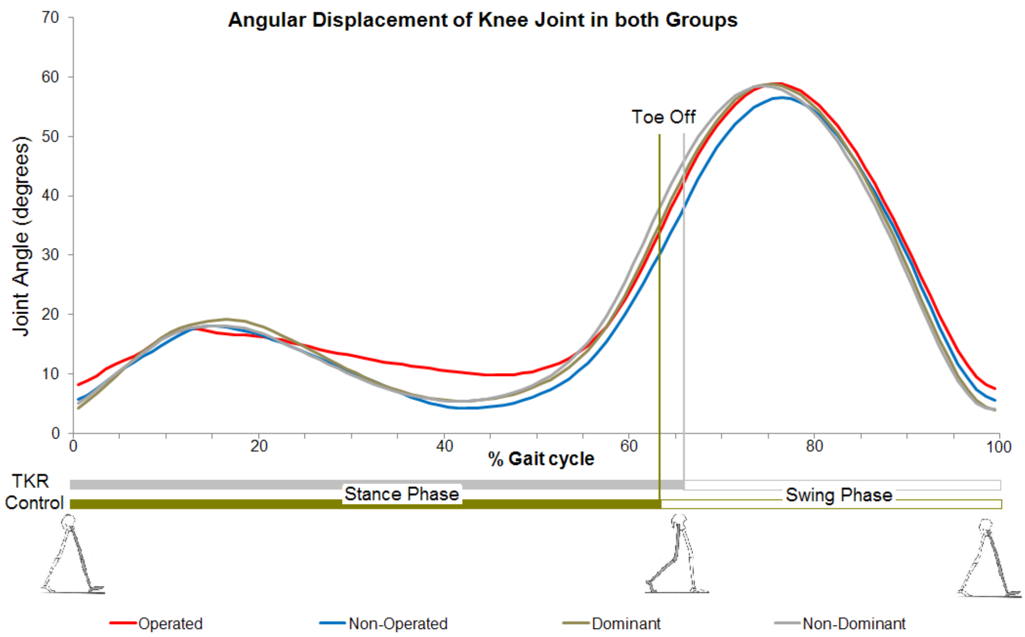


Figure 4.5. Angular displacement of knee joint for TKR and control groups.

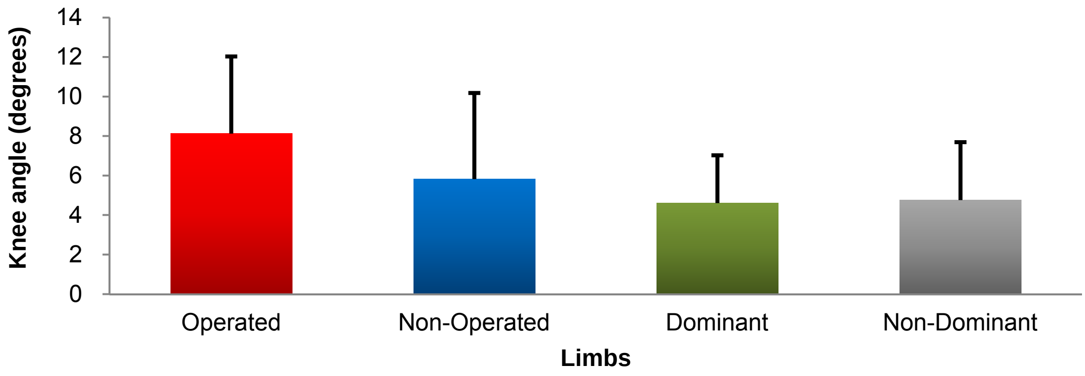


Figure 4.6. Knee angle at initial contact for TKR and control groups.

No significant differences were found between groups in the magnitude of maximal knee flexion during the stance phase. Angular displacement during the early stage of the stance phase was calculated by subtracting the knee angle at initial contact from the angle at maximal knee flexion for further comparison. Results indicated that this excursion range for the operated knee was significantly decreased when compared to the contralateral knee and that of the controls (Table 4.10). Following this knee flexion at the early stage of stance phase, the knee joint extends to approach maximal extension during late stance phase. At the time point of maximal extension angle, the degree of flexion of the operated knee was significantly higher than for the contralateral knee and that of the controls at a similar point in time. As a consequence, the degree of extension of the operated knee during this period of the stance phase was significantly smaller than that of the contralateral knee in TKR subjects and both knees of the control group.

Table 4.10

Knee kinematic characteristics during stance phase (Mean ± SD)

	TKR group		**Control group**		
	Operated	**Non-Operated**	**Dominant**	**Non-Dominant**	***p*-value**
Max. Flexion	17.8 ± 6.4	18.5 ± 5.8	19.6 ± 3.4	18.7 ± 4.1	0.810
Excursion range	9.7 ± 5.4[a]	12.7 ± 3.0	15.0 ± 2.4	14.0 ± 3.3	0.002
Max. Extension	9.2 ± 4.3[a]	4.0 ± 3.7	5.2 ± 3.4	4.4 ± 3.8	0.002
Extension range	8.6 ± 6.7[a]	14.6 ± 5.0	14.4 ± 4.8	14.3 ± 5.9	0.015

[a] Significant difference ($p < 0.05$) between operated side and non-operated knee of TKR group and both knees of control group.

4.3.4.3 Ankle

Dorsiflexion of the ankle joint of the operated leg was significantly higher than for the contralateral knee and knees of the control group between approximately 35% and 65% of the gait cycle (Figure 4.7). Reduced plantar flexion of the ankle joints in TKR subjects was also evident from the start of the swing phase at approximately 65% to 73% of the gait cycle.

Small, but non-significant differences in the magnitude of ankle dorsiflexion at initial contact were found between TKR and control groups (

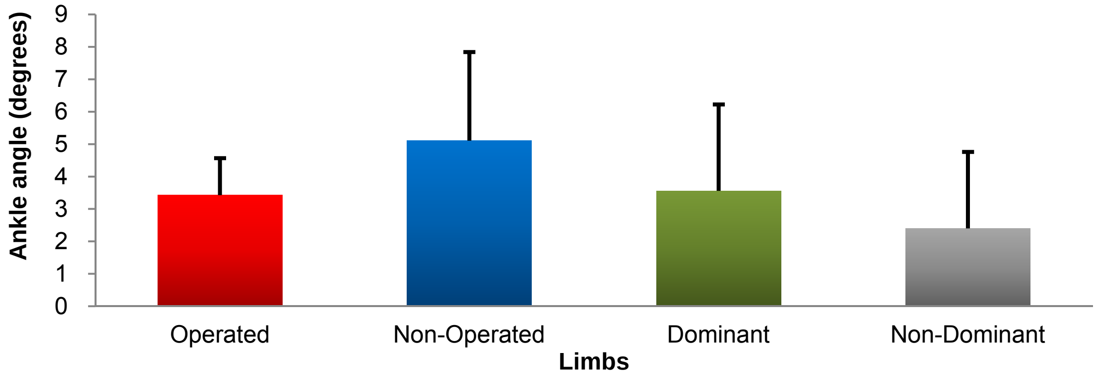


Figure *4.8*).

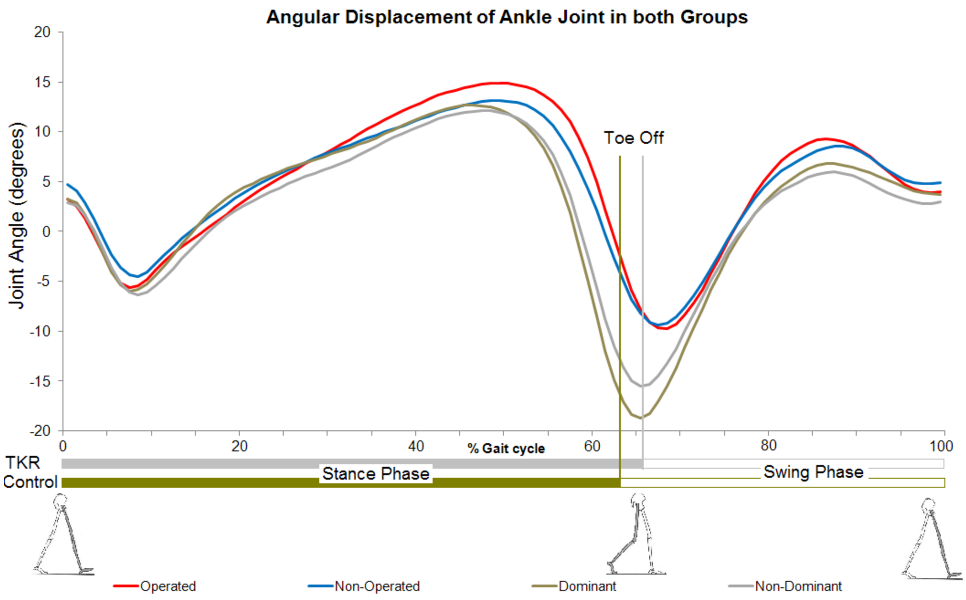


Figure 4.7. Angular displacement of ankle joint for TKR and control groups.

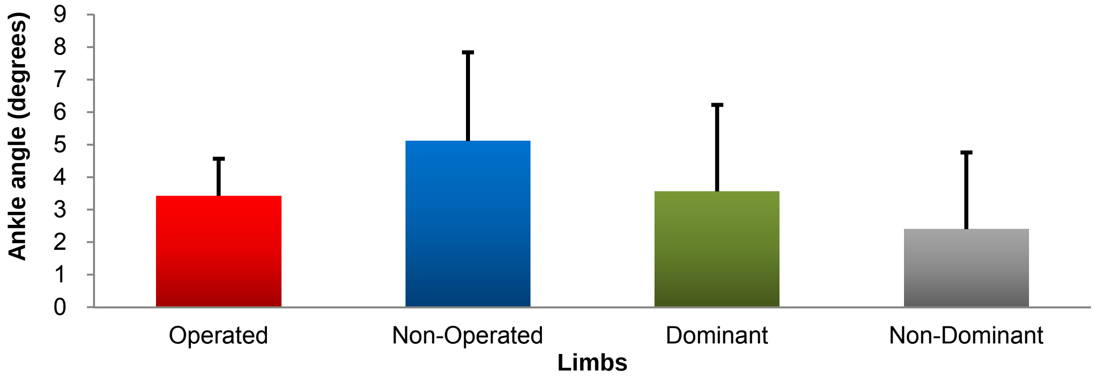


Figure 4.8. Ankle dorsi-flexion at initial heel contact for TKR and control groups.

As shown in Table 4.11, no significant differences were found between the 2 groups in the maximum degree of ankle plantar-flexion during the loading response phase and degree of ankle dorsiflexion during the pre-swing phase. In contrast, post-hoc analysis showed that the range of dorsiflexion during the stance phase of the operated limb was significantly (p < 0.05) greater than that of the non-operated limb and both ankle joints of the control subjects.

The maximum degree of ankle plantar-flexion during the initial swing phase of the gait cycle of the TKR subjects was significantly lower than that of the dominant limb of the control subjects. Thus both magnitude and range of plantar flexion were significantly reduced when compared with the same parameters of the dominant limb of the controls.

Table 4.11
Ankle kinematic characteristics at different stages of the gait cycle (Mean ± SD)

	TKR group		**Control group**		***p*-value**
	Operated	**Non-OP**	**Dominant**	**Non-D**	
Max. PF of loading	-6.1 ± 2.4	-4.9 ± 2.0	-4.9 ± 2.0	-6.5 ± 3.2	0.480
Max. DF of pre-swing	15.3 ± 3.7	13.6 ± 3.0	14.3 ± 5.6	13.1 ± 3.9	0.528
Dorsiflexion range	21.4 ± 3.0[b]	18.5 ± 3.9	19.5 ± 2.5	19.6 ± 4.0	0.165
Max. PF of initial swing	-11.8 ± 6.5[a]	-11.8 ± 6.2[a]	-18.6 ± 7.8	-16.3 ± 8.5	0.036
Plantar-flexion range	27.1 ± 5.0[a]	25.5 ± 4.3[a]	32.9 ± 5.6	29.4 ± 6.3	0.003

[a] Significant difference (p < 0.05) between the TKR group and the dominant limb of control group.
[b] Significant difference (p < 0.05) between the operated and non-operated limb in TKR group.
Non-OP: Non-operated side of TKS subjects.
Non-D: Non-dominant side of control subjects.
PF: Plantar-flexion.
DF: Dorsiflexion.

4.3.5 Continuous relative phase (CRP)

As illustrated in Figure 4.9 and Figure 4.10, analysis of the CRP for the hip-knee and knee-ankle joints revealed the adoption of different coordination and locomotor strategies used by the TKR patients when compared to the control subjects.

Similar CRP curve configurations were found for hip-knee and knee-ankle joint relationships for the dominant and non-dominant limbs of the control group. In contrast, the CRP curves for the TKR group showed significantly different configurations between the operated and non-operated sides. These differences were most evident from approximately 45% to 75% of the stance phase for the coordination between hip and knee joints (Figure 4.9). Similar CRP curve configurations were found for both limbs of the TKR subjects during the early and later phases of the stance phase. More significant deviations in the CRP curve configurations of the knee-ankle joint were found across most periods of the stance phase, with the exception of the later stage when a similar pattern of coordination was shown between both limbs of the TKR subjects (Figure 4.10).

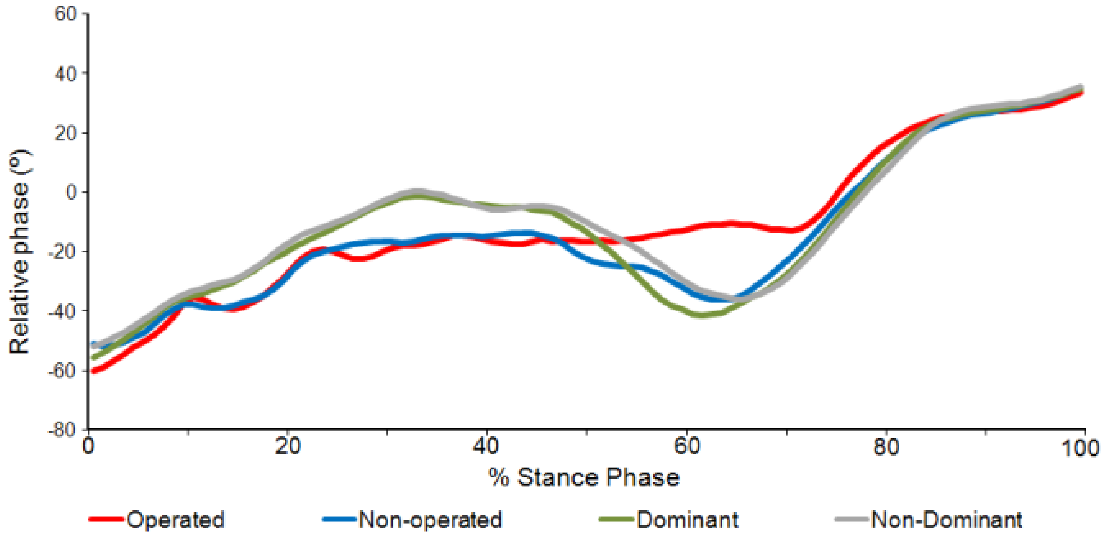


Figure 4.9. Relative phase between hip and knee joint for both the TKR and control groups during the stance phase.

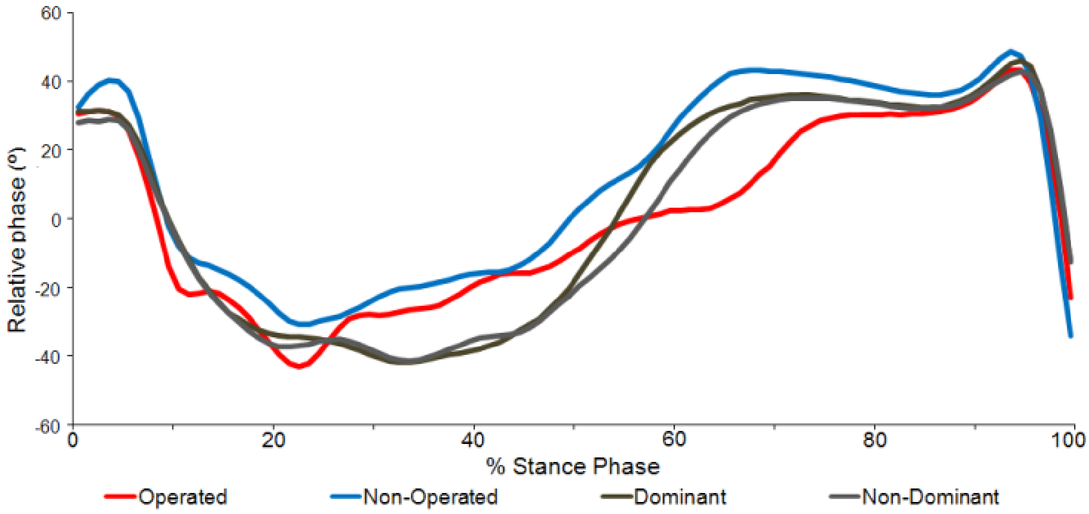


Figure 4.10. Relative phase between knee and ankle joints for both the TKR and control groups during the stance phase.

Variability of coordination associated with the interaction of hip-knee and knee-ankle joints for both limbs for the TKR subjects was significantly greater than that of the dominant side of the control group. In contrast, no significant differences were found in the inter-joint coordination and variability in coordination of the hip-knee and knee-ankle joints between the non-dominant and dominant limb for the control subjects (Table 4.12).

Table 4.12

Differences in coordination and variability of lower limb joints (Mean ± SD)

	TKR group		Control group
	Operated	Non-Operated	Dominant
$MARP_{diff}$ (hip-knee)	9.7 ± 7.7	5.5 ± 4.2	2.2 ± 3.9
	$p < 0.001$	$p < 0.001$	$p > 0.05$
$SARP_{diff}$ (hip-knee)	2.5 ± 2.0	1.7 ± 1.4	1.2 ± 2.1
	$p < 0.001$	$p < 0.001$	$p > 0.05$
$MARP_{diff}$ (knee-ankle)	9.4 ± 7.7	9.7 ± 6.8	2.5 ± 3.2
	$p < 0.001$	$p < 0.001$	$p > 0.05$
$SARP_{diff}$ (knee-ankle)	2.6 ± 2.2	2.1 ± 1.3	1.1 ± 2.0
	$p < 0.001$	$p < 0.001$	$p > 0.05$

4.3.6 Muscle co-activation

Electromyographic examination of the thigh muscles of both limbs of the TKR and control subjects revealed that the magnitude of peak EMG activity in the rectus femoris was significantly lower in the operated limb of the TKR group. In contrast, higher peak EMG activity was found for the biceps femoris of the operated knee of TKR subjects compared to their contralateral limb and the dominant and non-dominant limbs of the control group (

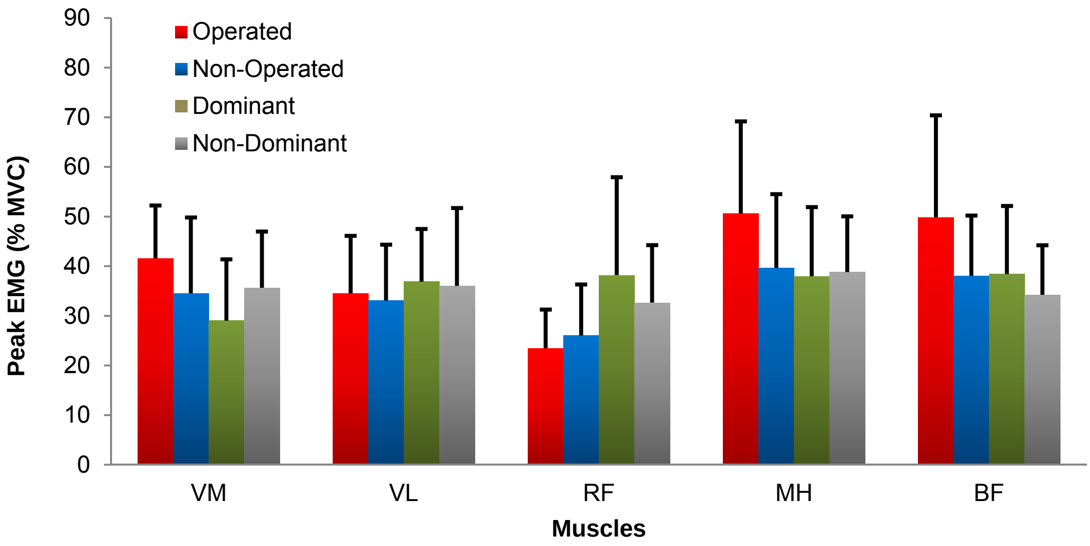


Figure *4.11*).

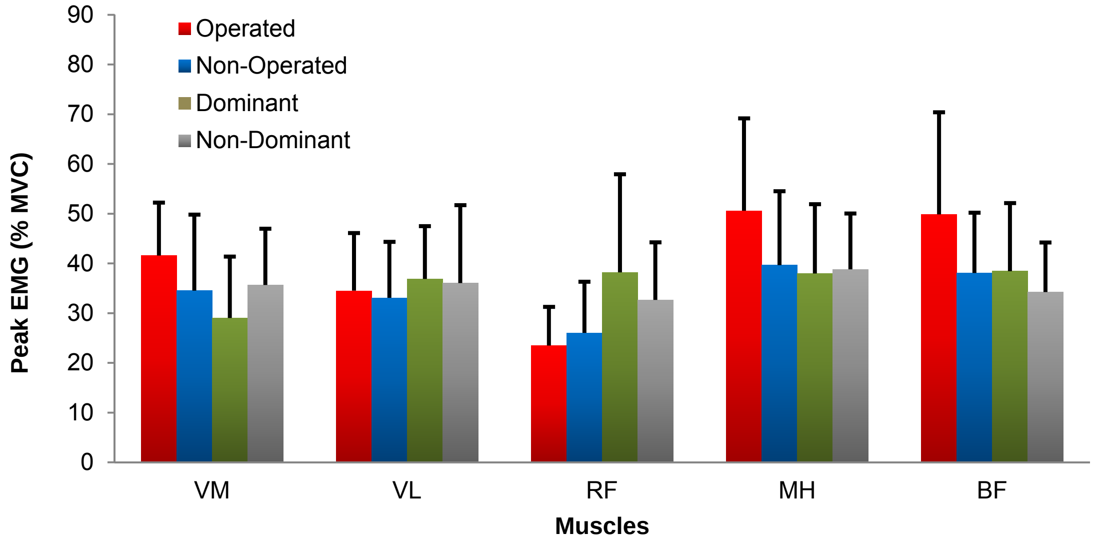


Figure 4.11. Magnitude of peak muscle activity during the gait cycle for vastus medialis (VM), vastus lateralis (VL), rectus femoris (RF), medial hamstrings (MH) and biceps femoris (BF).

As described in the methods section, the degree of co-activation between the knee extensors and knee flexors on the medial and lateral sides of the knee joint were calculated separately for the total gait cycle and for the duration of the stance phase, loading response and mid-stance sub-phases of the gait cycle. The degree of co-activation of muscles of the medial aspect of the knee joint was calculated as the ratio between the magnitude of vastus medialis and medial hamstrings. The lateral component was calculated as the ratio between the EMG magnitude of the vastus lateralis and biceps femoris.

As shown in

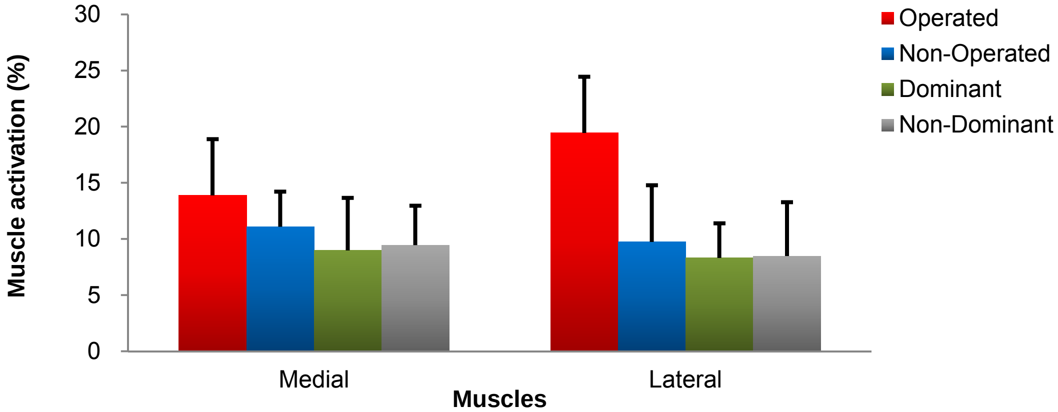


Figure *4.12*, the degrees of co-activation of the medial and lateral muscles of the knee joints in the TKR and control groups were significantly different. Post-hoc tests revealed that co-activation of the medial muscles of the operated leg of TKR group was significantly greater than for both limbs of the control subjects. Co-activation of the lateral muscles was also greater for the operated limb of the TKR subjects when compared to their contralateral limb and muscles of both limbs of the control subjects.

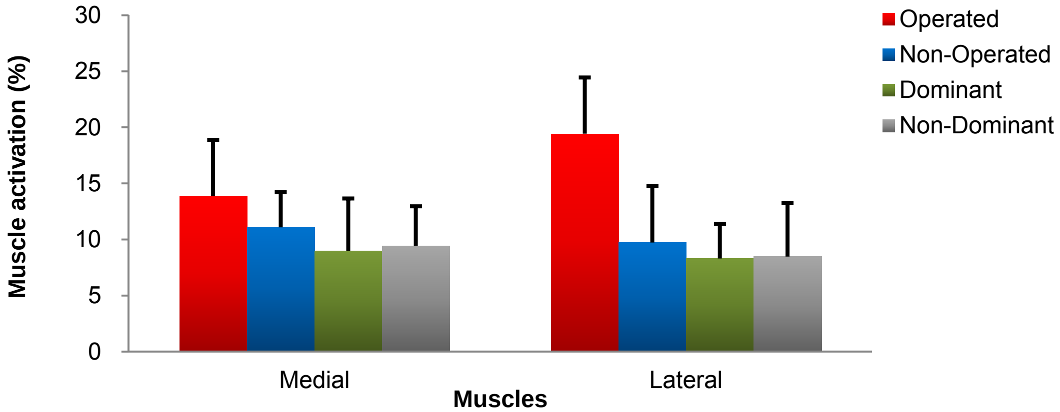


Figure 4.12. Muscle co-activation for TKR and control groups during the gait cycle.

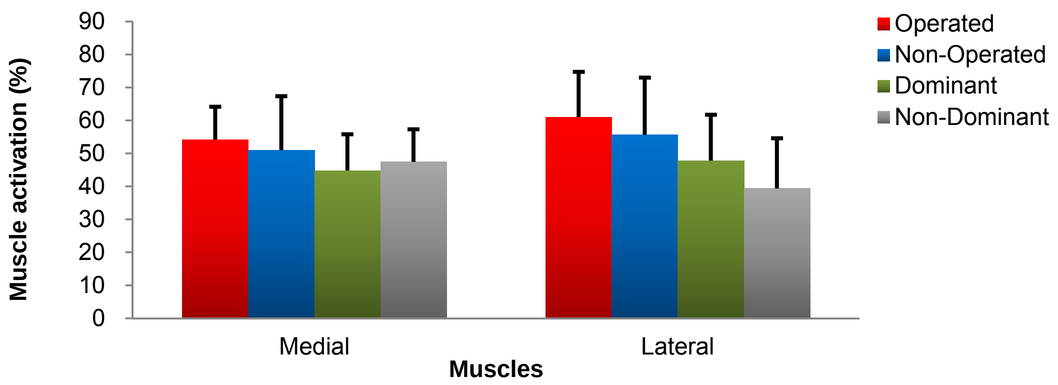


Figure 4.13. Muscle co-activation for TKR and control groups during the stance phase.

With respect to the magnitude of muscle co-activation during the stance phase, a significant difference was only found for muscles of the lateral aspect of the knee joints (

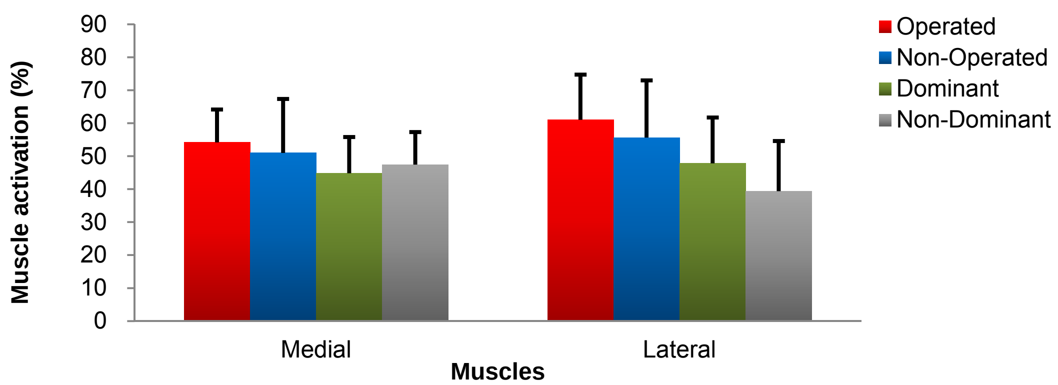


Figure *4.13*). Muscle co-activation of the operated limb was significantly higher than shown for the contralateral limb and both limbs of the control subjects.

Significantly increased muscle co-activation on the medial aspect of the operated leg was found during the loading response phase compared to the dominant leg of the control subjects (

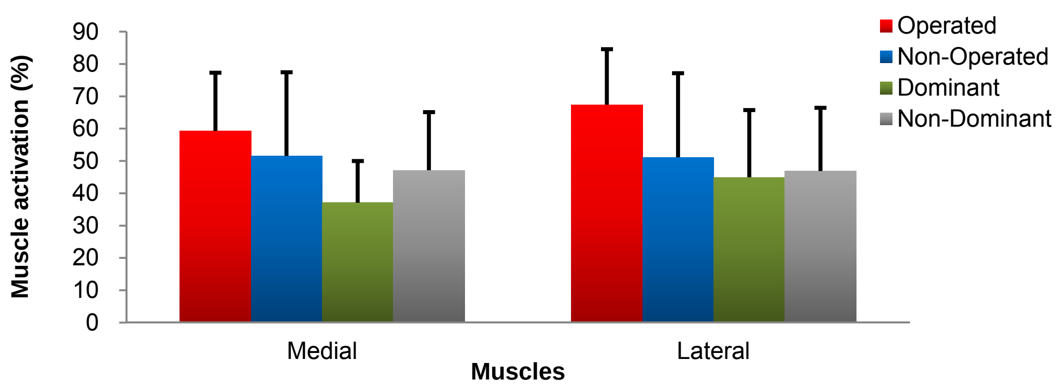


Figure *4.14*). No differences were found between operated and non-operated limbs of the TKR subjects. In contrast, significantly increased muscle co-activation was found for the lateral thigh muscles of the operated limb than for the contralateral limb and both limbs of the control subjects.

No significant differences were found in the magnitude of co-activation of the medial muscles of the thigh for the 2 groups during mid-stance phase of the gait cycle. In contrast, co-activation between the lateral muscles of the thigh of the operated limb of the TKR subjects was significantly greater than for the dominant and non-dominant limbs of the control subjects (

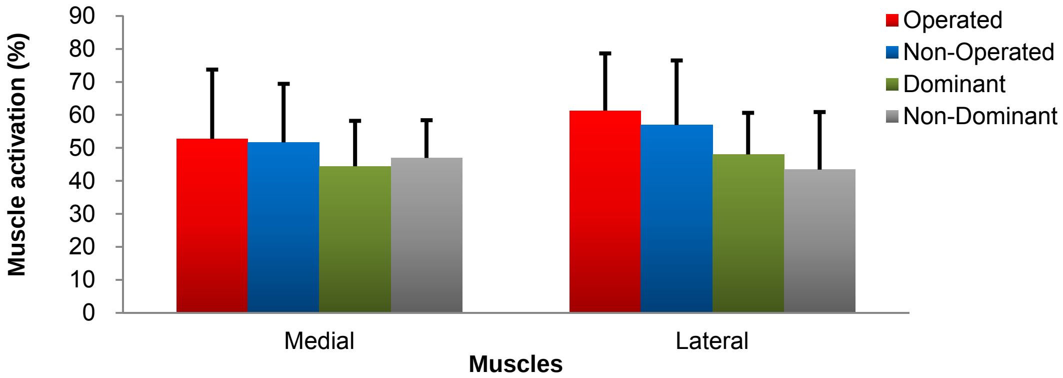


Figure *4.15*).

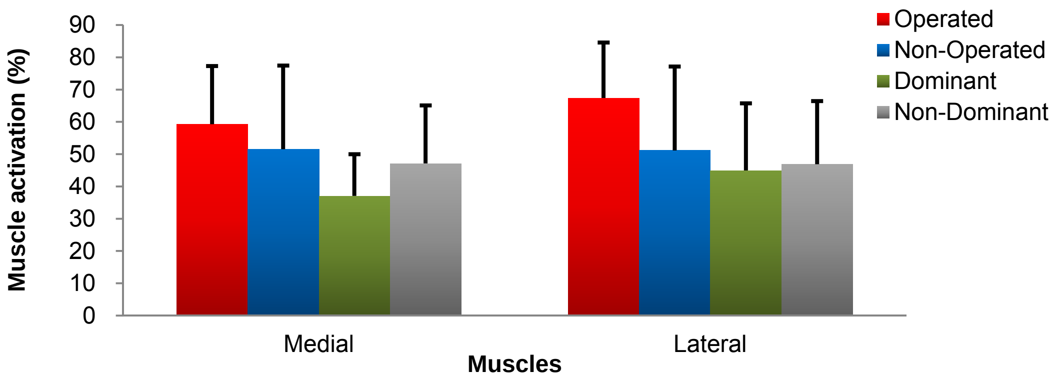


Figure 4.14. Muscle co-activation for TKR and control groups during the loading response phase.

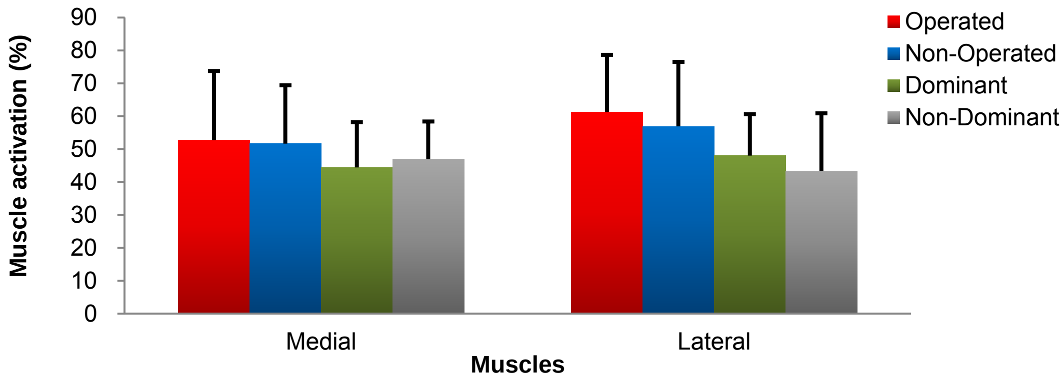


Figure 4.15. Relative EMG activation for TKR and control groups during mid stance.

Table 4.13

Correlations of muscle strength and self-reported functional performance

		R-WOMAC	**OKS**	**IKS knee**	**IKS function**
OP Extensor	Pearson's Coefficient	0.361	-0.435	0.283	0.473
	p-value	0.054	0.018*	0.136	0.010*
OP Flexor	Pearson's Coefficient	0.471	-0.534	0.474	0.507
	p-value	0.010*	0.003*	0.009*	0.005*
NOP Extensor	Pearson's Coefficient	0.119	-0.215	0.015	0.228
	p-value	0.538	0.262	0.938	0.235
NOP Flexor	Pearson's Coefficient	0.304	-0.393	0.280	0.373
	p-value	0.109	0.035*	0.141	0.046*

OP: Operated side of TKR subject.

NOP: Non-operated side of TKR subject.

* Significant difference ($p < 0.05$).

Table 4.14

Correlations of relative phase dynamics and dynamic joint position sense

		$MARP_{diff}$(HK)	**$MARP_{diff}$(KA)**	**$SARP_{diff}$(HK)**	**$SARP_{diff}$(KA)**
AE15	Pearson's Coefficient	0.065	-0.199	0.109	0.186
	p-value	0.626	0.134	0.413	0.161
AE30	Pearson's Coefficient	0.319	-0.289	0.180	0.214
	p-value	0.015*	0.028*	0.177	0.106
AE45	Pearson's Coefficient	0.218	-0.449	0.100	0.148
	p-value	0.100	<0.001*	0.454	0.267

AE60	Pearson's Coefficient	0.186	-0.406	0.014	0.007
	p-value	0.161	0.002*	0.914	0.958

HK: Hip-knee relative phase dynamics.

KA: Knee-ankle relative phase dynamics.

* Significant difference ($p < 0.05$).

4.3.7 Relationships between objective measurements and self-reported functional outcomes

Correlations between muscle strength and self-reported functional performance in both groups are presented in Table 4.13. Significant correlations were found between the self-reported functional outcomes and the muscle strength of knee flexors on the operated side of TKR subjects or dominant side of control subjects. Positive correlations were found between muscle strength and functional scores evaluated with R-WOMAC, IKS knee score and function score. In contrast, negative correlation was found between muscle strength and OKS, in which a higher score represents less positive functional performance.

Significant negative correlations were found between the coordination of knee-ankle joint and the measurement of DJPS measured at speeds ranging from 30 to 60 º/sec (Table 4.14). This suggests that the knee and ankle joints were coordinated differently to the control groups at a higher AE of DJPS.

Significant negative correlations were found between the coordination patterns of the hip-knee and knee-ankle joints and functional scores measured by IKS knee and function scores (Table 4.15). The negative correlation coefficients indicate that the greater the difference in coordination patterns between joints of operated and controls subjects was associated with less optimal self-reported functional outcomes.

Table 4.15
Correlations of relative phase dynamics and self-report function

		R-WOMAC	**OKS**	**IKS knee**	**IKS function**
$MARP_{diff}$(HK)	Pearson's Coefficient	-0.226	0.213	-0.388	-0.459
	p-value	0.238	0.266	0.037*	0. 012*
$MARP_{diff}$(KA)	Pearson's Coefficient	-0.242	0.240	-0.399	-0.467
	p-value	0.207	0.210	0.031*	0.011*
$SARP_{diff}$(HK)	Pearson's Coefficient	0.074	-0.140	-0.090	-0.007
	p-value	0.701	0.469	0.643	0.972
$SARP_{diff}$(KA)	Pearson's Coefficient	0.037	-0.095	-0.093	-0.069
	p-value	0.850	0.623	0.632	0.721

HK: Hip-knee relative phase dynamics .

KA: Knee-ankle relative phase dynamics.

* Significant difference ($p < 0.05$).

4.4 DISCUSSION

An important component in the execution of efficient movement is the coordinated interaction of related segments or joints of the human body. The value of joint kinematic information expressed by angular displacement as a function of time, obtained from gait analysis is limited, as the angle-time plot is unable to provide accurate descriptions of the interaction between functionally related segments or joints. This has stimulated the search for new methods to address this limitation and relative phase has been proposed as an index of inter-joint coordination under the theoretical framework of the dynamical systems theory (Glazier & Davids, 2009; Kurz & Stergiou, 2002). Although a relatively large number of studies have investigated gait performance in TKR patients using tempo-spatial, kinematic and kinetic parameters, to the author's knowledge, inter-joint coordination of the lower limb joints of this population has not previously been evaluated. In this study, relative phase between joint/segments was calculated as the difference in the phase angle of related joints such as between hip-knee and knee-ankle joints (Kurz & Stergiou, 2002). The phase angle of an individual joint is calculated using the angular displacement and velocity of displacement of the joint. As described in Chapter 3, DJPS involves integrated perception of the same movement parameters (Cordo et al., 1994). This information is further integrated by the central nervous system to regulate the movement by accurately controlling activation of the muscles. Therefore, it is expected that DJPS and the inter-joint coordination, expressed by the relative phase should be correlated.

As such, a primary goal of the present study was to compare the inter-joint coordination and variability in coordination of the lower limb joints in TKR and age-matched control subjects when performing level walking. Co-activation of the thigh muscles was investigated and compared between groups and followed by examination of the relationship between the DJPS and the pattern of inter-joint coordination. Self-reported functional performance and muscle strength measures were also included in the analysis to enable the comparison of the results of this study with previous studies of this population.

It was hypothesised that at 1 year following surgery, the physical and functional performance characteristics of TKR patients would be deficient by comparison with those of age-matched control subjects. This hypothesis was partially supported by the results of the present study which identified a number of deficiencies in specific physical parameters and objective and qualitative measures of functional performance.

4.4.1 Muscle strength

Results from the present study indicated that at an average of 11.5- months after surgery, the absolute value for muscle strength of the knee flexors of the TKR subjects was significantly lower than for age- and gender-matched controls. When normalised by body weight, muscle strength for both the extensors and flexors of the operated and non-operated knees in the TKR subjects remained weaker than for control subjects.

These results were consistent with previous studies which demonstrated that muscle weakness in patients following TKR surgery may persist for months to years (Berman et al., 1991; Rossi et al., 2002; Rossi & Hasson, 2004; Stevens et al., 2003; Walsh et al., 1998). When compared to healthy control subjects, deficits of 41.6% and 28.7% in quadriceps and hamstrings strength respectively have been found in patients at 3 to 6 months post-operatively. These deficits were reduced to 28.9% and 14.6% for these muscle groups respectively at approximately 1 year after surgery (Berman et al., 1991; Walsh et al., 1998). At 2 years post-operatively, quadriceps and hamstrings strength was still shown to be reduced by 18.8% and 39.1% respectively, when compared to healthy controls (Silva et al., 2003). The literature presents conflicting results with respect to the time course of recovery of the strength of knee extensors and flexors following TKR surgery. It has been suggested that the strength of the hamstrings recovers faster than that of the quadriceps (Berman et al., 1991). In contrast, other studies have shown that the 2 muscle groups have similar degrees of strength deficit during the recovery period following surgery (Silva et al., 2003; Walsh et al., 1998). Variance in the study design of these previous investigations, such as the measurement protocol, design of prosthesis and post-operative rehabilitation management makes direct comparison across studies difficult.

