Task-orientated rehabilitation can improve knee function and satisfaction in patients 12 months after knee replacement surgery for osteoarthritis

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To my dear son Arseniy Beliy, always loving and standing by me.

To the memory of my father
Gennadiy Fedorovich Kuznetsov (1937 – 1990),
my mother Nina Grigorievna Kuznetsova (1937 – 2011),
and my beloved sons Anton (1984 – 1990) and Arkadiy (1987 – 1990).

Declaration

I, Yelena Walters, confirm that the work presented in this thesis is my own.
Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

London, 18th December, 2017

Abstract

End-stage osteoarthritis (OA) requires joint replacement surgery. Although total knee arthroplasty (TKA) usually relieves pain, some patients are disappointed with their mobility, which may result from an abnormal gait. Post-operative physiotherapy following TKA is essential, although little consensus exists regarding longer-term rehabilitation. Typical rehabilitation has an internal focus on specific muscles and joints, but task-orientated rehabilitation (TOR) may be more effective. This study tested the hypothesis that TOR can improve gait and patient reported functional outcome following TKA. Seventy six patients were studied 12 months after TKA during follow up at the Royal National Orthopaedic Hospital, Stanmore. Patient reported functional outcome was assessed using the Oxford Knee Score (OKS) and gait characteristics were measured using inertial measurement units (IMUs). A subset of 21 patients, exhibiting abnormal gait, entered a 4-week TOR programme, based on daily walking and stair climbing. Patients were re-assessed with OKS and IMUs, and gait quantity compared pre- and post-intervention using pedometers. A subset of 4 patients' baseline gaits was compared to 5 controls, and to their own gait following the TOR, while subjected to differing treadmill conditions. Multiple regression analysis showed that stride duration significantly predicted OKS ($p<0.0001$, $n=76$). Higher OKS was observed in patients who have shorter stride duration, which was in turn a result of greater RoM of the leg joints and segments in the sagittal plane. TKA patients' response to the varying treadmill conditions was similar, but inferior in the gait parameters' values as compared to the healthy participants. Following TOR, 21 patients exhibited a significantly higher OKS ($p=0.001$, $n=21$). Stride duration, thigh, knee and calf sagittal range of motion and knee flexion in stance significantly increased in both limbs following TOR. In conclusion, the results indicate that there is scope to improve rehabilitation of patients after TKA. TOR improves gait quality and therefore has the potential to improve satisfaction in TKA patients.

Impact Statement

This thesis has the potential to make a significant impact on the future treatment of patients who have had knee joint replacement surgery and who, a year later, are still in pain or are disappointed with continued impaired mobility. The benefits of undertaking a programme of task-orientated rehabilitation (TOR) will greatly enhance their quality of life on completion of the programme and, if sustained, will benefit their future general health.

Equally, there will be a considerable impact firstly upon orthopaedic surgeons and then upon all other health care professionals, who will mediate the benefit to patients of TOR, such as physiotherapists, occupational therapists, osteopaths, GPs, etc. They will be informed and stimulated to apply TOR programmes not just for the rehabilitation of TKA patients, but also in the application of TOR to patients with musculoskeletal conditions in general. Such activities for TKA patients as increased walking on the flat and uphill would be encouraged to form a permanent and integral part of their lives.

There is no escaping the fact that increasing obesity, both in children and adults, in the UK has reached alarming proportions. It has been documented that most TKA (and THA) patients are obese, and strong encouragement for them, from informed health professionals, to persevere with increased daily activity will ultimately benefit not only their health, but also the public purse and the overstretched resources of the NHS.

It will be vital to disseminate the importance of TOR through presentations at relevant meetings and conferences, publications in appropriate journals, the teaching of future health professionals, and through informal networking with GPs and other involved carers.

As a practising osteopath in the process of studying for a PhD, I discovered for myself the importance and logic of the TOR approach, and why and how it works. As a result of which I have already incorporated the use of this approach in the rehabilitation of both acute and chronic musculoskeletal conditions, resulting in increasingly successful outcomes for my patients.

In broader terms, the ability for TKA patients to walk confidently is a crucial factor in making the difference between a fully functional member of society and a house bound individual, with a significant implication for public funds, and for their family and carers. The major impact of this study is on patients via involved health professionals in that they can be given a tool to regain their ability to walk with confidence, and most importantly to keep this ability into the future.

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Publications and presentations related to this thesis

Podium presentations:

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Walters, Y., McCarthy, I.D., Miles, J., and Birch, H.L. Can task-orientated rehabilitation improve knee function in patients 12 months after knee replacement surgery for osteoarthritis? *BORS Conference 2017,* September 2017, London, UK.

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Abbreviations

BMI	Body mass index
A_MMx	Ankle dorsiflexion moment
A_MMy	Ankle abduction moment
A_MMz	Ankle inversion moment
AIMS	Arthritis Impact Measurement Scale
CCR	Calf coronal RoM
CFI	Comparative Fit Index
CMIN	Chi-Square per df
Cor	Coronal
CR	Cruciate-retaining
GFI	Goodness of Fit index
GRAIL	Gait Real-time Analysis Interactive Lab
H_MMx	Hip flexion moment
H_MMy	Hip abduction moment
H_MMz	Hip internal rotation moment
HAQ	Health Assessment Questionnaire
Hip Thigh Calf SAG	Hip, thigh, and calf sagittal RoM for both legs
HSR	Hip sagittal Rom
HTCSAG	Hip, thigh, and calf sagittal RoM for both legs
IMU	Inertial measurement unit
K_MMx	Knee flexion moment
K_MMy	Knee adduction moment
K_MMz	Knee internal rotation moment
KFS	Knee flexion in stance
KMO	Kaiser-Meyer-Olkin
Knee SAG Flex TP Diff	Knee sagittal RoM, knee flexion in stance, and the difference between 2 peaks of thigh sagittal angle for both legs

KSR	Knee sagittal RoM
KSS	Knee Society Score
Limb SFT	Limb swing flexion time for both legs
MLL	The Motor Learning Laboratory
Non-op leg	Non-operated leg
OA	Osteoarthritis
OKS	Oxford Knee Score
Op leg	Operated leg
PCR	Pelvis coronal RoM
Pelvis Cor Sag	Pelvis coronal and sagittal RoM for both legs
PFC	Press-Fit Condylar
PSR	Pelvic sagittal RoM
RMSEA	Root Mean Square Error of Approximation
RNOH	The Royal National Orthopaedic Hospital
RoM	Range of motion
RPROMs	Patient Reported Outcome Measures
Sag	Sagittal
SD card	Storage device card
SEM	Structural equation modelling
SF-36	36-Item Short Form Health Survey
SFT	Swing flexion time
TCR	Thigh coronal RoM
THA	Total hip arthroplasty
Thigh Cor	Thigh coronal RoM for both legs
TKA	Total knee arthroplasty
TLI	Tucker Lewis Index
TOR	Task-orientated rehabilitation
WOMAC	The Western Ontario and McMaster Universities Osteoarthritis Index