In the present study, the deficit in the knee extensor strength of the operated limb compared to the dominant leg of the control subjects was 31.6%, which was within the range of 18 to 35% reported by earlier studies (Anchuela et al., 2001; Berman et al., 1991; Rossi, Brown, & Whitehurst, 2006). However, the strength of knee flexors was 43.3% weaker than that of the control subjects in the present study, which was considerably higher than found previous studies with a similar post-operative follow-up period (Berman et al., 1991; Silva, et al., 2003).

Different measurement protocols may partly contribute to the inconsistency in the magnitude of the muscle strength deficiency, where isometric and isokinetic strength assessment protocols were employed in the present and previous study respectively (Berman et al., 1991).

From a functional perspective, asymmetry in muscle strength between involved and non-involved lower limbs in subjects with different pathological knee conditions has been shown to have a substantial impact on movement patterns, which in turn may lead to excessive load on other joints of the lower limb (Farquhar, Reisman, & Snyder-Mackler, 2008; Lorentzen et al., 1999; Mizner & Snyder-Mackler, 2005). Consequently knowledge of such asymmetry following TKR surgery is important in designing effective rehabilitation protocols. In the present study an ASI of 19.4% (ASI measured by the absolute difference between limbs) was found between the knee extensors of the operated and non-operated limbs. Muscle weakness represented by ASI of knee extensors, ranging from approximately 18% to 35% for TKR subjects at 12 months post-operatively has been reported (Anchuela et al., 2001; Berman et al., 1991; Farquhar et al., 2008; Rossi, Brown, & Whitehurst, 2006). Although fewer studies have investigated the strength of the knee flexors, the results indicate reductions in the strength of the operated limb, by comparison with that of the non-operated limb, of approximately 14% to 18% at 1 year post-operatively (Anchuela et al., 2001; Berman et al., 1991; Ross et al., 2006). These findings were confirmed by the results of this study, which indicated that the strength of the knee flexors in the operated leg was 20.3% weaker than that of the contralateral leg in the TKR subjects at a similar time post-operatively.

The H/Q ratio, defined in this study as the balance in muscle strength between the knee flexors (hamstrings) and extensors (quadriceps), has also been proven to be a factor that may influence joint stability. A decreased H/Q ratio in the female compared to male was also found to be positively correlated with the higher risk of ACL rupture (Portes et al., 2007). Findings of this study indicated that the H/Q ratio of the operated limb of TKR subjects was 17.4% lower than that of the dominant limb of the control subjects. This was consistent with the results of a previous study which showed a 23% reduction (H/Q ratio=0.35) in the TKR group compared to an average H/Q ratio of 0.46 for age and gender matched control subjects (Silva et al., 2003).

The relative magnitude of the reduction in knee flexor strength was greater than that of the extensors, with values of 43.3% and 31.6% respectively when compared to those of the control subjects. This influence of strength decrements in TKR patients on the H/Q ratio was also shown in an earlier study (Silva et al., 2003) which found that when compared to the control subjects at 2 years post-operatively, the magnitude of reduction in the strength of knee flexors and extensors was 39.1and 18.8%, respectively.

Quadriceps strength, both pre- and post-operatively, has been identified as a predictor of short and longer-term functional outcomes in TKR patients following surgery (Rooks et al., 2006; Zeni & Snyder-Mackler, 2010). Better functional outcomes evaluated with IKS-function and OKS in the present study confirmed these earlier findings, as they were positively correlated with the greater quadriceps strength of the operated limb in the TKR subjects. The results of the present study, also indicated that a reduction in the flexor strength of the operated knee was associated with poor functional performance, measured by self-reported or physician administered questionnaires. Although significant relationships between muscle strength and functional performance were demonstrated, caution should be taken in interpretation of this finding with respect to any cause and effect relationship, considering the cross-sectional design of the study.

4.4.2 Gait performance

Self-reported or physician administered questionnaires, including but not limited to those used in this study, are widely used to evaluate functional outcomes following TKR surgery. However, due to the potential limitations inherent in more subjective measures, the validity of questionnaires such as the WOMAC has been challenged because of the confounding overlap of the pain and functional outcome subscales (Stratford & Kennedy, 2004). In a later study, the same authors found that the change in self-reported physical function was strongly associated with changes in pain (Stratford & Kennedy, 2006). More recently, a battery of tests including walking, stair climbing and TUG tests was found to be sensitive in detecting the physical functional changes, independent of pain over time, in joint replacement subjects (Stratford, Kennedy, & Riddle, 2009).

A number of more objective performance based tests such as the TUG, 6MWT and stair negotiation tests have been used to evaluate functional recovery following knee surgery. The criterion for performance on these tests is mainly expressed by the time required to complete the particular functional task which also allows the speed component to be used for comparative purposes. Although these tests have been shown to detect improvement in timing, they can be also be used to monitor functional changes over time (Boonstra et al., 2008; Kreibich et al., 1996; Ouellet & Moffet, 2002; Petterson et al., 2009; Walsh et al., 1998). However, their value in discriminating the potential advantages of the latest surgical technologies and procedures has not been shown. With the increasing number of younger patients undergoing TKR, changes in surgical procedures and different types of prostheses (AOA, 2012), more reliable and sensitive evaluation protocols during the performance of functional activities are required.

Level walking is a fundamental activity of daily living and as such is an essential component in the rehabilitation of TKR patients following surgery to ensure quality of life and independence. Altered gait patterns following TKR have been described in a large number of studies with follow-up periods ranging from 2 months to 10 years (Benedetti et al., 1999; Benedetti et al., 2003; Bolanos et al., 1998; Borden, Perry, Davis, Owings, & Grabiner, 1999; Fantozzi et al., 2003; Jolles et al., 2012; Judd et al., 2012; Lee et al., 1999; Mizner & Snyder-Mackler, 2005; Ouellet & Moffet, 2002; Wilson et al., 1996). Results of the present study showed that at approximately 1 year post-operatively, TKR subjects walked with a similar cadence, stride length and velocity to their age-matched controls. Stride length and walking velocity, normalised according to body height, were also similar to those of the control group, whose performance was comparable with that reported by previous studies using subjects of similar age and anthropometry (Blanke & Hageman, 1989; Hageman & Blanke, 1986; Ouellet & Moffet, 2002; Saari et al., 2005). Results of this study were in agreement with the results of 2 previous studies of TKR patients, which followed-up the patient for a period of 1 year after surgery and repeated the measurement of gait performance. The results of these earlier studies consistently showed improvements in stride length and cadence during the follow-up at 1 year post-operatively and the gait parameters were comparable to those of the age-matched controls (Benedetti et al., 1999; Wilson et al., 1996; Wiik, Manning, Strachan, Amis, & Cobb, 2013).

In contrast to the comparable performance with respect to cadence, stride length and walking velocity, alterations in other gait patterns in TKR patients are usually characterised by an increased duration of stance phase. These changes are associated with prolonged double support time and decreased single support time when compared to control subjects (Lee et al., 1999; Ouellet & Moffet, 2002; Smith, Lloyd, & Wood, 2006). These findings were confirmed by the results of the present study which indicated a reduced single support period as a percentage of stride time of approximately 34.85% compared to 38% for control subjects. Double support period increased to approximately 32% by comparison to 26.5% for control subjects.

Although TKR subjects walked at a similar speed to that of the control subjects, significant differences were demonstrated in the kinematics of the lower limb joints. The operated knee had reduced excursion of flexion and extension during the early or late stance phase respectively, which was characterised by greater flexion at initial heel contact and reduced extension prior to the start of swing phase. These alterations were associated with a slightly greater hip flexion and reduced ankle plantar flexion during the later stance phase and initial swing phase of the gait cycle. These findings were in agreement with the results of previous studies which indicated that the kinematic alterations are not localised and limited to the knee joint, with the movement patterns of other lower limb joints, including the hip and ankle being simultaneously changed (Benedetti et al., 1999; Benedetti et al., 2003; Fuchs, Skwara, & Rosenbaum, 2005; Ouellet & Moffet, 2002). Consistent with the results of longitudinal studies with a 2-year post-operative follow-up (Benedetti et al., 1999; Benedetti et al., 2003), the more apparent alterations in the kinematic characteristics of the knee joint occurred during the loading response and terminal stance phases of the gait cycle.

According to the principles of dynamical systems theory, movement patterns are developed from the synergistic organisation of the neuromuscular system based on anatomical, biomechanical and environmental factors and task constraints. Optimal interaction of these factors enables the performance of smooth and effective goal-directed movements (Glazier & Davids, 2009). Segments or joints need to be coordinated by the central nervous system with involvement of the neuromuscular system. Inter-joint coordination is the relationship between the motions of 2 joints, including angular displacements and velocities which are associated with the information from afferent joint receptors (Burgess-Limerick et al., 1993). Therefore, evaluation of inter-joint coordination may provide information on how the central nervous system organises adjacent joints in the performance of different functional activities.

Variable methods including angle-angle plots and relative phase plots have been proposed to study inter-joint coordination (Burgess-Limerick et al., 1993; Kurz & Stergiou, 2002; Schmidt & Lee, 1999). In addition, the method of relative phase integrates information derived from joint angular displacements and velocities with the term continuous relative phase obtained derived by subtracting the phase angle of the distal joint from that of the proximal joint at corresponding time points in the gait cycle (Burgess-Limerick et al., 1993; Kurz & Stergiou, 2002; Hutin et al., 2010).

The hypothesis that TKR subjects demonstrate altered relative phase dynamics when compared with the age-matched controls was supported by the results of the present study. TKR subjects showed a different coordination pattern between the hip-knee and knee-ankle joints compared to that of the controls. As mentioned previously, the most apparent kinematic alteration in the hip, knee and ankle mainly occurred during the stance phase of the gait cycle. As such, the analysis focused on the coordination of joints during the stance phase.

No previous study was found which has examined relative phase dynamics during level walking in TKR subjects preventing direct comparison with the results of this study. However, a study which investigated the relative phase dynamics during a sit-to-stand task, found that at 1 year post-operatively, TKR subjects were able to stand up from the lower and higher chair using patterns of joint coordination similar to those of control subjects (Boonstra et al., 2007). Other studies which have investigated locomotor strategies in patients following ACL reconstruction (Kurz et al., 2005) or patients with a history of iliotibial band syndrome (Miller, Meardon, Derrick, & Gillette, 2008), found that the relative phase dynamics of the lower extremity was significantly different from that of the control subjects during functional activities including walking and running.

One potential mechanism which may contribute to the observed alterations in coordination is the potential changes in proprioception as a function of reduced sensory information provided by the reconstructed knee following ACL rupture (Kurz et al., 2005). Knee joint proprioception is critical for accurate and appropriate neuromuscular control of the knee joint and maintenance of appropriate or adequate coordination with the hip and ankle joints to accomplish different functional activities. Proprioceptive information from the afferent joint receptors is an essential factor which is integrated by the central nervous system to discriminate and regulate total posture and segmental posture (joint stability) (Riemann & Lephart, 2002a, 2002b). Although previous studies have evaluated proprioception of the replaced knee joint with the PAR protocol, no study was found which employed a DJPS protocol. Dynamic JPS integrates the afferent information with respect to joint displacement and velocity. Therefore, it is likely that the inter-joint coordination measured by relative phase dynamics would be impacted by DJPS. This hypothesis was supported by results of the present study which indicated that impaired DJPS was correlated with less optimal inter-joint coordination of knee-ankle joints in TKR subjects. A relatively larger number of studies have investigated knee joint proprioception in TKR subjects using PAR testing or using a threshold for detection of passive movement. However, to the author’s knowledge, this is the first study which has investigated knee joint proprioception in this population using DJPS and which has explored the relationship between DJPS and inter-joint coordination.

The results of the present study also indicated that alterations in inter-joint coordination following TKR, are not only limited to the operated limb, but also affect coordination patterns between joints of the contralateral lower limb. Inter-joint coordination patterns between hip-knee and knee-ankle of the contralateral limb of TKR subjects were different from those of the control subjects. These findings were consistent with previous studies which found changes in joint kinetic characteristics and muscle activation occurred simultaneously at the ipsilateral and contralateral lower extremities in TKR subjects during stepping-up (Byrne et al., 2002), walking and when transferring from sitting to standing (Mizner & Snyder-Mackler, 2005).

4.4.3 Muscle activity

Muscular co-activation is generally considered to be augmented when uncertainty or insecurity exists in the required task, or when compensatory force is anticipated to be required during the task (De Luca & Mambrito, 1987; Larsen, Puggaard, Hamalainen, & Aagaard, 2008). In the current study, walking at a self-selected speed on a level surface was used as the functional task for all groups. This is a task commonly used in daily living and although conducted in the laboratory the opportunity for subjects to familiarise with the laboratory based procedures should improve confidence in performing the task and increase the reliability of the outcomes.

The potential role of muscle co-activation in joint stability and injury prevention has stimulated interest in defining appropriate patterns and degree of agonist-antagonist co-activation required to maintain dynamic knee joint stability in populations with joint stability problems (Hubley-Kozey, Deluzio, Landry, McNutt, & Stanish, 2006). Excessive levels of co-activation may lead to impaired movement performance, decrements in movement efficiency and increased energy consumption (Mian, Thom, Ardigo, Narici, & Minetti, 2006). This in turn, may alter loading patterns and result in accelerated degradation of tissues such as articular cartilage (Hurley, 1999) and failure of prosthesis in subjects following TKR surgery (Benedetti et al., 2003). Consequently, it is important to investigate muscle co-activation following TKR to enable the design of appropriate rehabilitation and muscle re-education strategies.

Elevated co-activation of knee flexors and extensors was identified in this study during walking on a level surface. These results were partly supported by a previous study which also found significantly elevated hamstrings-quadriceps co-activation in the operated leg, compared to that of the non-operated contralateral limb and that of the controls (Stevens-Lapsley, Balter, Kohrt, & Eckhoff, 2010). However, in contrast to the present study which investigated co-activation during walking, this earlier study only evaluated co-activation during maximal quadriceps contraction.

It is proposed that agonist and antagonist co-activation is further magnified during weight-bearing compared with non-weight-bearing activities (Busse, Wiles, & van Deursen, 2006; Lutz, Palmitier, An, & Chao, 1993). For example, Busse et al., (2006), found the average (SD) co-activation of the hamstrings and quadriceps during a sit-to-stand task was 0.21 (0.13) compared with 0.12 (0.06) during isometric maximal knee extension. This finding lends support to this proposition and indicates the need to evaluate co-activation during weight-bearing activities associated with performance of functional activities of daily living such as walking and stair climbing.

Consistent with the findings from previous studies (Benedetti et al., 1999; Benedetti et al., 2003; Yoshida, Mizner, & Snyder-Mackler, 2013) the results of the present study indicate that muscle co-activation during the stance phase (including the loading response, mid-stance sub-phases and entire stance phase) was significantly higher when compared with that of the control subjects at 12 months post-operatively. Benedetti et al., (2003) also found that most patients still had significantly prolonged muscle activation of agonist-antagonists during the stance phase of level walking 2 years after surgery. A case study which evaluated co-activation patterns at different stages of recovery also showed progressive increases in co-activation of knee flexors and extensors at 3, 6, 12 and 24 months post-operatively which was associated with altered knee movement patterns and loading of the knee joint during stance (Benedetti et al., 1999).

In addition to the identification of phasic differences in muscle co-activation patterns during the gait cycle, another important finding of the present study is that the level of co-activation was greater in muscles located around the lateral aspect of the replaced knee joint than for those located medially. Although similar findings have been indicated in patients with knee OA (Hubley-Kozey, Deluzio, & Dunbar, 2008; Hubley-Kozey et al., 2006), no previous studies were found which have shown this level of discrimination and diversity in muscle co-activation patterns following TKR.

Differences between lateral and medial hamstrings, suggest different activation patterns between the muscles relative to the control and stabilisation required following initial heel contact (Hubley-Kozey et al., 2008). The higher level of activity of the lateral hamstrings and the higher co-activation in the lateral aspect of the knee joint supports the assumption that the lateral muscles are working to increase lateral force, leading to decreased medial joint loading (Andriacchi, 1994; Hubley-Kozey et al., 2006).

Using instrumented knee prostheses, imbedded with force transducers Mundermann, Dyrby, D'Lima, Colwell, & Andriacchi (2008) found that when performing activities of daily living, TKR subjects experienced loading on the medial compartment of the knee 70% higher than that of the lateral compartment. This provides further support to the hypothesis based on the findings of the present study, that the increased muscle co-activation of the lateral knee muscles is adopted as an active compensatory strategy to compensate in part for the loading on the medial component of the knee joint.

EMG signal intensity and relative phasing may be influenced by walking speed and a speed variation of greater than 30% has previously been shown to influence EMG activation patterns (Shiavi, Bugle, & Limbird, 1987; Detrembleur, Willems, & Plaghki, 1997). In the present study, a difference of 7.6% in the average walking velocity between the 2 groups was found which suggests that walking velocity is unlikely to be a crucial factor in determining differences in EMG patterns.

Different methods of normalising EMG patterns have been used for gait analysis including isometric maximal voluntary contractions (MVC) first introduced in 1976 (Dubo et al., 1976). Although the reliability of this measure of MVC has been questioned recently (Zech, Witte, & Pfeifer, 2008), it has been shown to be useful across a range of studies which have adopted appropriate procedures including familiarization through practice and real time feedback of subjects as used in the present study. Studies of subjects with knee osteoarthritis (Lewek, Rudolph, & Snyder-Mackler, 2004; Machner, Pap, & Awiszus, 2002) or following TKR (Berth et al., 2007) showed that following these procedures subjects with knee conditions were able to recruit muscles and produce reliable measures of MVC comparable to those of control subjects (Lewek et al., 2004).

In summary, TKR subjects showed significantly increased co-activation of muscles around knee joint during the stance phase of level walking. Interestingly, muscle co-activation associated with the lateral aspect of the knee joint was greater than that of the medial aspect. This increase in co-activation of muscles of the lateral compartment may be adopted as an active neuromuscular compensatory strategy, to compensate in part for the loading on the medial component of the knee joint.

4.4.4 Relationships between self-reported outcomes and objective measures of functional performance

As indicated earlier, the validity of self-reported questionnaires such as WOMAC, has been questioned recently due to the overlap between the subscales of pain and function (Stratford & Kennedy, 2004) and a number of items of the self-administered OKS could not be accurately completed by unassisted patients (Whitehouse et al., 2005). In spite of these observations, these surveys are still widely used in routine clinical services to evaluate the efficacy of surgical procedures and rehabilitation interventions in TKR and other patient groups (Stratford & Kennedy, 2004). The questionnaires are designed to evaluate multiple aspects such as pain, stiffness and mobility capacity, but may lack the sensitivity to detect key functional outcomes or factors which influence these outcomes as derived from more objective measurement procedures. As such it is important to determine the relationship between self-reported outcomes with the more objective performance based measurements as used in this study.

Increased muscle strength was found to be positively associated with better functional performance in the present study. The finding is consistent with those of previous studies which showed that quadriceps strength was associated with functional performance during recovery following TKR (Fuchs et al., 2000; Mizner, Petterson, & Snyder-Mackler, 2005). In contrast to the large number of studies which have examined the relationship between quadriceps strength and recovery following TKR, information regarding the predictive value of hamstring strength is more limited (Berman et al., 1991; Lorentzen et al., 1999; Silva et al., 2003; Walsh et al., 1998) and the correlation between hamstring strength and functional performance has not been demonstrated.

Although significant correlations were found between hamstrings strength of the operated knee and the functional performance in the present study, longitudinal studies are required to evaluate the contribution of hamstrings strength improvement to the progress of functional recovery. While there is considerable focus on quadriceps strengthening during post-operative rehabilitation, the results of this study emphasise the need to also focus on hamstring strengthening interventions. The hypothesis that more accurate DJPS is correlated to fewer alterations in inter-joint coordination was confirmed by the results of this study. Lack of similar evidence associated with the knee joint makes comparison and confirmation of this finding difficult. However, studies of DJPS of the ankle joint have shown that impaired proprioception of this joint was correlated to less than optimal coordination of the movement in elderly when compared to younger subjects with more accurate proprioception (Madhavan & Shields, 2005; Verschueren et al., 2002).

No significant relationship was found in this study between walking velocity and self-reported functional measures. In contrast, an association was found between improvements in walking velocity and stride length and decreases in pain over the period of 13 months post-operatively by a study using a repeated measurement design (Kroll et al.,1989). A possible reason for this inconsistency may relate to differences in study design and differences in the dependent variables used. The earlier study evaluated changes in cadence, stride length and pain over the 13-month period of time as the dependent variables for comparison. The inconsistency in findings may also reflect the fact that the TKS subject walked with an average velocity and cadence comparable to those of the control subjects, accompanied by significantly less optimal performance in self-reported functional measurements.

The IKS knee and function scores were found to be associated with the inter-joint coordination. This suggests that patients with significant alterations in their coordination patterns between hip-knee and knee-ankle joints had a lower functional score. This result confirmed the findings of a previous study, which indicated that a higher WOMAC score was correlated with more optimal inter-joint coordination and less variability in inter-joint coordination of the hip-knee and knee-ankle joints during performance of a sit-to-stand transfer test (Boonstra et al., 2007). In contrast, no significant correlation was found in the present study between the outcomes of the reduced version of the WOMAC and the inter-joint coordination pattern. The conflicting findings may be attributed to the different functional tasks used in these 2 studies. As mentioned earlier, task constraints are one of the important determinants of movement patterns which arise from the synergistic organisation of the neuromuscular system (Glazier & Davids, 2009). For example, the sit-to-stand task has been shown to be more biomechanically demanding than level walking, which was employed in the current study. Knee forces generated during rising from a chair without the aid of the arms can be up to 7 times body weight (Ellis, Seedhom, & Wright, 1984; Varadarajan, Moynihan, D'Lima, Colwell, & Li, 2008), which is approximately double the force (3.4 x body weight) produced at the knee joint at foot strike during level walking (Messier et al., 2005).

In summary, the muscle strength of both knee extensors and flexors is associated with functional performance measured by self-reported questionnaires. Functional performance measured by IKS was also correlated to the inter-joint coordination patterns between hip-knee and knee-ankle joints. Further studies with more biomechanically demanding functional tasks are required to explore the relationships between inter-joint coordination and other self-reported questionnaires.

4.5 CONCLUSIONS

- Although the TKR subjects were able to walk at a velocity and step and stride length similar to that of the controls, their gait was characterised by a significantly prolonged double support time, accompanied by decreased swing time and single support time.
- Strength scores of the extensors and flexors of both limbs for TKR subjects normalised by body weight were significantly lower than those of the control subjects.
- When comparing inter-joint coordination and variability of coordination of the hip-knee and knee-ankle joints, TKR subjects demonstrated significant differences to controls with respect to alterations in the patterns of coordination and increased variability of coordination.
- The hypothesis that more accurate DJPS is correlated to less alterations in the inter-joint coordination was confirmed by the results of this study.
- Greater errors with respect to DJPS were positively correlated to greater deviation in knee-ankle coordination and variability of coordination between the knee and ankle joints.
- Co-activation of the knee extensors and flexors of TKR subjects was also significantly increased, particularly in the lateral aspect of the knee joint, for a majority of the stance period during level walking.
- Identification of phasic differences in muscle co-activation patterns during the gait cycle was another important finding of the present study indicated by a greater level of co-activation of muscles located around the lateral aspect of the replaced knee joint than for those located medially. Although similar findings have been indicated in patients with knee OA (Hubley-Kozey et al., 2008; Hubley-Kozey et al., 2006), no previous studies were found which have shown this level of discrimination and diversity in muscle co-activation patterns following TKR.
- Functional outcomes measured by self-reported questionnaires were correlated to inter-joint coordination between the knee-ankle joints of the operated limb and improved functional outcomes measured qualitatively were positively correlated to the strength of the muscles of the operated knee.

- Muscle strength of both knee extensors and flexors was shown to be associated with functional performance outcomes measured by self-reported questionnaires. The functional performance measured by IKS was also correlated to the inter-joint coordination patterns between hip-knee and knee-ankle joints.
- No significant relationship was found between walking velocity and self-reported functional measures.

The results of Study 2 involving gait characteristics of TKR patients was further evaluated and extended in Study 3 involving key activities of daily living evaluated at 6 months post-operatively.

Chapter 5: Functional performance and neuromuscular adaptations in simulated activities of daily living in patients following unilateral TKR

5.1 INTRODUCTION

The previous chapter identified the potential importance of incorporating objective measures in the evaluation of post-operative functional performance of TKR patients using gait analysis techniques. While the findings from this and previous studies identified some key differences between TKR subjects and controls during walking, further research is required to understand the kinematic and kinetic differences during participation in other potentially higher risk activities of daily living. As such, the research presented in this chapter was implemented to further explore the objective outcome measures using responses to simulations of activities of daily living (ADL) including those associated with walking, turning and stair negotiation. As in the previous studies the objective functional outcomes from this study were also compared with qualitative outcomes from previously validated clinical survey tools.

The ability to accomplish fundamentally different locomotor activities in a variety of settings is essential in ensuring active independent living for older people and greater longevity. For example, turning during walking comprises approximately 35% to 45% of the steps taken during a typical day (Glaister, Bernatz, Klute, & Orendurff, 2007). Stair ascent and descent is also an essential functional requirement for people who wish to return to normal community or occupational activities (Startzell, Owens, Mulfinger, & Cavanagh, 2000).

Safe performance of these functional activities is also important in reducing the incidence of injury in older members of the community. Many falls in the elderly occur during postural transitions, as occurs when changing direction and initiating walking. In a prospective observational study of 118 subjects with knee OA (average age of 73.5 years), 24.2% reported falling in the last 3 months before TKR surgery (Swinkels, Newman, & Allain, 2009). Although the overall fall rate decreased to 11.8% in the first year post-operatively, 45.8% of those who fell pre-operatively fell again in the first year after surgery. Stair negotiation is also one of the more challenging and hazardous activities of daily living for older people, with stair falls accounting for more than 10% of fatal fall accidents in people older than 60 (Startzell et al., 2000).

Maintenance of dynamic balance is a key component when performing postural transitions and managing stair negotiation safely. However, the ability of elderly subjects to safely manage these more challenging locomotor tasks is impaired as their dynamic balance control is compromised by age-related loss of vision, vestibular sense, muscle strength, proprioception and increased reaction time (Nadeau, McFadyen, & Malouin, 2003; Startzell et al., 2000; Thigpen, Light, Creel, & Flynn, 2000). For example, in a study of 12,716 randomly selected individuals, 22% of people older than 50 reported difficulty in climbing stairs (Freedman & Martin, 1998). At an average follow-up period of 15 months after TKR surgery, approximately 50% of subjects still experienced difficulty in stepping onto a 20cm high platform (Byrne et al., 2002).

Significantly altered kinematic and kinetic patterns of lower limb joints have been demonstrated in patients either before or after TKR (Andriacchi & Hurwitz, 1997; Benedetti et al., 2003; Berman, Zarro, Bosacco, & Israelite, 1987; Bolanos et al., 1998; Ishii et al., 1998; Smith et al., 2006). A majority of these studies have evaluated gait characteristics during straight-line walking on a level surface and their results showed an asymmetric kinematic pattern between the operated and non-operated limbs of TKR subjects. Although perturbations to normal walking are common, (Glaister et al., 2007; Sedgman, Goldie, & Iansek, 1994), there is a paucity of information to indicate the response of TKR patients to these sometimes unexpected but very prevalent locomotor tasks.

Two main strategies associated with step and spin turning have been demonstrated (Hase & Stein, 1999). The step turn involves changing to a new direction opposite to the supporting limb. That is, the turn makes a movement to the right during which time the left limb functions as the supporting limb. In contrast, the spin turn refers to a change of direction toward the same side as the supporting limb. For instance, the right limb crosses in front of the left or supporting limb when turning to the left side. Increased range of motion in the transverse plane and greater muscular demand has been shown in spin turning than step turning, but with the latter shown to be more stable by providing a wider base of support (Taylor, Dabnichki, & Strike, 2005; Taylor, Strike, & Dabnichki, 2006).

Previous studies have demonstrated that able-bodied subjects with right-leg dominance show a preference towards turning to the left in response to an external disturbance (Segal, Orendurff, Czerniecki, Shofer, & Klute, 2008; Taylor et al., 2006). Increased medial impulses of GRF in the medio-lateral direction which spanned the entire stance phase were found in earlier studies when compared to that of the straight-line walking, in which the pattern of GRF was characterised by a brief medial impulse at the time of heel strike, followed by a lateral impulse (Glaister, Orendurff, Schoen, Bernatz, & Klute, 2008). Additional joint moment has also been shown in all 3 axial planes in lower extremity joints when responding to gait disturbance and particularly at the knee joint (Taylor et al., 2005). In TKR patients, this loading may logically lead to extra risk of prosthesis loosening. Therefore, strategies adopted by TKR subjects when changing direction during walking warrant further investigation. Although not involving TKR subjects, Sedgman et al. (1994) found that a majority of turns used in daily living occur between 76º and 120º of deviation from the direction of progression. This suggests that a study of turns should focus on turns which occur within this range, which represents a realistic simulation of the daily living environment.

The common element for initiating a locomotor activity is to move the body from a position of quiet standing to a dynamic state. This requires performance of 2 conflicting tasks which occur simultaneously in this process involving: (i) generation of momentum in the forward direction and towards the stance limb; and (ii) maintenance of balance (Polcyn, Lipsitz, Kerrigan, & Collins, 1998). Under control of the central nervous system, during gait initiation, people voluntarily move the centre of pressure (COP) backward and toward the foot that is to be lifted first (leading foot/leg) before detection of movement of the body's centre of mass (COM) (Crenna & Frigo, 1991; Polcyn et al., 1998; Xu, Carlton, & Rosengren, 2004). This initial postural response known as APA serves a dual role in facilitating the subsequent voluntary movement. It has been suggested (Bouisset & Zattara, 1981; Martinez-Mendez, Sekine, & Tamura, 2011) that the "APA tends to create inertial forces, which, at the appropriate time, will counterbalance the disturbance to postural equilibrium due to the intentional forthcoming movement". Significant changes during gait initiation were found in patients with knee OA (Viton et al., 2000), who showed slower gait initiation, irrespective of whether or not the sound or involved limb was bearing the load. This change was also accompanied by a lengthened postural and shortened monopodal phase when supported by the affected leg (Viton et al., 2000).

The ability to perform stair climbing was found to be directly related to the function of the knee extensors and for healthy aged subjects, 56% of the variance during stair ascent and descent was attributed to knee extensor strength (Lindeman, Leffers, Reulen, Spaans, & Drukker, 1998). As indicated earlier, decreased strength of the thigh muscles in patients before and after TKR surgery has been demonstrated up to 13 years post-operatively and was confirmed by the results described in the preceding chapter at the 12-month period. Previous studies have shown that TKR patients rely more on the contralateral limb to complete stair ascent. This is evidenced by the fact that the moment of force in the operated knee was always shown to be less than that of the contralateral limb and controls (Byrne et al., 2002). From a kinematic perspective, a greater range of motion of the knee joint is required during stair ascent and descent than during walking on a level surface. Knee joint flexion of 90~95º is required to ascend (Mian, Thom, Narici, & Baltzopoulos, 2007; Saari et al., 2004; Startzell et al., 2000) and approximately 90~100º of knee flexion is required to descend a stair with an angle to the horizontal of 30º (Mian et al., 2007; Startzell et al., 2000). Results of 3 studies indicated that following TKR, patients tended to ascend more slowly and with a smaller total range of knee flexion than controls (Byrne et al., 2002; Fantozzi et al., 2003; Saari et al., 2004). Although these studies only investigated stair ascent, other studies have shown that larger forces and consequently greater moments of force are generated at the knee joint during stair descent compared to stair ascent and level walking (Andriacchi, Galante, & Fermier, 1982; Riener, Rabuffetti, & Frigo, 2002; Reid, Lynn, Musselman, & Costigan, 2007). This finding suggests that stair descent is more challenging than stair ascent, however the single stair procedure used in these studies does not fully represent 'real world' situations where it is necessary to handle both ascent and descent using multiple steps. Consequently, a test climbing protocol which simulates the normal environment should provide a more meaningful insight into factors involved in accomplishing these functional activities which present challenges and risk of injury for TKR patients.

The role of impaired proprioception and decreased muscle strength associated with the operated knee joint, has not been previously investigated, with respect to inter-joint coordination during biomechanically demanding tasks such as stair ascent and descent. In addition, although the patients' perception of their ability to perform functional activities, such as walking and stair ascent and descent, has been included in questionnaires such as the IKS function scale, the relationship between these and more objective outcome measures has not been determined. Greater understanding of these relationships between everyday functional activities and the biomechanical and neuromuscular processes is critical in understanding of the recovery process and the design and evaluation of effective interventions. Consequently, the aims of this study were to:

1. Examine the biomechanical, neuromuscular responses of TKR patients to simulated tasks of functional activities of daily living at 6 months post-operatively;
2. Identify the biomechanical and neuromuscular factors associated with the adaptation or compensation strategies used by TKR patients by comparison with age-matched controls during performance of simulated functional tasks;
3. Explore the relationship between objective measures of functional performances on simulated tasks of daily living with functional outcomes measured by self-reported surveys.

5.1.1 Hypotheses

By comparison with control subjects, TKR patients will:

1. Adopt different strategies of step turning and spin turning during walking and turning tasks;
2. Demonstrate increased reaction time and time required to complete the turning tasks;
3. Demonstrate different movement characteristics of COP during APA at gait initiation;
4. Demonstrate increased muscle co-activation patterns in the operated lower limb during performance of simulated functional activities of daily living including gait initiation and stair ascent/descent;
5. Adopt modified inter-joint coordination patterns for the operated limb of TKR subjects; and
6. Indicate perceptions of functional recovery which are associated with the results of objective functional evaluations including muscle strength, proprioception, temporal-spatial parameters of simulated functional task and inter-joint coordination during stair ascent and descent.

5.2 METHODS

5.2.1 Subjects

Subjects recruited for this study were involved in an ongoing randomised control study designed to evaluate the advantages of using a computer-assisted navigation system during surgery, by comparison with a more conventional surgical approach. Participants were firstly screened by the orthopaedic surgeon and those subjects who satisfied the inclusion criteria used in Study 1 and Study 2 and described earlier (Table 3.1), were referred to the project. This was followed by a detailed verbal introduction to the project with each recruit and with reference to the previously signed informed consent form for the overall study. Control subjects were recruited from the community following procedures described in Chapter 3. The project was reviewed and approved by the UHREC of QUT and the randomised control study was approved by the Ethics Committee of the Prince Charles Hospital.

A total of 14 subjects (6 males and 8 females) who had undergone primary unilateral TKR approximately 6 months earlier participated in the current study. Nine subjects were operated on the left knee joint and the other 5 subjects had their right knee replaced. In addition, 9 subjects (3 males and 6 females) with no history of knee replacement surgery and who satisfied the criteria for inclusion as described in Chapter 3 acted as control subjects. Both TKR and control groups were matched as closely as possible for age and had an average age of 68.4 ± 5.0 and 64.4 ± 3.2 years respectively. To preserve the integrity and continuity of the randomised double blind control study, identification of the surgical technique used did not occur. However there was consistency in the procedure with respect to the type of prosthesis used, with all patients receiving a Triathlon posterior stabilised prosthesis (Stryker Orthopaedics, Michigan, USA) and with all patella resurfacing during surgery undertaken by one senior surgeon.

5.2.2 Instruments

As described in the previous chapter, gait analyses were conducted in the gait laboratory of IHBI at QUT. In this study, kinematic data were recorded using an 11-camera motion analysis system (VICON MX 13 and VICON MX 40, OMG, UK) at a sampling rate of 100Hz. Two force plates (OR-6-6, AMTI, USA) embedded in the middle of the walkway were used to collect GRF data during gait initiation at a sampling rate of 1000Hz. A 16-channel wireless sEMG system (ZeroWire, Aurion, Italy) was used to collect sEMG signals from the muscles of interest and recorded at a sampling rate of 1000Hz. All kinematic data, GRF and sEMG data were synchronised during the process of real time data collection and recorded using VICON Nexus software (Version 1.4, VICON Motion Analysis Inc, OMG, UK) for further offline analysis.

For recording of data during the 3 functional locomotor tasks, (gait initiation, turning and stair ascent/descent), 16 spherical retrospective markers (14mm in diameter) were used to define different segments of the pelvis and lower limbs in accordance with the VICON Plug-in Gait Model (Lower Limb Standard Model). These markers were placed bilaterally on anatomically well-defined points as described in the manual of procedures for the Vicon Plug-in Gait Model. The landmarks for marker positioning were the same as those described in Chapter 4 (page74).

A customised 3-step staircase was constructed for the recording of ascent and descent during stair climbing. The step dimensions were consistent with a previous study of older subjects of similar age to the study population and reference to recommended dimensions for stair construction for the elderly (Stacoff et al., 2005). The steps had a 17 cm riser and were 28 cm in depth and 80 cm wide (Figure 5.1). The staircase was firmly attached to the floor and positioned adjacent to 2 force plates located in the middle of the walkway. Two force plates (Kistler model 9286AA) were also embedded in the first and second steps of the staircase which allowed recording from force plates during the stair ascent and descent protocols.

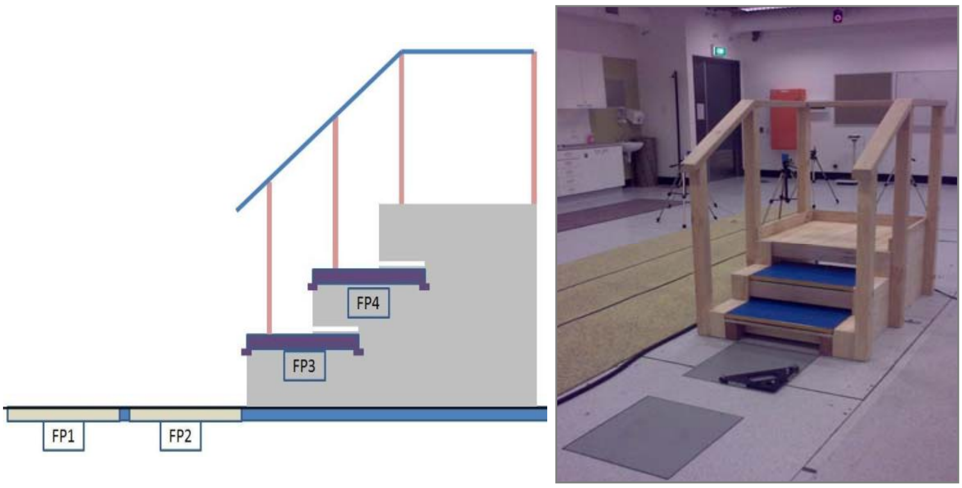


Figure 5.1. Diagrammatic and pictorial representation of staircase and adjacent walkway.

A system to provide visual stimulus signals during gait initiation and walking and turning tests was designed to be incorporated and integrated with the motion analysis and EMG recording systems. The tests were introduced by a specialised program developed with LabView (Version 8.1, National Instruments, Austin, TX, USA). This program was designed to produce directional signals (Figure 5.2) which were displayed on a 17-inch screen to provide visual instructions for participants. The second monitor (Figure 5.3) was positioned on a 1.5 metre high platform located at the end of the walkway facing the participants. A rectangular electrical pulse with a magnitude of 2.5v was generated at the time the visual signal appeared and was input to a customised data logging system (DAS) for further synchronisation with sEMG and kinematic data.

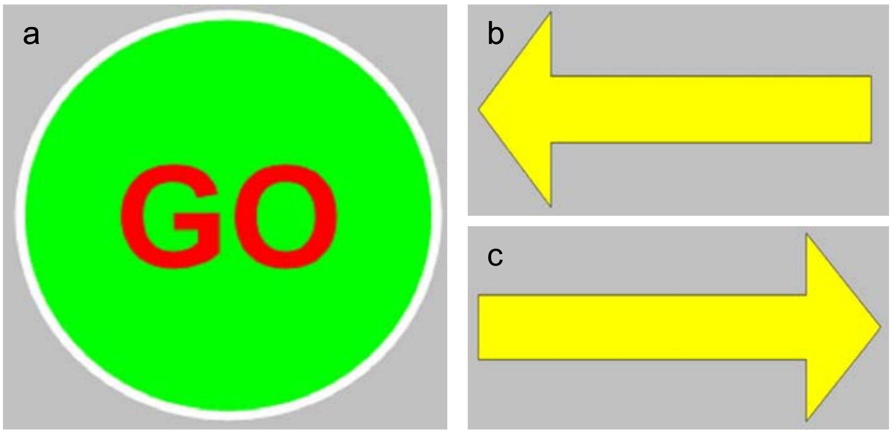


Figure 5.2. Visual signals displayed on the second monitor for activity induction.

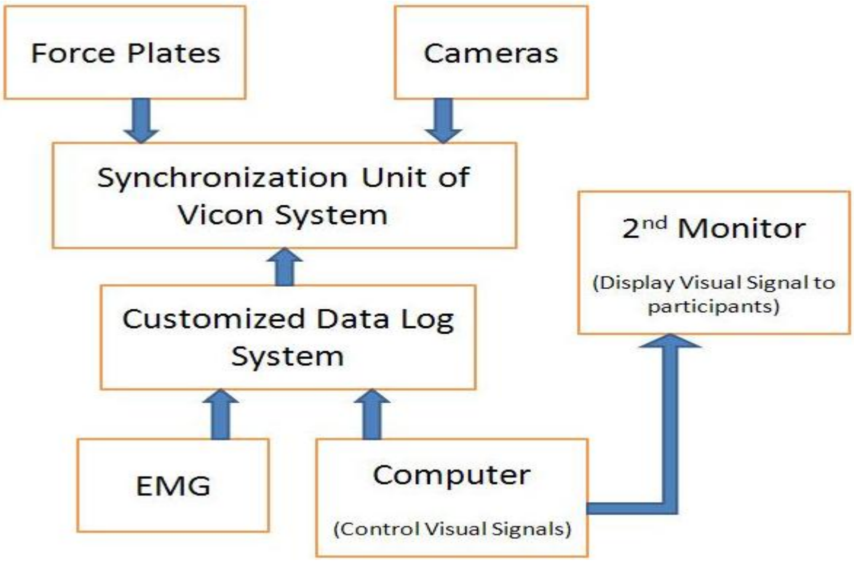


Figure 5.3. Schematic of inter connection of different units used for data collection.

In order to synchronise sEMG signals and visual instruction recording, a DAS was developed using two NI USB-6008 data acquisition units (National Instruments, Austin, TX, USA) and with technical support from the School of Human Movement Studies. The DAS system allowed input for the 16 channels of the wireless sEMG system and the rectangular electrical pulse. This represented the starting point of the visual signals and input into the synchronisation unit of the VICON motion capture system for synchronisation and recording purposes. A flow chart representing the integrated system with examples of some of the signals monitored and recorded are presented in Figure 5.4a and 5.4b respectively.

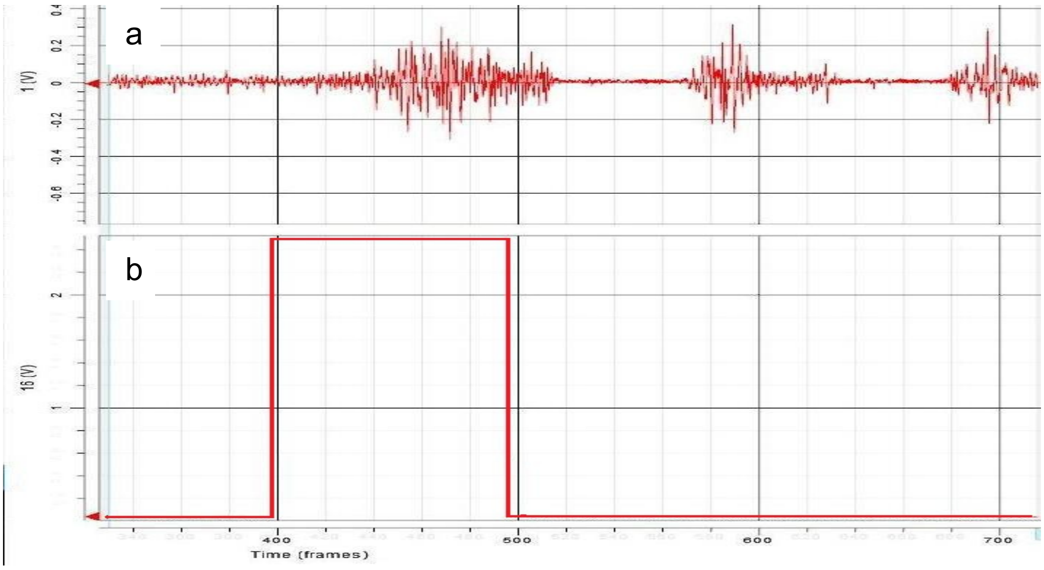


Figure 5.4. Example of sEMG (a) and visual signal (b) recorded during gait initiation.

5.2.3 Experimental protocol

Prior to data collection, participants completed a screening questionnaire which was designed to identify potential performance risks such as uncontrolled blood pressure and heart related symptoms during participation in physical activity. All subjects referred by the orthopaedic surgeon satisfied the screening criteria for participation. To ensure patient safety and reduce the risk of falling, an overhead harness system was attached to the subject during the stair climbing activities.

5.2.4 Subjective assessment of knee functionality

As described in Chapter 3, the knee function of all participants in both TKR and control groups was assessed using the R-WOMAC, OKS and the IKS knee score and function score.

The latter survey was also administered pre-operatively as a component of the ongoing randomised control study in which subjects in the TKR group were involved. This additional survey allowed comparison of pre- and post-operative data for TKR patients.

5.2.5 Analysis of functional performance

Kinematic, sEMG and GRF measurements were recorded during walking and turning (W/T), gait initiation and stair ascent/descent tests. Additional signals for visual instruction during gait initiation and W/T tests were recorded and synchronised with sEMG signals as described earlier. All information was recorded using VICON Nexus software (Version 1.4, VICON Motion Analysis Inc, OMG, UK) for further off-line analysis.

In organisation of the functional activity test simulations, the walking/turning and gait initiation tests were conducted first. This allowed greater familiarisation with the environment and equipment, with the aim of reducing any risk which may be inherent in the more difficult stair climbing test. A 3- to 5-minute rest period was given between the 2 walking related tasks and 10 to 15 minutes between the walking and stair climbing activities. Participants were given several practice trials to familiarise with the tasks before testing began.

For the W/T test, subjects walked at a self-selected speed along a straight trajectory from the start of the walkway. During walking, participants were required to respond to the visual directional information (right or left arrow as shown in Figure 5.2.b and Figure 5.2.c), turning right or left as quickly as possible. After making a 90° right/left turn, participants continued walking in the assigned direction for additional steps. This procedure involved 6 trials of 90° turns to the left and to the right respectively. The sequence of turning direction was randomised using the random digital table and participants were unaware of the direction in which they would be required to move.

Each trial in which gait initiation was tested, began with subjects standing quietly on the first force plate embedded in the middle of the walk way. Subjects adopted the most comfortable and relaxed posture, with both feet apart at a self-selected distance. All subjects were also asked to look straight ahead with both arms relaxed at their sides (Patchay, Gahery, & Serratrice, 2002). For the 6 repetitions, 3 trials started with the left leg and 3 trials with the right leg respectively. The order of trials was determined randomly and subjects were advised which leg to start with before each trial. Subjects were asked to start walking as soon as possible in response to the visual signal of ‘GO’ displayed in green on the second computer monitor as described earlier (Figure 5.2.a). All subjects were asked to continue walking to the end of the walkway to approach a constant walking speed.

Subjects started the stair ascent protocol from a position of double-limb stance in front of the first force plate embedded in the walkway. Stair ascent occurred first, followed by stair descent, which also commenced from a position of double-support stance at the top of the staircase on an 80cm square platform (Figure 5.5). Participants were instructed to use a reciprocal pattern during ascent and descent at a self-selected pace. They were also advised to use the handrail during testing when necessary, but only trials without use of the handrail were further analysed.

Subjects were informed as to which leg to start with prior to testing. They were required to ascend/descend the stairs starting 3 trials with the right leg and another 3 trials with the left leg. The order of these repetitions was randomly determined and kept consistent during the study.

Figure 5.5. Schematic of foot displacement during testing of stair ascent/descent.

5.2.5.1 Electromyographic (sEMG) recording

The protocol for the collection of sEMG data was consistent with that used in Study 2 and described in Chapter 4. As in the earlier study, sEMG was evaluated bilaterally involving the RF, VM, VL, MH and BF.

5.2.5.2 Measurement of muscle strength and proprioception

Procedures used in the measurement of muscle strength and proprioception were consistent with those described in Chapter 4. MVC of the knee extensors and flexors of both limbs were measured simultaneously with the strength measures. Following completion of the strength testing protocol and a 5-minute recovery period, proprioception was measured using the DJPS protocol involving both knees for each participant.

5.2.6 Data processing

Kinematic and kinetic data were recorded and stored for further off-line analysis. The raw kinematic data, representing both lower limbs during W/T, gait initiation and stair climbing, were manipulated using the dynamic plug-in gait model (Oxford Metrics) and exported for further analysis with customised functions developed with MATLAB. The dynamic plug-in gait model is based on the Newington-Helen Hayes gait model and marker set. A profile of the subjects anthropometric measurements presented in Table 4.1 was also used to create outputs of the joint kinematics and kinetics for gait analysis (Davis et al., 1991; Vicon, 2008). This approach was selected because it has been validated for gait analysis purposes and is widely used in clinical practice (Davis et al., 1991; Taylor et al., 2005; Vicon, 2008).

The beginning of the turn (Turn-start) was defined as the time of the first noticeable change in foot orientation. The end of the turning (Turn-end), was defined as the time of heel contact of the first step in the new direction following the turn (Dite & Temple, 2002; Lam & Luttmann, 2009; Thigpen et al., 2000). The time points of Turn-start and Turn-end were identified by the time shown on the digital timer on the interface of Nexus software. Reaction time (Turn-RT, in milliseconds) during the W/T test was calculated by subtracting the time of onset of the visual signal from the time when turning began (Turn-start). The time required to complete a turn (Turn-time, in milliseconds) was defined as the time interval between the Turn-start and Turn-end.

Reaction time during gait initiation was calculated as the time interval between the onset of the visual signal and the time when the first impulse was recorded in the antero-posterior axis (Fx) on the first force plate. The threshold for onset of Fx was set at 2N (Delva, et al., 2007) and the onset time was extracted with a MATLAB function. In addition, muscle coactivation during the period of reaction time was calculated as described in Chapter 4.

The COP pattern was divided into 3 segments by identifying 2 landmarks (Figure 5.6). The first section (S1) began with the initiation command and ended with the COP located at its most posterior and lateral position toward the limb which was to be lifted first (leading limb) (Landmark 1). The second segment (S2) was characterised by a lateral translation of the COP towards the stance limb (contralateral limb of the leading limb) ending at Landmark 2, which was defined as the point at which the COP shifts from lateral to anterior motion.

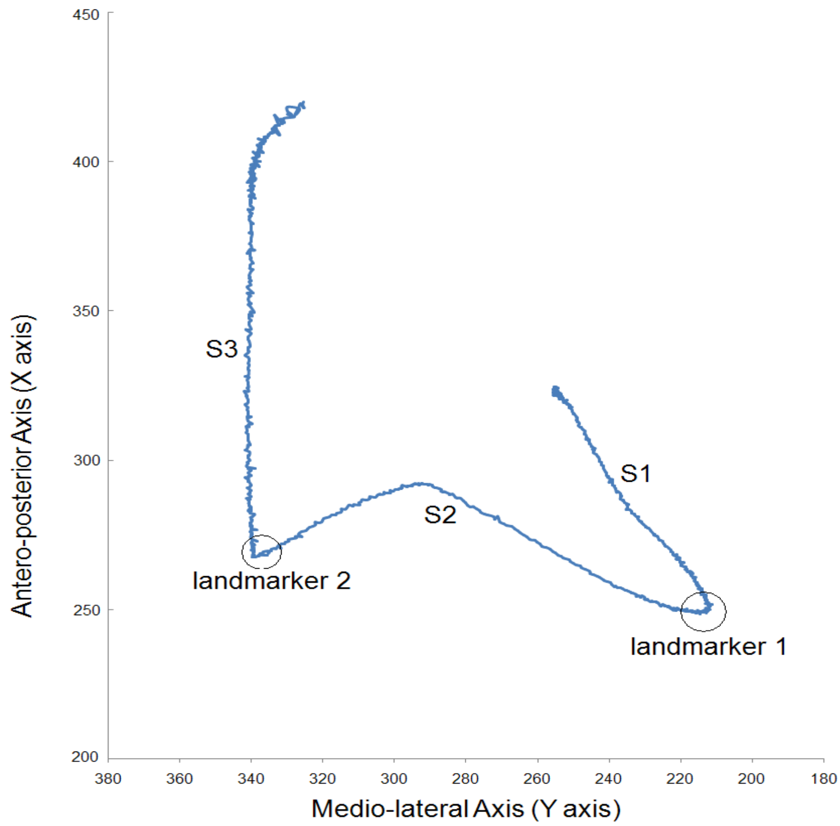


Figure 5.6. Example of path of the COP during APA of gait initiation led by the right leg.

The third segment (S3) extended from Landmark 2 until toe-off of the initial stance limb as the COP translated anteriorly. Four variables were computed during these 3 sub-phases of gait initiation: (1) displacement of the COP in the Fx (X) axis; (b) displacement of the COP in the medio-lateral (Y) axis; (c) average velocity of the COP in the X axis; and (d) average velocity of the COP in the Y axis (Hass et al., 2004; Hass, Waddell, Wolf, Juncos, & Gregor, 2008). The variables selected were consistent with procedures adopted by earlier studies which investigated the influence of Tai Chi exercise on COP trajectory (Hass et al., 2004) and gait initiation characteristics of older adults with postural instability (Hass et al., 2008). For displacement and velocity in the Y axis, a reversal in the direction of movement occurred during the whole process of gait initiation when started with the left or right leg. The average of the group means for displacement and velocity in the Y axis in subjects following TKR was calculated according to the operated and non-operated sides. Some patients had been operated on their right knee, while others on their left knee. After clustering of the data with respect to the operated and non-operated knees, the original values representing positive or negative signs will cancel each other out. Therefore, the absolute value of displacement in the Y axis was used and velocity was computed using the absolute value of displacement in the Y axis.

Although the focus of the current study was to identify the characteristics of the supporting leg during stair negotiation, temporal parameters of strides during stair ascent/descent were also included as fundamental to the description of stair climbing capacity. A stride cycle during ascent was defined as the time period starting when the foot contacted with the second force plate (FP2 as shown in Figure 5.5) and ending at the next foot contact with FP4. Stride cycle for the contralateral limb started from the foot contact with FP3 and ended at the next foot contact on top of the staircase. During descent, the stride cycle began with the foot contact of FP4 and ended at the next foot contact on FP2. The gait cycle of the contralateral limb started at the time of foot contact on FP3 and ended at foot contact on FP1. For comparison purposes with respect to the kinematic, kinetic and EMG patterns of subjects during stair ascent/descent, stance phase was defined as starting with foot contact on FP3 or FP4 respectively and ending at toe-off from the same force plate.

Hip, knee and ankle joint angles in the sagittal plane during the stance phase of stair ascent/descent were extracted from the exported files from the motion capture software with functions developed with MATLAB. Angular velocities were further computed as a first derivative of the joint angle data. Using this information, the parameters of inter-joint coordination were calculated with equations described in Chapter 4. Muscle co-activation was also computed and compared as detailed in the previous study.

5.2.7 Statistical analysis

All analyses were performed using SPSS with $p < 0.05$ regarded as statistically significant. Student's t-test was used to assess differences between the 2 groups in relation to their anthropometric characteristics and the survey findings. Differences between the TKR (operated limb) and control group (dominant limb) in the coordination and variability in stride characteristics during stair climbing were determined using Student's t-test. These differences were recognised as significant if $MARP_{diff}$ and $SARP_{diff}$ were significantly different ($p < 0.05$) from 0.

The Kruskal-Wallis test was used to determine whether differences existed during turning tasks with respect to reaction time, total turn time and in the turning strategies used. This represented the time when subjects were instructed to turn towards the operated or non-operated side in the TKR group and for turning towards the dominant and non-dominant side in the control group. When main effects were detected, the Mann-Whitney U tests were used for post-hoc comparison.

Repeated measurement ANOVA was used to test differences in functional scores between TKR and control subjects when evaluated with the IKS survey pre- and post-operatively. ANOVA was used to test group differences among operated and non-operated limbs in the TKR group and the dominant and non-dominant limbs of the control group. LSD tests were performed for post-hoc testing when appropriate.

One-way ANOVA was also used to test the differences in reaction time during gait initiation and W/T testing between limbs in 2 groups. The time required to complete the turning task, the muscle co-contraction ratio during gait initiation, W/T testing and stair climbing was also statistically compared with one-way ANOVA. LSD tests were conducted for post-hoc comparison when main effects for groups were detected.

The relationships between the qualitative functional measures and other objective measures such as, DJPS, $MARP_{diff}$ and $SARP_{diff}$ and muscle co-activation, reaction time (RT), first step velocity and length during gait initiation, turning time and stair ascent/descent stride time were determined using the Pearson's correlation coefficient.

5.3 RESULTS

5.3.1 Anthropometric profiles

No significant differences were found in the age and anthropometric profiles of the TKR and control groups (Table 5.1).

Table 5.1
Age and anthropometric characteristics for TKR (n=14) and control subjects (n=9) (Mean ± SD)

Characteristics	TKR group	Control group	t-value	*p*-value
Age (years)	68.4 ± 5.0	64.4 ± 3.2	2.079	0.060
Weight (kg)	88.4 ± 18.4	74.1 ± 18.4	2.104	0.058
Height (cm)	169.9 ± 8.2	170.4 ± 8.5	0.131	0.897

5.3.2 Muscle strength and proprioception characteristics

Significant differences in the absolute and normalised values of muscle strength in the knee extensors and flexors were found between the TKR and control groups (Table 5.2). Absolute values in muscle strength, of the extensors and flexors of the operated side of the TKR subjects were decreased when compared to the muscle strength of the control group. When normalised for body weight, extensor and flexor strength of both operated and non-operated limbs in the TKR group were weaker than those of the control group. Post-hoc analysis also revealed that the muscle strength of the operated limb was consistently weaker than that of the contralateral limb when evaluated by absolute strength or muscle strength values normalised by body weight.

Table 5.2
Muscle strength (Nm) for TKR and control groups (Mean ± SD)

	TKR group		Control group		*p*-value
	Operated	Non-Operated	Dominant	Non-Dominant	
Extensors (Nm)	92.0 ± 38.7[a,,b]	133.3 ± 55.7	156.3 ± 55.3	134.8 ± 50.2	0.024
Flexors (Nm)	47.9 ± 18.6[a,,b]	57.8 ± 20.8	67.8 ± 18.4	60.2 ± 20.9	0.030
Normalised-Extensors	1.03 ± 0.35[a,,b]	1.49 ± 0.53[a]	2.09 ± 0.55	1.80 ± 0.48	<0.001
Normalised-Flexors	0.53 ± 0.16[a,,b]	0.65 ± 0.18[a]	0.91 ± 0.14	0.80 ± 0.17	<0.001
H/Q ratio	0.54 ± 0.15	0.46 ± 0.13	0.45 ± 0.07	0.46 ± 0.11	0.210

[a] Significant difference ($p < 0.05$) between TKR and control group.

[b] Significant difference ($p < 0.05$) between operated and non-operated sides in TKR group.

Results for the measurement of DJPS including AE of both knees for each subject during different movement velocities are presented in Table 5.3. Significant differences in DJPS were found between the TKR and control groups. Post-hoc tests revealed that the AE of DJPS of the operated knee was significantly greater than similar scores obtained from their contralateral non-operated knee and those of control subjects regardless of the movement velocity. However, no significant differences in AE were found between the non-operated knee and that of the control subjects.

Table 5.3
Absolute error of DJPS *testing for TKR and control groups (Mean ± SD)*

	TKR group		**Control group**		
AE	**Operated**	**Non-Operated**	**Dominant**	**Non-Dominant**	***p*-value**
15°/s	4.69 ± 1.21[a,b]	3.34 ± 0.79	3.42 ± 0.82	3.43 ± 0.97	0.002
30°/s	5.48 ± 1.59[a,b]	4.22 ± 1.07	3.72 ± 0.66	4.03 ± 0.81	0.003
45°/s	7.04 ± 2.53[a,b]	5.26 ± 1.67	4.83 ± 0.71	5.70 ± 1.48	0.027
60°/s	8.78 ± 3.08[a,b]	6.55 ± 3.01	5.48 ± 1.02	6.46 ± 1.70	0.021

[a] Significant difference (p < 0.05) between the TKR and control groups.
[b] Significant difference (p < 0.05) between operated and non-operated sides in TKR group.

5.3.3 Qualitative self-reported functional outcomes

Significant improvements in the IKS knee score and function score were shown for the TKR patients when compared prior to surgery and 6 months post-operatively. However as shown in Table 5.4, scores for the TKR group were significantly lower on both tests when compared to those of the control subjects.

Higher scores on the OKS as well as all 3 subscales of the R-WOMAC were found in the TKR group when compared to controls (Table 5.5). The overall score for the R-WOMAC in the TKR group was significantly lower than that of the control group.

Table 5.4
IKS score for TKR (pre- and post-operative) and control groups (Mean ± SD)

	TKR group		**Control group**	***p*-value**
	Pre-operative	**Post-operative**		
IKS knee score	56.5 ± 9.4[a]	79.9 ± 13.7[b]	99.7 ± 1.3	<0.01
IKS function score	56.6 ± 17.1[a]	77.9 ± 15.8[b]	100 ± 0	<0.01

[a] Significant difference (p < 0.05) between pre- and post-operative values in TKR group.
[b] Significant difference (p < 0.05) between the post-operative value and that of the control group.

Table 5.5

Oxford Knee Score and R-WOMAC Scores for TKR and control groups (Mean ± SD)

	TKR group	Control group	*p*-value
OKS	20.3 ± 5.4	12.1 ± 0.3	<0.001
R-WOMAC	84.7 ± 10.7	100 ± 0	<0.001
Pain	2.6 ± 2.7	0 ± 0	<0.001
Stiffness	1.9 ± 1.3	0 ± 0	<0.001
Function	4.1 ± 2.9	0 ± 0	<0.001

*Significant difference (p < 0.05).

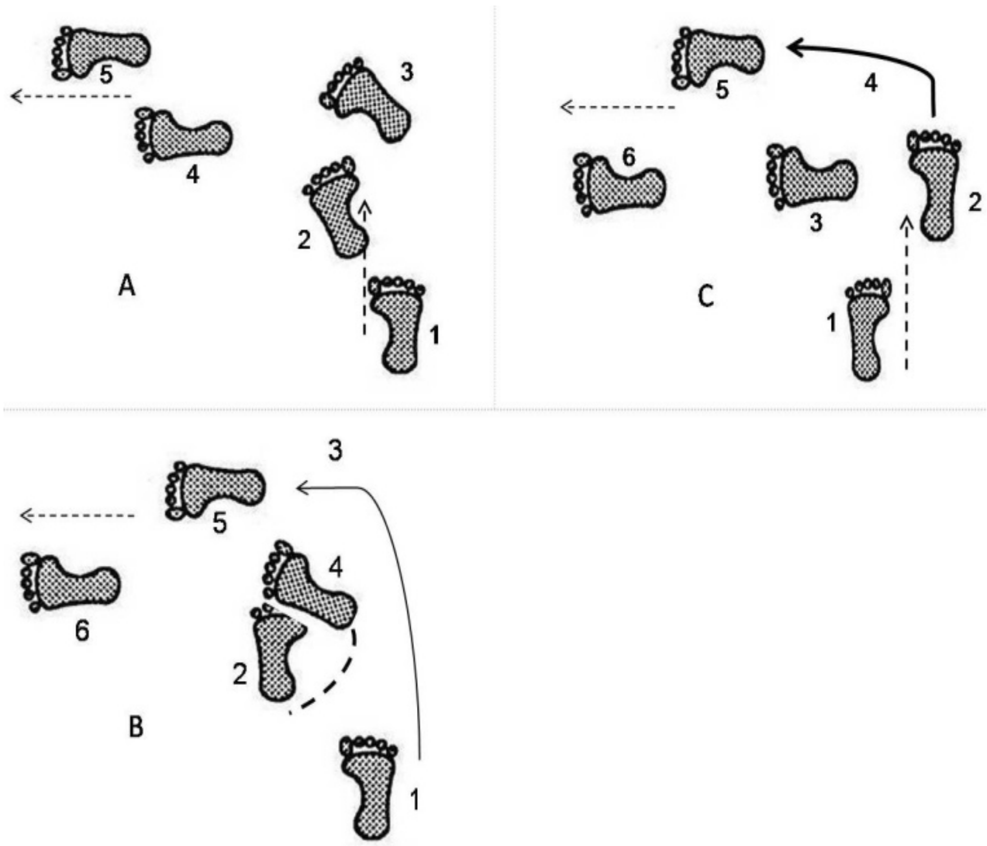


Figure 5.7. Diagrammatic representations of the footprints for left turning: (A) Two-steps ipsilateral limb support turning; (B) One-step ipsilateral limb support turning (pivot turning); and(C) Contralateral limb support turning.

5.3.4 Functional outcomes of daily activity simulations

5.3.4.1 Movement strategies for turning

Different movement strategies were identified in the W/T tests as shown in Figure 5.7. These strategies were divided into 2 distinct categories, defined as spin turn, or step turn. The body was supported by the contralateral limb during step turn (CLST), while the ipsilateral limb was used as the supporting limb during spin turn (ILST). The spin turn (ILSTP) was divided into 2 sub-strategies according to the number of steps needed to complete the turn. These sub-strategies included 2-step ipsilateral limb support turning (Figure 5.7.A) and 1-step ipsilateral pivot turning (Figure 5.7.B) described in the following sections.

When responding to the visual signal to change direction, the ipsilateral limb, which corresponded with the intended direction of change, was placed slightly closer to the midline than found during straight walking and in front of the contralateral limb with the toe pointing laterally. The contralateral limb was swung around the ipsilateral limb and was placed with the toe pointing medially at approximately 45º. This limb then functioned as the supporting limb, followed by the ipsilateral limb which was rotated and swung completely towards the new direction (Figure 5.7.A).

Change of direction was also accomplished using a pivot or spin pattern of movement, in which the ipsilateral limb functioned as a support leg and pivotal point during turning. As the contralateral limb swung past the supporting ipsilateral limb, the ipsilateral limb rotated approximately 90º in the direction indicated by the visual signal. This movement was immediately followed by placement of the contralateral limb in the new direction (Figure 5.7.B).

During contralateral limb support turning (Figure 5.7.C), the contralateral limb was usually placed in a direction which was similar to straight walking. This functioned to support the body while the ipsilateral limb was placed towards the new direction at a position adjacent to this supporting limb.

In order to compare the strategies used by TKR subjects with those of control subjects, the number of trials associated with the different turning strategies were counted and are presented in Table 5.6. Significant differences were found between groups when turning to either the operated or non-operated side by TKR subjects and to the dominant or non-dominant side for the control group (chi square = 10.282, p=0.016). Post-hoc tests indicated that the TKR patients used their contralateral limb as the supporting limb more frequently than for the control subjects when changing direction, either towards the operated side, or non-operated side.

Table 5.6
Numbers of trials using different strategies for turning (ISLT/CSLT)

	TKR group			Control group	
	Operated	**Non-Operated**		**Dominant**	**Non-Dominant**
S1	0 / 6	2 / 4	C1	1 / 5	3 / 3
S2	0 / 6	1 / 5	C2	4 / 2	4 / 2
S3	0 / 6	5 / 1	C3	1 / 5	4 / 2
S4	2 / 4	4 / 2	C4	1 / 5	2 / 5
S5	5 / 1	0 / 6	C5	1 / 5	5 / 1
S6	0 / 6	2 / 4	C6	2 / 4	3 / 3
S7	0 / 6	0 / 6	C7	0 / 6	3 / 3
S8	4 / 2	2 / 4	C8	3 / 3	0 / 6
S9	0 / 6	2 / 4	C9	1 / 5	1 / 5
S10	2 / 4	0 / 6			
S11	0 / 6	0 / 6			
S12	0 / 6	1 / 5			
S13	0 / 6	1 / 5			
S14	2 / 4	1 / 5			

5.3.4.2 Characteristics of first step of gait initiation

A significantly reduced step length for the first step following gait initiation was shown for the TKR subjects when compared to controls when gait was initiated with the operated limb (Table 5.7). The velocity of the first step of TKR subjects was significantly slower than that of the control subjects, irrespective of whether or not walking was initiated by the operated or non-operated limb. No significant differences in step length and velocity were found between steps initiated either with the operated or the non-operated limb for TKR subjects.

Table 5.7
Characteristics of first step after gait initiation (Mean ± SD)

	TKR group		Control group		
	Operated	**Non-Operated**	**Dominant**	**Non-Dominant**	***p*-value**
1st step length (m)	0.58 ± 0.09[a]	0.60 ± 0.09	0.67 ± 0.06	0.67 ± 0.06	<0.001
1st step velocity(m/s)	0.90 ± 0.17[a]	0.94 ± 0.19[a]	1.20 ± 0.10	1.25 ± 0.09	0.03

[a] Significant difference ($p < 0.05$) from that of the control group.

5.3.4.3 Temporal-spatial parameters of stair ascent and descent

No differences were found in the temporal parameters of stride for the right and left limbs respectively during stair ascent/descent, when comparing data extracted from the 3 trials started with the right limb and another 3 trials started with the left limb. Therefore, the mean values were averaged across the 6 trials and grouped based on the operated and non-operated knee of the TKR subjects, or the dominant and non-dominant limbs of the control subjects respectively.

A significantly reduced single support period was found in TKR subjects when compared to that of the controls during stair ascent or descent (Table 5.8 *Average temporal parameters of stair ascent/descent for TKR and control groups (Mean ± SD)*

	TKR group		Control group		*p-value*
	Operated	**Non-Operated**	**Dominant**	**Non-Dominant**	
Ascent					
Cadence (steps/min)	75.6 ± 23.8	77.9 ± 18.9	96.3 ± 12.4	86.3 ± 13.5	0.059
Stride time (s)	1.84 ± 0.96	1.65 ± 0.50	1.27 ± 0.18	1.42 ± 0.23	0.152
Single support (%)	33.0 ± 5.4a,b	36.1 ± 2.7a	37.4 ± 2.2	37.1 ± 2.3	0.021
Double support (%)	31.3 ± 7.8a	29.1 ± 2.7	25.2 ± 3.3	26.9 ± 3.6	0.043
Stance phase (%)	65.0 ± 3.2	65.2 ± 2.7	62.6 ± 2.2	64.4 ± 2.8	0.145
Descent					
Cadence (steps/min)	74.0 ± 24.6	77.9 ± 21.1	95.6 ± 16.8	84.9 ± 17.3	0.104
Stride time (s)	1.85 ± 0.81	1.67 ± 0.50	1.30 ± 0.29	1.48 ± 0.35	0.149
Single support (%)	35.2 ± 4.0a,b	38.5 ± 4.3	39.3 ± 2.9	39.8 ± 3.5	0.023
Double support (%)	28.1 ± 4.8	25.6 ± 3.5	24.5 ± 4.3	24.4 ± 5.3	0.178
Stance phase (%)	63.3 ± 3.6	66.3 ± 2.6	63.9 ± 3.3	64.2 ± 4.8	0.137

[a] Significant difference ($p < 0.05$) from that of the control group.

[b] Significant difference ($p < 0.05$) from that of the Non-Operated limb of TKR subjects.

). However, the percentage of double support time was only found to be prolonged in the operated limb during stair ascent. No significant differences were found during stair descent, although an average double support value of 28.1% of the stride time was shown in the operated limb. This was approximately 3.5% longer than that for the contralateral limb and the control subjects. Marginal, but non-significant differences were found with respect to slower cadence and increased stride time in TKR subjects found either during stair ascent or descent when compared to control subjects.

Higher variability in the cadence of TKR subjects was found when compared to that of the control subjects. The CV of cadence of the operated and non-operated limbs of TKR subjects during stair ascent was 31.5% and 24.3% respectively. In contrast, CV of cadence of the dominant and non-dominant limbs of control subjects were 12.9% and 15.6% respectively. Similar results indicated higher variability for TKR subjects for cadence during descent and stride time of stair ascent/descent when compared to the values for controls.

Table 5.8
Average temporal parameters of stair ascent/descent for TKR and control groups (Mean ± SD)

	TKR group		**Control group**		***p*-value**
	Operated	**Non-Operated**	**Dominant**	**Non-Dominant**	
Ascent					
Cadence (steps/min)	75.6 ± 23.8	77.9 ± 18.9	96.3 ± 12.4	86.3 ± 13.5	0.059
Stride time (s)	1.84 ± 0.96	1.65 ± 0.50	1.27 ± 0.18	1.42 ± 0.23	0.152
Single support (%)	33.0 ± 5.4[a,b]	36.1 ± 2.7[a]	37.4 ± 2.2	37.1 ± 2.3	0.021
Double support (%)	31.3 ± 7.8[a]	29.1 ± 2.7	25.2 ± 3.3	26.9 ± 3.6	0.043
Stance phase (%)	65.0 ± 3.2	65.2 ± 2.7	62.6 ± 2.2	64.4 ± 2.8	0.145
Descent					
Cadence (steps/min)	74.0 ± 24.6	77.9 ± 21.1	95.6 ± 16.8	84.9 ± 17.3	0.104
Stride time (s)	1.85 ± 0.81	1.67 ± 0.50	1.30 ± 0.29	1.48 ± 0.35	0.149
Single support (%)	35.2 ± 4.0[a,b]	38.5 ± 4.3	39.3 ± 2.9	39.8 ± 3.5	0.023
Double support (%)	28.1 ± 4.8	25.6 ± 3.5	24.5 ± 4.3	24.4 ± 5.3	0.178
Stance phase (%)	63.3 ± 3.6	66.3 ± 2.6	63.9 ± 3.3	64.2 ± 4.8	0.137

[a] Significant difference ($p < 0.05$) from that of the control group.
[b] Significant difference ($p < 0.05$) from that of the Non-Operated limb of TKR subjects.

5.3.4.4 Kinematics of stair ascent and descent

Group averaged patterns of joint movement during stair ascent and descent are shown in Figure 5.8 and Figure 5.9 respectively. Similar movement patterns were shown between the TKR and control groups, however when comparing the joint kinematics during stair ascent and descent, considerable within group differences were found for both TKR or control groups.

Stair ascent began with the lower limb in a position of hip and knee flexion and the ankle joint dorsiflexed. With progression of the stance phase during stair ascent, both hip and knee joints extended gradually and approached full extension. This was accompanied by rapid plantar-flexion of the ankle joint which occurred at approximately 90% of the stance phase. In contrast to stair ascent, during stair descent the hip joint was slightly flexed at the time of initial foot contact accompanied by almost full extension of the knee joint and ankle plantar-flexion. The hip joint was slightly extended during the remainder of the stance phase until reversal to flexion which occurred at approximately 90% of the stance phase. The maximum degree of flexion of the hip was reached at the end of the stance phase (toe-off). Knee joint flexion reached a maximum range when approaching the end of the stance phase. The ankle joint was dorsiflexed for most of the stance phase and moved into plantar-flexion at approximately 85% of the stance phase.

Although similar patterns of joint movement were shown in the 2 groups during the stance phase of stair ascent and descent respectively, some subtle differences with respect to the magnitude of angles could be identified from the graphical representations of joint movements as shown in Figure 5.8 and Figure 5.9. Kinematic characteristics of lower limb joints at specific events in the gait cycle, such as, initial contact and toe-off and the maximum and minimum angles during the stance phase during stair ascent/descent, were analysed for comparison (Table 5.9). Significant alterations mainly occurred at the hip and ankle joint, while no significant differences in the knee joint between the TKR and control groups were found.

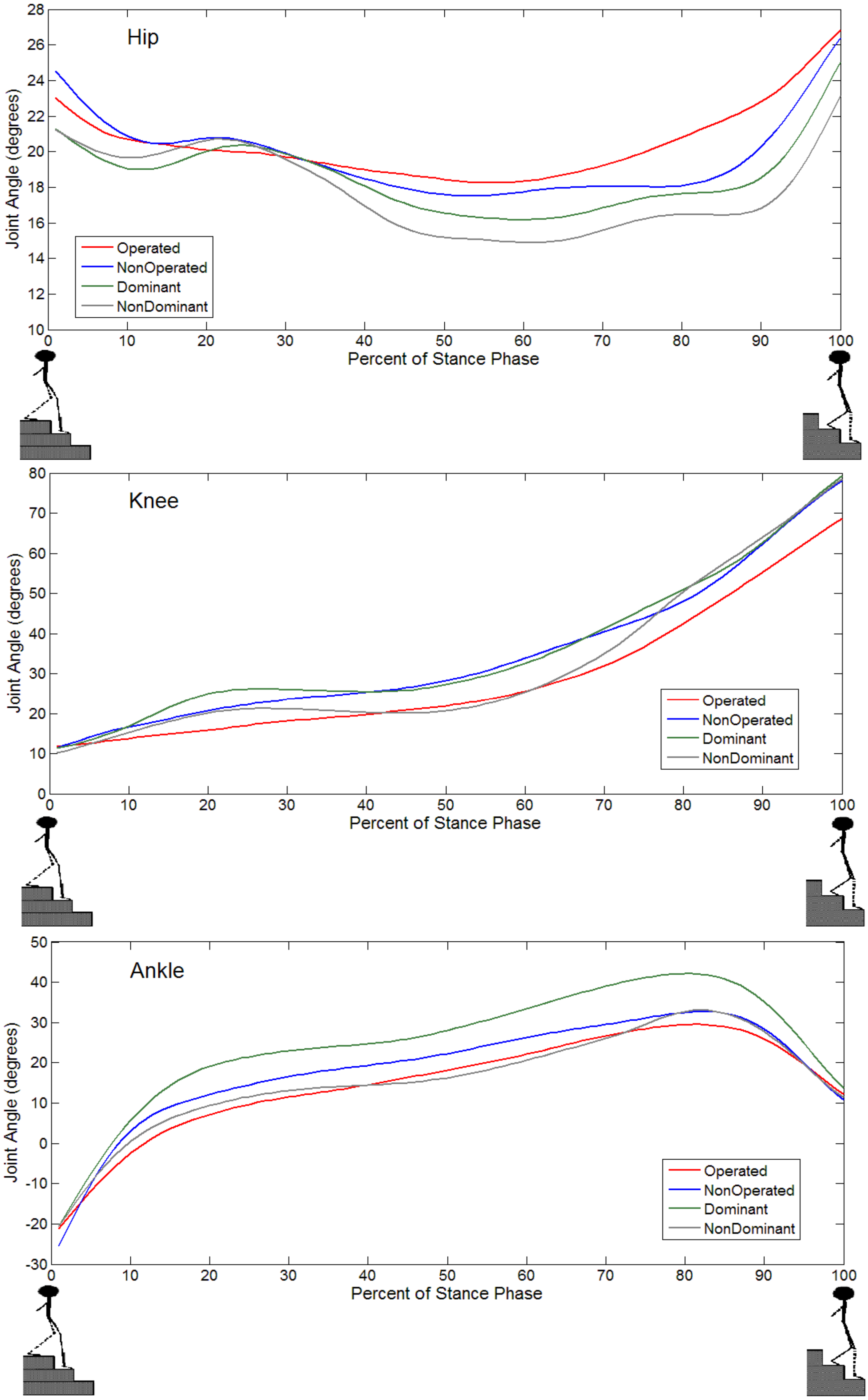


Figure 5.8. Joint angles during stair ascent.

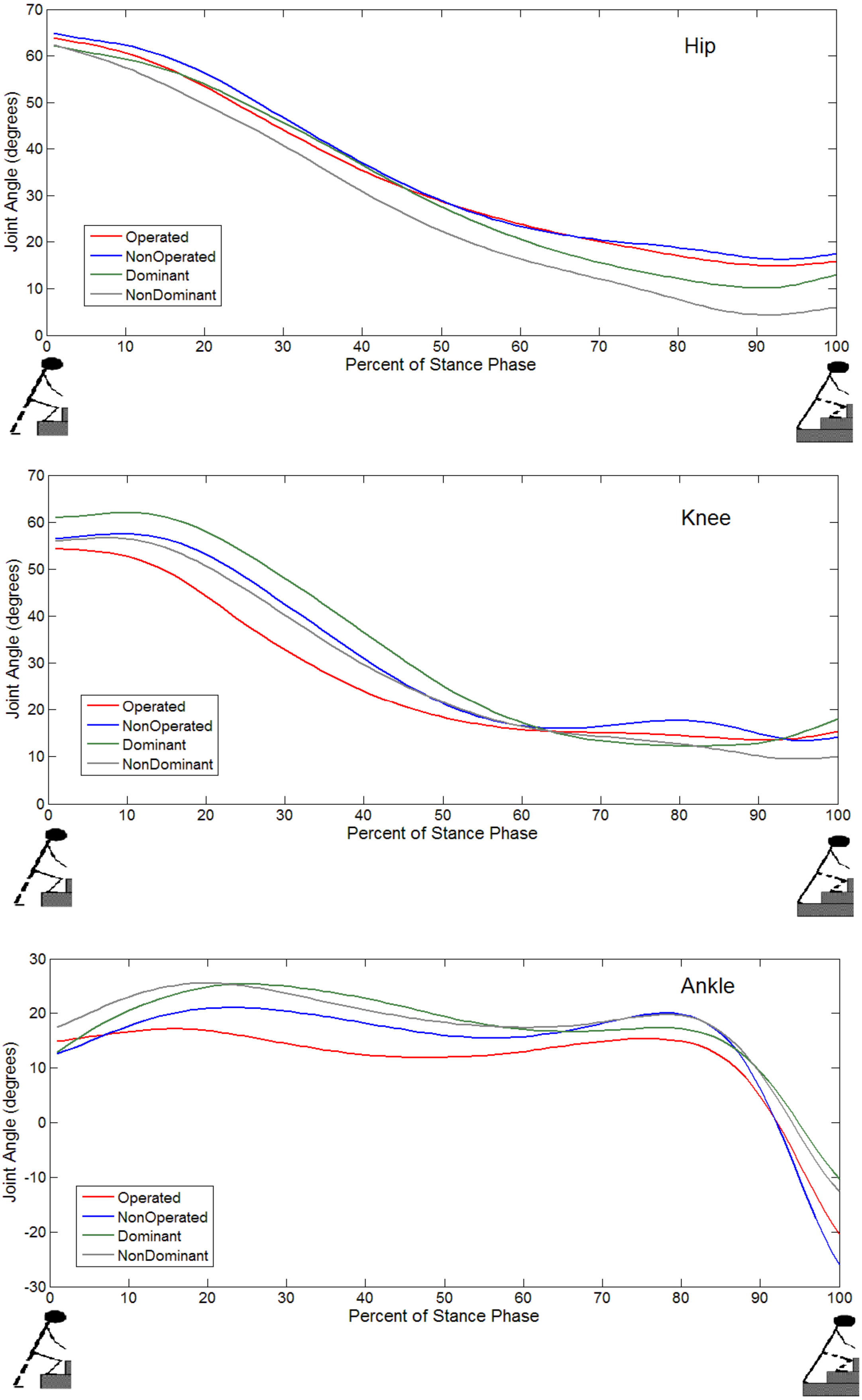


Figure 5.9. Joint angles during stair descent.