Chapter 1 Introduction

1.1 General Introduction

1.1.1 Demographics of osteoarthritis

Osteoarthritis (OA) is the most common and debilitating orthopaedic condition affecting people aged 45 years and over in the UK. The major contributor and cause of the growing burden of disability in UK in 2010, after mental and behavioural disorders, was musculoskeletal disorders (30.5%), among which was osteoarthritis, which increased 16% between 1990 and 2010 (Murray et al., 2013). This resulted in major socioeconomic implications in the developed world (Martin et al., 1988). In the UK alone, a total of 8.75 million have sought treatment for OA, and more than half of them (4.7 million) for the knee joint, as it is one of the largest and most complicated of all the joints. It is predicted that the number of people with knee OA will reach 8.3 million by 2035 (Arthritis Research UK, 2013). Community-based studies in the UK suggested that 10% of people over the age of 55 had disabling knee symptoms, and 25% of these were severely disabled (Peat et al., 2001). Knee OA – after stroke, depression, and hip fracture – is considered a greater cause of disability than any other diseases in the elderly population living in their own homes (Guccione et al., 1994).

1.1.2 Risk factors for osteoarthritis

Even though the mechanisms of osteoarthritis are not fully defined, and there is still controversy over the aetiology and pathophysiology of OA (Pelletier et al., 2001), the contributing risk factors and, in particular, the combination of them which leads to the progression of disease have been well documented (Garstang and Stitik, 2006, Cicuttini and Wluka, 2014, Mueller et al., 2017, Felson et al., 1997). This current evidence supports the presence of multiple aetiological factors in the genesis of OA, namely systemic (metabolic and inflammatory), and mechanical (see Figure 1-1).

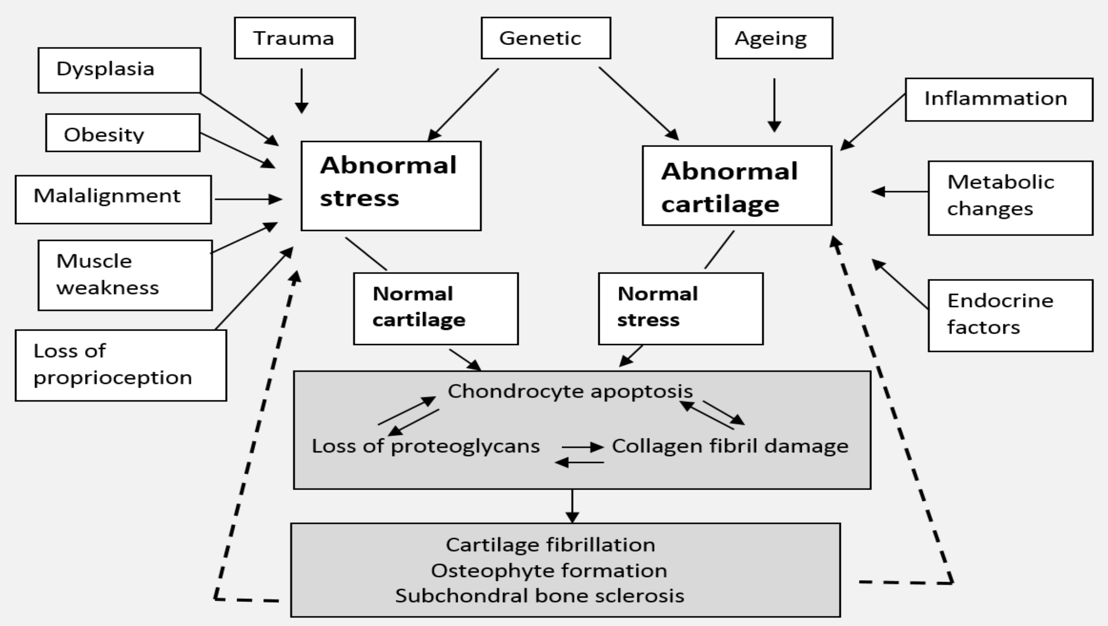


Figure 1-1: The development of osteoarthritis (adapted from Garstang and Stitik, 2006)

Age, gender, genetics (Neame et al., 2004, Valdes and Spector, 2010), and increased bone density (Teichtahl et al., 2017) operate as systemic risk factors that influence susceptibility to OA. In addition, local biomechanical risk factors, such as injury, obesity, anatomical deformity and muscle weakness determine the site and severity of the disease (Hunter and Felson, 2006). The profiles for these numerous domains overlap but are not identical in individual cases of OA (Sharma, 2001), and the mechanisms by which these risk factors affect the joints may be specific to different joints (Cicuttini and Wluka, 2014). Visser *et al.*'s (2015) study found that mechanical stresses were the most profound risk factor in knee OA, as compared to hand OA, where systemic processes, such as inflammation caused by altered metabolic regulation were responsible for pathogenesis in this joint. Cicuttini and Wluka (2014) suggested that systemic metabolic factors are dominant in the early stages of knee OA, whereas mechanical factors play a major role in the later stages. Initiation and progression of cartilage damage and subchondral bone remodelling were associated with obesity-related metabolites, especially adipokines, initiating inflammatory cytokines (Wang et al., 2015).

The major risk factors among others for knee OA, and those that reflect the current tendency in the growing population, are age as a result of increased life expectancy, and the rise in obesity (Murray et al., 2013, Coggon et al., 2001, Reijman et al., 2007, Arthritis Research UK, 2013).

1.1.3 Symptoms of osteoarthritis of the knee

Progression of knee osteoarthritis leads to standing and walking becoming extremely stiff and painful, and at the end stage of the disease limits the mobility and independence of the affected person (Arthritis Research UK, 2013, Guccione et al., 1994, Martin et al., 1988, Hunter and Felson, 2006). The impaired functions, such as walking and stair climbing, and consequent loss of mobility will contribute to multi-morbidity and frailty. A substantial body of evidence demonstrates that decline in functions is the leading predictor of mortality (Landi et al., 2010, Landi et al., 2016, St John et al., 2014, Huang et al., 2017).

1.1.4 Treatment of end stage knee osteoarthritis

There is no cure for OA (Hunter and Felson, 2006, Krasnokutsky et al., 2008), and the treatment of choice for the end stage of knee OA is total knee arthroplasty (TKA). Over the period of 2003 to 2015, osteoarthritis was the most common reason for primary replacement surgery in 96.1% of knee operations, with an annual average over this period of 69,820 surgeries (National Joint Registry, 2016). It is estimated that there will be 118,666 TKA in 2035 in UK, if 2010 rates for TKA and changes in age, gender and BMI are applied (Culliford et al., 2015).