Table 5.9

Lower limb angles at special time points during stance phase of stair ascent/descent (Mean ± SD)

Angles at particular events (º)	TKR group		Control group		
	Operated	Non-Operated	Dominant	Non-Dominant	*p*-value
Ascent					
Hip at initial contact	63.7 ± 11.2	64.7 ± 11.0	62.1 ± 5.2	62.1 ± 6.8	0.890
Knee at initial contact	54.2 ± 7.5	56.5 ± 6.5	60.9 ± 5.5	55.9 ± 13.4	0.334
Ankle at initial contact	14.9 ± 7.2	12.7 ± 5.8	13.0 ± 4.9	17.5 ± 6.3	0.289
Hip at toe-off	18.0 ± 11.9	20.0 ± 7.4	13.3 ± 4.6	7.9 ± 4.6[a]	0.007
Knee at toe-off	15.6 ± 7.6	14.4 ± 6.0	18.5 ± 4.4	11.2 ± 5.3	0.108
Ankle at toe-off	-18.0 ± 14.8	-27.4 ± 14.1[b]	-11.1 ± 7.9[b]	-18.5 ± 6.7	0.025
Max hip flexion	63.9 ± 10.9	65.0 ± 10.8	62.4 ± 4.6	62.1 ± 6.8	0.874
Max hip extension	13.8 ± 13.2	14.8 ± 9.7	9.2 ± 5.5	3.0 ± 6.1[a]	0.034
Max knee flexion	55.3 ± 7.3	58.9 ± 7.2	63.4 ± 4.7	58.6 ± 11.5	0.136
Max knee extension	11.3 ± 6.9	11.4 ± 5.3	10.8 ± 4.8	7.8 ± 5.5	0.463
Max ankle dorsiflexion	21.3 ± 4.2	22.6 ± 3.9	26.0 ± 3.2[a]	23.6 ± 7.2[a]	0.003
Max ankle plantar-flexion	-21.8 ± 20.0	-27.4 ± 14.1	-11.1 ± 7.9	-13.4 ± 15.0	0.061
Descent					
Hip at initial contact	26.0 ± 9.5	28.3 ± 9.8	19.2 ± 4.2[a]	18.9 ± 4.4[a]	0.016
Knee at initial contact	13.5 ± 6.3	13.1 ± 5.2	11.5 ± 4.1	10.2 ± 5.0	0.474
Ankle at initial contact	-19.6 ± 8.5	-22.0 ± 12.8	-20.2 ± 2..9	-20.4 ± 5.8	0.907
Hip at toe-off	32.1 ± 12.1	30.5 ± 11.7	15.7 ± 9.4[a]	24.0 ± 7.4	0.004
Knee at toe-off	75.2 ± 18.3	81.9 ± 9.4	81.0 ± 7.0	80.3 ± 10.7	0.534
Ankle at toe-off	11.2 ± 8.0	9.9 ± 6.1	11.2 ± 7.2	9.5 ± 5.2	0.910
Max hip flexion	33.7 ± 10.3	32.6 ± 9.3	21.8 ± 6.9[a]	25.6 ± 6.2[b]	0.007
Max hip extension	18.9 ± 10.0	16.4 ± 11.6	5.1 ± 5.0[a]	11.2 ± 5.2	0.006
Max knee flexion	75.3 ± 18.1	81.9 ± 9.4	81.0 ± 7.1	80.3 ± 10.7	0.536
Max knee extension	12.3 ± 6.1	12.4 ± 5.6	11.4 ± 4.1	9.4 ± 5.5	0.574
Max ankle dorsiflexion	34.3 ± 12.4	35.8 ± 6.1	43.6 ± 7.4	36.6 ± 6.1	0.099
Max ankle plantar-flexion	-19.8 ± 8.2	-23.2 ± 12.4	-20.2 ± 6.0	-21.1 ± 8.6	0.739

[a] Significant difference ($p < 0.05$) from that of the TKR subjects.

[b] Significant difference ($p < 0.05$) from that of the operated limb of the TKR subjects.

5.3.5 Neuromuscular mechanisms

5.3.5.1 Reaction time during W/T tests and gait initiation

Significantly prolonged reaction time was found for the TKR group when subjects turned toward either the operated or non-operated side (Table 5.10). Similarly, the time required to complete the turning was longer in TKR subjects when turning to the operated side. However, neither reaction time during turning, nor the time of turning was different when turning to the operated or non-operated side in the TKR subjects, or when turning towards the dominant and non-dominant sides for the controls.

Table 5.10
Reaction time and turning time for TKR and control groups (Mean ± SD)

	TKR group		Control group		
	Operated	**Non-Operated**	**Dominant**	**Non-Dominant**	***p*-value**
Turn RT (ms)	868.6 ± 257[a]	770.0 ± 231[a]	501.1 ± 116	600.0 ± 251	0.002
Turn Time (ms)	1060.0 ± 222[a]	960.7 ±167	861.1 ± 156	867.8 ± 143	0.036

[a] Significant difference ($p < 0.05$) from that of turning to operated side in TKR group and either directions in control group.

Reaction times were significantly longer in TKR patients when initiating walking with the operated limb when compared to control subjects. In contrast, no significant differences in reaction time were found during gait initiation between the non-operated limb and that of the control subjects, irrespective of the gait being initiated with the dominant or non-dominant limb (

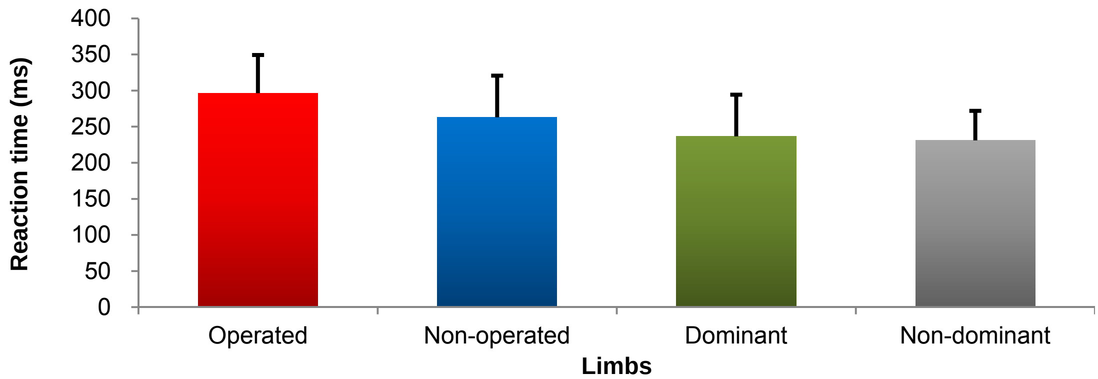


Figure 5.10).

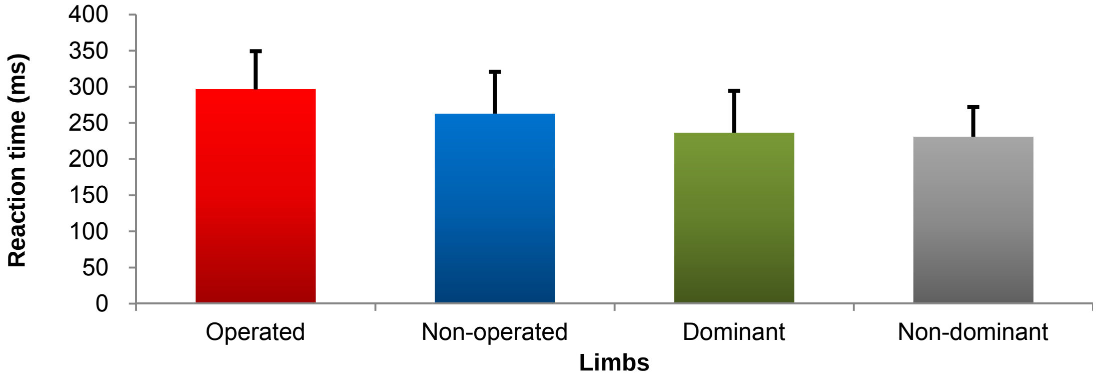


Figure 5.10. Reaction times during gait initiation in response to visual signal.

5.3.5.1 Characteristics of APA during gait initiation

Significant differences between the TKR and control groups were found for COP displacement (

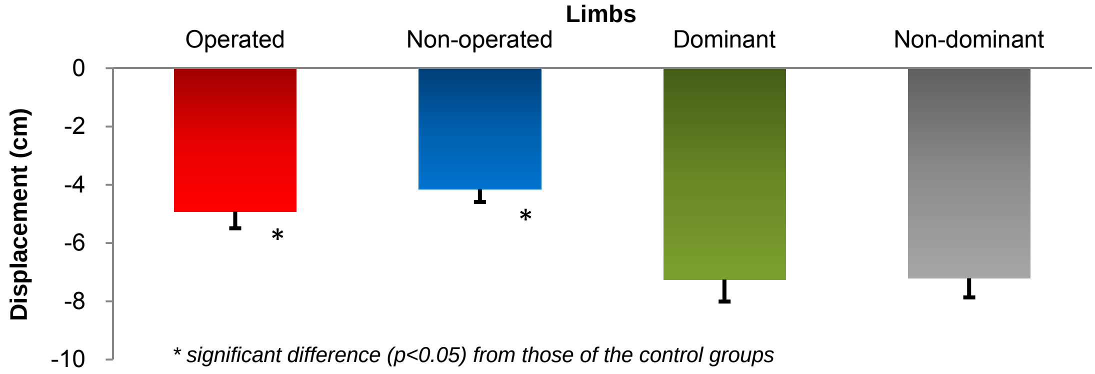


Figure *5.11*) and velocity (

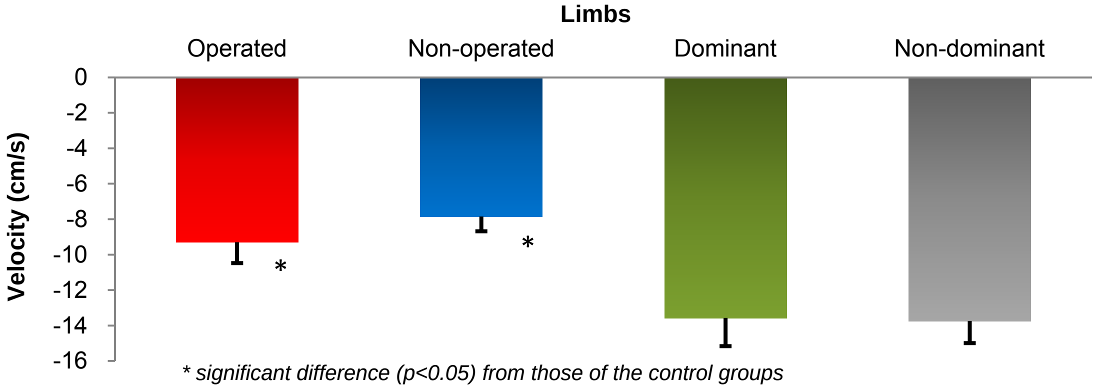


Figure *5.12*) in the X axis during the S1 segment. Post-hoc tests revealed that TKR subjects produced significantly less posterior displacement of the COP compared to the control subjects, irrespective of whether the movement was initiated by the operated or non-operated limb. The TKR subjects also moved the COP more slowly in the posterior direction than the control subjects, however no differences were found between TKR and control subjects with respect to the magnitude of displacement (

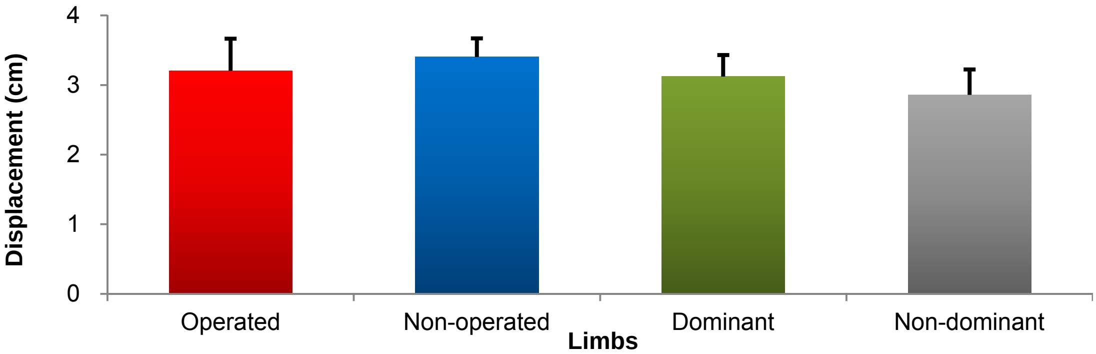


Figure 5.13) and velocity (

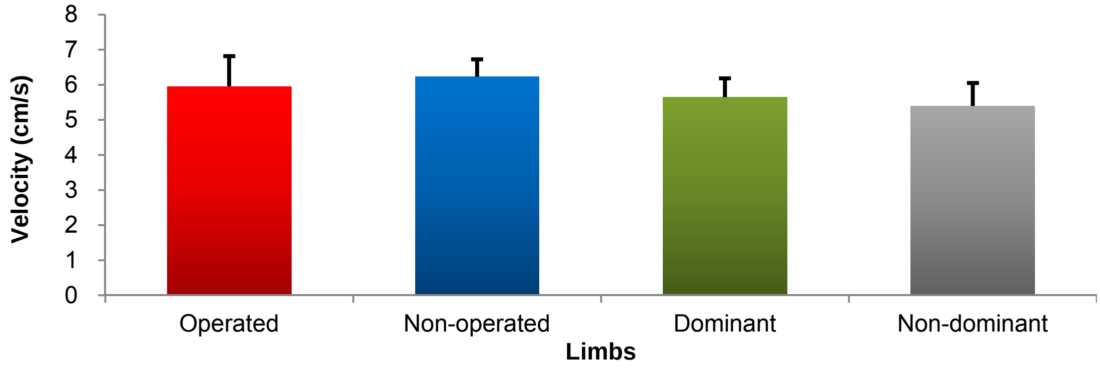


Figure *5.14*) in the medio-lateral direction.

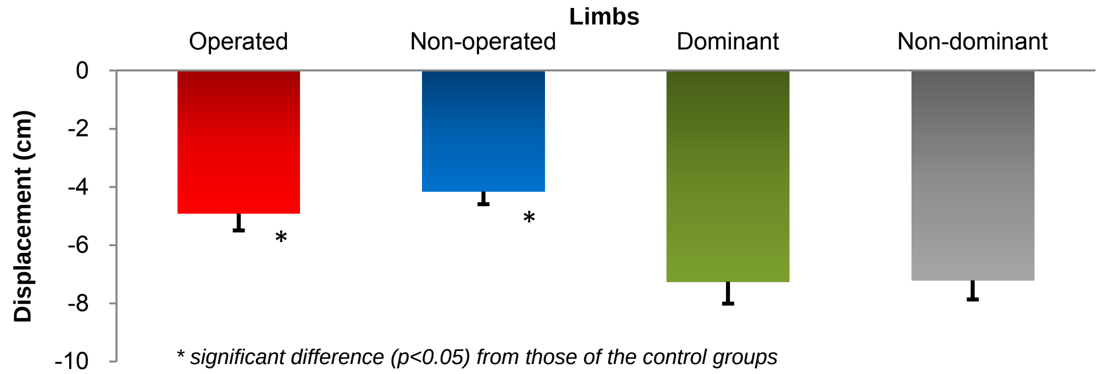


Figure 5.11. Antero-posterior displacement of COP during S1 period.

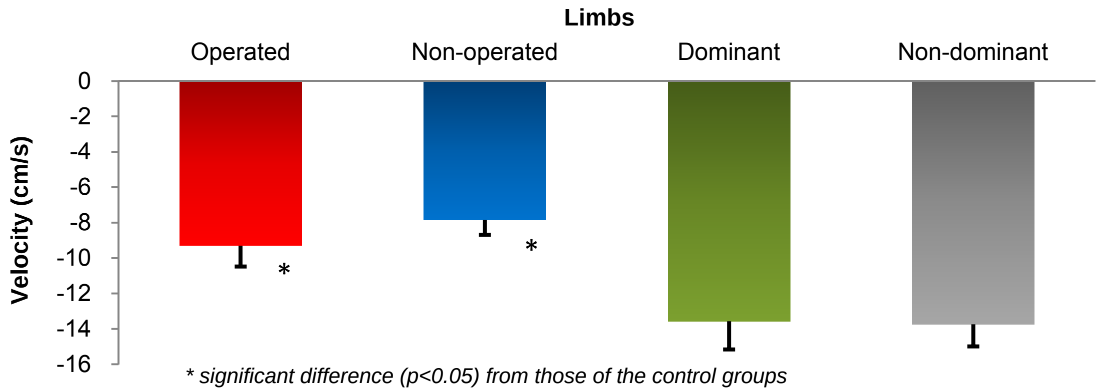


Figure 5.12. Antero-posterior velocity of COP during S1 period.

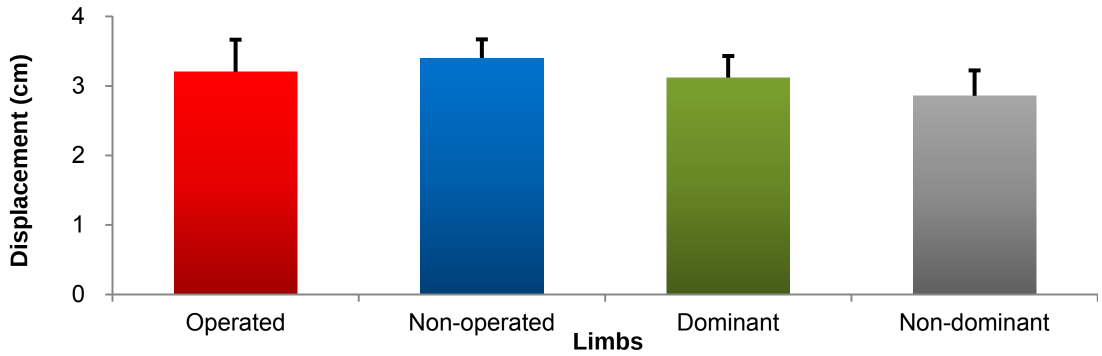


Figure 5.13. Medio-lateral displacement of COP during S1 period.

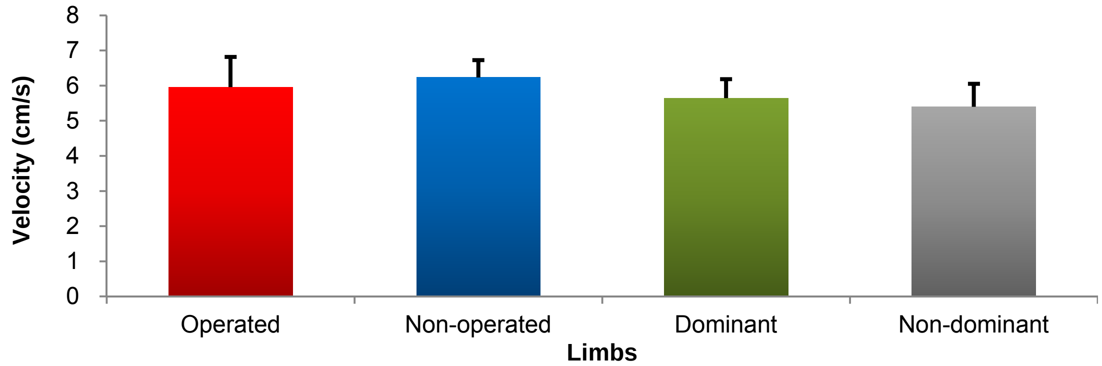


Figure 5.14. Medio-lateral velocity of COP displacement during S1 period.

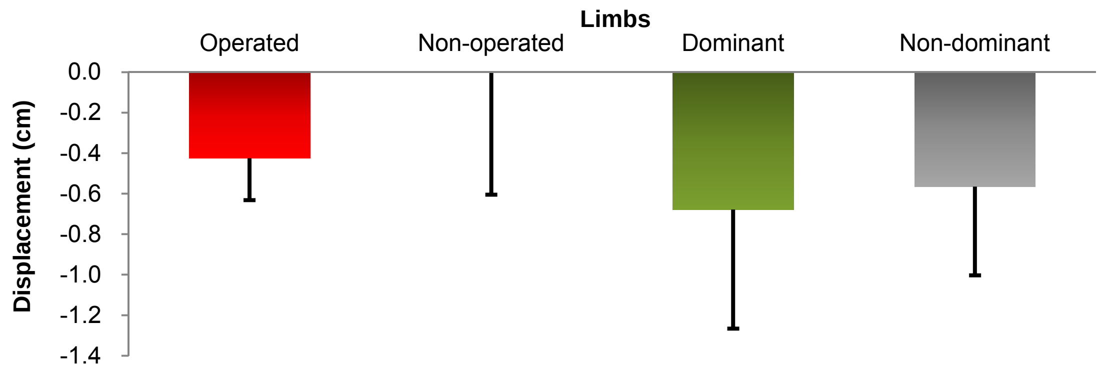


Figure 5.15. Antero-posterior displacement of COP during S2 period.

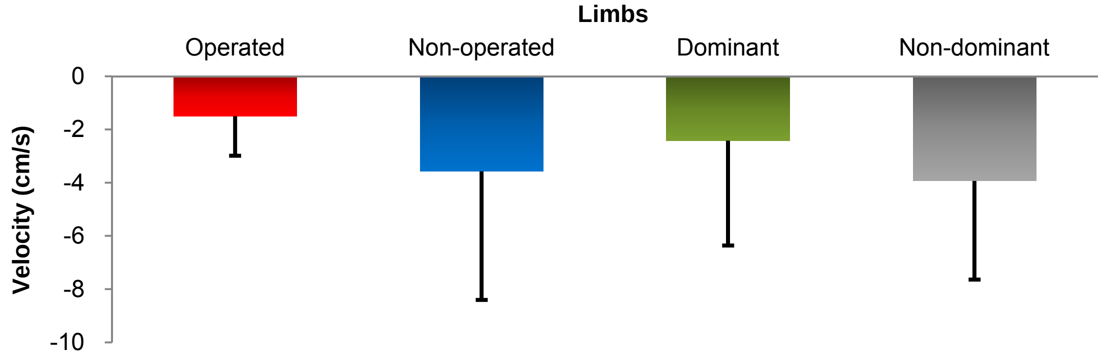


Figure 5.16. Antero-posterior velocity of COP during S2 period.

No significant differences were found between groups for the S2 segment of the COP traces in the 4 variables tested (

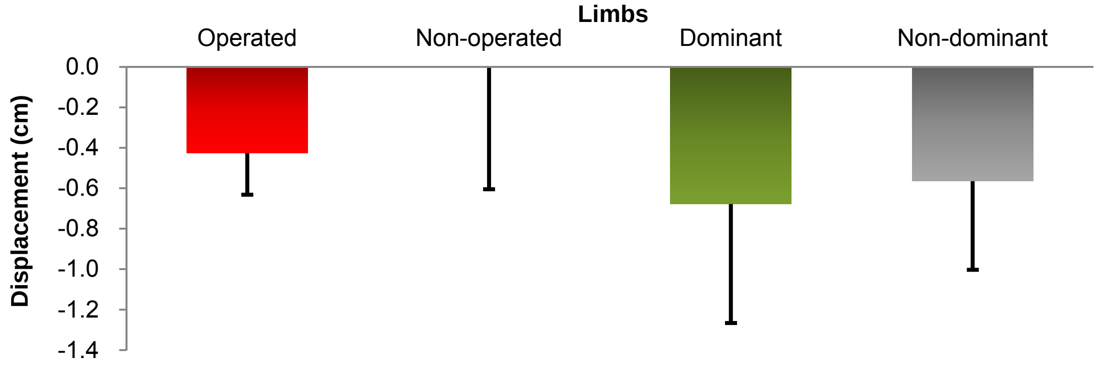


Figure *5.15* to

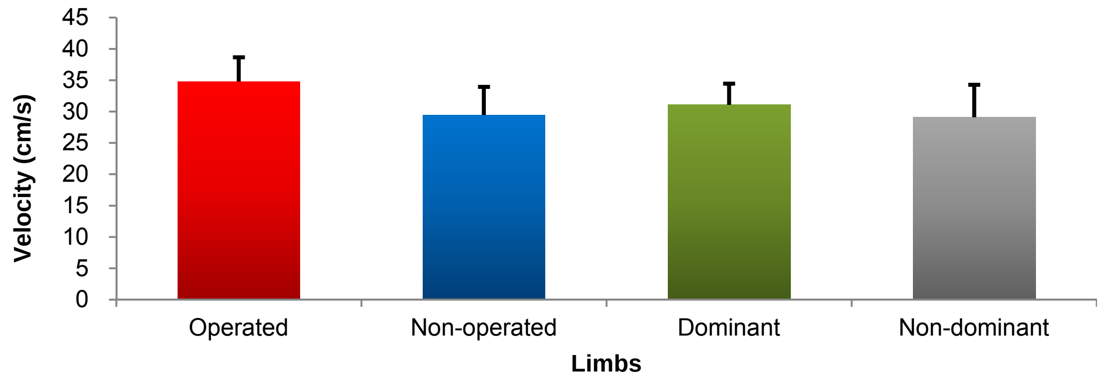


Figure *5.18*). Small posterior displacements with similar posterior movement velocity were found in all participants regardless of the limb used to initiate walking. Small, but non-significant increases in displacement (8.55cm) towards the supporting leg when initiated by the operated limb of TKR subjects were found, compared to approximately 6cm for the control group (

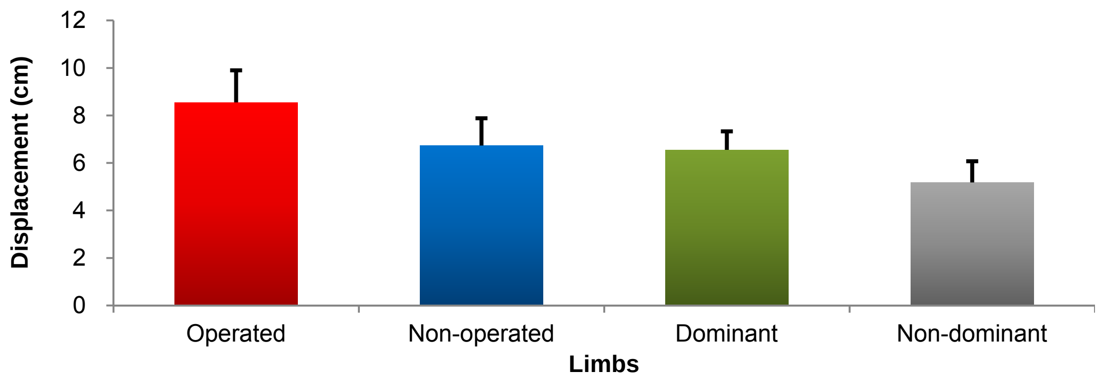


Figure *5.17*).

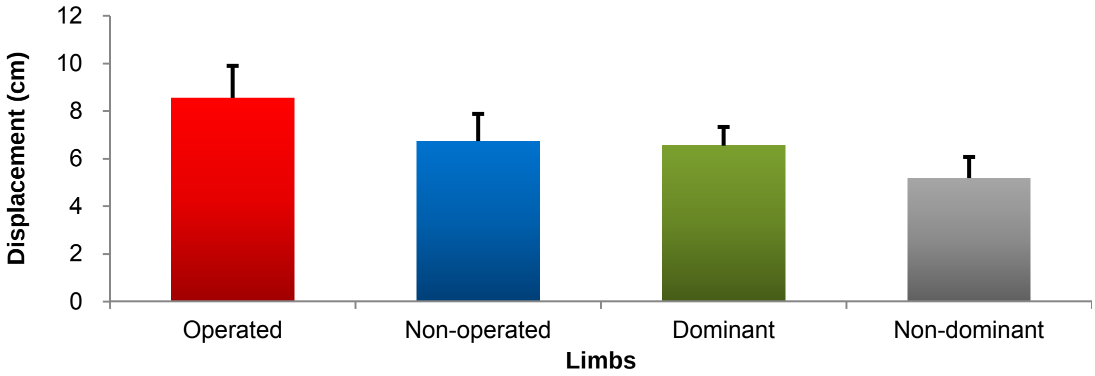


Figure 5.17. Medio-lateral displacement of COP during S2 period.

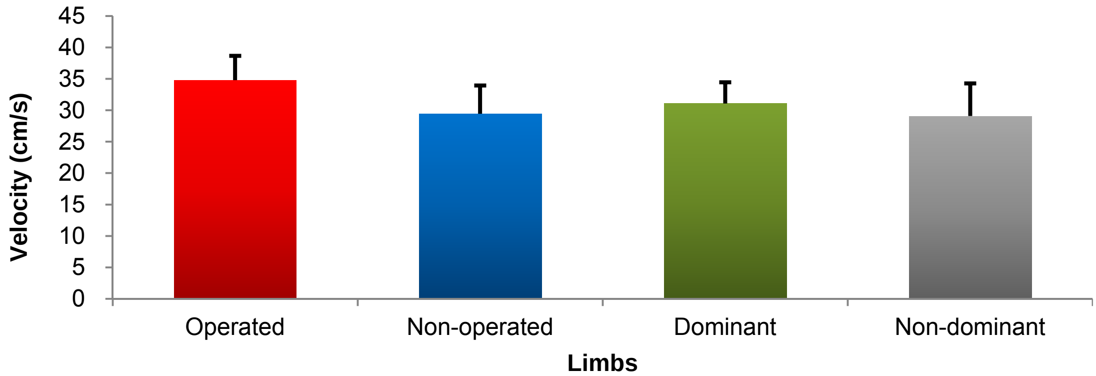


Figure 5.18. Medio-lateral velocity of COP during S2 period.

No significant differences were found between groups in the displacement of the COP in both antero-posterior (

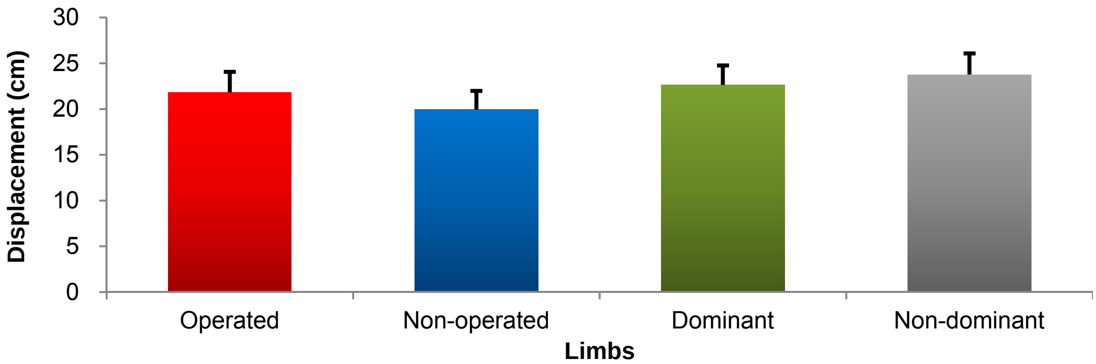


Figure *5.19*) and medio-lateral (

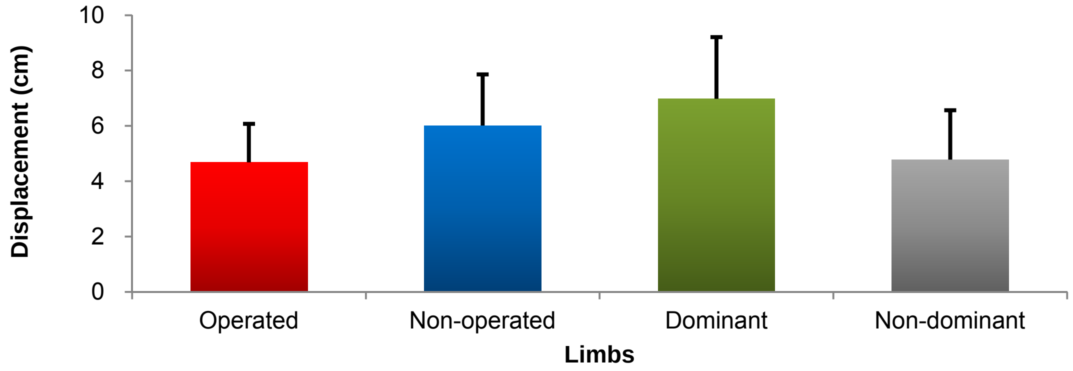
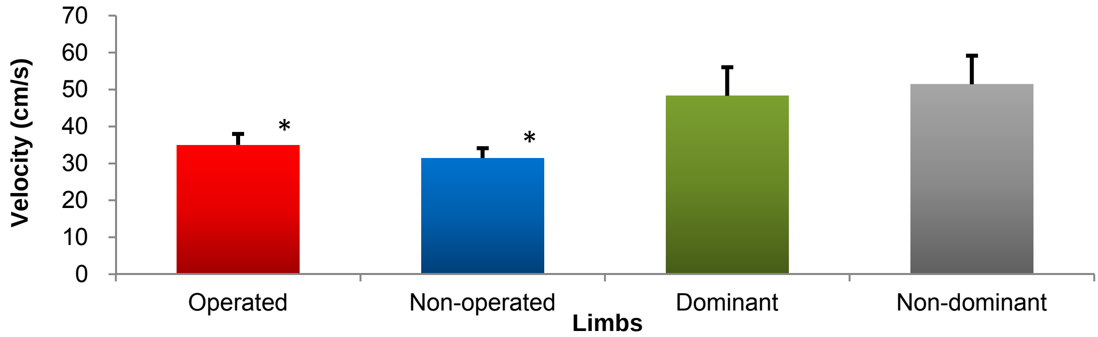
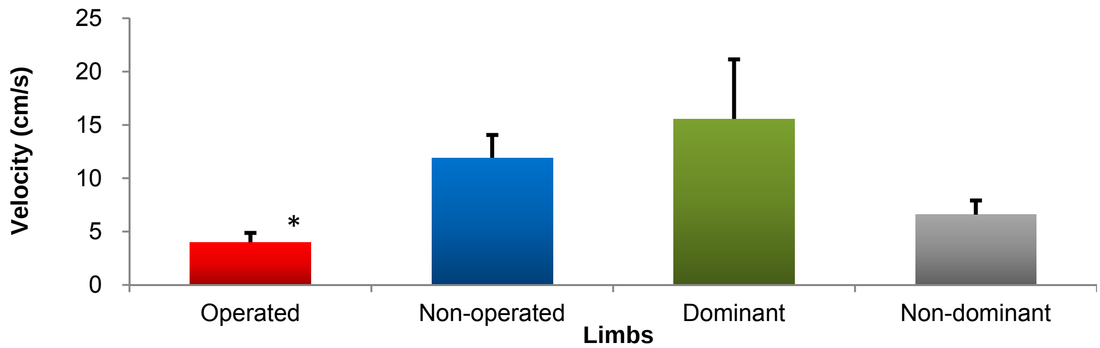


Figure *5.21*) directions. In contrast, comparison of movement velocity of COP indicated that the TKR subjects moved significantly slower in the antero-posterior direction when compared to the controls, regardless of the gait being initiated with the operated or non-operated limb (



** significant difference (p<0.05) from those of the control groups*

Figure *5.20*). A significantly lower velocity was only found in the medio-lateral direction when gait was initiated with the operated limb (



** significant difference (p < 0.05) from that of the non-operated side of the TKR subjects and those of the control groups*

Figure *5.22*).

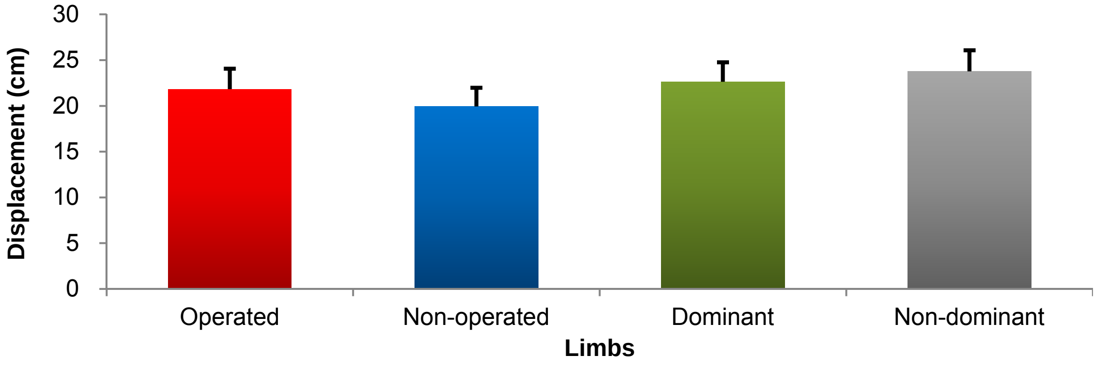
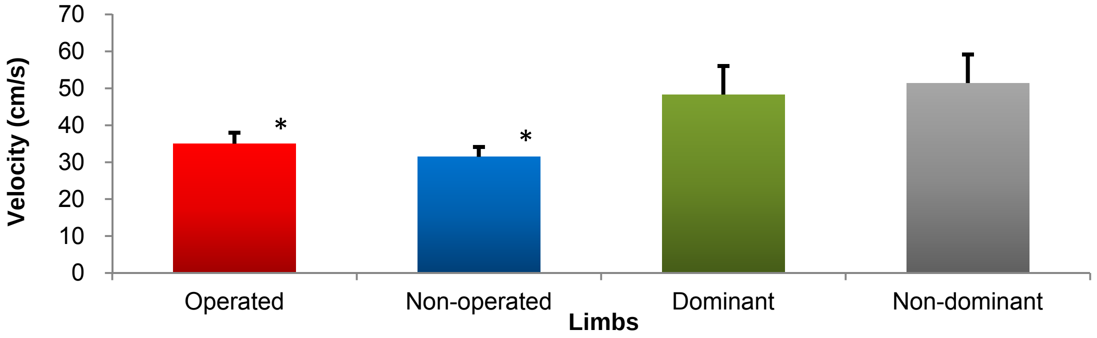


Figure 5.19. Antero-posterior displacement of COP in S3 period.



** significant difference (p<0.05) from those of the control groups*

Figure 5.20. Antero-posterior velocity of COP in S3 period.

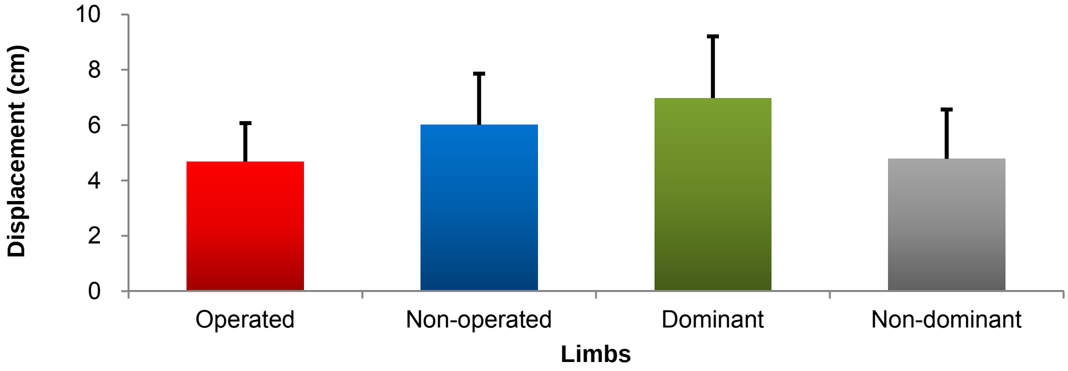
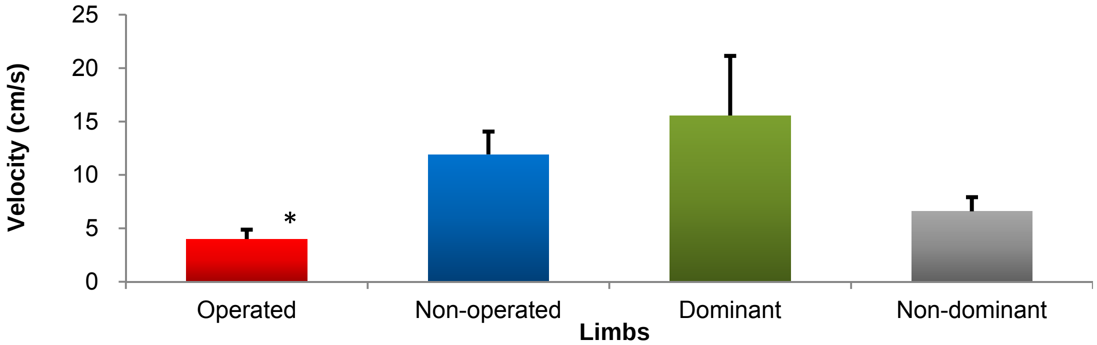


Figure 5.21. Medio-lateral displacement of COP in S3 period.



** significant difference (p < 0.05) from that of the non-operated side of the TKR subjects and those of the control groups*

Figure 5.22. Medio-lateral velocity of COP in S3 period.

5.3.5.2 Correlation between APA and characteristics of first step of gait initiation

As shown in Table 5.11, the length of the first step after gait initiation was negatively correlated with the magnitude of posterior displacement of the COP and the velocity of COP displacement during the S1 section of postural adjustment. This finding indicated that the greater the displacement in the posterior direction, the greater the length of the first step. The length of the first step was also found to be positively correlated with the velocity of COP displacement in the anterior direction during the S3 section of APA. The velocity of the first step was only found to be correlated with the COP movement pattern of S1 section during APA. Results showed that the greater posterior displacement resulted in greater anterior movement of the first step. However, the medio-lateral displacement towards the supporting limb during gait initiation was negatively correlated to the velocity of the first step after gait initiation. This result was consistent with the finding that the TKR subjects had a greater lateral displacement and slower velocity when taking the first step.

Table 5.11
Correlations between the first step of gait initiation and COP patterns during anticipatory postural adjustment

	First step length		**First step velocity**	
	Pearson's Coefficient	***p*-value**	**Pearson's Coefficient**	***p*-value**
S1COPDisplacementX	-0.486*	0.001	-0.617*	<0.001
S1COPDisplacementY	-0.246	0.100	-0.294*	0.047
S1COPVelocityX	-0.464*	0.001	-0.609*	<0.001
S1COPVelocityY	-0.277	0.062	-0.294*	0.048
S2COPDisplacementX	0.039	0.798	-0.031	0.839
S2COPDisplacementY	-0.290	0.051	-0.178	0.236
S2COPVelocityX	-0.078	0.609	-0.114	0.452
S2COPVelocityY	-0.238	0.112	-0.060	0.841
S3COPDisplacementX	-0.103	0.495	-0.099	0.513
S3COPDisplacementY	0.077	0.611	-0.014	0.927
S3COPVelocityX	0.293*	0.048	0.341	0.020
S3COPVelocityY	0.175	0.244	0.030	0.845

* Significant difference (p < 0.05).

Table 5.12

Muscle co-activation (%) during the period of reaction time of gait initiation (Mean ± SD)

	TKR group		Control group		
	Operated	**Non-Operated**	**Dominant**	**Non-Dominant**	***p*-value**
Support Medial	15.5 ± 9.2[a]	17.0 ± 13.17[a]	6.5 ± 4.2	9.3 ± 4.3	0.04
Support Lateral	12.6 ± 9.4	14.8 ± 10.0	9.6 ± 5.3	9.0 ± 3.3	0.30
Leading Medial	12.4 ± 11.4	11.4 ± 6.3	6.9 ± 4.2	7.6 ± 4.8	0.27
Leading Lateral	10.2 ± 9.1	14.1 ± 13.6	17.6 ± 12.6	13.5 ± 11.1	0.48

[a] Significant difference ($p < 0.05$) from those of both sides of the control group.

Table 5.13

Muscle co-activation (%) during stair ascent/descent (Mean ± SD)

	TKR group		Control group		
	Operated	**Non-Operated**	**Dominant**	**Non-Dominant**	***p*-value**
Ascent					
Stance phase medial	27.0 ± 10.3	22.4 ± 8.3	21.0 ± 7.4[a]	16.1 ± 5.2[a]	0.033
Stance phase lateral	28.3 ± 11.0	25.1 ± 9.8	21.1 ± 4.3[a]	18.4 ± 3.5[a]	0.045
1st DSP medial	32.2 ± 13.2	28.0 ± 12.5	23.2 ± 8.3	30.0 ± 11.9	0.367
1st DSP lateral	53.3 ± 14.8	36.0 ± 18.2[a]	50.6 ± 19.6	29.5 ± 11.6[a]	0.003
Single SP medial	27.8 ± 7.4	25.4 ± 12.3	21.1 ± 7.2	17.2 ± 6.6[a,b]	0.044
Single SP lateral	42.8 ± 8.2	29.3 ± 16.9[a]	27.6 ± 5.7[a]	24.5 ± 11.5[a]	0.002
2nd DSP medial	25.0 ± 14.8	16.7 ± 5.9[a]	11.8 ± 9.9[a]	10.1 ± 3.9[a]	0.004
2nd DSP lateral	25.8 ± 10.0	16.3 ± 7.7[a]	11.7 ± 14.0[a]	11.4 ± 5.4[a]	0.002
Descent					
Stance phase medial	26.4 ± 10.3	25.9 ± 13.2	14.7 ± 8.7[a]	14.6 ± 9.4[a]	0.012
Stance phase lateral	30.3 ± 10.6	19.2 ± 10.0[a]	22.3 ± 6.4[a]	19.5 ± 10.9[a]	0.017
1st DSP medial	29.4 ± 15.7	25.8 ± 16.2	9.3 ± 4.1[a]	15.0 ± 5.4[a]	0.002
1st DSP lateral	27.1 ± 11.4	21.2 ± 12.2	25.9 ± 11.0	26.2 ± 9.9	0.531
Single SP medial	33.1 ± 13.0	25.3 ± 14.7	16.0 ± 6.8[a]	17.0 ± 6.9[a]	0.003
Single SP lateral	34.5 ± 12.3	23.0 ± 10.9[a]	23.9 ± 3.7[a]	19.4 ± 9.9[a]	0.005
2nd DSP medial	36.8 ± 16.8	23.5 ± 11.1[a]	21.9 ± 12.3[a]	24.2 ± 12.8[a]	0.030
2nd DSP lateral	16.6 ± 7.5	25.6 ± 20.6	22.4 ± 10.8	22.1 ± 12.0	0.410

[a] Significant difference ($p < 0.05$) from that of the operated limb of TKR subjects.

[b] Significant difference ($p < 0.05$) from that of the non-operated limb of TKR subjects.

DSP: double support phase.

SP: single support phase.

5.3.5.1 Muscle co-activation during daily activity simulations

Gait initiated with either the non-operated or operated limb of the TKR subjects, showed increased co-activation of the muscles of the medial aspect of the knee joint of the supporting limb (

Table 5.12). In contrast, no significant differences were found in co-activation of the lateral muscles of the knee joint of the supporting limb.

For comparison purposes, the stance phase during stair ascent and descent were divided into first double support, single support and second double support sub-phases. Patterns of muscle co-activation during stair ascent/descent were calculated for medial (MH-VM) and lateral (BF-VL) aspects of the knee joint for the whole stance phase. This included the first double support, double support and second double support sub-phases respectively.

As shown in Table 5.13, significant differences in co-activation of knee joint muscles were found between the TKR and control groups during the stance phase of either stair ascent or descent. Compared to the values for control subjects, muscle co-activation was increased in both the medial and lateral aspects of the operated and non-operated knees of TKR subjects. However, no significant differences were found when comparing co-activation patterns of the operated limb and non-operated limb of TKR subjects and the dominant to non-dominant knees of control subjects.

When compared to the contralateral knee and that of the control subjects, significantly increased co-activation was found in the lateral muscles of the operated knee of the TKR subjects in each of the 3 sub-phases. However, no significant differences were found in co-activation of the medial muscles of the knee during the first double support and single support phases of stair ascent.

In contrast, during stair descent, increased muscle co-activation was mainly found in the medial muscles of the knee joint when compared to findings for control subjects. As shown in Table 5.13, muscle co-activation was significantly increased in the muscles of the medial aspect of the operated knee in the TKR subjects when compared with findings for the contralateral knee and the knees in control subjects. In contrast, increased co-activation of the lateral muscles was only found in the single support phase for the operated knee. No differences were found in co-activation of the lateral muscles of the knee joint when compared during the first and second double support sub-phases during stair descent.

5.3.5.2 Inter-joint coordination between lower joints during stair ascent and descent

In addition to the differences in magnitude of joint angles during stair ascent and descent, subtle phasic deviations can be identified in the kinematic profiles of the lower limb segments in the 2 groups (Figure 5.8 and Figure 5.9). This allowed analysis of the CRP which represents the patterns of inter-joint coordination during stair ascent/descent and comparisons between groups during the various tasks.

During stair ascent/descent, significant differences in the inter-joint coordination for hip-knee and knee-ankle joints were found in both the operated and non-operated limbs of TKR subjects when compared to similar measures for the dominant limb of control subjects (**Error! Not a valid bookmark self-reference.**). Similarly, the variability of the inter-joint coordination of TKR group differed from the dominant side of the control subjects. In contrast, at the ankle joint, inter-joint coordination of the non-dominant limb of control subjects differed from that of the contralateral limb during stair ascent.

Table 5.14
Differences in coordination measures of operated and contralateral limb of TKR subjects and non-dominant limb of control subjects (Mean ± SD)

	TKR group		**Control group**
	Operated	**Non-Operated**	**Non-Dominant**
Ascent			
$MARP_{diff}$ (hip-knee)	12.6 ± 7.6[a]	9.3 ± 3.7[a]	2.9 ± 6.4
$SARP_{diff}$ (hip-knee)	10.5 ± 6.5[a]	8.4 ± 4.2[a]	2.3 ± 4.3
$MARP_{diff}$ (knee-ankle)	10.5 ± 6.5[a]	8.4 ± 4.2[a]	4.3 ± 2.3[a]
$SARP_{diff}$ (knee-ankle)	16.9 ± 6.6[a]	15.0 ± 7.6[a]	6.9 ± 2.2[b]
Descent			
$MARP_{diff}$ (hip-knee)	21.8 ± 7.4[a]	21.6 ± 11.0[a]	2.8 ± 3.9
$SARP_{diff}$ (hip-knee)	14.8 ± 4.9[a]	8.2 ± 3.11[a]	3.9 ± 7.3
$MARP_{diff}$ (knee-ankle)	19.8 ± 7.6[a]	15.1 ± 5.5[a]	3.4 ± 4.7
$SARP_{diff}$ (knee-ankle)	13.8 ± 5.4[a]	11.4 ± 4.6[a]	3.5 ± 7.2

[a] Significant difference ($p < 0.001$) from that of the dominant limb of control subjects
[b] Significant difference ($p < 0.01$) from that of the dominant limb of control subjects

5.3.6 Relationships between objective measurements and self-reported functional outcomes

As shown in Table 5.15, the strength of the knee extensors of the operated limb and flexors of both limbs was positively correlated with scores achieved for the R-WOMAC and IKS knee score and function score, where the higher score represents better functionality. In contrast, the strength of the knee extensors and flexors of the operated limb was negatively correlated with the results for the OKS, in which a high score is indicative of lower function.

Table 5.15

Correlations of muscle strength normalised for body weight and self-reported measures of functional performance

		R-WOMAC	OKS	IKS knee	IKS function
OP Extensors	Pearson's Coefficient	0.612	-0.680	0.658	0.682
	p-value	0.002[b]	<0.001[b]	0.001[b]	<0.001[b]
OP Flexors	Pearson's Coefficient	0.610	-0.569	0.628	0.506
	p-value	0.002[b]	0.005[b]	0.001[b]	0.014[a]
NOP Extensors	Pearson's Coefficient	0.158	-0.176	0.273	0.275
	p-value	0.471	0.421	0.208	0.205
NOP Flexors	Pearson's Coefficient	0.458	-0.392	0.424	0.463
	p-value	0.028[a]	0.064	0.044[a]	0.026[a]

D: dominant side of control subject; ND: non-dominant side of control subject.

OP: operated side of TKR subject; NOP: non-operated side of TKR subject.

[a] Significant difference ($p < 0.05$).

[b] Significant difference ($p < 0.01$).

Correlations between scores of self-reported functional questionnaires and objective measures derived from analyses of the functional activity simulations are presented in Table 5.16. Functional capacity scores measured by the R-WOMAC, IKS knee score and function score were positively correlated to the velocity and step length of the first step of gait initiation. In contrast, scores from the OKS were negatively correlated with these measures. Reaction time when turning to the operated side of TKR subjects during the W/T tests was found to be negatively correlated with the self-reported functional scores measured by the R-WOMAC and IKS scales, while a positive relationship was shown between reaction time and the OKS. Similarly, the stride time for stair ascent/descent was also negatively correlated with scores on the R-WOMAC, IKS knee score and function score. Stride time during stair negotiation was positively correlated to the score derived from the OKS scale.

Table 5.16

Correlations between self-report functional performance and temporal-spatial parameters during simulated activities of daily living

		R-WOMAC	OKS	IKS knee	IKS function
GI 1st step velocity	Pearson's Coefficient	0.575	-0.453	0.613	0.604
	p-value	<0.001[b]	0.002[b]	<0.001[b]	<0.001[b]
GI 1st step length	Pearson's Coefficient	0.359	-0.254	0.346	0.357
	p-value	0.014[a]	0.088	0.019[a]	0.015[a]
RT: To D/OP:	Pearson's Coefficient	-0.466	0.516	-0.416	-0.570
	p-value	0.025[a]	0.012[a]	0.048[a]	0.004[b]
TT: To D/OP:	Pearson's Coefficient	-0.158	0.334	-0.290	-0.484
	p-value	0.473	0.119	0.179	0.019[a]
RT: To ND/NOP	Pearson's Coefficient	-0.067	0.166	-0.252	-0.372
	p-value	0.760	0.449	0.246	0.081
TT: To ND/NOP	Pearson's Coefficient	-0.092	0.322	-0.329	-0.321
	p-value	0.676	0.135	0.125	0.135
Stair Ascent stride time	Pearson's Coefficient	-0.565	0.487	-0.613	-0.344
	p-value	<0.001[b]	0.001[b]	<0.001[b]	0.019[a]
Stair Descent stride time	Pearson's Coefficient	-0.522	0.523	-0.687	-0.432
	p-value	<0.001[b]	<0.001[b]	<0.001[b]	0.003[b]

D: dominant side of control subject; ND: non-dominant side of control subject.

OP: operated side of TKR subject; NOP: non-operated side of TKR subject.

[a] Significant difference ($p < 0.05$).

[b] Significant difference ($p < 0.01$).

Functional scores measured by R-WOMAC and IKS knee and function scores were found to be negatively correlated with the inter-joint coordination of the knee-ankle joint during stair ascent (Table 5.17). In contrast, a positive correlation coefficient was found between inter-joint relative phase dynamics of stair ascent and the OKS. Moreover, the self-reported functional outcomes were significantly correlated to the inter-joint relative phase dynamics of hip-knee and knee-ankle joints during stair descent.

Table 5.17

Correlations of relative phase dynamics during stair ascent/descent and self-reported function

		R-WOMAC	OKS	IKS knee	IKS function
Ascent					
$MARP_{diff}$ (HK)	Pearson's Coefficient	-0.184	0.126	-0.228	-0.085
	p-value	0.275	0.459	0.175	0.617
$MARP_{diff}$ (KA)	Pearson's Coefficient	-0.620	0.676	-0.560	-0.519
	p-value	<0.001[b]	<0.001[b]	<0.001[b]	0.001[b]
$SARP_{diff}$ (HK)	Pearson's Coefficient	-0.194	0.120	-0.188	0.045
	p-value	0.250	0.480	0.264	0.790
$SARP_{diff}$ (KA)	Pearson's Coefficient	-0.520	0.517	-0.476	-0.428
	p-value	0.001[b]	0.001[b]	0.003[b]	0.008[b]
Descent					
$MARP_{diff}$ (HK)	Pearson's Coefficient	-0.581	0.577	-0.554	-0.560
	p-value	<0.001[b]	<0.001[b]	<0.001[b]	<0.001[b]
$MARP_{diff}$ (KA)	Pearson's Coefficient	-0.446	0.503	-0.532	-0.424
	p-value	0.006[b]	0.002[b]	0.001[b]	0.009[b]
$SARP_{diff}$ (HK)	Pearson's Coefficient	-0.487	0.478	-0.448	-0.484
	p-value	0.002[b]	0.003[b]	0.005[b]	0.002[b]
$SARP_{diff}$ (KA)	Pearson's Coefficient	-0.390	0.478	-0.491	-0.417
	p-value	0.017[a]	0.003[b]	0.002[b]	0.010[a]

HK: hip-knee relative phase dynamics.

KA: knee-ankle relative phase dynamics.

[a] Significant difference ($p < 0.05$).

[b] Significant difference ($p < 0.01$).

Irrespective of whether performing stair ascent or descent, inter-joint coordination of the knee-ankle joint was found to be positively correlated with DJPS measured at movement speeds from 15º/s to 45º/s (Table 5.18). This positive correlation suggests that coordination of the knee and ankle joints is a much less optimal pattern compared to that of the control subjects when the TKR subjects showed decreased DJPS. Moreover, greater errors in DJPS were also found to be associated with greater variability in inter-joint coordination between knee and ankle joints. However, no significant relationships were found between DJPS measured at 60º/s and inter-joint coordination and the variability of coordination between hip-knee and knee-ankle joints irrespective of stair ascent or descent.

Table 5.18

Correlations of relative phase dynamics and dynamic joint position sense

		AE15	AE30	AE45	AE60
Ascent					
$MARP_{diff}$ (HK)	Pearson's Coefficient	0.303	0.240	0.050	0.050
	p-value	0.068	0.153	0.767	0.770
$MARP_{diff}$ (KA)	Pearson's Coefficient	0.512	0.423	0.405	0.286
	p-value	0.001[b]	0.009[b]	0.013[a]	0.086
$SARP_{diff}$ (HK)	Pearson's Coefficient	0.245	0.181	0.100	0.128
	p-value	0.143	0.285	0.557	0.450
$SARP_{diff}$ (KA)	Pearson's Coefficient	0.551	0.448	0.403	0.263
	p-value	<0.001[b]	0.005[b]	0.013[a]	0.116
Descent					
$MARP_{diff}$ (HK)	Pearson's Coefficient	0.423	0.315	0.180	0.071
	p-value	0.009[b]	0.057	0.286	0.678
$MARP_{diff}$ (KA)	Pearson's Coefficient	0.595	0.609	0.385	0.305
	p-value	<0.001[b]	<0.001[b]	0.019[a]	0.066
$SARP_{diff}$ (HK)	Pearson's Coefficient	0.438	0.330	0.189	0.081
	p-value	0.007[b]	0.046[a]	0.263	0.633
$SARP_{diff}$ (KA)	Pearson's Coefficient	0.571	0.629	0.399	0.288
	p-value	<0.001[b]	0.001[b]	0.014[a]	0.084

HK: hip-knee relative phase dynamics.

KA: knee-ankle relative phase dynamics.

[a] Significant difference ($p < 0.05$).

[b] Significant difference ($p < 0.01$).

5.4 DISCUSSION

Increases in the number of patients undergoing TKR and advances in surgical techniques and prosthesis design, have stimulated increased interest in the identification of more objective functional outcome measures which may influence post-operative recovery. These measures include biomechanical and neuromuscular parameters which are known to change following surgery. However, the degree to which they may change and influence performance of key activities of daily living requires further investigation and was a key goal of this study. Information derived from TKR patients at 6 months post-operatively was compared with age-matched control subjects.

As in Study 2 the relationship between the objective performance outcomes on the task simulations and patients' perceptions of functional recovery was also examined.

Functional testing protocols were designed using simulated activities of daily living, such as walking, stopping and turning and stair climbing. Understanding of performance of these activities is considered as important clinical indicators of recovery. Such tests involving measurement of associated biomechanical and neuromuscular factors will provide greater objectivity and utility in understanding adaptation to these fundamental locomotor activities known to be potential risk factors for injury in the older population.

In Australia the average age of those seeking knee replacement is 68.7 years with an increase in the proportion of patients aged less than 65 years from 29.7% to 33.9% in the last 5 years (AOA, 2012). Therefore, it is anticipated that some age-related changes in physical capacity and sensory functions may influence overall motor behaviour and adaptation to the implant. For example, decreases in muscle strength, flexibility and alterations in sensory characteristics such as proprioceptive function and reaction time, may affect dynamic balance control and in turn the functional performance of this population (Nadeau et al., 2003; Startzell et al., 2000; Thigpen et al., 2000).

5.4.1 Muscle strength, proprioception and self-reported outcomes

In a prospective study of patient expectations of functional recovery prior to and post TKR surgery indicated that prior to surgery patients estimated their average time for recovery at 4 months post-surgery (Nilsdotter, Toksvig-Larsen, & Roos, 2009). This expectation was not met and patients reported that their best walking ability occurred at 12 months, with 28% able to walk without assistance at this time period. Many factors influence the functional outcomes including gains in muscle strength and improvements in neuromuscular functioning. In the present study which indicated that the strength of the knee extensors and flexors of the operated limb was still weaker than that of the contralateral limb and control subjects at 6 months post-operatively. The ASI for muscle strength for the operated and non-operated limbs in the TKR subjects was approximately 31% and 17% for knee extensors and flexors respectively. This finding was consistent with previous investigations which evaluated muscle strength at the same time period post-operatively (Silva et al., 2003; Stevens-Lapsley et al., 2010).

Consistent results with respect to reduced strength of the knee extensors post-operatively have been shown with strength decrements of 17% to 40% for the operated knee compared to the contralateral limb depending on the post-operative time (Iwamoto, Takeda, & Sato, 2007; Lorentzen et al., 1999; Maffiuletti, Bizzini, Widler,

& Munzinger, 2010; Stevens-Lapsley et al., 2010; Stevens et al., 2004). More limited information is available concerning the strength of the knee flexors following TKR and the results are inconsistent. In 2 studies, the hamstring strength of the operated limb was 17.3% (Stevens-Lapsley et al., 2010) and 39% (Lorentzen et al., 1999) less than that of the contralateral limb, respectively. This difference may reflect differences in the average age of subjects in these studies of 64.3 and 74 years (Lorentzen et al., 1999).

In the present study, the strength of the knee extensors and flexors was 31.7% and 20.4% less than that of the non-dominant limb of the control subjects, respectively. However, decrements in the strength of knee extensors and flexors increased to 41.2 and 29.4%, respectively, when compared to the dominant side of the control subjects. These results are consistent with those from earlier studies which have shown that knee extensor and flexor strength was approximately 30 and 36 to 39% less than that of the controls respectively (Lorentzen et al., 1999; Stevens-Lapsley et al., 2010).

Greater discrepancy in the muscle strength of the operated knee of TKR subjects, when compared to the non-dominant and dominant limbs of the control subjects, was found in the present study. This finding may be attributed to the small but non-significant differences in muscle strength between the dominant and non-dominant limbs of the control subjects, where the muscle strength was 13.7% and 11.2% stronger for knee extensors and flexors respectively in the dominant limb. However, comparison with earlier results was not possible, as these studies did not consider dominant and non-dominant comparison of knee muscle strength as in the present study. In a study of 35 subjects aged older than 65 years, asymmetry in the muscle strength of both limbs was more than 10% in 25 of the subjects (Skelton, Kennedy, & Rutherford, 2002).

Results of the present study with respect to DJPS measurement indicated decreased proprioceptive accuracy in the operated knee when compared to the contralateral limb of TKR subjects and both knees of the control subjects. This finding was consistent with the results at 12 months post-operatively reported in Chapter 3. Impaired proprioception of the replaced knee has been previously demonstrated in patients following TKR at different time periods post-operatively, although variable measurement protocols have been used in these studies (Attfield et al., 1996; Swanik et al., 2004; Wada et al., 2002; Warren et al., 1993).

Findings from the surveys of functional recovery following TKR showed that although perceptions of functional performance outcomes were less positive than for control subjects, significant improvements occurred in the IKS knee and function scores compared with pre-operative values. For example, an improvement of approximately 29% was shown in this study measured by IKS scores, which was similar to the magnitude of improvement evaluated using the WOMAC survey in patients at 6 months post-operatively (Jones, Voaklander, & Suarez-Alma, 2003). Mean pre-operative IKS clinical scores of between 30.7 and 52.6 and function scores of 52.6 to 58.2 were reported by previous studies. As indicated earlier, a score of 100 would be assigned to the clinical and functional scores for patients with an optimally functioning knee (Biasca, Wirth, & Bungartz, 2009; Mullaji & Shetty, 2009; Peterlein, Schofer, Fuchs-Winkelmann, & Scherf, 2009; Renkawitz et al., 2010; Yang, Seo, Moon, & Kim, 2009). At 6 months post-operatively, the IKS knee and function scores were reported to be improved to approximately 75 and 85 respectively with a sum total for the IKS knee and function scores of 149.1 to 193 (Biasca et al., 2009; Spencer et al., 2007).

Lower strength measures of knee extensors and flexors were associated with less positive perceptions of functional performance outcomes. In contrast, consistent with the findings for patients at 12 months post-operatively, stronger knee extensors and flexors of the operated limb at 6 months following TKR, were associated with more positive self-reported functional performance measured by the questionnaires used in this study. Moderate correlations were also found between the strength of the knee flexors of the non-operated limb of TKR subjects and self-reported functional scores. As indicated earlier, quadriceps strength of the operated knee has been identified as an important predictor and determinant of long term functional ability in patients following TKR (Mizner, Petterson, & Snyder-Mackler, 2005; Yoshida, Mizner, Ramsey, & Snyder-Mackler, 2008). Knowledge that patients following surgery rely more on the contralateral limb during weight-bearing activities (Mizner, Petterson, Stevens et al., 2005), has stimulated interest in examination of the relationship between the strength of muscles of the non-operated limb and functional outcomes. During a 3-year post-operative follow-up of 50 subjects following unilateral TKR, quadriceps strength of the non-operated knee was found to be decreased over a 1-year period contributing to decreased functional performance. The decrease in muscle strength explained 44% of the variance of the distance walked during the 6MWT (Farquhar & Snyder-Mackler, 2010). This earlier finding regarding the relationship between functional outcome and muscle strength of the contralateral limb was partly confirmed by the present study, which indicated that increased flexor strength was associated with more positive self-reported functional outcomes.

In summary, muscle strength and proprioceptive function of the operated knee following TKR are lower than for their contralateral limb which was similar to control values. In addition to the muscle strength of the operated knee, flexor strength of the contralateral knee may also contribute to the impairments measured by self-reported questionnaires. The association between patients' perceptions of improved functional performance and knee strength following TKR, lends support to the utility and validity of self report measures in evaluation of recovery.

5.4.2 Performance during functional activity simulations

Information from measures derived during performance of daily activities in the real world environment or simulation of these activities is limited for TKR subjects. As such, the findings from this study provide new information which is also sensitive to changes in function following TKR in relation to age.

The findings indicated that different turning strategies were adopted by TKR subjects when compared to those of the control subjects. Total knee replacement subjects were more likely to use the contralateral limb as the supporting limb and take step turning. The lack of similar information prevented comparison with other studies involving TKR subjects. However, when turning, older subjects have been shown to adopt both step and spin turning as basic strategies (Glaister et al., 2007; Sedgman et al., 1994). The inherently unstable bipedal gait is challenged further during turning and in the elderly or people with a disability or particular pathological condition, there is a tendency to decrease velocity and take more steps during turning (Ito, Odahara, Hiraki, & Idate, 1995; Thigpen et al., 2000). These adaptations occur to maintain equilibrium against the inertial forces which may threaten balance of the trunk and lower limbs (Courtine & Schieppati, 2003a, 2003b; Patla, Prentice, Robinson, & Neufeld, 1991).

Previous studies have shown that temporo-spatial, kinematic and kinetic characteristics of the inner and outer limb during turning become more asymmetrical than found during straight-line walking (Courtine & Schieppati, 2003b; Orendurff et al., 2006; Strike & Taylor, 2009). This was accompanied by slight but significant differences in muscle activity patterns between limbs (Courtine & Schieppati, 2003b). Able-bodied subjects with right-leg dominance, showed a preference to turn towards the left side using their dominant leg as the supporting limb (Segal et al., 2008; Taylor et al., 2006). The preference in turning strategies was partly confirmed by the results of the present study which indicated that TKR patients tended to use the contralateral non-operated leg as the supporting limb. In contrast to previous findings where the turning direction was voluntarily selected by the participants, all subjects in the present study were required to respond to a visual signal to change direction as soon as possible. This task was designed to simulate abrupt interruptions encountered during activities of daily living.

The differences between these 2 strategies adopted during 90º turning were investigated in an earlier study (Taylor et al., 2005) involving 10 younger subjects with a mean age of 22.8 (SD: 5.2) years. The results indicated that step turning provided a wider base of support than during spin turning and the COG was always found to be displaced between the feet during turning, and outside the base of support during spin turning. Step turning was actively selected by TKR subjects as the main strategy for turning. This may reflect the fact that the moments of force of both lower limbs during step turning were reduced to a level similar to straight-line walking (Taylor et al., 2005). This strategy minimises the risk of placing additional potentially damaging forces and moments on the replaced knee joint, in an active pattern to protect the implanted prosthesis.

Total knee replacement subjects initiated walking at a slower velocity and with a reduction in the length of the first step following gait initiation. Patterns of gait initiation in older adults and patients with chronic conditions such as Huntington's disease, Parkinson disease and knee arthritis have consistently shown that step length and velocity of the first step are reduced across these variable pathologic conditions (Delval et al., 2007; Halliday, Winter, Frank, Patla, & Prince, 1998; Hass et al., 2008; Polcyn et al., 1998; Viton et al., 2000; Welter et al., 2007). Control subjects in the present study showed similar results to earlier findings, where a step speed of 1.4 m/s and step length of 0.66 metre, was shown in a study of 15 subjects without pathologic conditions and with an average age of 47.9 years (Delval et al., 2007). Another study, involving 43 subjects with a mean age of 54.1 years, showed walking speeds ranging from 0.77 to 1.29 m/s and step lengths from 0.37 to 0.60 metre (Welter et al., 2007).

Findings of reduced magnitude and velocity of posterior displacement of COP for TKR subjects in the current study were consistent with earlier results involving older subjects (Hass et al., 2008). In the earlier studies, it was suggested that posterior displacement of the COP during the S1 period, generated the forward momentum needed to initiate gait (Hass et al., 2008; Polcyn et al., 1998) and that the amplitude and velocity of the APA in the sagittal plane are predictive of step velocity after reaching a constant pace (Ito, Azuma, & Yamashita, 2003). This proposal was confirmed by the current study which found that the magnitude and velocity of the posterior displacement of COP were correlated with the step length and velocity of the first step after gait initiation. The greater magnitude of displacement, coupled with faster speed of COP displacement were associated with greater step length and velocity.

Similar movement patterns of the COP and the characteristics of the first step after gait initiation were found in TKR subjects when initiated with either the operated or the non-operated limb. These results were consistent with those derived from a study which investigated the duration of APA during gait initiation of 12 unilateral knee arthritis patients with an average age of 69 years (Viton et al., 2000). Although slower velocity and reduced length of the first step were found in these patients, no difference existed between gait initiated with the involved limb and the sound one. The reason may be attributed to the neural control mechanisms of APA during the initiation of step, which was suggested to be controlled at the supraspinal level and may not be influenced by muscle and joint afferent information (Ito et al., 2003; Patla et al., 1991; MacKinnon et al., 2007).

No significant differences were found in cadence and stride time between the TKR subjects when compared to controls. In contrast, significantly decreased single support and prolonged double support times were found for the operated limb of TKR patients compared to their contralateral limb and controls. These results are consistent with those from previous studies involving gait analysis of TKR patients during level walking (Ouellet & Moffet, 2002; Saari et al., 2005), stair ascent (Kaufman, Hughes, Morrey, Morrey, & An, 2001; Mandeville, Osternig, & Chou, 2007; McClelland, Webster, & Feller, 2009) and descent (Kaufman et al., 2001), at a similar time interval post-operatively.

Marginal, but non-significant differences found in the cadence and stride time of stair negotiation between TKR and control subjects may be attributed to the relatively high inter-subject variability as evidenced by the greater CV values of cadence and stride time for TKR subjects, irrespective of whether performing stair ascent or descent. Previous research has also shown high individual variability. For example, for measures of temporo-spatial, kinematic and kinetic parameters during different activities such as walking, stair ascent/descent and sitting to standing transfer the variability was found to be as high as 29% to 50% in patients following TKR (McClelland et al., 2009). The author proposed that the high variability may contribute to the inconsistency of findings in earlier studies involving biomechanical characteristics (McClelland et al., 2009). The repeatability of joint kinematics changes as a function of the nature of different functional activity tasks. For example, the repeatability of knee joint kinematics when measured at an average of 22 days apart and involving performance of 13 types of functional activities including level walking, sit-to-stand transfer and stepping out of a bath (van der Linden, Rowe, & Nutton, 2008), showed significant differences between sessions in the knee joint angles. These ranged from 5.6º for the loading response during level walking to 39.8º for stepping out of a bath. This variation was considered to reflect the complexity of the activities.

Results of the current study showed that the kinematic alterations of the lower limb joints mainly occurred in the hip and ankle joints of the operated limb of TKR patient compared to that of the control subjects during both stair ascent and descent. Consistent with previous findings (Mian et al., 2007), using stairs of similar size, control subjects in this study climbed the stairs with comparable angular displacements of the lower limbs. Although no significant differences in the angular displacements of the knee joint at specific events during stair negotiation were found, the range of motion of the knee joint in the operated limb was significantly reduced. This was consistent with the kinematic patterns identified during level walking and stair negotiation (Fantozzi et al., 2003; Ouellet & Moffet, 2002; Saari et al., 2004). The finding of reduced range of movement at the knee joint was also supported by kinetic investigations, which indicated that the moment at the hip and ankle joints was increased to compensate for the decreased knee extensor moment during stair ascent in subjects at 6 months post-operatively (Mandeville et al., 2007; Saari et al., 2004).

The present study revealed that the TKR subjects actively selected a more stable turning strategy to change direction in response to an abrupt visual signal during straight-line walking. Secondly, slower gait initiation with decreased step length, accompanied by reduced magnitude and velocity of COP displacement during APA, was also found in TKR patients, regardless of gait being initiated with the operated or non-operated limb. Moreover, TKR subjects were able to ascend and descend the stairs at a speed comparable with that of the control subjects, although significantly greater inter-subject variability of tempo-spatial parameters was shown. Finally, significant kinematic alterations occurred mainly in the hip and knee joints of the operated limb of TKR subjects, which may be adopted as a compensatory strategy for the reduced functionality of the knee joint.

5.4.3 Neuromuscular adaptations during functional activity simulations

Slower movement responses and increased reaction time have been recognised as indicative of the normal ageing process (Sturnieks, St George, & Lord, 2008). Reaction time has been shown to be significantly prolonged in older people without diagnostic pathologic conditions during sway movement in response to an auditory signal (Tucker, Kavanagh, Barrett, & Morrison, 2008), or gait initiation in response to a simulated traffic light system (Henriksson & Hirschfeld, 2005). Changes in reaction time across the life span have also been investigated and an increase of 25% in reaction time was found between the ages of 20 to 60 years, followed by a further slowing of reaction time beyond 60 years (Fozard, Vercryssen, Reynolds, Hancock, & Quilter, 1994; Williams, Hultsch, Strauss, Hunter, & Tannock, 2005). No study was found which has investigated the reaction time and neuromuscular adaptations in patients following TKR during performance of simulations of ADL.

Reaction time of the TKR subjects in gait initiation, walking and turning (W/T) tests were longer than for the control subjects irrespective of whether the gait was initiated or supported by the operated or contralateral limb. The findings also indicated that reaction time during W/T testing was longer than during walk initiation, which is consistent with previous studies which have shown reaction time increases with increasing task complexity (Tucker et al., 2008).

Turning time, which has been used as measure of turning capacity in studies of elderly subjects (Dite & Temple, 2002; Thigpen et al., 2000) was also found to be prolonged during the W/T tests in TKR patients when compared to control subjects. This finding occurred irrespective of the direction of turning relative to the operated or non-operated limb. The longer reaction time and turning time indicates that the turning capacity of TKR subjects was impaired at 6 months post-operatively.

Displacement of the COP during the APA of gait initiation is important in ensuring effective and safe initiation of walking. The findings of the study showed that posterior displacement of the COP during S1 section of the APA was associated with the step length and velocity of the first step after gait initiation. A positive correlation was also found between the velocity of displacement of the COP during the S3 section of APA and the step length and velocity of the first step of gait initiation. COP displacement was also shown to be related to these characteristics of the first step of gait initiation. This further confirms the contribution of the COP displacement to the generation of forward velocity and the impaired capacity of TKR subjects in effective gait initiation (Ito et al., 2003; Patla et al., 1991).

Co-contraction of agonist and antagonist muscles during gait initiation increased in the medial muscles of the supporting limb in TKR subjects. This occurred irrespective of the support being provided by the operated or non-operated limb. This finding differed from that described in the previous chapter, which indicated that co-activation of the lateral muscles of the knee joint was greater than for the medial muscles of the knee joint during level walking.

No evidence from previous studies involving muscle co-activation during gait initiation and level walking was found to interpret or confirm these findings. It has been suggested that increased muscle co-activation in the lateral aspect of the knee joint may be a compensatory strategy to decrease loading of the medial compartment of the joint (Andriacchi, 1994; Hubley-Kozey et al., 2006). Muscle co-activation of both medial and lateral aspects of the operated knee was increased in the stance phase compared to the control subjects during stair negotiation. An increase in co-activation was also shown in muscles of the lateral aspect of the operated knee compared to the contralateral knee. This increased muscle co-activation may contribute to greater control of knee kinematics and stability during the stance phase, particularly when higher forces are imposed on the knee joint during stair negotiation (Banks et al., 2003; Benedetti et al., 2003). Joint forces during stair ascent and descent have been investigated in 2 previous studies using direct measurement from instrumented knee prosthesis (Heinlein et al., 2009; Mundermann et al., 2008). The results consistently showed significantly increased compressive forces in the knee joint (305% and 352% of body weight during stair ascent and descent, respectively), compared to 276% of body weight during level walking (Heinlein et al., 2009). Compressive forces on the knee joint were also found to be greater than 250% of body weight in more than 70% and 40% of the stance phase during stair ascent and descent, respectively (Mundermann et al., 2008). As muscle action is a major factor in joint loading, more investigation is required to examine the relationship between increased muscle co-activation and the increased joint compressive forces in this population. The findings may provide further insight into the role of these factors and the risk of wearing of the prosthesis.

Decreased range of motion of the knee joint during stair ascent and descent was found in the operated knee, accompanied by altered displacement of both hip and ankle joints of the operated limb. Knee movement during stair ascent and descent may have been influenced by muscle co-contraction of knee extensors and flexors as described by previous studies (Benedetti et al., 1999; Bolanos et al., 1998; Dorr et al., 1988; Fuchs, Rolauffs et al., 2005). However, it was suggested that reduction in knee flexion and range of motion may be representative of a compensatory effect to minimise eccentric contraction of the quadriceps and in turn reducing the compressive forces across the knee joint (Hinman, Bennell, Metcalf, & Crossley, 2002; Saari et al., 2004).

Movement of the hip increased during the stance phase for both stair ascent and descent and ankle joint movement was also found to be changed during the stair ascent. These results are partly supported by earlier findings involving unilateral TKR subjects at a 1 to 2-year follow-up (Saari et al., 2004). However, the previous study only compared the movement characteristics of the hip and knee joint. Greater range of movement of the ankle joint has previously been shown to be required during stair negotiation by older adults, with the need to apply maximal potential ROM of the lower limb joint (Hortobagyi, Mizelle, Beam, & Devita, 2003; Reeves, Spanjaard, Mohagheghi, Baltzopoulos, & Maganaris, 2008). This emphasises the importance of maintaining a range of motion of the lower limb sufficient to manage performance of activities such as stair negotiation.

As indicated in the preceding chapter, relative phase has been used as a method of investigating inter-joint coordination by integration of information related to joint angular displacements and velocities. By subtracting the phase angle of the distal joint from that of the proximal joint, at corresponding time points of the gait cycle, CRP between hip-knee and knee-ankle joint was able to be computed as the representative of the inter-joint coordination during stair negotiation (Burgess-Limerick et al., 1993; Kurz & Stergiou, 2002). In accordance with the pattern of inter-joint coordination reported in the preceding study during level walking and sit-to-stand transfer (Boonstra et al., 2007), significantly increased deviation in the coordination pattern and greater variability of the coordination were found in the TKR subjects when compared to that of the dominant side of the control subjects.

Coordination and variability in coordination of the knee-ankle joint was found to be associated with DJPS of the knee joint measured at speeds ranging from 15º/s to 45º/s. As shown in the previous chapter, this finding is in line with the results for TKR subjects when performing level walking. As suggested previously (Ghez & Sainburg, 1995), the impaired proprioception at the knee joint and its potential effect on perception of the knee joint position and movement, may in turn influence inter-joint coordination of the knee with other joints of the lower limb.

In summary, reaction time of the TKR subjects was longer than for controls when initiating gait or turning kin response to abrupt visual signals. At the same time, longer time was needed by TKR subjects to complete the turning by adopting a more stable strategy mainly using the contralateral limb as the supporting limb. Co-activation of the knee muscles was found to be evident only in the medial compartment during gait initiation, while both medial and lateral aspects of the operated knee joint showed increased co-activation during most of the time during stair negotiation. Although completion of the simulated activities of daily living was accomplished by the TKR subjects, significantly altered inter-joint coordination between knee and hip and ankle joint occurred as a function of the impaired proprioception.

5.4.4 Relationships between objective measurement and self-reported functional performance

Performance based evaluations such as the TUG test, 6MWT, stair climbing up and down have been used to assess the actual functional performance of TKR patients both pre- and post-operatively (Bruun-Olsen, Heiberg, & Mengshoel, 2009; Mintken, Carpenter, Eckhoff, Kohrt, & Stevens, 2007; Petterson et al., 2009; Rossi, Hasson et al., 2006). However, as indicated earlier, although age-related neuromuscular change may in turn affect the functional performance of this population, there is limited evidence to support this hypothesis.

In this study, quicker reaction time when turning to the operated side was found to be associated with better patient perceptions of self-reported functional performance outcomes. Similar positive relationships were also found between, greater velocity and increased length of the first step of gait initiation and functional scores. In contrast, a longer stride time during stair ascent and descent was associated with less than optimal performance. Reduced velocity and step length during gait initiation have been shown to be key indicators in patients with walking difficulties such as those with Parkinson's disease, older people with postural instability and other neurologic conditions (Delval et al., 2007; Hass et al., 2008; Rocchi et al., 2006). As shown in this study, velocity and length of the first step were correlated to duration and amplitude parameters of APA in the sagittal plane, and were shown to predict further step velocity when constant walking velocity was approached (Ito et al., 2003). Slower velocity when walking on a level surface, during stair negotiation as indicated by less distance/steps covered in a pre-determined period of time, as measured by the 6MWT and stair climbing tests, have also been correlated with less optimal functional recovery in TKR subjects (Mintken et al., 2007; Petterson et al., 2009).