Knee replacement usually results in relief from knee pain. However, although the surgical procedure may have been successful, and the survival rates of implants for knee and hip arthroplasty are comparable and good for both joints (National Joint Registry, 2016), patient satisfaction is much less for TKA than for THA (Bourne et al., 2010, Hamilton et al., 2012). Moreover, the outcome of the surgery may not meet the patients' expectations of regaining a full range of movement for their age. The patient's gait often does not return to a normal pattern, and their expectations of improved mobility are not fulfilled. Additionally the likelihood of contralateral knee replacement in a 5 to 10 years period is about 40% (Ritter et al., 1994, Mont et al., 1995). When the interval is determined by the patients, 50% of them underwent TKA on the contralateral limb one year after their first TKA (Ishii et al., 2014). This has become increasingly relevant in the light of evidence that knee patients' satisfaction 12 months after TKA, is at 81%, based on current accepted scoring systems, and is inferior to the satisfaction of hip patients, which is at 91% (Hamilton et al., 2012).

Although some of the risk factors for a less successful outcome after TKA have been established, the likely potential for improvement has not been fully explored.

Even though post-operative early rehabilitation after knee arthroplasty is an established practice, currently there is no consensus as to what is the most effective exercise regime for such patients, and for how long it should be continued. Typical prescribed rehabilitation exercises have an internal focus on, for example, a specific muscle, e.g. quadriceps strengthening or hamstrings stretching for increasing knee range of movement, which are intended to improve patients' ambulation. However, these types of exercises focus only on a small part of a complex movement, and therefore may have a limited influence on improving walking or carrying out everyday activities. Movement is a complex process, driven by coordinated interaction between different muscles and the peripheral and central nervous systems, suggesting that practising activities that form part of everyday life (task-orientated rehabilitation), may be a more effective way of rehabilitating patients after TKA.

Provided that no complications following surgery have occurred, patients are discharged from the hospital's care one year after knee replacement, and their course of physiotherapy and follow-up appointments are completed by then. These patients, therefore, are a good cohort for studying baseline aspects of functions and satisfaction in the longer term after TKA. They are representative of a general population group who have undergone the same surgery, consequently they represent a good cohort for initiating task-orientated rehabilitation aimed at improving function and outcome for two reasons. Firstly, they will not be given rehabilitation as a matter of routine, and therefore it is less likely that there will be confounding effects. Secondly, they are expected to have reached a plateau in their recovery at this stage, so that any benefits are likely to be due to the task-orientated rehabilitation.

1.2 Relevant anatomy and biomechanics of the knee joint

The knee is not a simple hinge joint, it combines both gliding and rolling. It is a compound joint between the distal femur and the proximal tibia with the patello-femoral articulation anteriorly, all enclosed in a capsule lined with synovial membrane. The bone ends are lined with articular cartilage, which is not only remarkably frictionless in function and self-lubricating, but is also to a degree selfrenewing. However, due to disruption of the normal breakdown and repair mechanisms of the body, as occurs in OA, chondrocytes slowly lose their ability to maintain and restore the matrix materials (Buckwalter et al., 2005, Einhorn et al., 2007). Therefore the integrity of articular cartilage is of the highest priority for joint health, and injury to this cartilage is a well known cause of knee joint morbidity (Sophia Fox et al., 2009).

The medial and lateral menisci aid in fitting the rounded condyles of the femur to the flatter plateau of the tibia, protecting the joint surfaces and assisting in rotation. The knee is stabilised by the anterior and posterior cruciate ligaments, and by the medial and lateral collateral ligaments (Figure 1-2). Further dynamic stability is provided by muscles and tendons, particularly quadriceps femoris, the hamstrings, popliteus, and the ilio-tibial band (Miller, 2008).

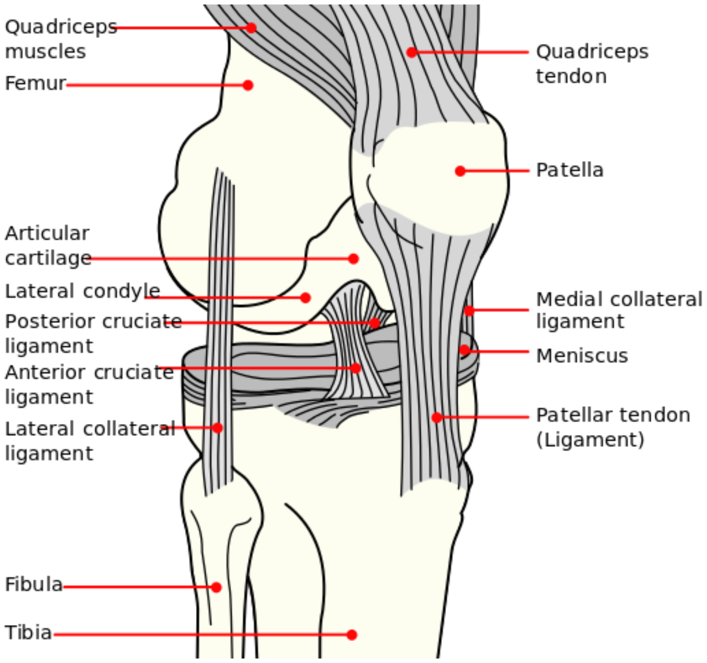


Figure 1-2: Diagram of right knee (adapted from Mysid, 2011)

1.3 Structural and gait changes in knee OA

Articular cartilage differs from other tissues in that it does not have a blood, lymph or sensory nerve supply (Sophia Fox et al., 2009). Consequently, structural changes have little correlation to symptoms, and pain is felt as a result of damage to, and reaction in the joint capsule, the synovial membrane, the ligaments and associated muscles, which are essential to the maintenance of joint stability, mobility and function (Felson, 2004, Roos et al., 2011). Research studying the morphology of mouse and human articular cartilage, using atomic force microscopy and advanced MRI scanning, found that previously undetectable changes in articular cartilage can be demonstrated before documented radiographic changes occur (Qazi et al., 2007, Stolz et al., 2009). Furthermore, it has been shown that poor correlation exists between these radiographic changes and the severity of pain and the decline in functions (Dieppe et al., 1997, Debi et al., 2011). Of the 33% of patients over 55 years of age who had radiographic evidence of OA in at least one joint, only 12% were symptomatic (Lawrence et al., 1998).

Muscle weakness, resulting from the 'quadriceps avoidance' gait pattern, which is adopted in order to reduce pain and load on the knee joint, is thought to be one of the earliest and most frequent findings in patients with OA. This may be a better predictor of disability than either pain or joint space narrowing (Palmieri-Smith et al., 2010, Roos et al., 2011).