The increased muscular demand and greater range of movement makes the task of stair negotiation extremely difficult for TKR subjects (Mian et al., 2007; Saari et al., 2004; Startzell et al., 2000). Fifty per cent of the total score of 100 for of the IKS function score described relates to the ability to ascend and descend a flight of stairs, without using a handrail or other assistive device (Insall et al., 1989). In a study of 2990 female TKR subjects, the IKS score improved from an average of 42.4 pre-operatively to 76.1 at 6 months post-operatively. The stairs score also improved from 29.2 to 35.5 at the same follow-up period (Ritter, Wing, Berend, Davis, & Meding, 2008). Information with respect to stair negotiation performance is limited which may due to the fact that a large proportion of patients experience difficulty in performing this activity in the early stages following surgery. At 2 months post-surgery, 3 of 16 patients (average age of 66.8 years), were unable to ascend stairs using alternating steps (Ouellet & Moffet, 2002). At later stages of recovery (1-2 years), only approximately 50% of older subjects were able to ascend a 20cm high step without assistance (Byrne et al., 2002), or to ascend and descend the stairs in a reciprocal manner without using a handrail (Ouellet & Moffet, 2002).

Better outcomes measured by self-reported and physician administered questionnaires have been correlated with improved function evaluated with the performance based criteria, including walking speed, stair ascent/descent time and 6MWT (Finch, Walsh, Thomas, & Woodhouse, 1998; Gandhi, Tsvetkov, Davey, Syed, & Mahomed, 2009; Kennedy, Stratford, Pagura, Walsh, & Woodhouse, 2002; Parent & Moffet, 2002). However, the responses obtained from these 2 methods of evaluation have been shown to be different, particularly during the early stage following surgery. In contrast to the significant improvement in functional outcome evaluated with WOMAC, no post-operative improvement using the 6MWT was found when compared to pre-operative values (Parent & Moffet, 2002).

Results of the present study showed a more prolonged reaction time for TKR subjects at initiation of gait and turning. Unfortunately, from a comparative perspective no previous studies were found in the literature which had investigated these parameters in TKR patients. Age related changes in reactive response and in reaction time when turning has been shown by previous studies. For example, longer reaction time was found in older people when compared to young adults when performing gait initiation or step adjustment in response to an external stimulus (George, Ruiz, & Sloan, 2008; Rogers, Kukulka, Brunt, Cain, & Hanke, 2001). The decrement in the reactive responses of TKR patients may then reflect age related responses together with the neuromuscular adaptation in functional performance as a function of the surgery.

Moderate, but significant correlations were found between the self-reported functional outcomes and inter-joint coordination and variability in the coordination between knee-ankle during stair ascent. Coordination and variability in inter-joint coordination of lower-limb joints during stair descent was negatively correlated to self-reported functional outcomes. Greater differences in coordination and variability in coordination compared to the pattern of inter-joint coordination of the dominant side of the control subjects were associated with less optimal self-reported functional performance, irrespective the questionnaires used for evaluation in the present study. These results were consistent with a previous study which investigated the relationship between the inter-joint coordination characteristics during sit-to-stand transfer and WOMAC scores of patients following unilateral TKR (Boonstra et al., 2007).

5.5 CONCLUSION

The major aim of Study 3 was to examine the biomechanical and neuromuscular responses during simulated activities of daily living such as gait initiation, stair climbing, and directional change during walking of TKR patients at 6 months post surgery. Changes in self reported functional outcomes at baseline and at 6 months post-operatively were also used to examine the relationship between objective and self report measures of functional performance. By comparison with age matched controls the findings indicated:

5.5.1 Characteristics of first step of gait initiation

- Irrespective of whether or not initiated by the operated or non-operated limb, there was significantly slower gait initiation, with reduced length and velocity of the first step of gait initiation and significantly less posterior displacement of COP;
- Movement velocity of COP indicated that the TKR subjects moved significantly slower in the antero-posterior direction, regardless of the gait being initiated with the operated or non-operated limb;
- Significantly lower velocity only found in the medio-lateral direction when gait was initiated with the operated limb;
- Length of the first step after gait initiation negatively correlated with the magnitude of posterior displacement of the COP and the velocity of COP displacement during the S1 section of postural adjustment;

- Longer movement time required when turning to operated side;
- Increased reaction time when turning toward either operated or non-operated side and when initiating walking with operated limb;
- A tendency to use the contralateral leg as the supporting limb when turning towards the operated or non-operated side and a preference to adopt step turning rather than spin turning; and
- Significantly prolonged reaction time when turning toward either the operated or non-operated side.

5.5.2 Stair ascent and descent

- Comparable speeds during stair ascent and descent, but with significantly prolonged double support phase and reduced single support times;
- Significant changes in movements of the hip and ankle joints at foot contact and toe-off during stair ascent and descent;
- Significant alterations in Inter-joint coordination and variability of inter-joint coordination between lower limb joints, accompanied by significantly increased muscle co-activation between knee extensors and flexors;
- An association between patterns of inter-joint coordination between lower-limb joints and decrements in proprioception of the knee joint;
- Reduced muscle strength and knee joint proprioception were also accompanied by altered functional performance during simulations of activities of daily living;
- Inter-joint coordination found to be positively correlated with DJPS measured at movement speeds from 15 to 45 degrees/sec;
- Significant differences in co-activation of knee joint muscles during the stance phase of either stair ascent or descent with increased muscle co-activation mainly found in the medial muscles during stair descent;
- During simulated activities, muscle co-activation significantly increased in muscles of the medial aspect of the operated knee in the TKR subjects when compared with findings for the contra-lateral knee and controls; and
- Significantly increased co-activation in the lateral muscles of the operated knee of the TKR subjects in each of the 3 sub-phases.

5.5.3 Self report outcomes

Although significant improvement was shown when compared to the pre-operative IKS score, the movement and activity profiles of TKR subjects were still characterised by reduced functional performance. Additional findings indicated that self-reported outcomes were associated with:

- Stronger muscle strength, on both operated and non-operated knees;
- Longer stride time during stair ascent/descent; and
- More accurate proprioception measures and more optimal inter-joint coordination patterns.

Chapter 6: Summary and conclusions

Relief of pain and recovery of knee function to enable satisfactory performance of activities of daily living are key objectives when undertaking total knee replacement. Although pain has been shown to be successfully relieved after surgery, functional performance of TKR patients has been shown to be generally lower when compared to their age-matched peers, as measured with self-report or physician administered questionnaires. Similar results have been shown with more objective measurements, including strength of knee extensors and flexors and other performance based evaluations such as the TUG test, 6MWT and timed stair climbing.

The role of muscle strength and reduced ROM in the functionality of TKR subjects has been investigated previously and the findings used to guide the design and evaluation of rehabilitation interventions. However, functional recovery is still less than optimal, which may reflect the appropriateness of the exercise program, lack of compliance and the need for most patients to engage in the exercise at home, or in an out-patient setting.

Functional recovery, particularly in areas of balance and stability, may also be more limited following TKR as a function of age-related changes in proprioception. Proprioception plays a critical role in modulating the activation of muscles around the knee joint, contributing to neuromuscular control and inter-joint coordination of the lower limbs. While the data comparing pre- and post-operative changes in proprioception following TKR is inconsistent, decrements in joint position sense have been shown to play a key role in the development of knee OA and contributing to limitations in functional performance and knee injuries, often resulting from falls. There is increasing interest in examining the relationship between proprioception and TKR outcomes and a major goal of this study was to extend knowledge of the neuromuscular factors, including proprioception, associated with recovery following TKR and their influence on the performance of activities of daily living.

This inconsistency in previous findings may represent differences in the measurement protocols used and their limited reliability. Consequently, the aim of Study 1 was to examine the reliability of different proprioception protocols, with comparison between TKR and age-matched control subjects. Fourteen TKR subjects who had undertaken unilateral TKR at an average of 11.5 months prior to testing and 15 control subjects who satisfied the inclusion criteria were recruited and tested at 2 sessions, 1 week apart. The protocols included measurement of passive angular reproduction (PAR) and dynamic joint position sense (DJPS). Although each of the 3 parameters used to represent PAR and DJPS showed good to excellent inter-session reliability, the PAR protocol of the first session was unable to discriminate differences between the operated and non-operated knees. In contrast, the absolute error (AE) of PAR obtained in Session 2, showed significant differences between the operated and contralateral knees of the TKR subjects and controls subjects. Significantly increased AE of DJPS of the operated knee during both sessions was also found for the operated knee compared to the contralateral knee and the knee of control subjects. The conclusions from this study were:

- Both PAR and DJPS protocols were reliable in the measurement of proprioception associated with the operated and non-operated knee joints of TKR subjects and healthy control subjects;
- AE of DJPS showed more reliability when used to discriminate differences in proprioception between the operated and contralateral knees and both knees of control subjects; and
- No significant relationships were identified between proprioception and functional outcomes following TKR.

Using the same subject groups, the second study compared differences in gait performance and associated neuromuscular factors between TKR patients and age-matched controls at 11.5 months post-operatively.

Evaluation of gait patterns included kinematic analysis including lower limb inter-joint coordination, and co-activation of knee extensors and flexors. The relationship between these factors and knee proprioception using the more reliable measurement protocol identified in Study 1 was also evaluated. Findings of this study supported the following conclusions:

- When normalised by body height, TKR subjects showed increased velocity and stride length and double support time accompanied by decreased swing and single support times;
- Although the TKR subjects were able to walk at a velocity similar to that of the control subjects, significant differences were found between the 2 groups in the kinematic characteristics of the lower limb joints with respect to patterns and variability of lower-limb joint coordination. The latter was accompanied by significantly increased muscle co-activation of the knee

extensors/flexors, particularly for muscles of the lateral aspect of the knee joint;

- In addition to the correlation between muscle strength and survey based performance evaluation, the association between the inter-joint coordination of the lower-limb joints and dynamic joint position sense was found to be significant only in knee-ankle coordination during level walking; and
- TKR participants perceptions of functional outcomes, evaluated with self-reported or physician administered questionnaires, indicated functionality was not were not restored to the level of age-matched controls at 11.5 months post-operatively.

In summary, the findings of the second study identified significant adaptations and compensatory strategies in the kinematics of the lower-limb joint following TKR, expressed by differences in the coordination patterns of these joints between TKR subjects and controls. However, the hypothesis that the pattern and variability of hip-knee joint coordination was correlated to the dynamic joint position sense of the knee joint was not supported by the current study. The long term impact of these adaptive and compensatory strategies on the replaced joint and other parts of the body requires further investigation.

The major aim of Study 3 was to examine the biomechanical and neuromuscular responses during simulated activities of daily living such as gait initiation, stair climbing, and directional change during walking of TKR patients at 6 months post surgery. Changes in self reported functional outcomes at baseline and at 6 months post-operatively were also used to examine the relationship between objective and self report measures of functional performance.

By comparison with age matched controls TKR subjects showed:

- Lower strength measures of knee extensors and flexors were associated with less positive perceptions of functional performance outcomes;
- Significantly slower gait initiation, with reduced length and velocity of the first step of gait initiation and significantly less posterior displacement of COP; regardless of the gait being initiated with the operated or non-operated limb;
- Significantly slower movement in the antero-posterior direction as indicated by movement velocity of COP, regardless of the gait being initiated with the operated or non-operated limb;

- Significantly lower velocity only in the medio-lateral direction when gait was initiated with the operated limb;
- The length of the first step after gait initiation was negatively correlated with the magnitude of posterior displacement of the COP and the velocity of COP displacement during the S1 section of postural adjustment;
- Longer movement time required when turning to operated side;
- Increased reaction time when initiating walking with operated limb and when turning toward either the operated or non-operated side; and
- A tendency to use the contralateral leg as the supporting limb when turning towards the operated or non-operated side and a preference to adopt step turning rather than spin turning.

Responses to simulated activities

- Increased muscle co-activation in muscles of the medial aspect of the operated knee when compared with findings for the contra-lateral knee and controls;
- Reduced muscle strength and knee joint proprioception, accompanied by altered functional performance; and
- Increased co-activation in muscles of the medial aspect of the operated knee;

During stair ascent and descent

- Comparable speeds, but with significantly prolonged double support phase and reduced single support times;
- Significant changes in movements of the hip and ankle joints at foot contact and toe-off;
- Significant alterations in Inter-joint coordination and variability of inter-joint coordination between lower limb joints, accompanied by significantly increased muscle co-activation between knee extensors and flexors;
- An association between patterns of inter-joint coordination between lower-limb joints and decrements in knee joint proprioception;
- Significant differences in co-activation of knee joint muscles during the stance phase of either stair ascent or descent with increased muscle co-activation mainly found in the medial muscles during stair descent; and

- Significantly increased co-activation in the lateral muscles of the operated knee of the TKR subjects in each of the 3 sub-phases.

Self report outcomes

Although significant improvement was shown when compared to the pre-operative IKS score, the movement and activity profiles of TKR subjects were still characterised by reduced functional performance. Additional findings indicated that:

- AE during dynamic testing of JPS was significantly related to functional outcomes;
- More accurate proprioception measures and improved inter-joint coordination patterns were associated with improved functional outcomes;
- Increased strength of knee extensors and flexors at 6 and 12 months was associated with more positive self reported functional outcomes;
- Inter-joint coordination and variability in the coordination between knee-ankle joints during stair ascent;
- Coordination and variability in inter-joint coordination of lower-limb joints during stair descent was negatively correlated to self-reported functional outcomes; and
- Greater differences in coordination and variability in coordination compared to the pattern of inter-joint coordination of the dominant side of the control subjects were associated with less optimal self-reported functional performance.

In summary, the findings of the thesis provide important evidence to improve understanding of the biomechanical and neuromuscular adaptations when performing key daily activities at 6 and 12 month recovery periods following TKR. The study also addressed previous inconsistencies associated with the reliability of proprioception measurement with identification of a reliable protocol used to evaluate this important parameter and its influence on functional outcome measures.

Comparison of objective measures of functional outcomes and clinically validated survey tools was also of value in determining the relationships between the 2 methods and their potential validity. Importantly, the results of the study will further inform understanding of the outcomes of the TKR procedure and provide the basis for selection of potential outcome measures of use in the evaluation of new surgical procedures and prosthesesmeasurement procedures and the design, implementation and evaluation of interventions during rehabilitation following TKR

6.1 STRENGTHS OF THE STUDY

The study identified a reliable protocol shown to be effective for evaluation of proprioception following TKR surgery using dynamic joint position sense. This outcome will enable more reliable and accurate measurement of this important factor known to be affected by joint surgery and tissue restructure, with the potential to reduce the inconsistency shown in previous research in this domain. The outcome was also important in evaluation of the influence of proprioception on other aspects of recovery following TKR examined in studies 2 and 3 in this research program and in future research.

For the first time, the study evaluated the functional performance of TKR patients at 2 different periods post TKR surgery using simulations of activities of daily living. The activities selected are known to place TKR patients at higher risk of injury and are commonly associated with falls and injury in the older population. Identification of kinematic and neuromuscular adaptations made by TKR patients when performing these tasks provides valuable measurement protocols, which may be used in the design and evaluation of new surgical techniques and prostheses and the efficacy of rehabilitation procedures.

Integration of demographic and anthropometric variables in the data analysis provided an additional reference point to identify the locomotor, neuromuscular and performance adaptations of the TKR subjects and abnormalities and neuromuscular responses during different locomotor tasks.

Clinically, considerable use is made of validated survey tools to measure lifestyle and functional outcomes following TKR. Evaluation of the relationship between these easily applied tools and the more objective outcome measures contributes to increased understanding of utility of this information and the identification of the priority areas of objective measurement that are required.

6.2 LIMITATIONS OF THE STUDY

The results of this study may be limited by the small sample size for both groups which is expressed in the relatively high variability associated with the kinematic variables and performance during the testing of proprioception for the TKR subjects. The smaller sample size may have caused some bias by limiting the opportunity to identify differences between outcomes for TKR patients with respect to whether or not the operated limb involved the dominant or non-dominant limb.

The study was also limited by the cross-sectional design which precluded pre- and post-operative comparison of the more objective variables used in the study. An exception to this was the evaluation of functional performance using self-reported or physician administered questionnaires.

Although every attempt was made to recruit control subjects of similar age and anthropometric profiles (including body weight and height), difficulties in subject recruitment, presented difficulties in controlling for body mass index (BMI) which was significantly different between TKR and control subjects. The impact of this potential confounder was reduced by normalising temporo-spatial parameters during walking by body height, in accordance with previous studies (Blanke & Hageman, 1989; Saari et al., 2005).

Finally, the accuracy of kinematic characteristics may be influenced by the skin motion artefact of the markers, particularly as the TKR group comprised subjects who were more obese than their control counterparts.

6.3 RECOMMENDATIONS FOR FUTURE RESEARCH

The results provide guidance for future research with opportunities to confirm and extend the findings of this study in addressing the following questions:

1. **What are the longer term locomotor and functional adaptations identified in this research?**

This question identifies the need for more prospective studies designed to address the potential neuromuscular adaptations and functional changes which occur progressively during the recovery period following TKR surgery. Such investigations should also consider the age diversity in the TKR population with recognition the increasing number of younger patients undergoing TKR.

Prospective studies would improve the opportunity for examination of the relationship between functional recovery and interventions designed to progress the recovery process.

2. **How do the functional outcomes reflect the surgical techniques used for TKR?**

Surgical techniques for TKR are being progressively modified to improve patient outcomes by using new procedures and prostheses for better individual customisation designed to improve loading and movement patterns and prosthesis longevity. The protocols used in this study provide the opportunity to explore further the functional outcomes of new prostheses and surgical techniques.

3. **What is the potential impact of the anthropometric profile of the TKR subjects on their locomotor performance?**

Development of knee OA and other joint conditions is increased in overweight individuals and management of overweight is an important factor in rehabilitation following surgery and restoration of functional activities. Subjects who developed knee OA and have finally undertaken the TKR procedure generally have a relatively higher BMI. Although a similar average body weight and height have been demonstrated in the present study, the impact of the relatively higher BMI on the locomotor performance and the kinetic characteristics of this population need to be further investigated in order to identify potential compensatory mechanisms. . Furthermore, the longer-term effects of these compensatory mechanisms on the longevity of the prosthesis need to be determined.

4. **What is the relationship between dynamic joint position sense at speeds specific to the velocity of joint movement and objective functional measures outcomes examined across a range of activities of daily living?**

Different proprioception performance has been demonstrated by this thesis when tested at a relatively small range of movement velocities between 15~60°/s, which may indicate the velocity specific characterises of proprioception. Furthermore, different joint or segment of movement velocities were adopted when undertaking variable activities of daily living. The relationship between activities-specific proprioception performance and objective functional outcome measures might provide insight into the neuromuscular mechanisms involved during the process of rehabilitation following the surgery.

Bibliography

Aagaard, P., Simonsen, E. B., Beyer, N., Larsson, B., Magnusson, P., & Kjaer, M. (1997). Isokinetic muscle strength and capacity for muscular knee joint stabilization in elite sailors. *Int J Sports Med, 18*(7), 521-525.

Aagaard, P., Simonsen, E. B., Magnusson, S. P., Larsson, B., & Dyhre-Poulsen, P. (1998). A new concept for isokinetic hamstring: quadriceps muscle strength ratio. *Am J Sports Med, 26*(2), 231-237.

AAOS (2008). United States Bone and Joint Decade: The Burden of Musculoskeletal Diseases in the United States. American Academy of Orthopaedic Surgeons Rosemont, IL.

Ackerman, I. N., & Bennell, K. L. (2004). Does pre-operative physiotherapy improve outcomes from lower limb joint replacement surgery? A systematic review. [Review]. *Aust J Physiother, 50*(1), 25-30.

Ageberg, E., Flenhagen, J., & Ljung, J. (2007). Test-retest reliability of knee kinesthesia in healthy adults. BMC Musculoskelet Disord, 8, 57. doi:10.1186/1471-2474-8-57

Alnahdi, A. H., Zeni, J. A., & Snyder-Mackler, L. (2011). Gait after unilateral total knee arthroplasty: frontal plane analysis. *J Orthop Res, 29*(5), 647-652. doi: 10.1002/jor.21323

Anchuela, J., Gomez-Pellico, L., Ferrer-Blanco, M., Slocker, M., & Rodriguez, R. (2001). Muscular function and bone mass after knee arthroplasty. Int Orthop, 25(4), 253-256. doi: 10.1007/s002640100234

Anderson, J. G., Wixson, R. L., Tsai, D., Stulberg, S. D., & Chang, R. W. (1996). Functional outcome and patient satisfaction in total knee patients over the age of 75. *J Arthroplasty, 11*(7), 831-840. doi.:10.1016/S0883-5403(96)80183-5

Andrews, A. W., Thomas, M. W., & Bohannon, R. W. (1996). Normative values for isometric muscle force measurements obtained with hand-held dynamometers. *Phys Ther, 76*(3), 248-259.

Andriacchi, T. P. (1994). Dynamics of knee malalignment. *Orthopedic Clinics of North America, 25*(3), 395-403. PMID:8028883

Andriacchi, T. P., & Hurwitz, D. E. (1997). Gait biomechanics and the evolution of total joint replacement. *Gait and Posture, 5*(2), 256-264. doi: 10.1016/S0966-6362(97)00013-1

Andriacchi, T. P., Galante, J. O., & Fermier, R. W. (1982). The influence of total knee-replacement design on walking and stair-climbing. *Journal of Bone and Joint Surgery. American Volume, 64*(9), 1328-1335. PMID:7142241

Anouchi, Y. S., McShane, M., Kelly, F., Jr., Elting, J., & Stiehl, J. (1996). Range of motion in total knee replacement. *Clin Orthop Relat Res, 331*, 87-92.

AOA (2009). Australia Orthopaedic Association National Joint Replacement Registry. Annual Report. Adelaide: AOA.

AOA (2012). Australia Orthopaedic Association National Joint Replacement Registry. Annual Report. Adelaide: AOA.

AOA (2013). Australia Orthopaedic Association National Joint Replacement Registry. Annual Report. Adelaide: AOA.

Apostolopoulos, A., Lallos, S., Mastrokalos, D., Michos, I., Darras, N., Tzomaki, M., & Efstathopoulos, N. (2011). Kinematic and kinetic analysis of the knee joint before and after a PCL retaining total knee replacement during gait and single step ascent. *J Long Term Eff Med Implants, 21*(4), 339-348. doi: 10.1615/JLongTermEffMedImplants.v21.i4.70

Attfield, S. F., Wilton, T. J., Pratt, D. J., & Sambatakakis, A. (1996). Soft-tissue balance and recovery of proprioception after total knee replacement. *J Bone Joint Surg Br, 78*(4), 540-545.

Ayers, D. C., Franklin, P. D., Ploutz-Snyder, R., & Boisvert, C. B. (2005). Total knee replacement outcome and coexisting physical and emotional illness. *Clin Orthop Relat Res, 440*, 157-161.

Bach, C. M., Nogler, M., Steingruber, I. E., Ogon, M., Wimmer, C., Gobel, G., & Krismer, M. (2002). Scoring systems in total knee arthroplasty. [Comparative Study]. *Clinical Orthopaedics and Related Research*(399), 184-196.

Baker, V., Bennell, K., Stillman, B., Cowan, S., & Crossley, K. (2002). Abnormal knee joint position sense in individuals with patellofemoral pain syndrome. *Journal of Orthopaedic Research, 20*(2), 208-214. doi: 10.1016/S0736-0266(01)00106-1

Banks, S., Bellemans, J., Nozaki, H., Whiteside, L. A., Harman, M., & Hodge, W. A. (2003). Knee motions during maximum flexion in fixed and mobile-bearing arthroplasties. *Clin Orthop Relat Res*(410), 131-138. doi: 10.1097/01.blo.0000063121.39522.19

Barr, S., Bellamy, N., Buchanan, W. W., Chalmers, A., Ford, P. M., Kean, W. F., . . . Campbell, J. (1994). A comparative study of signal versus aggregate methods of outcome measurement based on the WOMAC Osteoarthritis Index. Western Ontario and McMaster Universities Osteoarthritis Index. *J Rheumatol, 21*(11), 2106-2112. PMID:7869318

Barrack, R. L., Schrader, T., Bertot, A. J., Wolfe, M. W., & Myers, L. (2001). Component rotation and anterior knee pain after total knee arthroplasty. *Clin Orthop Relat Res, 392*, 46-55.

Barrack, R. L., Skinner, H. B., & Buckley, S. L. (1989). Proprioception in the anterior cruciate deficient knee. *American Journal of Sports Medicine, 17*(1), 1-6.

Barrett, D. S., Cobb, A. G., & Bentley, G. (1991). Joint proprioception in normal, osteoarthritic and replaced knees. *J Bone Joint Surg Br, 73*(1), 53-56.

Bathis, H., Perlick, L., Tingart, M., Luring, C., Perlick, C., & Grifka, J. (2004a). Radiological results of image-based and non-image-based computer-assisted total knee arthroplasty. *Int Orthop*, 28(2), 87-90. doi: 10.1007/s00264-003-0533-y

Bathis, H., Perlick, L., Tingart, M., Luring, C., Zurakowski, D., & Grifka, J. (2004b). Alignment in total knee arthroplasty. A comparison of computer-assisted surgery with the conventional technique. *J Bone Joint Surg Br*, 86(5), 682-687. doi:10.1302/0301-620X.86B5.14927

Becker, M. W., Insall, J. N., & Faris, P. M. (1991). Bilateral total knee arthroplasty. One cruciate retaining and one cruciate substituting. *Clin Orthop Relat Res, 271*, 122-124.

Bejek, Z., Paroczai, R., Szendroi, M., & Kiss, R. M. (2011). Gait analysis following TKA: comparison of conventional technique, computer-assisted navigation and minimally invasive technique combined with computer-assisted navigation. *Knee Surg Sports Traumatol Arthrosc, 19*(2), 285-291. doi: 10.1007/s00167-010-1219-9

Bellamy, N., Buchanan, W. W., Goldsmith, C. H., Campbell, J., & Stitt, L. W. (1988). Validation study of WOMAC: a health status instrument for measuring clinically important patient relevant outcomes to antirheumatic drug therapy in patients with osteoarthritis of the hip or knee. *J Rheumatol, 15*(12), 1833-1840. PMID:3068365

Bellamy, N., Kirwan, J., Boers, M., Brooks, P., Strand, V., Tugwell, P., Lequesne, M. (1997). Recommendations for a core set of outcome measures for future phase III clinical trials in knee, hip, and hand osteoarthritis. Consensus development at OMERACT III. *J Rheumatol, 24*(4), 799-802.

Bellemans, J., Vandenneucker, H., & Vanlauwe, J. (2005). Total knee replacement. [Review]. *Current Orthopaedics, 19(6)*, 446-452. doi: 10.1016/j.cuor.2005.09.007

Benedetti, M. G., Bonato, P., Catani, F., D'Alessio, T., Knaflitz, M., Marcacci, M., & Simoncini, L. (1999). Myoelectric activation pattern during gait in total knee replacement: relationship with kinematics, kinetics, and clinical outcome. *IEEE Trans Rehabil Eng, 7*(2), 140-149. doi: 10.1109/86.769404

Benedetti, M. G., Catani, F., Bilotta, T. W., Marcacci, M., Mariani, E., & Giannini, S. (2003). Muscle activation pattern and gait biomechanics after total knee replacement. *Clin Biomech (Bristol, Avon), 18*(9), 871-876. doi: 10.1016/S0268-0033(03)00146-3

Benjaminse, A., Sell, T. C., Abt, J. P., House, A. J., & Lephart, S. M. (2009). Reliability and precision of hip proprioception methods in healthy individuals. *Clinical Journal of Sport Medicine, 19*(6), 457-463. doi: 10.1097/JSM.0b013e3181bcb155

Bennell, K. L., Hinman, R. S., Metcalf, B. R., Crossley, K. M., Buchbinder, R., Smith, M., & McColl, G. (2003). Relationship of knee joint proprioception to pain and disability in individuals with knee osteoarthritis. *Journal of Orthopaedic Research, 21*(5), 792-797. doi: 10.1016/S0736-0266(03)00054-8

Bergami, E., Gildone, A., Zanoli, G., Massari, L., & Traina, G. C. (2005). Static and dynamic baropodometry to evaluate patients treated by total knee replacement with a mobile meniscus. *Chir Organi Mov, 90*(4), 387-396. PMID:16878774

Berman, A. T., Bosacco, S. J., & Israelite, C. (1991). Evaluation of total knee arthroplasty using isokinetic testing. *Clin Orthop Relat Res, 271*, 106-113.

Berman, A. T., Zarro, V. J., Bosacco, S. J., & Israelite, C. (1987). Quantitative gait analysis after unilateral or bilateral total knee replacement. *Journal of Bone and Joint Surgery. American Volume, 69*(9), 1340-1345.

Bernstein, N. (1967). *The Coordination and Regulation of Movement*. London, UK: Pergamon Press.

Berth, A., Urbach, D., & Awiszus, F. (2002). Improvement of voluntary quadriceps muscle activation after total knee arthroplasty. *Arch Phys Med Rehabil*, *83*(10), 1432-1436. doi: 1053/apmr.2002.34829

Berth, A., Urbach, D., Neumann, W., & Awiszus, F. (2007). Strength and voluntary activation of quadriceps femoris muscle in total knee arthroplasty with midvastus and subvastus approaches. *J Arthroplasty, 22*(1), 83-88. doi: 10.1016/j.arth.2006.02.161

Berti, L., Benedetti, M. G., Ensini, A., Catani, F., & Giannini, S. (2006). Clinical and biomechanical assessment of patella resurfacing in total knee arthroplasty. *Clin Biomech (Bristol, Avon), 21*(6), 610-616. doi: 10.1016/j.clinbiomech.2006.01.002

Biasca, N., Wirth, S., & Bungartz, M. (2009). Mechanical accuracy of navigated minimally invasive total knee arthroplasty (MIS TKA). *Knee, 16*(1), 22-29. doi: 10.1016/j.knee.2008.09.010

Birmingham, T. B., Kramer, J. F., Kirkley, A., Inglis, J. T., Spaulding, S. J., & Vandervoort, A. A. (2001). Knee bracing for medial compartment osteoarthritis: effects on proprioception and postural control. *Rheumatology, 40*(3), 285-289. doi: 10.1093/rheumatology/40.3.285

Blanke, D. J., & Hageman, P. A. (1989). Comparison of gait of young men and elderly men. *Phys Ther, 69*(2), 144-148.

Boese, C. K., Gallo, T. J., & Plantikow, C. J. (2011). Range of motion and patient satisfaction with traditional and high-flexion rotating-platform knees. *Iowa Orthop J, 31*, 73-77.

Bolanos, A. A., Colizza, W. A., McCann, P. D., Gotlin, R. S., Wootten, M. E., Kahn, B. A., & Insall, J. N. (1998). A comparison of isokinetic strength testing and gait analysis in patients with posterior cruciate-retaining and substituting knee arthroplasties. *J Arthroplasty, 13*(8), 906-915. doi: 10.1016/S0883-5403(98)90198-X

Bolton, J. W., Hornung, C. A., & Olsen, G. N. (1994). Determinants of achievement in stair climbing as an exercise test. *Mil Med, 159*(10), 644-646. PMID:7870321

Bombardier, C., Melfi, C. A., Paul, J., Green, R., Hawker, G., Wright, J., & Coyte, P. (1995). Comparison of a generic and a disease-specific measure of pain and physical function after knee replacement surgery. *Med Care, 33*(4 Suppl), AS131-144.

Bonfim, T. R., Jansen Paccola, C. A., & Barela, J. A. (2003). Proprioceptive and behavior impairments in individuals with anterior cruciate ligament reconstructed knees. *Archives of Physical Medicine and Rehabilitation, 84*(8), 1217-1223. doi: 10.1016/S0003-9993(03)00147-3

Bonutti, P. M., Dethmers, D. A., McGrath, M. S., Ulrich, S. D., & Mont, M. A. (2008). Navigation did not improve the precision of minimally invasive knee arthroplasty. *Clin Orthop Relat Res, 466*(11), 2730-2735. doi: 10.1007/s11999-008-0359-4

Boonstra, M. C., De Waal Malefijt, M. C., & Verdonschot, N. (2008). How to quantify knee function after total knee arthroplasty? *Knee, 15*(5), 390-395. doi: 10.1016/j.knee.2008.05.006

Boonstra, M. C., Jenniskens, A. T., Barink, M., van Uden, C. J., Kooloos, J. G., Verdonschot, N., & de Waal Malefijt, M. C. (2007). Functional evaluation of the TKA patient using the coordination and variability of rising. *J Electromyogr Kinesiol, 17*(1), 49-56. doi: 10.1016/j.jelekin.2005.11.009

Borden, L. S., Perry, J. E., Davis, B. L., Owings, T. M., & Grabiner, M. D. (1999). A biomechanical evaluation of one-stage vs two-stage bilateral knee arthroplasty patients. *Gait Posture, 9*(1), 24-30. doi: 10.1016/S0966-6362(98)00039-3

Borsa, P. A., Lephart, S. M., Irrgang, J. J., Safran, M. R., & Fu, F. H. (1997). The effects of joint position and direction of joint motion on proprioceptive sensibility in anterior cruciate ligament-deficient athletes. *Am J Sports Med, 25*(3), 336-340. doi: 10.1177/036354659702500311

Bouisset, S., & Zattara, M. (1981). A sequence of postural movements precedes voluntary movement. *Neuroscience Letters, 22*(3), 263-270. doi: 10.1016/0304-3940(81)90117-8

Bruun-Olsen, V., Heiberg, K. E., & Mengshoel, A. M. (2009). Continuous passive motion as an adjunct to active exercises in early rehabilitation following total knee arthroplasty - a randomized controlled trial. *Disability and Rehabilitation, 31*(4), 277-283. doi: 10.1080/09638280801931204

Bullock-Saxton, J. E., Wong, W. J., & Hogan, N. (2001). The influence of age on weight-bearing joint reposition sense of the knee. *Experimental Brain Research*, 136(3), 400-406. doi: 10.1007/s002210000595

Burden, A. M., Trew, M., & Baltzopoulos, V. (2003). "Normalisation of gait EMGs: a re-examination." *Journal of Electromyography and Kinesiology,* 13(6), 519-532.

Burgess-Limerick, R., Abernethy, B., & Neal, R. J. (1993). Relative phase quantifies interjoint coordination. *J Biomech, 26*(1), 91-94. doi: 0021-9290(93)90617-N

Busse, M. E., Wiles, C. M., & van Deursen, R. W. (2006). Co-activation: its association with weakness and specific neurological pathology. *J Neuroeng Rehabil, 3*, 26. doi: 10.1186/1743-0003-3-26

Byrne, J. M., Gage, W. H., & Prentice, S. D. (2002). Bilateral lower limb strategies used during a step-up task in individuals who have undergone unilateral total knee arthroplasty. *Clin Biomech (Bristol, Avon), 17*(8), 580-585. doi:10.1016/S0268-0033(02)00061-X

Callaghan, M. J., Selfe, J., McHenry, A., & Oldham, J. A. (2008). Effects of patellar taping on knee joint proprioception in patients with patellofemoral pain syndrome. *Manual Therapy, 13*(3), 192-199. doi: 10.1016/j.math.2006.11.004

Cash, R. M., Gonzalez, M. H., Garst, J., Barmada, R., & Stern, S. H. (1996). Proprioception after arthroplasty: role of the posterior cruciate ligament. *Clin Orthop Relat Res, 331*, 172-178.

Catani, F., Ensini, A., Belvedere, C., Feliciangeli, A., Benedetti, M. G., Leardini, A., & Giannini, S. (2009). In vivo kinematics and kinetics of a bi-cruciate substituting total knee arthroplasty: A combined fluoroscopic and gait analysis study. *J Orthop Res, 27*(12), 1569-1575. doi: 10.1002/jor.20941

Cattaneo, D., Regola, A., & Meotti, M. (2006). Validity of six balance disorders scales in persons with multiple sclerosis. *Disabil Rehabil, 28*(12), 789-795. doi:10.1080/09638280500404289

Chang, C. W., & Yang, C. Y. (2006). Kinematic navigation in total knee replacement--experience from the first 50 cases. *J Formos Med Assoc, 105*(6), 468-474. doi: 10.1016/S0929-6646(09)60186-8

Chauhan, S. K., Clark, G. W., Lloyd, S., Scott, R. G., Breidahl, W., & Sikorski, J. M. (2004). Computer-assisted total knee replacement. A controlled cadaver study using a multi-parameter quantitative CT assessment of alignment (the Perth CT Protocol). *J Bone Joint Surg Br, 86*(6), 818-823. doi: 10.1302/0301-620X.86B6.15456

Chauhan, S. K., Scott, R. G., Breidahl, W., & Beaver, R. J. (2004). Computer-assisted knee arthroplasty versus a conventional jig-based technique. A randomised, prospective trial. *J Bone Joint Surg Br, 86*(3), 372-377. doi: 10.1302/0301-620X.86B3.14643

Chin, P. L., Yang, K. Y., Yeo, S. J., & Lo, N. N. (2005). Randomized control trial comparing radiographic total knee arthroplasty implant placement using computer navigation versus conventional technique. *J Arthroplasty, 20*(5), 618-626. doi: 10.1016/j.arth.2005.04.004

Chiu, K. Y., Ng, T. P., Tang, W. M., & Lam, P. (2001). Bilateral total knee arthroplasty: One mobile-bearing and one fixed-bearing. *J Orthop Surg (Hong Kong), 9*(1), 45-50.

Chiu, S. L., & Chou, L. S. (2012). Effect of walking speed on inter-joint coordination differs between young and elderly adults. *J Biomech, 45*(2), 275-280. doi: 10.1016/j.jbiomech.2011.10.028

Chiu, S. L., & Chou, L. S. (2013). Variability in inter-joint coordination during walking of elderly adults and its association with clinical balance measures. *Clin Biomech (Bristol, Avon), 28*(4), 454-458. doi: 10.1016/j.clinbiomech.2013.03.001

Clifford, P. E., & Mallon, W. J. (2005). Sports after total joint replacement. *Clin Sports Med, 24*(1), 175-186. doi: 10.1016/j.csm.2004.08.009

Confalonieri, N., Manzotti, A., Pullen, C., & Ragone, V. (2005). Computer-assisted technique versus intramedullary and extramedullary alignment systems in total knee replacement: a radiological comparison. *Acta Orthop Belg, 71*(6), 703-709.

Cordo, P., Bevan, L., Gurfinkel, V., Carlton, L., Carlton, M., & Kerr, G. (1995). Proprioceptive coordination of discrete movement sequences: mechanism and generality. *Canadian Journal of Physiology and Pharmacology, 73*(2), 305-315. doi: 10.1139/y95-041

Cordo, P., Carlton, L., Bevan, L., Carlton, M., & Kerr, G. K. (1994). Proprioceptive coordination of movement sequences: role of velocity and position information. *J Neurophysiol, 71*(5), 1848-1861.

Cordo, P., Gurfinkel, V., & Levik, Y. (2000). Position sense during imperceptibly slow movements. *Exp Brain Res, 132*(1), 1-9. doi: 10.1007/s002219900319

Courtine, G., & Schieppati, M. (2003a). Human walking along a curved path. I. Body trajectory, segment orientation and the effect of vision. *European Journal of Neuroscience, 18*(1), 177-190. doi: 10.1046/j.1460-9568.2003.02736.x

Courtine, G., & Schieppati, M. (2003b). Human walking along a curved path. II. Gait features and EMG patterns. *European Journal of Neuroscience, 18*(1), 191-205. doi: 10.1046/j.1460-9568.2003.02737.x

Crenna, P., & Frigo, C. (1991). A motor programme for the initiation of forward-oriented movements in humans. *J Physiol, 437*, 635-653.

Curb, J. D., Ceria-Ulep, C. D., Rodriguez, B. L., Grove, J., Guralnik, J., Willcox, B. J., . . . Chen, R. (2006). Performance-based measures of physical function for high-function populations. *J Am Geriatr Soc, 54*(5), 737-742. doi: 10.1111/j.1532-5415.2006.00700.x

Cushnaghan J., Bennet, J., Reading, I., Croft, P., Byng, P., Cox, K., . . . Cooper, C. (2009). Long- term outcome following total knee arthroplasty: a controlled longitudinal study. *Ann Rheum Dis*, 68: 642-647. doi:10.1136/ard.2008.093229

Davis, R. B., Õunpuu, S., Tyburski, D., & Gage, J. R. (1991). A gait analysis data collection and reduction technique. *Human Movement Studies, 10*(5), 575-587. doi: 10.1016/0167-9457(91)90046-Z

Dawson, J., Fitzpatrick, R., Murray, D., & Carr, A. (1998). Questionnaire on the perceptions of patients about total knee replacement. *J Bone Joint Surg Br, 80*(1), 63-69.

De Luca, C. J., & Mambrito, B. (1987). Voluntary control of motor units in human antagonist muscles: coactivation and reciprocal activation. *J Neurophysiol, 58*(3), 525-542.

Decking, R., Markmann, Y., Fuchs, J., Puhl, W., & Scharf, H. P. (2005). Leg axis after computer-navigated total knee arthroplasty: a prospective randomized trial comparing computer-navigated and manual implantation. *J Arthroplasty, 20*(3), 282-288. doi: 10.1016/j.arth.2004.09.047

Decking, R., Markmann, Y., Mattes, T., Puhl, W., & Scharf, H. P. (2007). On the outcome of computer-assisted total knee replacement. *Acta Chir Orthop Traumatol Cech, 74*(3), 171-174.

Delp, S. L., Stulberg, S. D., Davies, B., Picard, F., & Leitner, F. (1998). Computer assisted knee replacement. *Clin Orthop Relat Res*(354), 49-56.

Delval, A., Krystkowiak, P., Blatt, J. L., Labyt, E., Bourriez, J. L., Dujardin, K., . . . Defebvre, L. (2007). A biomechanical study of gait initiation in Huntington's disease. *Gait and Posture, 25*(2), 279-288. doi: 10.1016/j.gaitpost.2006.04.001

Dennis, D. A., Komistek, R. D., & Mahfouz, M. R. (2003). In vivo fluoroscopic analysis of fixed-bearing total knee replacements. *Clin Orthop Relat Res, 410*, 114-130. doi: 10.1097/01.blo.0000062385.79828.72

Dennis, D. A., Komistek, R. D., Stiehl, J. B., Walker, S. A., & Dennis, K. N. (1998). Range of motion after total knee arthroplasty: the effect of implant design and weight-bearing conditions. *J Arthroplasty, 13*(7), 748-752. doi: 10.1016/S0883-5403(98)90025-0

Deshpande, N., Connelly, D. M., Culham, E. G., & Costigan, P. A. (2003). Reliability and validity of ankle proprioceptive measures. *Archives of Physical Medicine and Rehabilitation, 84*(6), 883-889. doi: 10.1016/S0003-9993(03)00016-9

Detrembleur, C., Willems, P., & Plaghki, L. (1997). Does walking speed influence the time pattern of muscle activation in normal children? *Dev Med Child Neurol, 39*(12), 803-807. doi: 10.1111/j.1469-8749.1997.tb07546.x

Diduch, D. R., Insall, J. N., Scott, W. N., Scuderi, G. R., & Font-Rodriguez, D. (1997). Total knee replacement in young, active patients. Long-term follow-up and functional outcome. *J Bone Joint Surg Am, 79*(4), 575-582.

Dite, W., & Temple, V. A. (2002). Development of a clinical measure of turning for older adults. *Am J Phys Med Rehabil, 81*(11), 857-866.

Dorr, L. D., Ochsner, J. L., Gronley, J., & Perry, J. (1988). Functional comparison of posterior cruciate-retained versus cruciate-sacrificed total knee arthroplasty. *Clin Orthop Relat Res, 236*, 36-43.

Dowsey, M. M., & Choong, P.F.M. (2013). The utility of outcome measures in total knee replacement surgery. *Int J Rheum,* Vol. 2013, Article ID 506518, doi: 10.1155/2013/506518

Drouin, J. M., Valovich-mcLeod, T. C., Shultz, S. J., Gansneder, B. M., & Perrin, D. H. (2004). Reliability and validity of the Biodex system 3 pro isokinetic dynamometer velocity, torque and position measurements. *European journal of applied physiology*, 91(1), 22-29. doi: 10.1007/s00421-003-0933-0

Dubo, H. I., Peat, M., Winter, D. A., Quanbury, A. O., Hobson, D. A., Steinke, T., & Reimer, G. (1976). Electromyographic temporal analysis of gait: normal human locomotion. *Arch Phys Med Rehabil*, 57(9), 415-420. PMID:962568

Dvir, Z. (1995). Isokinetics, muscle testing, interpretation and clinical application. Edinburgh: Churchill Livingstone. p61.

Ellis, M. I., Seedhom, B. B., & Wright, V. (1984). Forces in the knee joint whilst rising from a seated position. *J Biomed Eng, 6*(2), 113-120. doi: 10.1016/0141-5425(84)90053-0

Ensini, A., Catani, F., Leardini, A., Romagnoli, M., & Giannini, S. (2007). Alignments and clinical results in conventional and navigated total knee arthroplasty. *Clin Orthop Relat Res, 457*, 156-162. doi: 10.1097/BLO.0b013e3180316c92

Escobar, A., Quintana, J. M., Bilbao, A., Arostegui, I., Lafuente, I., & Vidaurreta, I. (2006). Responsiveness and clinically important differences for the WOMAC and SF-36 after total knee replacement. *Osteoarthritis Cartilage*, 273-280. doi: 10.1016/j.joca.2006.09.001

Ethgen, O., Bruyere, O., Richy, F., Dardennes, C., & Reginster, J. Y. (2004). Health-related quality of life in total hip and total knee arthroplasty. A qualitative and systematic review of the literature. *J Bone Joint Surg Am, 86-A*(5), 963-974.

Fantozzi, S., Benedetti, M. G., Leardini, A., Banks, S. A., Cappello, A., Assirelli, D., & Catani, F. (2003). Fluoroscopic and gait analysis of the functional performance in stair ascent of two total knee replacement designs. *Gait Posture, 17*(3), 225-234. doi: 10.1016/S0966-6362(02)00096-6

Farquhar, S. J., Reisman, D. S., & Snyder-Mackler, L. (2008). Persistence of altered movement patterns during a sit-to-stand task 1 year following unilateral total knee arthroplasty. *Phys Ther, 88*(5), 567-579. doi: 10.2522/ptj.20070045

Farquhar, S., & Snyder-Mackler, L. (2010). The Chitranjan Ranawat Award: The nonoperated knee predicts function 3 years after unilateral total knee arthroplasty. *Clin Orthop Relat Res, 468*(1), 37-44. doi: 10.1007/s11999-009-0892-9

Fehring, T. K. (2006). Ligamentous balancing in rotating-platform knees. *Orthopedics, 29*(9 Suppl), S56-59. PMID:17002151

Felson, D. T., Lawrence, R. C., Dieppe, P. A., Hirsch, R., Helmick, C. G., Jordan, J. M., . . . Zhang, Y. (2000). Osteoarthritis: new insights. Part 1: the disease and its risk factors. *Annals of internal medicine, 133*(8), 635-646. doi:10.7326/0003-4819-133-8-200010170-00016

Felson, D. T., Zhang, Y., Hannan, M. T., Naimark, A., Weissman, B. N., Aliabadi, P., & Levy, D. (1995). The incidence and natural history of knee osteoarthritis in the elderly, the framingham osteoarthritis study. *Arthritis & Rheumatism, 38*(10), 1500-1505. doi: 10.1002/art.1780381017

Finch, E., Walsh, M., Thomas, S. G., & Woodhouse, L. J. (1998). Functional ability perceived by individuals following total knee arthroplasty compared to age-matched individuals without knee disability. *Journal of Orthopaedic and Sports Physical Therapy, 27*(4), 255-263. doi:10.2519/jospt.1998.27.4.255

Fisher, N. M., White, S. C., Yack, H. J., Smolinski, R. J., & Pendergast, D. R. (1997). Muscle function and gait in patients with knee osteoarthritis before and after muscle rehabilitation. *Disability & Rehabilitation*, *19*(2), 47-55.

Fischer-Rasmussen, T., & Jensen, P. E. (2000). Proprioceptive sensitivity and performance in anterior cruciate ligament-deficient knee joints. *Scandinavian Journal of Medicine and Science in Sports, 10*(2), 85-89. doi: 10.1034/j.1600-0838.2000.010002085.x

Fitzpatrick, C. K., Clary, C. W., & Rullkoetter, P. J. (2012). The role of patient, surgical, and implant design variation in total knee replacement performance. [Research Support, Non-U.S. Govt]. *J Biomech, 45*(12), 2092-2102. doi: 10.1016/j.jbiomech.2012.05.035

Fonseca, S. T., Ocarino, J. M., Silva, P. L., Guimaraes, R. B., Oliveira, M. C., & Lage, C. A. (2005). Proprioception in individuals with ACL-deficient knee and good muscular and functional performance. *Research in Sports Medicine, 13*(1), 47-61. doi: 10.1080/15438620590922095

Foran, J. R., Mont, M. A., Etienne, G., Jones, L. C., & Hungerford, D. S. (2004). The outcome of total knee arthroplasty in obese patients. *J Bone Joint Surg Am, 86-A*(8), 1609-1615.

Forster, M. C., Kothari, P., & Howard, P. W. (2002). Minimum 5-year follow-up and radiologic analysis of the all-polyethylene tibial component of the Kinemax Plus system. *J Arthroplasty, 17*(2), 196-200. doi: 10.1054/arth.2002.30283

Fozard, J. L., Vercryssen, M., Reynolds, S. L., Hancock, P. A., & Quilter, R. E. (1994). Age differences and changes in reaction time: the Baltimore Longitudinal Study of Aging. *Journal of Gerontology, 49*(4), P179-189. doi: 10.1093/geronj/49.4.P179

Franchi, A., Zaccherotti, G., & Aglietti, P. (1995). Neural system of the human posterior cruciate ligament in osteoarthritis. *J Arthroplasty, 10*(5), 679-682. doi: S0883-5403(05)80215-3

Freedman, V. A., & Martin, L. G. (1998). Understanding trends in functional limitations among older Americans. *American Journal of Public Health, 88*(10), 1457-1462. doi: 10.2105/AJPH.88.10.1457

Fremerey, R. W., Lobenhoffer, P., Zeichen, J., Skutek, M., Bosch, U., & Tscherne, H. (2000). Proprioception after rehabilitation and reconstruction in knees with deficiency of the anterior cruciate ligament: a prospective, longitudinal study. *Journal of Bone and Joint Surgery. British Volume, 82*(6), 801-806.

Fuchs, S., Floren, M., Skwara, A., & Tibesku, C. O. (2002). Quantitative gait analysis in unconstrained total knee arthroplasty patients. *Int J Rehabil Res, 25*(1), 65-70.

Fuchs, S., Frisse, D., Tibesku, C. O., Laass, H., & Rosenbaum, D. (2002). Proprioceptive function, clinical results, and quality of life after unicondylar sledge prostheses. *American Journal of Physical Medicine and Rehabilitation, 81*(7), 478-482.

Fuchs, S., Rolauffs, B., Plaumann, T., Tibesku, C. O., & Rosenbaum, D. (2005). Clinical and functional results after the rehabilitation period in minimally-invasive unicondylar knee arthroplasty patients. *Knee Surg Sports Traumatol Arthrosc,* 13(3), 179-186. doi: 10.1007/s00167-004-0517-5

Fuchs, S., Skwara, A., & Rosenbaum, D. (2005). Preliminary results after total knee arthroplasty without femoral trochlea: evaluation of clinical results, quality of life and gait function. *Knee Surg Sports Traumatol Arthrosc,* 13(8), 664-669. doi: 10.1007/s00167-005-0617-x

Fuchs, S., Thorwesten, L., & Niewerth, S. (1999). Proprioceptive function in knees with and without total knee arthroplasty. *American Journal of Physical Medicine and Rehabilitation, 78*(1), 39-45.

Fuchs, S., Tibesku, C. O., Floren, M., & Thorwesten, L. (2000). Interdependence of clinical and isokinetic results after bicondylar knee prostheses with special emphasis on quality of life results. *Int Orthop, 24*(5), 268-271.

Fuchs, S., Tibesku, C. O., Genkinger, M., Laass, H., & Rosenbaum, D. (2003). Proprioception with bicondylar sledge prostheses retaining cruciate ligaments. *Clin Orthop Relat Res, 406*, 148-154.

Fuchs, S., Tibesku, C. O., Genkinger, M., Volmer, M., Laass, H., & Rosenbaum, D. (2004). Clinical and functional comparison of bicondylar sledge prostheses retaining all ligaments and constrained total knee replacement. *Clin Biomech (Bristol, Avon), 19*(3), 263-269. doi: 10.1016/j.clinbiomech.2003.11.004

Gandhi, R., Tsvetkov, D., Davey, J. R., Syed, K. A., & Mahomed, N. N. (2009). Relationship between self-reported and performance-based tests in a hip and knee joint replacement population. *Clinical Rheumatology, 28*(3), 253-257. doi: 10.1007/s10067-008-1021-y

George, L. K., Ruiz, D., Jr., & Sloan, F. A. (2008). The effects of total knee arthroplasty on physical functioning in the older population. *Arthritis and Rheumatism, 58*(10), 3166-3171. doi: 10.1002/art.23888

Ghazavi, M. T., Stockley, I., Yee, G., Davis, A., & Gross, A. E. (1997). Reconstruction of massive bone defects with allograft in revision total knee arthroplasty. *J Bone Joint Surg Am, 79*(1), 17-25.

Ghez, C., & Sainburg, R. (1995). Proprioceptive control of interjoint coordination. *Canadian Journal of Physiology and Pharmacology, 73*(2), 273-284. doi: 10.1139/y95-038

Glaister, B. C., Bernatz, G. C., Klute, G. K., & Orendurff, M. S. (2007). Video task analysis of turning during activities of daily living. *Gait and Posture, 25*(2), 289-294. doi: 10.1016/j.gaitpost.2006.04.003

Glaister, B. C., Orendurff, M. S., Schoen, J. A., Bernatz, G. C., & Klute, G. K. (2008). Ground reaction forces and impulses during a transient turning maneuver. *Journal of Biomechanics, 41*(14), 3090-3093. doi: 10.1016/j.jbiomech.2008.07.022

Glazier, P. S., & Davids, K. (2009). Constraints on the complete optimization of human motion. *Sports Med, 39*(1), 15-28. doi: 0112-1642/09/0001-0015

Gleeson, R. E., Evans, R., Ackroyd, C. E., Webb, J., & Newman, J. H. (2004). Fixed or mobile bearing unicompartmental knee replacement? A comparative cohort study. *Knee, 11*(5), 379-384. doi: 10.1016/j.knee.2004.06.006

Goble, D. J., Coxon, J. P., Wenderoth, N., Van Impe, A., & Swinnen, S. P. (2009). Proprioceptive sensibility in the elderly: degeneration, functional consequences and plastic-adaptive processes. *Neuroscience and Biobehavioral Reviews, 33*(3), 271-278. doi: 10.1016/j.neubiorev.2008.08.012

Grob, K. R., Kuster, M. S., Higgins, S. A., Lloyd, D. G., & Yata, H. (2002). Lack of correlation between different measurements of proprioception in the knee. *Journal of Bone and Joint Surgery. British Volume, 84*(4), 614-618. doi: 10.1302/0301-620X.84B4.11241

Guyatt, G. H., Feeny, D. H., & Patrick, D. L. (1993). Measuring health-related quality of life. *Ann Intern Med, 118*(8), 622-629. doi:10.7326/0003-4819-118-8-199304150-00009

Guyatt, G. H., Sullivan, M. J., Thompson, P. J., Fallen, E. L., Pugsley, S. O., Taylor, D. W., & Berman, L. B. (1985). The 6-minute walk: a new measure of exercise capacity in patients with chronic heart failure. *Can Med Assoc J, 132*(8), 919-923. PMCID: PMC1345899

Haaker, R. G., Stockheim, M., Kamp, M., Proff, G., Breitenfelder, J., & Ottersbach, A. (2005). Computer-assisted navigation increases precision of component placement in total knee arthroplasty. *Clin Orthop Relat Res, 433*, 152-159. doi: 10.1097/01.blo.0000150564.31880.c4

Hageman, P. A., & Blanke, D. J. (1986). Comparison of gait of young women and elderly women. *Phys Ther, 66*(9), 1382-1387.

Halder, A., Kutzner, I., Graichen, F., Heinlein, B., Beier, A., & Bergmann, G. (2012). Influence of Limb Alignment on Mediolateral Loading in Total Knee ReplacementIn Vivo Measurements in Five Patients. *The Journal of Bone & Joint Surgery*, *94*(11), 1023-1029. doi: 10.2106/JBJS.K.00927

Halliday, S. E., Winter, D. A., Frank, J. S., Patla, A. E., & Prince, F. (1998). The initiation of gait in young, elderly, and Parkinson's disease subjects. *Gait and Posture, 8*(1), 8-14. doi: 10.1016/S0966-6362(98)00020-4

Hase, K., & Stein, R. B. (1999). Turning strategies during human walking. *Journal of Neurophysiology, 81*(6), 2914-2922.

Hass, C. J., Gregor, R. J., Waddell, D. E., Oliver, A., Smith, D. W., Fleming, R. P., & Wolf, S. L. (2004). The influence of Tai Chi training on the center of pressure trajectory during gait initiation in older adults. *Archives of Physical Medicine and Rehabilitation, 85*(10), 1593-1598. doi: 10.1016/j.apmr.2004.01.020

Hass, C. J., Waddell, D. E., Wolf, S. L., Juncos, J. L., & Gregor, R. J. (2008). Gait initiation in older adults with postural instability. *Clin Biomech (Bristol, Avon), 23*(6), 743-753. doi: 10.1016/j.clinbiomech.2008.02.012

Hassan, B. S., Mockett, S., & Doherty, M. (2001). Static postural sway, proprioception, and maximal voluntary quadriceps contraction in patients with knee osteoarthritis and normal control subjects. *Ann Rheum Dis, 60*(6), 612-618. doi: 10.1136/ard.60.6.612

Hawker, G., Melfi, C., Paul, J., Green, R., & Bombardier, C. (1995). Comparison of a generic (SF-36) and a disease specific (WOMAC) (Western Ontario and McMaster Universities Osteoarthritis Index) instrument in the measurement of outcomes after knee replacement surgery. *J Rheumatol, 22*(6), 1193-1196. PMID:7674255

Heinlein, B., Kutzner, I., Graichen, F., Bender, A., Rohlmann, A., Halder, A. M., Bergmann, G. (2009). Complete data of total knee replacement loading for level walking and stair climbing measured in vivo with a follow-up of 6-10 months. *Clinical biomechanics (Bristol, Avon), 24*(4), 315-326. doi: 10.1016/j.clinbiomech.2009.01.011

Henriksson, M., & Hirschfeld, H. (2005). Physically active older adults display alterations in gait initiation. *Gait and Posture, 21*(3), 289-296. doi: 10.1016/j.gaitpost.2004.03.001

Hinman, R. S., Bennell, K. L., Metcalf, B. R., & Crossley, K. M. (2002). Delayed onset of quadriceps activity and altered knee joint kinematics during stair stepping in individuals with knee osteoarthritis. *Archives of Physical Medicine and Rehabilitation, 83*(8), 1080-1086. doi: 10.1053/apmr.2002.33068

Hogervorst, T., & Brand, R. A. (1998). Mechanoreceptors in joint function. *Journal of Bone and Joint Surgery. American Volume, 80*(9), 1365-1378.

Hopper, D. M., Creagh, M. J., Formby, P. A., Goh, S. C., Boyle, J. J., & Strauss, G. R. (2003). Functional measurement of knee joint position sense after anterior cruciate ligament reconstruction. *Archives of Physical Medicine and Rehabilitation, 84*(6), 868-872. doi: 10.1016/S0003-9993(03)00007-8

Hortobagyi, T., Garry, J., Holbert, D., & Devita, P. (2004). Aberrations in the control of quadriceps muscle force in patients with knee osteoarthritis. *Arthritis and Rheumatism, 51*(4), 562-569. doi: 10.1002/art.20545

Hortobagyi, T., Mizelle, C., Beam, S., & Devita, P. (2003). Old adults perform activities of daily living near their maximal capabilities. *The Journals of Gerontology, 58A*(5), 453. doi: 10.1093/gerona/58.5.M453

Huang, C. H., Cheng, C. K., Lee, Y. T., & Lee, K. S. (1996). Muscle strength after successful total knee replacement: a 6- to 13-year followup. *Clin Orthop Relat Res, 328*, 147-154.

Hubley-Kozey, C.L., Deluzio, K. J., Landry, S. C., McNutt, J. S., & Stanish, W. D. (2006). Neuromuscular alterations during walking in persons with moderate knee osteoarthritis. *J Electromyogr Kinesiol, 16*(4), 365-378. doi: 10.1016/j.jelekin.2005.07.014

Hubley-Kozey, C., Deluzio, K., & Dunbar, M. (2008). Muscle co-activation patterns during walking in those with severe knee osteoarthritis. *Clin Biomech (Bristol, Avon), 23*(1), 71-80. doi: 10.1016/j.clinbiomech.2007.08.019

Hurkmans, E. J., van der Esch, M., Ostelo, R. W., Knol, D., Dekker, J., & Steultjens, M. P. (2007). Reproducibility of the measurement of knee joint proprioception in patients with osteoarthritis of the knee. *Arthritis and Rheumatism, 57*(8), 1398-1403. DOI: 10.1002/art.23082

Hurley, M. V. (1999). The role of muscle weakness in the pathogenesis of osteoarthritis. *Rheum Dis Clin North Am, 25*(2), 283-298, vi. Doi: 10.1016/S0889-857X(05)70068-5

Hurley, M. V. (2003). Muscle dysfunction and effective rehabilitation of knee osteoarthritis: what we know and what we need to find out. *Arthritis and Rheumatism, 49*(3), 444-452. doi: 10.1002/art.11053

Hurley, M. V., Scott, D. L., Rees, J., & Newham, D. J. (1997). Sensorimotor changes and functional performance in patients with knee osteoarthritis. *Ann Rheum Dis, 56*(11), 641-648. doi:10.1136/ard.56.11.641

Hutin, E., Pradon, D., Barbier, F., Gracies, J. M., Bussel, B., & Roche, N. (2010). Lower limb coordination in hemiparetic subjects: impact of botulinum toxin injections into rectus femoris. *Neurorehabil Neural Repair, 24*(5), 442-449. doi: 10.1177/1545968309354535

Insall, J. N., Dorr, L. D., Scott, R. D., & Scott, W. N. (1989). Rationale of the Knee Society clinical rating system. *Clin Orthop Relat Res*(248), 13-14.

Insall, J. N., Ranawat, C. S., Aglietti, P., & Shine, J. (1976). A comparison of four models of total knee-replacement prostheses. [Comparative Study]. *The Journal of bone and joint surgery. American volume, 58*(6), 754-765.

Isaac, S. M., Barker, K. L., Danial, I. N., Beard, D. J., Dodd, C. A., & Murray, D. W. (2007). Does arthroplasty type influence knee joint proprioception? A longitudinal prospective study comparing total and unicompartmental arthroplasty. *Knee, 14*(3), 212-217. doi: 10.1016/j.knee.2007.01.001

Ishii, Y., Noguchi, H., Matsuda, Y., Takeda, M., Kiga, H., & Toyabe, S. (2008). Range of motion during the perioperative period in total knee arthroplasty. *Arch Orthop Trauma Surg, 128*(8), 795-799. doi: 10.1007/s00402-007-0448-y

Ishii, Y., Terajima, K., Koga, Y., Takahashi, H. E., Bechtold, J. E., & Gustilo, R. B. (1998). Gait analysis after total knee arthroplasty. Comparison of posterior cruciate retention and substitution. *J Orthop Sci, 3*(6), 310-317.

Ishii, Y., Terajima, K., Terashima, S., Bechtold, J. E., & Laskin, R. S. (1997). Comparison of joint position sense after total knee arthroplasty. *J Arthroplasty, 12*(5), 541-545. doi: 10.1016/S0883-5403(97)90177-7

Ito, S., Odahara, S., Hiraki, M., & Idate, M. (1995). Evaluation of imbalance of the vestibulo-spinal reflex by "the circular walking test". *Acta Otolaryngol Suppl, 519*, 124-126.

Ito, T., Azuma, T., & Yamashita, N. (2003). Anticipatory control in the initiation of a single step under biomechanical constraints in humans. *Neuroscience Letters, 352*(3), 207-210. doi: 10.1016/j.neulet.2003.09.002

Itokazu, M., Uemura, S., Aoki, T., & Takatsu, T. (1998). Analysis of rising from a chair after total knee arthroplasty. *Bull Hosp Jt Dis, 57*(2), 88-92. PMID:9725064

Iwamoto, J., Takeda, T., & Sato, Y. (2007). Effect of muscle strengthening exercises on the muscle strength in patients with osteoarthritis of the knee. *Knee, 14*(3), 224-230. doi: 10.1016/j.knee.2007.03.002

Jacobs, W., Anderson, P., Limbeek, J., & Wymenga, A. (2004). Mobile bearing vs fixed bearing prostheses for total knee arthroplasty for post-operative functional status in patients with osteoarthritis and rheumatoid arthritis. *Cochrane Database of Systematic Reviews*(2). doi: 10.1002/14651858.CD003130.pub2.

Jeffery, R. S., Morris, R. W., & Denham, R. A. (1991). Coronal alignment after total knee replacement. *J Bone Joint Surg Br, 73*(5), 709-714.

Jenny, J. Y., & Boeri, C. (2001). Computer-assisted implantation of total knee prostheses: a case-control comparative study with classical instrumentation. *Comput Aided Surg, 6*(4), 217-220. doi: 10.1002/igs.10006

Joglekar, S., Gioe, T. J., Yoon, P., & Schwartz, M. H. (2012). Gait analysis comparison of cruciate retaining and substituting TKA following PCL sacrifice. [Clinical Trial Comparative Study]. *Knee, 19*(4), 279-285. doi: 10.1016/j.knee.2011.05.003

Johansson, H., Sjolander, P., & Sojka, P. (1991). A sensory role for the cruciate ligaments. *Clin Orthop Relat Res, 268*, 161-178.

Jolles, B. M., Grzesiak, A., Eudier, A., Dejnabadi, H., Voracek, C., Pichonnaz, C., . . . Martin, E. (2012). A randomised controlled clinical trial and gait analysis of fixed- and mobile-bearing total knee replacements with a five-year follow-up. [Randomized Controlled Trial]. *The Journal of bone and joint surgery. British volume, 94*(5), 648-655. doi: 10.1302/0301-620X.94B5.27598

Jones, C. A., Voaklander, D. C., & Suarez-Alma, M. E. (2003). Determinants of function after total knee arthroplasty. *Physical Therapy, 83*(8), 696-706. Retrieved from http://ptjournal.apta.org/content/83/8/696

Jones, C. A., Voaklander, D. C., Johnston, D. W., & Suarez-Almazor, M. E. (2000). Health related quality of life outcomes after total hip and knee arthroplasties in a community based population. *J Rheumatol, 27*(7), 1745-1752. PMID:10914862

Judd, D. L., Eckhoff, D. G., & Stevens-Lapsley, J. E. (2012). Muscle strength loss in the lower limb after total knee arthroplasty. *Am J Phys Med Rehabil, 91*(3), 220-226; quiz 227-230. doi: 10.1097/PHM.0b013e3182411e49

Juul-Kristensen, B., Lund, H., Hansen, K., Christensen, H., Danneskiold-Samsoe, B., & Bliddal, H. (2008). Test-retest reliability of joint position and kinesthetic sense in the elbow of healthy subjects. *Physiotherapy Theory and Practice, 24*(1), 65-72. doi:10.1080/09593980701378173

Kamat, Y. D., Aurakzai, K. M., Adhikari, A. R., Matthews, D., Kalairajah, Y., & Field, R. E. (2008). Does computer navigation in total knee arthroplasty improve patient outcome at midterm follow-up? *Int Orthop*, In press. doi: 10.1007/s00264-008-0690-0

Kane, R. L., Saleh, K. J., Wilt, T. J., & Bershadsky, B. (2005). The functional outcomes of total knee arthroplasty. *Journal of Bone and Joint Surgery. American Volume, 87*(8), 1719-1724. doi: 10.2106/JBJS.D.02714

Kannus, P. (1994). Isokinetic evaluation of muscular performance: implications for muscle testing and rehabilitation. *Int J Sports Med, 15 Suppl 1*, S11-18. doi: 10.1055/s-2007-1021104

Kaufman, K. R., Hughes, C., Morrey, B. F., Morrey, M., & An, K. N. (2001). Gait characteristics of patients with knee osteoarthritis. *Journal of Biomechanics, 34*(7), 907-915. doi: 10.1016/S0021-9290(01)00036-7

Kennedy, D., Stratford, P. W., Pagura, S. M., Walsh, M., & Woodhouse, L. J. (2002). Comparison of gender and group differences in self-report and physical performance measures in total hip and knee arthroplasty candidates. *Journal of Arthroplasty, 17*(1), 70-77. doi: 10.1054/arth.2002.29324

Khabie, V., Schwartz, M. C., Rokito, A. S., Gallagher, M. A., Cuomo, F., & Zuckerman, J. D. (1998). The effect of intraarticular anesthesia and elastic bandage on elbow proprioception. *Journal of Shoulder and Elbow Surgery, 7*(5), 501-504. doi: S1058-2746(98)90202-6 [pii]

Kim, J. G., Lee, S. W., Ha, J. K., Choi, H. J., Yang, S. J., & Lee, M. Y. (2011). The effectiveness of minimally invasive total knee arthroplasty to preserve quadriceps strength: a randomized controlled trial. [Randomized Controlled Trial]. *Knee, 18*(6), 443-447. doi: 10.1016/j.knee.2010.08.008

Kim, Y. H., Kim, J. S., & Yoon, S. H. (2007). Alignment and orientation of the components in total knee replacement with and without navigation support: a prospective, randomised study. *J Bone Joint Surg Br, 89*(4), 471-476. doi: 10.1302/0301-620X.89B4.18878

Knoop, J., Steultjens, M. P., van der Leeden, M., van der Esch, M., Thorstensson, C. A., Roorda, L. D., . . . Dekker, J. (2011). Proprioception in knee osteoarthritis: a narrative review. *Osteoarthritis Cartilage, 19*(4), 381-388. doi: 10.1016/j.joca.2011.01.003

Koralewicz, L. M., & Engh, G. A. (2000). Comparison of proprioception in arthritic and age-matched normal knees. *Journal of Bone and Joint Surgery. American Volume, 82-A*(11), 1582-1588.

Kotani, A., Yonekura, A., & Bourne, R. B. (2005). Factors influencing range of motion after contemporary total knee arthroplasty. *J Arthroplasty, 20*(7), 850-856. doi: 10.1016/j.arth.2004.12.051

Kramer, J., Handfield, T., Kiefer, G., Forwell, L., & Birmingham, T. (1997). Comparisons of weight-bearing and non-weight-bearing tests of knee proprioception performed by patients with patello-femoral pain syndrome and asymptomatic individuals. *Clinical Journal of Sport Medicine, 7*(2), 113-118.

Kreibich, D. N., Vaz, M., Bourne, R. B., Rorabeck, C. H., Kim, P., Hardie, R., . . . Kirkley, A. (1996). What is the best way of assessing outcome after total knee replacement? *Clin Orthop Relat Res, 331*, 221-225.

Krogsgaard, M. R., Dyhre-Poulsen, P., & Fischer-Rasmussen, T. (2002). Cruciate ligament reflexes. *J Electromyogr Kinesiol, 12*(3), 177-182. Doi: 10.1016/S1050-6411(02)00018-4

Kroll, M. A., Otis, J. C., Sculco, T. P., Lee, A. C., Paget, S. A., Bruckenstein, R., & Jensen, D. A. (1989). The relationship of stride characteristics to pain before and after total knee arthroplasty. *Clin Orthop Relat Res, 239*, 191-195.

Kurtz, S., Mowat, F., Ong, K., Chan, N., Lau, E., & Halpern, M. (2005). Prevalence of primary and revision total hip and knee arthroplasty in the United States from 1990 through 2002. *J Bone Joint Surg Am, 87*(7), 1487-1497. doi: 10.2106/JBJS.D.02441

Kurtz, S., Ong, K., Lau, E., Mowat, F., & Halpern, M. (2007). Projections of primary and revision hip and knee arthroplasty in the United States from 2005 to 2030. *The Journal of Bone & Joint Surgery, 89*(4), 780-785. doi: 10.2106/JBJS.F.00222

Kurz, M. J., & Stergiou, N. (2002). Effect of normalization and phase angle calculations on continuous relative phase. *J Biomech, 35*(3), 369-374. doi: 10.1016/S0021-9290(01)00211-1

Kurz, M. J., Stergiou, N., Buzzi, U. H., & Georgoulis, A. D. (2005). The effect of anterior cruciate ligament reconstruction on lower extremity relative phase dynamics during walking and running. *Knee Surg Sports Traumatol Arthrosc, 13*(2), 107-115. doi 10.1007/s00167-004-0554-0

Lam, T., & Luttmann, K. (2009). Turning capacity in ambulatory individuals poststroke. *American Journal of Physical Medicine and Rehabilitation, 88*(11), 873-883. doi: 10.1097/PHM.0b013e3181bc0ddf

Larsen, A. H., Puggaard, L., Hamalainen, U., & Aagaard, P. (2008). Comparison of ground reaction forces and antagonist muscle coactivation during stair walking with ageing. *Journal of Electromyography and Kinesiology, 18*(4), 568-580. doi: 10.1016/j.jelekin.2006.12.008

Laskin, R. S. (2003). Articular constraint: use only what you need. *Orthopedics, 26*(9), 975-976. PMID:14503773

Laskin, R. S., & Beksac, B. (2006). Computer-assisted navigation in TKA: where we are and where we are going. *Clin Orthop Relat Res, 452*, 127-131. doi: 10.1097/01.blo.0000238823.78895.dc

Lattanzio, P. J., Chess, D. G., & MacDermid, J. C. (1998). Effect of the posterior cruciate ligament in knee-joint proprioception in total knee arthroplasty. *Journal of Arthroplasty, 13*(5), 580-585. doi: 10.1016/S0883-5403(98)90059-6

Lee, T. H., Tsuchida, T., Kitahara, H., & Moriya, H. (1999). Gait analysis before and after unilateral total knee arthroplasty. Study using a linear regression model of normal controls -- women without arthropathy. *J Orthop Sci, 4*(1), 13-21.

Lephart, S. M., Pincivero, D. M., & Rozzi, S. L. (1998). Proprioception of the ankle and knee. *Sports Med, 25*(3), 149-155. doi: 10.2165/00007256-199825030-00002

Lewek, M. D., Rudolph, K. S., & Snyder-Mackler, L. (2004). Quadriceps femoris muscle weakness and activation failure in patients with symptomatic knee osteoarthritis. *J Orthop Res, 22*(1), 110-115. doi: 10.1016/S0736-0266(03)00154-2

Lewis, B., Bellomo, R., Lewis, D., & Cumming, G. (1995). A clinical procedure for assessment of severity of knee pain. *Pain, 63*(3), 361-364. doi: 10.1016/0304-3959(95)00064-X

Li, K., Ackland, D. C., McClelland, J. A., Webster, K. E., Feller, J. A., de Steiger, R., & Pandy, M. G. (2013). Trunk muscle action compensates for reduced quadriceps force during walking after total knee arthroplasty. *Gait Posture, 38*(1), 79-85. doi: 10.1016/j.gaitpost.2012.10.018

Liang, M. H., Fossel, A. H., & Larson, M. G. (1990). Comparisons of five health status instruments for orthopedic evaluation. *Med Care, 28*(7), 632-642.

Liebs, T. R., Herzberg, W., Gluth, J., Ruther, W., Haasters, J., Russlies, M., & Hassenpflug, J. (2013). Using the patient's perspective to develop function short forms specific to total hip and knee replacement based on WOMAC function items. *Bone Joint J, 95-B*(2), 239-243. doi: 10.1302/0301-620X.95B2.28383

Lim, E. C., & Tan, M. H. (2009). Side-to-side difference in joint position sense and kinesthesia in unilateral functional ankle instability. *Foot and Ankle International, 30*(10), 1011-1017. doi: 10.3113/FAI.2009.1011

Lim, J. T., Luscombe, K. L., Jones, P. W., & White, S. H. (2006). The effect of preoperative symptom severity on functional outcome of total knee replacement--patients with the lowest preoperative scores achieve the lowest marks. *Knee, 13*(3), 216-219. doi: 10.1016/j.knee.2006.01.006

Lindeman, E., Leffers, P., Reulen, J., Spaans, F., & Drukker, J. (1998). Quadriceps strength and timed motor performances in myotonic dystrophy, Charcot-Marie-Tooth disease, and healthy subjects. *Clinical Rehabilitation, 12*(2), 127-135. doi: 10.1191/026921598667776775

Lingard, E. A., Katz, J. N., Wright, R. J., Wright, E. A., & Sledge, C. B. (2001). Validity and responsiveness of the Knee Society Clinical Rating System in comparison with the SF-36 and WOMAC. *J Bone Joint Surg Am, 83-A*(12), 1856-1864.

Liow, R. Y., Walker, K., Wajid, M. A., Bedi, G., & Lennox, C. M. (2003). Functional rating for knee arthroplasty: comparison of three scoring systems. *Orthopedics, 26*(2), 143-149. PMID:12597217

Lonn, J., Crenshaw, A. G., Djupsjobacka, M., & Johansson, H. (2000). Reliability of position sense testing assessed with a fully automated system. *Clinical Physiology, 20*(1), 30-37. doi: 10.1046/j.1365-2281.2000.00218.x

Lord, S. R., Rogers, M. W., Howland, A., & Fitzpatrick, R. (1999). Lateral stability, sensorimotor function and falls in older people. *J Am Geriatr Soc, 47*(9), 1077-1081.

Lorentzen, J. S., Petersen, M. M., Brot, C., & Madsen, O. R. (1999). Early changes in muscle strength after total knee arthroplasty. A 6-month follow-up of 30 knees. *Acta Orthop Scand, 70*(2), 176-179.

Luring, C., Bathis, H., Oczipka, F., Trepte, C., Lufen, H., Perlick, L., & Grifka, J. (2006). Two-year follow-up on joint stability and muscular function comparing rotating versus fixed bearing TKR. *Knee Surg Sports Traumatol Arthrosc, 14*(7), 605-611. doi: 10.1007/s00167-005-0020-7

Luring, C., Beckmann, J., Haibock, P., Perlick, L., Grifka, J., & Tingart, M. (2008). Minimal invasive and computer assisted total knee replacement compared with the conventional technique: a prospective, randomised trial. *Knee Surg Sports Traumatol Arthrosc, 16*(10), 928-934. doi: 10.1007/s00167-008-0582-2

Lutz, G. E., Palmitier, R. A., An, K. N., & Chao, E. Y. (1993). Comparison of tibiofemoral joint forces during open-kinetic-chain and closed-kinetic-chain exercises. *J Bone Joint Surg Am, 75*(5), 732-739.

Lutzner, J., Krummenauer, F., Wolf, C., Gunther, K. P., & Kirschner, S. (2008). Computer-assisted and conventional total knee replacement: a comparative, prospective, randomised study with radiological and CT evaluation. *J Bone Joint Surg Br, 90*(8), 1039-1044. doi: 10.1302/0301-620X.90B8.20553

MacDonald, P. B., Hedden, D., Pacin, O., & Sutherland, K. (1996). Proprioception in anterior cruciate ligament-deficient and reconstructed knees. *American Journal of Sports Medicine, 24*(6), 774-778. doi: 10.1177/036354659602400612

Machner, A., Pap, G., & Awiszus, F. (2002). Evaluation of quadriceps strength and voluntary activation after unicompartmental arthroplasty for medial osteoarthritis of the knee. Journal of orthopaedic research, 20(1), 108-111. doi: 10.1016/S0736-0266(01)00068-7

MacKinnon, C. D., Bissig, D., Chiusano, J., Miller, E., Rudnick, L., Jager, C., . . . Rogers, M. W. (2007). Preparation of anticipatory postural adjustments prior to stepping. *J Neurophysiol, 97*(6), 4368-4379. doi: 10.1152/jn.01136.2006

Madhavan, S., & Shields, R. K. (2005). Influence of age on dynamic joint position sense: evidence using a sequential movement task. *Exp Brain Res, 164*(1), 18-28. doi: 10.1007/s00221-004-2208-3

Maffiuletti, N. A., Bizzini, M., Widler, K., & Munzinger, U. (2010). Asymmetry in quadriceps rate of force development as a functional outcome measure in TKA. *Clin Orthop Relat Res, 468*(1), 191-198. doi: 10.1007/s11999-009-0978-4

Mahaluxmivala, J., Bankes, M. J., Nicolai, P., Aldam, C. H., & Allen, P. W. (2001). The effect of surgeon experience on component positioning in 673 Press Fit Condylar posterior cruciate-sacrificing total knee arthroplasties. *J Arthroplasty, 16*(5), 635-640. doi: 10.1054/arth.2001.23569

Mandeville, D., Osternig, L. R., & Chou, L. S. (2007). The effect of total knee replacement on dynamic support of the body during walking and stair ascent. *Clin Biomech (Bristol, Avon)*. doi: 10.1016/j.clinbiomech.2007.04.002

Manzotti, A., Pullen, C., & Confalonieri, N. (2008). Computer-assisted alignment system for tibial component placement in total knee replacement: a radiological study. *Chir Organi Mov, 91*(1), 7-11. doi: 10.1007/s12306-007-0002-7

Marks, R. (1994). An investigation of the influence of age, clinical status, pain and position sense on stair walking in women with osteoarthrosis. *International Journal of Rehabilitation Research, 17*(2), 151-158.