It has been documented that the higher dynamic joint load imposed on a knee, caused by contralateral hip OA, resulted in progressive degenerative changes in this knee. This asymmetric loading of the contralateral knee joint was sustained long after THR (Shakoor et al., 2003, Foucher and Wimmer, 2012). Altered biomechanics, and consequently altered gait parameters, was found to be an important contributing factor in the progression of knee OA, and in the onset of OA in the joints adjacent to the knee joints. Widespread evidence supports characteristic alterations in the kinematic parameters of patients with severe osteoarthritic changes in their knees – reduction of maximum knee flexion angle in the stance phase of their gait, and decreased knee flexion range of motion (RoM) during the swing phase of their gait cycle (Astephen et al., 2008, Zeni and Higginson, 2009, Nagano et al., 2012, McCarthy et al., 2013). Therefore gait analysis was widely used to identify the parameters that are most affected at the different stages of the progression of knee OA (Kaufman et al., 2001, Astephen et al., 2008, Mundermann et al., 2005, McCarthy et al., 2013).

1.4 Structural and gait changes after TKA

Evidence suggests that gait abnormalities persist even after successful TKA. Li *et al.*'s study on 14 patients 12 months after TKA and 14 healthy matched controls, combining three-dimensional gait analysis and musculoskeletal modelling tailored for each participant, revealed the presence of a 'quadriceps avoidance' pattern in TKA patients in early stance, characterized by reduced knee extension moment (Li et al., 2013). Yoshida *et al.* (2012) in their longitudinal cross-sectional study analysed gait patterns in patients 3 years after TKA, and in healthy controls. They found that kinematic and kinetic gait parameters of patients and controls differed at this time. Furthermore, the presence of quadriceps strength symmetry between the operated and non-operated legs was achieved by progressive weakness of these muscles in the non-operated leg (Yoshida et al., 2012). The quality of gait after knee replacement surgery was largely determined by its quality before the operation, equally whether the patellar was resurfaced or not (Smith et al., 2006). This suggests that OA patients keep their gait biomechanics long after their knee replacement surgery.

In a similar fashion, gait analysis was used to monitor the recovery of these altered biomechanical parameters after TKA. In a cross-sectional study looking at 5 groups of participants – pre-operatively to TKA, 8, 28 and 52 weeks post-operatively, and the healthy participants – knee flexion during the stance phase was the main parameter identifying the difference between the patients and the controls. One patient out of 29 pre-operatively was in the controls' range of this parameter, as compared to 9 patients out of 28 who were in the controls' range at 52 weeks post-operatively. Knee flexion in swing was comparable with its pre-operative level, and stride duration remained around 25% slower for all stages post-operatively, as compared to controls (Rahman et al., 2015). Systematic reviews assessing studies looking at gait analysis of patients after TKA found consistency in decrease in knee total RoM, and reduced range of knee flexion during stance (ability to bend the knee under load when the leg is on the ground) for the operated leg (McClelland et al., 2007, Milner, 2009). The above research evidence demonstrates that knee flexion in stance reflects a consistent dynamic for different stages of knee OA, as well as different stages of recovery of knee function after TKA, and suggests that this gait parameter could be equally utilized in detecting the onset of OA and testing the progression of recovery after surgery. Ornetti *et al.*, on the contrary, in their systematic review concluded that kinematic gait analysis parameters were insufficient outcome measures in hip and knee OA due to their lack of significant differences (Ornetti et al., 2010).

In regards to altered gait kinetics in patients after knee replacement surgery the findings are contradictory and inconclusive, which might reflect the heterogeneity of the patients undergoing knee replacement surgery. Milner (2009) in her systematic review, analysing 5 studies on gait kinetics, summarized that a smaller peak knee flexion moment during the stance phase of the gait cycle for the operated limb, as compared to controls, may be present. In relation to the maximum knee extension in stance and adduction and abduction moments, results of the reviewed studies varied (Milner, 2009). In another review, changes in knee kinematics and kinetics for up to 24 months after TKA using three-dimensional gait analysis were considered in 19 studies. The main findings were a decrease in maximum knee adduction angle and moment, and an increase in peak knee flexion moment for the operated leg (Sosdian et al., 2014). Abnormal gait pattern in regards to the knee flexion and extension moments can be observed pre- and post- knee replacement surgery (Kaufman et al., 2001, Smith et al., 2004, Andriacchi and Hurwitz, 1997). Prediction of this abnormal gait pattern, as determined by altered knee flexor moment pattern 12 months after TKA, can be more accurately predicted based on gait analysis of such patients at 4 months after their surgery, rather than on their pre-operative gait pattern (Levinger et al., 2012b). These findings show that the pattern of the gait identified at 4 months after their TKA is likely to be their permanent gait pattern, suggesting that initiation of an appropriate rehabilitation programme aiming at improving their abnormal gait pattern at this stage, as compared to later, might be more effective.

Even though gait analysis is widely used in research, showing that it could be a powerful tool for objective assessment of functional outcome of patients after TKA, namely walking, it is not a routine test in the current healthcare of such patients in UK.

1.5 Gait analysis techniques

Different techniques for analysing gait quality and functional performance have been used in research settings, such as optical motion capture systems, force platforms, isometric strength testing, electromyography and ambulant motion sensors (van den Dikkenberg et al., 2002, Dobson et al., 2012), to identify factors contributing to less successful outcomes following total knee replacement. Gait analysis can provide kinematic and kinetic data. However, this process takes a long time to perform and analyse. Traditional gait analysis is, therefore, not suitable for routine clinical assessment of patients with knee osteoarthritis. New state-of-art equipment for gait analysis such as the instrumented treadmill supplied by Motek Medical is being increasingly used in clinical assessment of pathological gait patterns. This system allows all gait parameters to be monitored in real-time, and the assessment of biomechanical and physiological performance can be available within half an hour. However, the cost of purchasing and running these systems is prohibitive at the present time. There are other systems that are reasonably inexpensive, e.g. the GaitRite mat, which can measure step time and length, single and double support time, and can give the results immediately. Having said that, its limitation is that it does not measure joint angle. The main point is to have a system that is portable, easy to use by physiotherapists, and can deal with a high volume of patients.

On the other hand, inertial measurement units (IMUs) are small units, comprising accelerometers, gyroscopes and magnetometers, which can be strapped to the patient's leg during walking, and provide measurements for gait assessment. Accelerometers measure acceleration, and also the orientation of the IMU with respect to gravity; gyroscopes measure rotation; and the magnetometers measure the orientation of the device with respect to the magnetic field. A combination of these measurements allows calculation of the movement of the device and when two IMUs are put on the leg, knee joint angle can be calculated. The use of IMUs to assess lower limb kinematics has made objective functional assessment of patients available in the clinic, and in communities.

It has been demonstrated that gait analysis using IMUs can identify abnormalities of gait in patients about to undergo knee replacement surgery, and afterwards. The gait parameters of patients with early knee OA exhibit a characteristic pattern, with reduced knee flexion during stance (McCarthy et al., 2013), compared with healthy controls (Monda et al., 2015). After TKA it was found that although knee movement was improved at 52 weeks post-operatively, the range of motion and stride duration of two-thirds of these patients were inferior to that of the controls (Rahman et al., 2015). These studies' findings are in compliance with those presented earlier in this section, where gait kinematic parameters were measured in specially designated laboratories, equipped with much more expensive and elaborate equipment. The cost, portability, and ease of use allowed utilisation of this equipment in this study.

1.6 Post-operative assessment and care

Following TKA, patients are usually seen in an out-patient clinic by the arthroplasty team at 6 weeks and 52 weeks after their surgery to examine wound healing, and assess their pain, passive RoM, muscle power and functions indicating their ability to walk independently. At 52 weeks follow-up they will have an X-ray to assess implant position and alignment. If there are any concerns with the wound or implant, they will be seen as often as necessary, and will be discharged only when clinically appropriate. Additionally, patients complete an OKS questionnaire to assess their perception of functions and pain following their knee replacement surgery.

Even though the importance of pre- and post-operative physiotherapy intervention for improvement of physical impairments caused by the development of osteoarthritis is recognized, the effectiveness of perioperative physiotherapy programmes in terms of their content and duration lacks evidence. Protocols for rehabilitation of TKA patients are mainly dictated by the hospitals physiotherapy staff and may differ between hospitals, as accepted protocols do not exist. Moreover, there is no body of knowledge as to whether physical activity after TKA should be prescribed or avoided (National Institutes of Health, 2003), neither are there accepted guidelines laid down by NICE.

A hospital specific standardized course of physiotherapy begins next day after the operation, initially while the patient is still in bed, commencing with bedside exercises, aiming at quadriceps strengthening, improving knee RoM, especially knee flexion, and general mobility to and from bed. Provided that the patients' vital signs -

blood pressure, heart rate, and haemoglobin level - are normal they will progress on day 2 to supervised gait training with assistive devices (crutches or frame), and continue strengthening and RoM exercises. From day 3 onwards such patients will additionally increase their walking distance, start stair training and activities of daily living. After 4-5 days they are discharged to home, if they are able to bend their knee independently to 90 degrees. Patients are advised and given an instruction sheet on discharge to continue with the exercises at home for improving strength and RoM of their knee, as they have been taught during their hospital stay.

Their standard course of out-patient physiotherapy begins 10 to 14 days after their operation. TKA patients use crutches for up to 6 weeks and based on the results of the initial assessment of the strength of their lower limb muscle groups, core stability, RoM, and gait, they are either assigned to a knee class (one hour duration), normally for 6 sessions once a week or fortnight, or offered one-to-one sessions (30 minutes) once or twice weekly. The number of sessions varies and is based on their goals and their progress towards normal walking with good knee flexion, lack of pain, and normal gait. As a rule, patients should be walking independently between 6 weeks and 3 months after their surgery. By discharge patients will have been given long-term information on exercises and their progression, so that they can continue with exercises on their own.

Even though a rehabilitation exercise programme following surgery is standardized in relation to what components should be included in the programme, which are restoration of RoM, strength, functional activities and cardiovascular fitness, to date there is no consensus as to what is the most effective exercise regime for such patients. In fact it has been shown that most therapists’ application of their knowledge is intuitive and comes from their personal clinical experience (Fuhrer and Keith, 1998), demonstrating their diversity.

Thus, it can be seen that the current practice of supervised rehabilitation is normally completed approximately 4 months after TKA (provided the patient does not have any complications) and further progress of such patients relies entirely on their compliance with the set of exercises they have been given.

1.7 Why do TKA patients need to improve their gait?

Falls in older people constitute a well-known major public health concern, imposing a heavy burden on the whole of society every year (Wood et al., 2010). There were over 470,000 hospital consultant episodes in 2015/2016 for injuries resulting from falls in England, over 70% were for those aged 60 and over (National Health Service Digital, 2016). The cost of falls to the affected person encompasses painful injuries, hospitalization, mental and physical distress, loss of confidence, mobility and independence, and leads to premature mortality. According to NICE, the estimated annual cost of falls for the NHS in 2013 was more than £2.3 billion. All in all, the consequences of falling are a decline in the quality of life and health, and a rise in the healthcare costs, with serious implications for the families and carers of fall victims (National Institute for Health and Care Excellence, 2013).

Knee OA is a significant risk factor for falls (Arden et al., 2006, Doré et al., 2015) and a greater risk for women (Prieto-Alhambra et al., 2013). With increased longevity, it is predicted that the prevalence of knee OA and consequent falls will rise (Arnold and Gyurcsik, 2012, National Health Service Digital, 2016). The major risk factors associated with falls in older people are not dissimilar to those with knee OA such as muscle weakness, balance, gait deficit, and restricted mobility (Rubenstein, 2006). These problems are routinely addressed during post-operative rehabilitation of TKA patients as described above.

Knee pain and function show significant improvement after TKA (Bachmeier et al., 2001, Swinkels et al., 2009, Tsonga et al., 2016). Correspondingly, improvement in reduction of falls after TKA was documented across pre-operative fallers and non-fallers, with a greater risk for those who experienced falls before TKA and who experienced a fear of falls (Tsonga et al., 2016). Similarly, Swinkels *et al.* (2009) documented that out of those who experienced falls before their TKA almost 46% had fall reoccurrence within the first post-operative year, with an 8-fold increase in the risk of falls post-operatively. Interestingly, Matsumoto *et al.* concluded that all those who have had TKA are at greater risk of falls, as compared to unimpaired healthy counterparts. Reduced knee flexion and ankle plantar flexion were identified as the major risk factors (Matsumoto et al., 2012). Their findings imply that gait problems before and after TKA are a likely predictor of the risk of falling.

Gait deficiency at 12 months after TKA has been documented in numerous studies (Andriacchi and Hurwitz, 1997, Smith et al., 2004, McClelland et al., 2007, Milner, 2009, Levinger et al., 2012b, Yoshida et al., 2012, Sosdian et al., 2014, Rahman et al., 2015), however, the contribution of this deficiency and its propensity to increase falls risk was not investigated. It is shown that impaired gait leads to reduced mobility, which results in muscle weakness and further deterioration in gait, which, in turn, contributes to falls.

It is the serious consequence of falls that makes the prevention of falls of paramount importance. Gait improvement, which this study attempts to explore, is the key not only for prevention of falls, but also for improving mobility, cardiovascular fitness, and reducing progression of OA in other joints by more efficient load distribution on these joints.