Marks, R. (1996). Further evidence of impaired position sense in knee osteoarthritis. *Physiother Res Int, 1*(2), 127-136. doi: 10.1002/pri.6120010208

Marks, R., & Quinney, A. H. (1993). Reliability and validity of the measurement of position sense in women with osteoarthritis of the knee. *Journal of Rheumatology, 20*(11), 1919-1924. PMID:8308779

Martinez-Mendez, R., Sekine, M., & Tamura, T. (2011). Detection of anticipatory postural adjustments prior to gait initiation using inertial wearable sensors. *J Neuroeng Rehabil, 8*, 17. doi: 10.1186/1743-0003-8-17

Maruyama, S., Yoshiya, S., Matsui, N., Kuroda, R., & Kurosaka, M. (2004). Functional comparison of posterior cruciate-retaining versus posterior stabilized total knee arthroplasty. *J Arthroplasty, 19*(3), 349-353. doi: 10.1016/j.arth.2003.09.010

Matziolis, G., Krocker, D., Weiss, U., Tohtz, S., & Perka, C. (2007). A prospective, randomized study of computer-assisted and conventional total knee arthroplasty. Three-dimensional evaluation of implant alignment and rotation. *J Bone Joint Surg Am, 89*(2), 236-243. doi: 10.2106/JBJS.F.00386

McChesney, J. W., & Woollacott, M. H. (2000). The effect of age-related declines in proprioception and total knee replacement on postural control. *Journals of Gerontology. Series A, Biological Sciences and Medical Sciences, 55*(11), M658-666. doi: 10.1093/gerona/55.11.M658

McClelland, J. A., Webster, K. E., & Feller, J. A. (2007). Gait analysis of patients following total knee replacement: A systematic review. *Knee, 14*(4), 253-263. doi: 10.1016/j.knee.2007.04.003

McClelland, J. A., Webster, K. E., & Feller, J. A. (2009). Variability of walking and other daily activities in patients with total knee replacement. *Gait and Posture, 30*(3), 288-295. doi: 10.1016/j.gaitpost.2009.05.015

Meeuwsen, H. J., Sawicki, T. M., & Stelmach, G. E. (1993). Improved foot position sense as a result of repetitions in older adults. *Journal of Gerontology, 48*(3), P137-141. doi: 10.1093/geronj/48.3.P137

Mehrotra, C., Remington, P. L., Naimi, T. S., Washington, W., & Miller, R. (2005). Trends in total knee replacement surgeries and implications for public health, 1990-2000. *Public Health Rep, 120*(3), 278-282. PMCID: PMC1497711

Messier, S. P., DeVita, P., Cowan, R. E., Seay, J., Young, H. C., & Marsh, A. P. (2005). Do older adults with knee osteoarthritis place greater loads on the knee during gait? A preliminary study. *Arch Phys Med Rehabil, 86*(4), 703-709. doi: 10.1016/j.apmr.2004.05.015

Mian, O. S., Thom, J. M., Ardigo, L. P., Narici, M. V., & Minetti, A. E. (2006). Metabolic cost, mechanical work, and efficiency during walking in young and older men. *Acta Physiol (Oxf), 186*(2), 127-139. doi: 10.1111/j.1748-1716.2006.01522.x

Mian, O. S., Thom, J. M., Narici, M. V., & Baltzopoulos, V. (2007). Kinematics of stair descent in young and older adults and the impact of exercise training. *Gait and Posture, 25*(1), 9-17. doi: 10.1016/j.gaitpost.2005.12.014

Miller, R. H., Meardon, S. A., Derrick, T. R., & Gillette, J. C. (2008). Continuous relative phase variability during an exhaustive run in runners with a history of iliotibial band syndrome. *J Appl Biomech, 24*(3), 262-270.

Miner, A. L., Lingard, E. A., Wright, E. A., Sledge, C. B., & Katz, J. N. (2003). Knee range of motion after total knee arthroplasty: how important is this as an outcome measure? *J Arthroplasty, 18*(3), 286-294. doi: 10.1054/arth.2003.50046

Minns, R. J. (2005). The role of gait analysis in the management of the knee. *Knee, 12*(3), 157-162. doi: 10.1016/j.knee.2004.12.009

Minoda, Y., Kobayashi, A., Iwaki, H., Ohashi, H., & Takaoka, K. (2009). TKA sagittal alignment with navigation systems and conventional techniques vary only a few degrees. *Clin Orthop Relat Res, 467*(4), 1000-1006. doi: 10.1007/s11999-008-0449-3

Mintken, P. E., Carpenter, K. J., Eckhoff, D., Kohrt, W. M., & Stevens, J. E. (2007). Early neuromuscular electrical stimulation to optimize quadriceps muscle function following total knee arthroplasty: a case report. *Journal of Orthopaedic and Sports Physical Therapy, 37*(7), 364-371. doi:10.2519/jospt.2007.2541

Mizner, R. L., & Snyder-Mackler, L. (2005). Altered loading during walking and sit-to-stand is affected by quadriceps weakness after total knee arthroplasty. *Journal of Orthopaedic Research, 23*, 1083-1090. doi: 10.1016/j.orthres.2005.01.021

Mizner, R. L., Petterson, S. C., & Snyder-Mackler, L. (2005). Quadriceps strength and the time course of functional recovery after total knee arthroplasty. *J Orthop Sports Phys Ther, 35*(7), 424-436. doi:10.2519/jospt.2005.35.7.424

Mizner, R. L., Petterson, S. C., Stevens, J. E., Vandenborne, K., & Snyder-Mackler, L. (2005). Early quadriceps strength loss after total knee arthroplasty. The contributions of muscle atrophy and failure of voluntary muscle activation. *J Bone Joint Surg Am, 87*(5), 1047-1053. doi: 10.2106/JBJS.D.01992

Mizner, R. L., Stevens, J. E., & Snyder-Mackler, L. (2003). Voluntary activation and decreased force production of the quadriceps femoris muscle after total knee arthroplasty. *Phys Ther, 83*(4), 359-365. Retrieved from http://ptjournal.apta.org/content/83/4/359

Moffet, H. n., Collet, J.-P., Shapiro, S. H., Paradis, G., Marquis, F., & Lucille Roy, P. (2004). Effectiveness of Intensive Rehabilitation on Functional Ability and Quality of Life After First Total Knee Arthroplasty: A Single-Blind Randomized Controlled Trial. *Arch Phys Med Rehabil, 85*(4), 546-556. doi: 10.1016/j.apmr.2003.08.080

Mohammadi, F., Taghizadeh, S., Ghaffarinejad, F., Khorrami, M., & Sobhani, S. (2008). Proprioception, dynamic balance and maximal quadriceps strength in females with knee osteoarthritis and normal control subjects. *International Journal of Rheumatic Diseases, 11*(1), 39-44. doi: 10.1111/j.1756-185X.2008.00328.x

Mouchnino, L., Gueguen, N., Blanchard, C., Boulay, C., Gimet, G., Viton, J. M., Delarque, A. (2005). Sensori-motor adaptation to knee osteoarthritis during stepping-down before and after total knee replacement. *BMC Musculoskelet Disord, 6*, 21. Retrieved from http://www.biomedcentral.com/1471-2474/6/21 doi:10.1186/1471-2474-6-21

Moxley Scarborough, D., Krebs, D. E., & Harris, B. A. (1999). Quadriceps muscle strength and dynamic stability in elderly persons. *Gait Posture, 10*(1), 10-20. doi: 10.1016/S0966-6362(99)00018-1

Mullaji, A., & Shetty, G. M. (2009). Computer-Assisted Total Knee Arthroplasty for Arthritis With Extra-articular Deformity. *J Arthroplasty*, In press. doi: 10.1016/j.arth.2009.05.005

Mullaji, A., Kanna, R., Marawar, S., Kohli, A., & Sharma, A. (2007). Comparison of limb and component alignment using computer-assisted navigation versus image intensifier-guided conventional total knee arthroplasty: a prospective, randomized, single-surgeon study of 467 knees. *J Arthroplasty, 22*(7), 953-959. doi: 10.1016/j.arth.2007.04.030

Mundermann, A., Dyrby, C. O., D'Lima, D. D., Colwell, C. W., Jr., & Andriacchi, T. P. (2008). In vivo knee loading characteristics during activities of daily living as measured by an instrumented total knee replacement. *J Orthop Res, 26*(9), 1167-1172. doi: 10.1002/jor.20655

Muramoto, A., Imagama, S., Ito, Z., Hirano, K., Ishiguro, N., & Hasegawa, Y. (2012). Physical performance tests are useful for evaluating and monitoring the severity of locomotive syndrome. *J Orthop Sci, 17*(6), 782-788. doi: 10.1007/s00776-012-0283-z

Nadeau, S., McFadyen, B. J., & Malouin, F. (2003). Frontal and sagittal plane analyses of the stair climbing task in healthy adults aged over 40 years: what are the challenges compared to level walking? *Clin Biomech (Bristol, Avon), 18*(10), 950-959.

Naylor, J. M., Ko, V., Rougellis, S., Green, N., Mittal, R., Heard, R., . . . McEvoy, L. (2012). Is discharge knee range of motion a useful and relevant clinical indicator after total knee replacement? Part 2. *J Eval Clin Pract, 18*(3), 652-658. doi: 10.1111/j.1365-2753.2011.01656.x

NIH. (2004). NIH Consensus Statement on total knee replacement. December 8-10, 2003. *J Bone Joint Surg Am, 86-A*(6), 1328-1335. PMID:15173310

Nilsdotter, A. K., Toksvig-Larsen, S., & Roos, E. M. (2009). Knee arthroplasty: are patients' expectations fulfilled? A prospective study of pain and function in 102 patients with 5-year follow-up. *Acta Orthopaedica, 80*(1), 55-61. doi: 10.1080/17453670902805007

Noble, P. C., Gordon, M. J., Weiss, J. M., Reddix, R. N., Conditt, M. A., & Mathis, K. B. (2005). Does total knee replacement restore normal knee function? *Clin Orthop Relat Res*(431), 157-165. doi: 10.1097/01.blo.0000150130.03519.fb

Orendurff, M. S., Segal, A. D., Berge, J. S., Flick, K. C., Spanier, D., & Klute, G. K. (2006). The kinematics and kinetics of turning: limb asymmetries associated with walking a circular path. *Gait and Posture, 23*(1), 106-111. doi: 10.1016/j.gaitpost.2004.12.008

Ornetti, P., Maillefert, J. F., Laroche, D., Morisset, C., Dougados, M., & Gossec, L. (2010). Gait analysis as a quantifiable outcome measure in hip or knee osteoarthritis: a systematic review. *Joint Bone Spine*, 77(5), 421-425. doi: 10.1016/j.jbspin.2009.12.009

Ouellet, D., & Moffet, H. (2002). Locomotor deficits before and two months after knee arthroplasty. *Arthritis Rheum, 47*(5), 484-493. doi: 10.1002/art.10652

Pai, Y. C., Rymer, W. Z., Chang, R. W., & Sharma, L. (1997). Effect of age and osteoarthritis on knee proprioception. *Arthritis and Rheumatism, 40*(12), 2260-2265. doi: 10.1002/art.1780401223

Parent, E., & Moffet, H. (2002). Comparative responsiveness of locomotor tests and questionnaires used to follow early recovery after total knee arthroplasty. *Archives of Physical Medicine and Rehabilitation, 83*(1), 70-80. doi: 10.1053/apmr.2002.27337

Patchay, S., Gahery, Y., & Serratrice, G. (2002). Early postural adjustments associated with gait initiation and age-related walking difficulties. *Movement Disorders, 17*(2), 317-326. doi: 10.1002/mds.10074

Patla, A. E., Prentice, S. D., Robinson, C., & Neufeld, J. (1991). Visual control of locomotion: strategies for changing direction and for going over obstacles. *Journal of Experimental Psychology: Human Perception and Performance, 17*(3), 603-634. doi: 10.1037/0096-1523.17.3.603

Peppe, A., Chiavalon, C., Pasqualetti, P., Crovato, D., & Caltagirone, C. (2007). Does gait analysis quantify motor rehabilitation efficacy in Parkinson's disease patients? *Gait Posture, 26*(3), 452-462. doi: 10.1016/j.gaitpost.2006.11.207

Peterlein, C. D., Schofer, M. D., Fuchs-Winkelmann, S., & Scherf, F. G. (2009). Clinical outcome and quality of life after computer-assisted total knee arthroplasty: results from a prospective, single-surgeon study and review of the literature. *Musculoskelet Surg*. doi: 10.1007/s12306-009-0042-2

Petterson, S. C., Mizner, R. L., Stevens, J. E., Raisis, L., Bodenstab, A., Newcomb, W., & Snyder-Mackler, L. (2009). Improved function from progressive strengthening interventions after total knee arthroplasty: a randomized clinical trial with an imbedded prospective cohort. *Arthritis Rheum, 61*(2), 174-183. doi: 10.1002/art.24167

Pickard, C. M., Sullivan, P. E., Allison, G. T., & Singer, K. P. (2003). Is there a difference in hip joint position sense between young and older groups? *Journals of Gerontology. Series A, Biological Sciences and Medical Sciences, 58*(7), 631-635. doi: 10.1093/gerona/58.7.M631

Pincivero, D. M., Bachmeier, B., & Coelho, A. J. (2001). The effects of joint angle and reliability on knee proprioception. *Medicine and Science in Sports and Exercise, 33*(10), 1708-1712. doi: 0195-9131/01/3310-1708

Polcyn, A. F., Lipsitz, L. A., Kerrigan, D. C., & Collins, J. J. (1998). Age-related changes in the initiation of gait: degradation of central mechanisms for momentum generation. *Archives of Physical Medicine and Rehabilitation, 79*(12), 1582-1589. doi: 10.1016/S0003-9993(98)90425-7

Portes, E. M., Portes, L. A., Botelho, V. G., & Souza Pinto, S. (2007). Isokinetic torque peak and hamstrings/quadriceps ratios in endurance athletes with anterior cruciate ligament laxity. *Clinics, 62*(2), 127-132. doi: 10.1590/S1807-59322007000200006

Proske, U. (2006). Kinesthesia: the role of muscle receptors. *Muscle and Nerve, 34*(5), 545-558. doi: 10.1002/mus.20627

Rand, J. A., & Coventry, M. B. (1988). Ten-year evaluation of geometric total knee arthroplasty. *Clin Orthop Relat Res*(232), 168-173.

Rankin, G., & Stokes, M. (1998). Reliability of assessment tools in rehabilitation: an illustration of appropriate statistical analyses. *Clinical Rehabilitation, 12*(3), 187-199. doi: 10.1191/026921598672178340

Reeves, N. D., Spanjaard, M., Mohagheghi, A. A., Baltzopoulos, V., & Maganaris, C. N. (2008). The demands of stair descent relative to maximum capacities in elderly and young adults. *Journal of Electromyography and Kinesiology, 18*(2), 218-227. doi: 10.1016/j.jelekin.2007.06.003

Reid, S. M., Lynn, S. K., Musselman, R. P., & Costigan, P. A. (2007). Knee biomechanics of alternate stair ambulation patterns. *Med Sci Sports Exerc, 39*(11), 2005-2011. doi: 10.1249/mss.0b013e31814538c8

Reider, B., Arcand, M. A., Diehl, L. H., Mroczek, K., Abulencia, A., Stroud, C. C., . . . Staszak, P. (2003). Proprioception of the knee before and after anterior cruciate ligament reconstruction. *Arthroscopy, 19*(1), 2-12. doi: 10.1053/jars.2003.50006

Renkawitz, T., Rieder, T., Handel, M., Koller, M., Drescher, J., Bonnlaender, G., & Grifka, J. (2010). Comparison of two accelerated clinical pathways - after total knee replacement how fast can we really go? *Clinical Rehabilitation, 24*(3), 230-239. doi: 10.1177/0269215509353267

Riemann, B. L., & Lephart, S. M. (2002a). The Sensorimotor System, Part I: The Physiologic Basis of Functional Joint Stability. *J Athl Train, 37*(1), 71-79. PMCID: PMC164311

Riemann, B. L., & Lephart, S. M. (2002b). The Sensorimotor System, Part II: The Role of Proprioception in Motor Control and Functional Joint Stability. *J Athl Train, 37*(1), 80-84. PMCID: PMC164312

Riener, R., Rabuffetti, M., & Frigo, C. (2002). Stair ascent and descent at different inclinations. *Gait & Posture, 15*(1), 32-44. doi: 10.1016/S0966-6362(01)00162-X

Ritter, M. A., Wing, J. T., Berend, M. E., Davis, K. E., & Meding, J. B. (2008). The clinical effect of gender on outcome of total knee arthroplasty. *Journal of Arthroplasty, 23*(3), 331-336. doi:10.1016/j.arth.2007.10.031

Rocchi, L., Chiari, L., Mancini, M., Carlson-Kuhta, P., Gross, A., & Horak, F. B. (2006). Step initiation in Parkinson's disease: influence of initial stance conditions. *Neuroscience Letters, 406*(1-2), 128-132. doi: 10.1016/j.neulet.2006.07.027

Rodriguez, J. A., Bhende, H., & Ranawat, C. S. (2001). Total condylar knee replacement: a 20-year followup study. *Clin Orthop Relat Res, 388*, 10-17.

Rogers, M. W., Kukulka, C. G., Brunt, D., Cain, T. D., & Hanke, T. A. (2001). The influence of stimulus cue on the initiation of stepping in young and older adults. *Archives of Physical Medicine and Rehabilitation, 82*(5), 619-624. doi: 10.1053/apmr.2001.20833

Rooks, D. S., Huang, J., Bierbaum, B. E., Bolus, S. A., Rubano, J., Connolly, C. E., . . . Katz, J. N. (2006). Effect of preoperative exercise on measures of functional status in men and women undergoing total hip and knee arthroplasty. *Arthritis Rheum, 55*(5), 700-708. doi: 10.1002/art.22223

Rosenberger, R. E., Hoser, C., Quirbach, S., Attal, R., Hennerbichler, A., & Fink, C. (2008). Improved accuracy of component alignment with the implementation of image-free navigation in total knee arthroplasty. *Knee Surg Sports Traumatol Arthrosc, 16*(3), 249-257. doi: 10.1007/s00167-007-0420-y

Rossi, M. D., & Hasson, S. (2004). Lower-Limb Force Production in Individuals After Unilateral Total Knee Arthroplasty. *Arch Phys Med Rehabil, 85*(8), 1279-1284. doi: 10.1016/j.apmr.2003.11.034

Rossi, M. D., Brown, L. E., & Whitehurst, M. (2006). Knee extensor and flexor torque characteristics before and after unilateral total knee arthroplasty. *Am J Phys Med Rehabil*, *85*(9), 737-746. doi: 10.1097/01.phm.0000233178.22621.a5

Rossi, M. D., Brown, L. E., Whitehurst, M., Charni, C., Hankins, J., & Taylor, C. L. (2002). Comparison of Knee Extensor Strength Between Limbs in Individuals With Bilateral Total Knee Replacement. *Arch Phys Med Rehabil, 83*(4), 523-526. doi: 10.1053/apmr.2002.30935

Rossi, M. D., Eberle, T., Roche, M., Brunt, D., Wong, M., Waggoner, M., . . . Baxter, A. (2013). Use of a squatting movement as a clinical marker of function after total knee arthroplasty. *American journal of physical medicine & rehabilitation / Association of Academic Physiatrists, 92*(1), 53-60. doi: 10.1097/PHM.0b013e318269d8d0

Rossi, M. D., Hasson, S., Kohia, M., Pineda, E., & Bryan, W. (2006). Mobility and perceived function after total knee arthroplasty. *J Arthroplasty, 21*(1), 6-12. doi: 10.1016/j.arth.2005.02.013

Rudolph, K. S., Axe, M. J., Buchanan, T. S., Scholz, J. P., & Snyder-Mackler, L. (2001). Dynamic stability in the anterior cruciate ligament deficient knee. *Knee Surg Sports Traumatol Arthrosc, 9*(2), 62-71. doi: 10.1007/s001670000166

Saari, T., Tranberg, R., Zugner, R., Uvehammer, J., & Karrholm, J. (2004). Total knee replacement influences both knee and hip joint kinematics during stair climbing. *Int Orthop, 28*(2), 82-86. doi: 10.1007/s00264-003-0525-y

Saari, T., Tranberg, R., Zugner, R., Uvehammer, J., & Karrholm, J. (2005). Changed gait pattern in patients with total knee arthroplasty but minimal influence of tibial insert design: gait analysis during level walking in 39 TKR patients and 18 healthy controls. *Acta Orthop, 76*(2), 253-260. doi:10.1080/00016470510030661

Sabouret, P., Lavoie, F., & Cloutier, J. M. (2013). Total knee replacement with retention of both cruciate ligaments: a 22-year follow-up study. *The bone & joint journal, 95-B*(7), 917-922. doi: 10.1302/0301-620X.95B7.30904

Schmidt, R. A., & Lee, T. D. (1999). *Motor control and learning: A behavioral emphasis*. Champaign, IL: Human Kinetics.

Schoppen, T., Boonstra, A., Groothoff, J. W., de Vries, J., Goeken, L. N., & Eisma, W. H. (1999). The Timed "up and go" test: reliability and validity in persons with unilateral lower limb amputation. *Arch Phys Med Rehabil, 80*(7), 825-828. doi: 10.1016/S0003-9993(99)90234-4

Schultz, R. A., Miller, D. C., Kerr, C. S., & Micheli, L. (1984). Mechanoreceptors in human cruciate ligaments. A histological study. *J Bone Joint Surg Am, 66*(7), 1072-1076.

Sedgman, R., Goldie, P. A., & Iansek, R. (1994). *Development of a Measure of Turning During Walking.* Paper presented at the The Advancing Rehabilitation Conference, Melbourne, Australia.

Segal, A. D., Orendurff, M. S., Czerniecki, J. M., Shofer, J. B., & Klute, G. K. (2008). Local dynamic stability in turning and straight-line gait. *Journal of Biomechanics, 41*(7), 1486-1493. doi: 10.1016/j.jbiomech.2008.02.012

Selfe, J., Callaghan, M., McHenry, A., Richards, J., & Oldham, J. (2006). An investigation into the effect of number of trials during proprioceptive testing in patients with patellofemoral pain syndrome. *Journal of Orthopaedic Research, 24*(6), 1218-1224. doi: 10.1002/jor.20127

Seon, J. K., & Song, E. K. (2005). Functional impact of navigation-assisted minimally invasive total knee arthroplasty. *Orthopedics, 28*(10 Suppl), s1251-1254.

Seon, J. K., Song, E. K., Yoon, T. R., Park, S. J., Bae, B. H., & Cho, S. G. (2007). Comparison of functional results with navigation-assisted minimally invasive and conventional techniques in bilateral total knee arthroplasty. *Comput Aided Surg, 12*(3), 189-193.

Shakespeare, D., & Kinzel, V. (2005). Rehabilitation after total knee replacement: time to go home? *Knee, 12*(3), 185-189. doi: 10.1016/j.knee.2004.06.007

Shiavi, R., Bugle, H. J., & Limbird, T. (1987). Electromyographic gait assessment, Part 1: Adult EMG profiles and walking speed. *J Rehabil Res Dev, 24*(2), 13-23. PMID:3585781

Shrout, P. E., & Fleiss, J. L. (1979). Intraclass correlations: uses in assessing rater reliability. *Psychological Bulletin, 86*(2), 420-428. doi: 10.1037/0033-2909.86.2.420

Silva, M., Shepherd, E. F., Jackson, W. O., Pratt, J. A., McClung, C. D., & Schmalzried, T. P. (2003). Knee Strength After Total Knee Arthroplasty. *J Arthroplasty, 18*(5), 605-611. doi: 10.1016/S0883-5403(03)00191-8

Skelton, D. A., Kennedy, J., & Rutherford, O. M. (2002). Explosive power and asymmetry in leg muscle function in frequent fallers and non-fallers aged over 65. *Age and Ageing, 31*(2), 119-125. doi: 10.1093/ageing/31.2.119

Skinner, H. B. (1993). Pathokinesiology and total joint arthroplasty. *Clin Orthop Relat Res, 288*, 78-86.

Skinner, H. B., Barrack, R. L., & Cook, S. D. (1984). Age-related decline in proprioception. *Clin Orthop Relat Res, 184*, 208-211.

Skinner, H. B., Barrack, R. L., Cook, S. D., & Haddad, R. J., Jr. (1984). Joint position sense in total knee arthroplasty. *Journal of Orthopaedic Research, 1*(3), 276-283. doi: 10.1002/jor.1100010307

Smith, A. J., Lloyd, D. G., & Wood, D. J. (2006). A kinematic and kinetic analysis of walking after total knee arthroplasty with and without patellar resurfacing. *Clin Biomech (Bristol, Avon), 21*(4), 379-386. doi: 10.1016/j.clinbiomech.2005.11.007

Sparmann, M., Wolke, B., Czupalla, H., Banzer, D., & Zink, A. (2003). Positioning of total knee arthroplasty with and without navigation support. A prospective, randomised study. *J Bone Joint Surg Br, 85*(6), 830-835. doi: 10.1302/0301-620X.85B6.13722

Spencer, J. M., Chauhan, S. K., Sloan, K., Taylor, A., & Beaver, R. J. (2007). Computer navigation versus conventional total knee replacement: no difference in functional results at two years. *J Bone Joint Surg Br, 89*(4), 477-480. doi: 10.1302/0301-620X.89B4.18094

Stacoff, A., Diezi, C., Luder, G., Stussi, E., & Kramers-de Quervain, I. A. (2005). Ground reaction forces on stairs: effects of stair inclination and age. *Gait & Posture, 21*(1), 24-38. doi: 10.1016/j.gaitpost.2003.11.003

Startzell, J. K., Owens, D. A., Mulfinger, L. M., & Cavanagh, P. R. (2000). Stair negotiation in older people: a review. *Journal of the American Geriatrics Society, 48*(5), 567-580. PMID:10811553

Stevens, J. E., Mizner, R. L., & Snyder-Mackler, L. (2003). Quadriceps strength and volitional activation before and after total knee arthroplasty for osteoarthritis. *J Orthop Res, 21*(5), 775-779. doi: 10.1016/S0736-0266(03)00052-4

Stevens, J. E., Mizner, R. L., & Snyder-Mackler, L. (2004). Neuromuscular electrical stimulation for quadriceps muscle strengthening after bilateral total knee arthroplasty: a case series. *J Orthop Sports Phys Ther,* 34(1), 21-29. doi:10.2519/jospt.2004.34.1.21

Stevens-Lapsley, J. E., Balter, J. E., Kohrt, W. M., & Eckhoff, D. G. (2010). Quadriceps and Hamstrings Muscle Dysfunction after Total Knee Arthroplasty. *Clin Orthop Relat Res*. doi: 10.1007/s11999-009-1219-6

Stiehl, J. B. (2007). Computer navigation in primary total knee arthroplasty. *J Knee Surg, 20*(2), 158-164.

Stiehl, J. B., Dennis, D. A., Komistek, R. D., & Crane, H. S. (1999). In vivo determination of condylar lift-off and screw-home in a mobile-bearing total knee arthroplasty. *J Arthroplasty, 14*(3), 293-299. doi: 10.1016/S0883-5403(99)90054-2

Stiehl, J. B., Komistek, R., & Dennis, D. A. (2001). A novel approach to knee kinematics. *Am J Orthop, 30*(4), 287-293. PMID:11334450

Stiehl, J. B., Voorhorst, P. E., Keblish, P., & Sorrells, R. B. (1997). Comparison of range of motion after posterior cruciate ligament retention or sacrifice with a mobile bearing total knee arthroplasty. *Am J Knee Surg, 10*(4), 216-220. PMID:9421597

Stindel, E., Briard, J. L., Merloz, P., Plaweski, S., Dubrana, F., Lefevre, C., & Troccaz, J. (2002). Bone morphing: 3D morphological data for total knee arthroplasty. *Comput Aided Surg, 7*(3), 156-168. doi: 10.1002/igs.10042

Stöckl, B., Nogler, M., Rosiek, R., Fischer, M., Krismer, M., & Kessler, O. (2004). Navigation improves accuracy of rotational alignment in total knee arthroplasty. *Clin Orthop Relat Res*(426), 180-186. doi: 10.1097/01.blo.0000136835.40566.d9

Stratford, P. W., & Kennedy, D. M. (2004). Does parallel item content on WOMAC's pain and function subscales limit its ability to detect change in functional status? BMC Musculoskelet Disord, 5, 17. doi: 10.1186/1471-2474-5-17

Stratford, P. W., & Kennedy, D. M. (2006). Performance measures were necessary to obtain a complete picture of osteoarthritic patients. *J Clin Epidemiol, 59*(2), 160-167. doi: 10.1016/j.jclinepi.2005.07.012

Stratford, P. W., Kennedy, D. M., & Riddle, D. L. (2009). New study design evaluated the validity of measures to assess change after hip or knee arthroplasty. *J Clin Epidemiol, 62*(3), 347-352. doi: 10.1016/j.jclinepi.2008.06.008

Stratford, P. W., Kennedy, D. M., Woodhouse, L. J., & Spadoni, G. F. (2006). Measurement properties of the WOMAC LK 3.1 pain scale. *Osteoarthritis Cartilage, 15*(3), 266-272. doi: 10.1016/j.joca.2006.09.005

Straw, R., Kulkarni, S., Attfield, S., & Wilton, T. J. (2003). Posterior cruciate ligament at total knee replacement. Essential, beneficial or a hindrance? *J Bone Joint Surg Br, 85*(5), 671-674. doi: 10.1302/0301-620X.85B5.13812

Strike, S. C., & Taylor, M. J. (2009). The temporal-spatial and ground reaction impulses of turning gait: is turning symmetrical? *Gait and Posture, 29*(4), 597-602. doi: 10.1016/j.gaitpost.2008.12.015

Stucki, G., Ewert, T., & Cieza, A. (2002). Value and application of the ICF in rehabilitation medicine. *Disabil Rehabil, 24*(17), 932-938. doi:10.1080/09638280210148594

Stulberg, B. N., & Zadzilka, J. D. (2006). Computer-assisted surgery: a wine before its time: in opposition. *J Arthroplasty, 21*(4 Suppl 1), 29-32. doi: 10.1016/j.arth.2006.01.017

Stulberg, S. D., Yaffe, M. A., & Koo, S. S. (2006). Computer-assisted surgery versus manual total knee arthroplasty: a case-controlled study. *J Bone Joint Surg Am, 88 Suppl 4*, 47-54. doi: 10.2106/JBJS.F.00698

Sturnieks, D. L., St George, R., & Lord, S. R. (2008). Balance disorders in the elderly. *Neurophysiologie Clinique, 38*(6), 467-478. doi: 10.1016/j.neucli.2008.09.001

Swanik, C. B., Lephart, S. M., & Rubash, H. E. (2004). Proprioception, kinesthesia, and balance after total knee arthroplasty with cruciate-retaining and posterior stabilized prostheses. *J Bone Joint Surg Am, 86-A*(2), 328-334.

Swinkels, A., Newman, J. H., & Allain, T. J. (2009). A prospective observational study of falling before and after knee replacement surgery. *Age and Ageing, 38*(2), 175-181. doi: 10.1093/ageing/afn229

Szoeke, C., Cicuttini, F., Guthrie, J., Clark, M., & Dennerstein, L. (2006). Factors affecting the prevalence of osteoarthritis in healthy middle-aged women: data from the longitudinal Melbourne Women's Midlife Health Project. *Bone, 39*(5), 1149-1155. doi: 10.1016/j.bone.2006.05.016

Taylor, M. J., Dabnichki, P., & Strike, S. C. (2005). A three-dimensional biomechanical comparison between turning strategies during the stance phase of walking. *Hum Mov Sci, 24*(4), 558-573. doi: 10.1016/j.humov.2005.07.005

Taylor, M. J., Strike, S. C., & Dabnichki, P. (2006). Strategies used for unconstrained direction change during walking. *Perceptual and Motor Skills, 102*(2), 576-588. doi: 10.2466/pms.102.2.576-588

Thigpen, M. T., Light, K. E., Creel, G. L., & Flynn, S. M. (2000). Turning difficulty characteristics of adults aged 65 years or older. *Physical Therapy, 80*(12), 1174-1187.

Thijs, Y., Witvrouw, E., Evens, B., Coorevits, P., Almqvist, F., & Verdonk, R. (2007). A prospective study on knee proprioception after meniscal allograft transplantation. *Scandinavian Journal of Medicine and Science in Sports, 17*(3), 223-229. doi: 10.1111/j.1600-0838.2006.00565.x

Tingart, M., Luring, C., Bathis, H., Beckmann, J., Grifka, J., & Perlick, L. (2008). Computer-assisted total knee arthroplasty versus the conventional technique: how precise is navigation in clinical routine? *Knee Surg Sports Traumatol Arthrosc, 16*(1), 44-50. doi: 10.1007/s00167-007-0399-4

Tolk, J. J., Koot, H. W., & Janssen, R. P. (2012). Computer navigated versus conventional total knee arthroplasty. *J Knee Surg, 25*(4), 347-352. doi: 10.1055/s-0031-1299670

Tsang, W. W., & Hui-Chan, C. W. (2003). Effects of tai chi on joint proprioception and stability limits in elderly subjects. *Medicine and Science in Sports and Exercise, 35*(12), 1962-1971. doi: 10.1249/01.MSS.0000099110.17311.A2

Tucker, M. G., Kavanagh, J. J., Barrett, R. S., & Morrison, S. (2008). Age-related differences in postural reaction time and coordination during voluntary sway movements. *Hum Mov Sci, 27*(5), 728-737. doi: 10.1016/j.humov.2008.03.002

Udomkiat, P., Meng, B. J., Dorr, L. D., & Wan, Z. (2000). Functional comparison of posterior cruciate retention and substitution knee replacement. *Clin Orthop Relat Res, 378*, 192-201.

Unver, B., Karatosun, V., & Bakirhan, S. (2005). Ability to rise independently from a chair during 6-month follow-up after unilateral and bilateral total knee replacement. J Rehabil Med, 37(6), 385-387. doi: 10.1080/16501970510035070

Van Damme, G., Defoort, K., Ducoulombier, Y., Van Glabbeek, F., Bellemans, J., & Victor, J. (2005). What should the surgeon aim for when performing computer-assisted total knee arthroplasty? *J Bone Joint Surg Am, 87*(Suppl 2), 52-58. doi: 10.2106/JBJS.E.00447

van den Akker-Scheek, I., Stevens, M., Groothoff, J. W., Bulstra, S. K., & Zijlstra, W. (2007). Preoperative or post-operative self-efficacy: which is a better predictor of outcome after total hip or knee arthroplasty? *Patient Educ Couns, 66*(1), 92-99. doi: 10.1016/j.pec.2006.10.012

van der Esch, M., Steultjens, M., Harlaar, J., Knol, D., Lems, W., & Dekker, J. (2007). Joint proprioception, muscle strength, and functional ability in patients with osteoarthritis of the knee. *Arthritis Rheum, 57*(5), 787-793. doi: 10.1002/art.22779

van der Linden, M. L., Rowe, P. J., & Nutton, R. W. (2008). Between-day repeatability of knee kinematics during functional tasks recorded using flexible electrogoniometry. *Gait and Posture, 28*(2), 292-296. doi: 10.1016/j.gaitpost.2008.01.009

van der Linden, M. L., Rowe, P. J., Myles, C. M., Burnett, R., & Nutton, R. W. (2007). Knee kinematics in functional activities seven years after total knee arthroplasty. *Clin Biomech (Bristol, Avon), 22*(5), 537-542. doi: 10.1016/j.clinbiomech.2006.12.005

van Meeteren, J., Roebroeck, M. E., & Stam, H. J. (2002). Test-retest reliability in isokinetic muscle strength measurements of the shoulder. *Journal of rehabilitation medicine*, *34*(2), 91-95.

Varadarajan, K. M., Moynihan, A. L., D'Lima, D., Colwell, C. W., & Li, G. (2008). In vivo contact kinematics and contact forces of the knee after total knee arthroplasty during dynamic weight-bearing activities. *J Biomech, 41*(10), 2159-2168. doi: 10.1016/j.jbiomech.2008.04.021

Verschueren, S. M., Brumagne, S., Swinnen, S. P., & Cordo, P. J. (2002). The effect of aging on dynamic joint position sense at the ankle. *Behav Brain Res, 136*(2), 593-603. doi: 10.1016/S0166-4328(02)00224-3

Verweij, L. M., van Schoor, N. M., Deeg, D. J., Dekker, J., & Visser, M. (2009). Physical activity and incident clinical knee osteoarthritis in older adults. *Arthritis Care & Research, 61*(2), 152-157. doi: 10.1002/art.24233

Vicon. (2008). *Plug-in Gait Product Guide-Foundation Notes* Vol. Revision 1.0. Retrieved from http://www.vicon.com

Viton, J. M., Atlani, L., Mesure, S., Massion, J., Franceschi, J. P., Delarque, A., & Bardot, A. (2002). Reorganization of equilibrium and movement control strategies after total knee arthroplasty. *J Rehabil Med, 34*(1), 12-19.

Viton, J. M., Timsit, M., Mesure, S., Massion, J., Franceschi, J. P., & Delarque, A. (2000). Asymmetry of gait initiation in patients with unilateral knee arthritis. *Archives of Physical Medicine and Rehabilitation, 81*(2), 194-200. doi: 10.1016/S0003-9993(00)90140-0

Wada, M., Kawahara, H., Shimada, S., Miyazaki, T., & Baba, H. (2002). Joint proprioception before and after total knee arthroplasty. *Clin Orthop Relat Res, 403*, 161-167.

Walsh, M., Woodhouse, L. J., Thomas, S. G., & Finch, E. (1998). Physical impairments and functional limitations: a comparison of individuals 1 year after total knee arthroplasty with control subjects. *Phys Ther, 78*(3), 248-258. Retrieved from http://ptjournal.apta.org/content/78/3/248

Ware, J. E., Jr., & Sherbourne, C. D. (1992). The MOS 36-item short-form health survey (SF-36). I. Conceptual framework and item selection. *Med Care, 30*(6), 473-483.

Warren, P. J., Olanlokun, T. K., Cobb, A. G., & Bentley, G. (1993). Proprioception after knee arthroplasty. The influence of prosthetic design. *Clin Orthop Relat Res, 297*, 182-187.

Welter, M. L., Do, M. C., Chastan, N., Torny, F., Bloch, F., du Montcel, S. T., & Agid, Y. (2007). Control of vertical components of gait during initiation of walking in normal adults and patients with progressive supranuclear palsy. *Gait and Posture, 26*(3), 393-399. doi: 10.1016/j.gaitpost.2006.10.005

Whitehouse, S. L., Blom, A. W., Taylor, A. H., Pattison, G. T., & Bannister, G. C. (2005). The Oxford Knee Score; problems and pitfalls. *Knee, 12*(4), 287-291. doi: 10.1016/j.knee.2004.11.005

Whitehouse, S. L., Lingard, E. A., Katz, J. N., & Learmonth, I. D. (2003). Development and testing of a reduced WOMAC function scale. *J Bone Joint Surg Br, 85*(5), 706-711. doi: 10.1302/0301-620X.85B5.13681

Wiik, A. V., Manning, V., Strachan, R. K., Amis, A. A., & Cobb, J. P. (2013). Unicompartmental knee arthroplasty enables near normal gait at higher speeds, unlike total knee arthroplasty. *J Arthroplasty, 28*(9 Suppl), 176-178. doi: 10.1016/j.arth.2013.07.036

Wilk-Franczuk, M., Tomaszewski, W., Zemla, J., Noga, H., & Czamara, A. (2011). Analysis of rehabilitation procedure following arthroplasty of the knee with the use of complete endoprosthesis. Medical science monitor : international medical journal of experimental and clinical research, 17(3), CR165-168. doi: 10.12659/MSM.881451

Williams, B. R., Hultsch, D. F., Strauss, E. H., Hunter, M. A., & Tannock, R. (2005). Inconsistency in reaction time across the life span. *Neuropsychology, 19*(1), 88-96. doi: 10.1037/0894-4105.19.1.88

Wilson, S. A., McCann, P. D., Gotlin, R. S., Ramakrishnan, H. K., Wootten, M. E., & Insall, J. N. (1996). Comprehensive gait analysis in posterior-stabilized knee arthroplasty. *J Arthroplasty, 11*(4), 359-367. doi: 10.1016/S0883-5403(96)80023-4

Winter, D. A., Patla, A. E., Frank, J. S., & Walt, S. E. (1990). Biomechanical walking pattern changes in the fit and healthy elderly. *Phys Ther, 70*(6), 340-347.

Worland, R. L., Arredondo, J., Angles, F., Lopez-Jimenez, F., & Jessup, D. E. (1998). Home continuous passive motion machine versus professional physical therapy following total knee replacement. *J Arthroplasty, 13*(7), 784-787. doi: 10.1016/S0883-5403(98)90031-6

Worland, R. L., Johnson, G. V., Alemparte, J., Jessup, D. E., Keenan, J., & Norambuena, N. (2002). Ten to fourteen year survival and functional analysis of the AGC total knee replacement system. *Knee, 9*(2), 133-137. doi: 10.1016/S0968-0160(01)00146-6

Xu, D., Carlton, L. G., & Rosengren, K. S. (2004). Anticipatory postural adjustments for altering direction during walking. *J Mot Behav, 36*(3), 316-326. doi: 10.3200/JMBR.36.3.316-326

Yang, J. H., Seo, J. G., Moon, Y. W., & Kim, M. H. (2009). Joint line changes after navigation-assisted mobile-bearing TKA. *Orthopedics, 32*(10 Suppl), 35-39. doi: 10.3928/01477447-20090915-57

Yoshida, Y., Mizner, R. L., & Snyder-Mackler, L. (2013). Association between long-term quadriceps weakness and early walking muscle co-contraction after total knee arthroplasty. *Knee*. doi: 10.1016/j.knee.2012.12.008

Yoshida, Y., Mizner, R. L., Ramsey, D. K., & Snyder-Mackler, L. (2008). Examining outcomes from total knee arthroplasty and the relationship between quadriceps strength and knee function over time. *Clin Biomech (Bristol, Avon), 23*(3), 320-328. doi: 10.1016/j.clinbiomech.2007.10.008

You, S. H. (2005). Joint position sense in elderly fallers: a preliminary investigation of the validity and reliability of the SENSERite measure. *Archives of Physical Medicine and Rehabilitation, 86*(2), 346-352. doi: 10.1016/j.apmr.2004.01.035

Zech, A., Witte, K., & Pfeifer, K. (2008). Reliability and performance-dependent variations of muscle function variables during isometric knee extension. *J Electromyogr Kinesiol, 18*(2), 262-269. doi: 10.1016/j.jelekin.2006.08.013

Zeni, J. A., Jr., & Snyder-Mackler, L. (2010). Early post-operative measures predict 1- and 2-year outcomes after unilateral total knee arthroplasty: importance of contralateral limb strength. *Phys Ther, 90*(1), 43-54. doi: 10.2522/ptj.20090089

Zhang, G. Q., Chen, J. Y., Chai, W., Liu, M., & Wang, Y. (2011). Comparison between computer-assisted-navigation and conventional total knee arthroplasties in patients undergoing simultaneous bilateral procedures: a randomized clinical trial. *The Journal of bone and joint surgery. American volume, 93*(13), 1190-1196. doi: 10.2106/JBJS.I.01778