1.8 Patients' satisfaction one year after knee replacement surgery

The follow up data on more than 20 years of primary TKA (1981 – 2001) showed consistent success for the outcome of the surgery, with about 90% of patients experiencing marked and speedy relief of pain, improvement in everyday living functions, and general quality of life. However, a small but significant 15% of patients reported an unacceptable level of pain and a deficit in functions after their surgery (National Institutes of Health, 2003). The predisposing factors for poor outcome in this group of the population are not entirely clear, but taking into account the growing size and age of the population, the number of knee replacement operations will steadily rise, inevitably increasing the number of patients with poor outcome. Singh and Lewallen (2014) found worsening in patient-reported function and pain outcomes, in their study of 7,229 TKA patients over a period of 12 years (from 1993 to 2005). The patients were assessed prior to their knee replacement and 2 years after, showing more dissatisfied patients in 2002-2005 as compared to 1993-1995 (Singh and Lewallen, 2014). Interestingly, TKA patients from UK having equal pain relief at one and two years after their surgery, demonstrated an inferior functional outcome, as compared to patients in United States and Australia (Lingard et al., 2004). In the absence of mechanical failure of the implant itself, there is no recognized treatment available for them.

Patients' assessments of the benefits or otherwise of their surgery are quantified using patient-reported outcome measures (PROMs) and there are a number of different PROMs currently in use. A systematic review evaluating the most widely researched PROMs, which are the Oxford knee Score (OKS), Knee Society Score (KSS), Osteoarthritis Outcome Score and Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC) concluded that there is no consensus on the most reliable PROM in respect of TKA patients' priorities, and consequently no clear definition of a successful outcome of the surgery (Ramkumar et al., 2015). Nevertheless the OKS is widely used in the current healthcare of patients with OA in the UK for monitoring OA progression, and recovery after surgery. As a measure of outcome of TKA, it is short (12 questions), reliable, valid and sensitive for identifying clinically significant changes over time (Dawson et al., 1998). The score from 0 to 29 indicates moderate to severe OA, from 30 to 39 indicates mild to moderate OA, and score from 40 to 48 may be indicative of satisfactory joint function (Kurer and Gooding, 2005). The OKS is a validated outcome measure, but it does not explicitly measure satisfaction. There is however a body of evidence showing that satisfaction is related to PROM scores (Dunbar, 2001, Dunbar et al., 2013, Pivec et al., 2015, Choi and Ra, 2016), therefore it is possible to infer satisfaction from it. In any case, for the current study the decision was made to use a validated PROM rather than unratified ways to assess satisfaction.

The major factor for inferior patient satisfaction, and greater variability in their PROMs has been ascribed to unmet expectations in regards to demanding physical activity and return to normal function. This has become more relevant with the growing younger and more active group of patients who now require knee replacement surgery (Nilsdotter et al., 2009, Dunbar et al., 2013, Hamilton et al., 2013, Witjes et al., 2017). In regard to older TKA patients, despite a reliable reported reduction in pain and improvement in functions, it is rare for their strength and abilities to be restored to normal levels, making them predisposed to future disability with further ageing (Silva et al., 2003, Mizner et al., 2003, Senden et al., 2011, Stevens-Lapsley et al., 2011).

1.9 Has task-orientated rehabilitation a potential to offer improvement of gait quality for patients from 12 months after TKA?

The aims of rehabilitation of the patients after knee replacement are to restore a full range of painless movement in the knee joint and return these patients to their normal functions, while the repair and adaptation processes following surgery are taking place. However, patients need to overcome a number of barriers to recover their functions: the major ones are the structural changes to the tissues as a result of poor repair and healing after their surgery (lack of load on the tissues) (Buckwalter and Grodzinsky, 1999, Tohyama and Yasuda, 1998); altered motor control as a protective mechanism (van Dieën et al., 2003); then pain (Lamothe et al., 2014); lack of motivation and compliance for whatever reason (Sirur et al., 2009); and, not uncommonly, a lack of confidence in their new knee joint (Unver et al., 2014). Although the ability to learn complex tasks has been found to diminish with increasing age, no difference was observed in the ability of those with advancing age to learn gross-motor-skills, such as walking (Voelcker-Rehage, 2008), suggesting that improved gait is achievable in older individuals. What remains unknown is the best way to overcome the barriers associated with poor gait following TKA.

Movement is necessary for survival, and we need to understand its nature and how it is controlled. Movement produced by an individual is tailored by the demands of the task performed within a specific environment (Shumway-Cook and Woollacott, 2007). Consequently, the organization of the movement is constrained by constituents in the individual (action, perception (Bernstein (1967) and Rosenbaum (1991) as cited by Shumway-Cook and Woollacott (2007), and cognition), the task (stability, mobility, and manipulation (Gentile, 2000)), and the environment (regulatory and non-regulatory (Gordon, 2000)). Motor control studies that address only an individual, and miss out the environment and the tasks which are performed in the given environment, will produce an incomplete portrayal (Shumway-Cook and Woollacott, 2007). Equally, rehabilitation that focuses only on an individual's strength, RoM and flexibility, without taking into account all aspects of the individual, their daily tasks, and their specific environment in which these daily tasks are performed, would probably be less effective, due to overlooking some of these aspects. The process of motor learning (which could be applied either to acquisition or modification and recovery of function) should be taken in the context of how a person solves a functional task in a defined environment (Higgins, 1991, Newell, 1991). Task-orientated rehabilitation (TOR) is an approach based on the interplay between these three integral concepts of movement, namely, the individual, the task and the environment, which are required for successful motor control, motor learning and rehabilitation (Shumway-Cook and Woollacott, 2007).

Normally, anyone after injury, or post-surgery, will make efforts to reproduce impaired movement, gradually regaining lost function. Bayona et al. opined that it makes intuitive sense that the best way to relearn a given task is to train specifically for that task (Bayona et al., 2005). This is natural recovery behaviour, observed in animals and humans after injury or immobilisation. As a result of the experience gained in doing this, the person acquires the knowledge that movement goals can be reached by repeating particular actions (Higgins, 1991, Newell, 1991, Shumway-Cook and Woollacott, 2007, Lederman, 2013). This learning leads to a permanent change in motor behaviour, and the securing of skilled behaviour (Shumway-Cook and Woollacott, 2007).

The majority of the task-specific training research was done in relation to rehabilitation of post-stroke patients (French et al., 2008, Pollock et al., 2014), where the beneficial effect of such training for this group of patients was shown. A randomized controlled trial (RCT) on rehabilitation of sub-acute stroke patients confirmed that a 4 week meaningful task-specific training produced significant and clinically relevant improvements in the upper extremity motor recovery of such patients, as compared to the control group participants, who were taking part in a dose-matched standard training programme (Narayan Arya et al., 2012). The relevance of task-specific training was also documented for patients with post-traumatic brain injury (Canning et al., 2003) and a spinal cord injury (Betker et al., 2007), and Parkinson’s disease (Mak and Hui-Chan, 2008). However, the evidence for use of task-specific rehabilitation in patients with joint replacement is sparse. Drabsch *et al.* found that a 6 week task-specific walking training may aid improvement in walking performance in THR patients 12 months post-surgery

(Drabsch et al., 1998). Bruun-Olsen *et al.* found that a 6-8 week walking-skill programme in patients after TKA was more beneficial for improving walking of such patients than conventional physiotherapy (Bruun-Olsen et al., 2013).

It could be suggested that patients with limitations in their knee movement after knee replacement surgery will attempt to walk more and more, gradually increasing the swinging of their limbs, thereby increasing their range of movement; they will cover longer distances in shorter times, consequently generating more force at greater speed, and eventually gaining better ambulation.

The majority of patients do recover naturally, but can the above approach be prescribed to those who do not redeem their normal walking pattern? To do so, one needs to know what the algorithm and essential components are that make this recovery of movement possible. There are three identifiable features in recovery behaviour that benefit the process of improving range of movement and regaining fully functional movement:

a. The movement ought to be as close as possible to the functional task performed by the affected part of the body on an everyday basis.
b. The physical demand on this affected body part should be gradually increased by requiring progressively exaggerated movements.
c. It should be exercised as often as possible throughout the day.

These essential components resemble the specificity, overloading and repetition principles employed to enhance sports performance. Thus an algorithm of a RoM rehabilitation programme can be formulated by engaging these three elements. This type of rehabilitation of RoM is referred to as “managed recovery behaviour”, on the basis that the patients are self-sufficient and compliant with their rehabilitation programme (Lederman, 2013). Therefore task-orientated (functional) rehabilitation is managed recovery behaviour aimed at returning impeded movement to normal function.

The concept of specificity in rehabilitation should be considered in the context of the complexity of the whole movement, which requires coordinated interplay between different muscles and the peripheral and central nervous systems, and driven by the task-orientated goals. Nicholson *et al.* in their study using fMRI, found that the goals (goal task) of everyday actions are primarily linked to object (object task), rather than motor-kinematic (movement task) information (Nicholson et al., 2017). Applying this finding, the rehabilitation needs to be tailored to the persons' specific needs. The participants with knee replacement all require their own specific goal tasks and object tasks to achieve the best possible outcome for them. For example, the goal task for TKA patients could be to buy food for existence, and the object task would be to visit the shop. By carrying out these tasks, they may gradually master their walking.

Motor adaptation can be facilitated by mental practice in a very similar way to physical practice (Schmidt and Lee, 2005). Imagining a movement activates cortical motor areas in similar patterns to those activated during actual physical practice (Jeannerod, 2001).

Numerous studies show that a lost skill, such as correct walking, can be regained irrespective of when this skill was originally learnt (Higgins, 1991, Newell, 1991, Schmidt and Lee, 2005). Providing the person with feedback on their current skill, and showing and explaining to them how to perform it correctly, has an important role in the learning and/or modification and recovery of motor tasks (Bilodeau et al., 1959, Schmidt and Lee, 2005).

1.9.1 Internal vs external focus

In standard hospital physiotherapy practice for improving patients' walking, rehabilitation mainly focuses on specific muscles' strength and lengthening for achieving increased RoM in a specific joint, in the case of knee OA, the knee joint, normally using single planes of motion. Research demonstrated that rehabilitation focusing on the details of the learners own actions (internal focus) rather than being directed to the goals of the movement (external focus) was less beneficial for the recovery of a deficient walking pattern (McNevin et al., 2000). Furthermore, prescriptive agendas for rehabilitation were inferior to those allowing individuals to choose their training routine themselves (McNevin et al., 2000). Moreover, walking, as with most functional activities (or task-orientated activities), is a complex active multi-planar movement, which requires a combination of acceleration, deceleration, and dynamic stabilization (Sahrmann, 2002). Movement may appear to be one plane dominant, which, in the case of walking, is sagittal, however, in order to achieve the best possible neuromuscular control, the other planes need to be dynamically stabilized (Clark, 2001).

Any movement has a focus of attention to achieve an aim or fulfil a purpose, which in the case of walking would be to reach the point of destination (external focus); fortunately, we do not have to decide which muscle to contract, or joints to flex, before starting to walk (Jackson, 1889). When we want to carry out a task, the thought of the outcome triggers the required movement, and all the anticipatory muscle engagement which is involved in this action (Koch et al., 2004). Muscle recruitment is task specific, ergo different tasks demand the use of different muscles (McGill et al., 2003, Carpenter et al., 2008, Boettcher et al., 2010). Studies investigating motor control and learning demonstrated that external focus of attention, i.e. focus on the effect of the action rather than on the body movement, resulted in a more accurate movement executed in a more efficient way, by augmenting the economy of the movement (Zachry et al., 2005, Lohse et al., 2010). This suggests that external focus of attention might be a more effective rehabilitative strategy, where improvement is achieved in the whole movement, rather than in its fragmented parts.

Although the outcome of rehabilitation, applying either internal or external focus, may be the same – as in the case of achieving full range of flexion after TKA – their practical application for handling RoM challenges differs significantly. In the internal focus the therapist will target strengthening knee flexors and elongating knee extensors, improving core stability, etc., with concomitant explanations of each exercise movement pattern, and how to perform it correctly. These static exercises are more likely to be done either lying or sitting, which is not the position from which the patient will commence walking. Consequently, these exercises may have little relevance to the functional application of walking. Using an external or goal approach, the patient is encouraged to walk trying to take longer strides, gradually increasing the target distances, their speed and the complexity of walking tasks such as walking uphill, upstairs, different terrains, etc. External focus is more economical from a clinical point of view as minimal instructions produce a maximum effect, as the patient does not need to be aware of which muscle needs to be worked on to improve their walking, and what happens with the muscle as his/her walking gets better. There is evidence that more distant focus of attention facilitates more enhanced learning by encouraging the recruitment of more natural control mechanisms, and a reverse effect when the focus is directed towards the body itself (McNevin et al., 2003). Such an approach to the rehabilitation process uses what the patient already knows (how to walk), and what he/she is working towards, i.e. walking better. Thus, the patient requires only minimal instruction to increase control of their movement. In other words, improvement of movement pattern is within the task itself, which makes for a natural process of improvement, and the gains of this type of training can be smoothly transferred from rehabilitation to functional activities (Kurtzer et al., 2003, McNevin et al., 2000, Zachry et al., 2005, Lohse et al., 2010).

1.9.2 Specificity, generalisation, transfer skills within and between tasks

Task specificity occupies a starting point, and is the most important role in functional adaptation. The concept of specificity is to rehabilitate the lost movement by practicing using similar movement. It has been documented that learning particular motor skills is specific to the task in hand (Kurtzer et al., 2003). Motor control, tissue and physiological adaptation are tailored to that individual specific task (Withers et al., 1981, Haga et al., 2008, Millet et al., 2009), enabling the least energy consumption, less stress on body structures, and more efficient body biomechanics for the execution of this task. Adkin *et al.* (2006) studied changes in the structure and function of the human motor cortex and spinal cord while these were subjected to skills, strength or endurance training and found that anatomical and physiological patterns of plasticity of the corticospinal system are adapted to the specifics of exposure to different motor activities (Adkins et al., 2006). Applying the principle of task specificity in the training for achieving better mobility, by means of improving the walking pattern in patients with a replaced knee, such training should be relevant to the patient’s ability and conducted in the context of this particular patient’s environment (Shumway-Cook and Woollacott, 2007).

Specificity does not mean a unique movement, as soon as the required movement is learned, variations of this unique movement can be performed without the need to practice and learn them individually (Shadmehr, 2004, Krakauer et al., 2006, Wilde and Shea, 2006). This ability to use what has been learned in one setting in many other settings is called generalisation (Krakauer et al., 2006). The brain has the ability to predict the complicated biomechanics of our limbs by adapting the specific force requirements of the given task, while the movement is being performed (Shadmehr, 2004). The more productive practice for improving the retention and transfer of a learned task, and consequently for expanding its generalisation (Schmidt and Lee, 2005), needs to be random in its application, i.e. incorporating a variety of settings and contexts, physical demands and sequences of actions (Bayona et al., 2005, Rotem-Lehrer and Laufer, 2007).

Following the above concepts, training practice is clearly more effective if it is task-specific, and driven by rehabilitation goals (Hubbard et al., 2009). In the case of walking, the most effective way to improve is by doing more walking. The variations of learned movement transfer are only possible within the walking task (Wilde and Shea, 2006, Muehlbauer et al., 2007, Dean et al., 2008, Buchanan et al., 2007, Leirdal et al., 2008). Research demonstrates that task specificity is the most effective form of training or practice, whereas the transfer of skills between different tasks is either insignificant or entirely absent (Schmidt and Lee, 2005, Hartmann et al., 2009, Magnusson and Renström, 2006).

For task-specific rehabilitation to be effective it requires to be repetitive and to entail extensive practice (Schmidt and Lee, 2005). This requires practicing the deficient activity in all possible variations, involving greater ranges of motions and speeds, using different settings for practicing the activity, and designating a longer period of time for this practice. Assistive technology such as pedometers can be used to encourage consistent practice. It has been shown that pedometers are an important part of self-rehabilitation (motivation, drive, being able to see what has been done on each day, etc.). For example, a study of older adults with symptomatic OA, investigating the use of pedometers for the daily monitoring of the number of steps walked with the goal of a gradual increase in the number of steps, demonstrated a 23% increase in the number of steps in the group which was using the pedometers as compared to the group which was not, where the number of steps decreased by 15% on the completion of a 12 week programme (Talbot et al., 2003).

Research shows that the successful performance of the task can only be achieved with progressively more intensive practice (Blennerhassett and Dite, 2004, Bayona et al., 2005). This may be the reason why current rehabilitation of patients after TKA is not always effective. The patients see their physiotherapist once a week, if not once a fortnight, and their prescribed exercise practice depends on their understanding in regards of repetitions, compliance, correct execution of prescribed exercise, and the time devoted for the prescribed exercises. Successful task-specific training could be simply consciously embedded in their daily routine, avoiding unnecessary worries in relation to correctness. Patients would know from provided feedback (their gait assessment) how to adjust their walking to make it better. In task specific training the patient can choose walking distance based on their pedometer recorded progress ensuring the targets set are feasible. The ability to set their own targets adds meaning and provides empowerment (they are in charge of their own progress) and consequently motivation for this type of rehabilitation.

Task-orientated rehabilitation is based on the idea that deficient moments and, as a result, lost RoM, whether as a result of injury, immobilisation, or surgery, can be restored by using a repertoire of the individual's daily activities. These activities should be executed with gradually increased amplitude of the movements normally used in performing these actions. Results are achieved by a greater loading of body structures involved in these movements and the consequent action, repeatedly, consistently and for a prolonged length of time, facilitating this physiological adaptation.

This study looks at whether task-orientated rehabilitation can improve reduced knee flexion in the stance phase of walking following TKA, as previous studies have shown that it is this gait parameter that is the most affected.

1.10 Conclusion

Evidence shows that OA of the knee is the most common and debilitating orthopaedic condition affecting people aged 45 years and over in the UK. It is a major cause of disability, and end-stage OA requires joint replacement surgery. Even though the surgical procedure may have been successful in terms of relieving pain, patient reported functional outcomes, as measured by OKS, are not as good for TKA as for THA. Patients are often disappointed with mobility, which may have resulted from an abnormal gait acquired with the progression of the disease, and which has remained long after surgery. Understanding the relationship between gait and mobility in patients after their knee replacement surgery is of significant importance, so that better rehabilitation can be designed and implemented to improve patient satisfaction, as the potential for improvement has not been fully explored. Specific TOR programmes, where all aspects of movement are involved, hold great promise for an improved outcome for TKA patients following surgery.

Chapter 2 Aim, hypotheses and objectives

2.1 Study aim

The aim of this study was to improve the quality and quantity of patients' gait and thereby their satisfaction with their mobility following TKA using a novel task orientated regime.

2.2 Hypotheses

1. Lower patient reported functional outcome scores in patients following TKA are associated with impaired gait.
2. The outcome of TKA may be enhanced by specific task-orientated rehabilitation (TOR) directed towards improving gait at 12 months after surgery.

2.3 Objectives

2.3.1 Primary objectives

In order to test these hypotheses, the specific primary objectives of this study were:

1. To determine the relationship between the quality of patients' gait and their functional outcome as measured by a standard PROM score.
2. To determine whether a specific task-orientated rehabilitation programme in patients with a poor gait pattern 12 months after surgery can improve the quality of their gait.
3. To assess whether the rehabilitation programme improves functional outcome as measured by a standard PROM score.
4. To investigate whether there is a relationship between patients' activity level and changes in their gait and PROM scores on completion of their rehabilitation programme.

2.3.2 Secondary objectives

In order to create differing controlled conditions in relation to speed and gradient, which allow stressing of the participants gait deficiencies more profoundly, and therefore to reveal any changes in gait kinematic, and, additionally gait kinetic variables which were not available from the GaitSmart system, an instrumented treadmill (a clinic based tool) was used to test the secondary objectives of this study:

1. To explore the effect of speed and slope on the hip, knee and ankle joint kinetics and kinematics of healthy participants, and of patients 12 months after TKA using the instrumented treadmill and IMUs;
2. To explore the effect of the rehabilitation programme on the hip, knee and ankle joint kinetics and kinematics of patients 12 months after TKA, walking at different speeds and on an incline using the instrumented treadmill and IMUs.

Thesis layout

General methods (Chapter 3)

The general method outlines the relationship between the four experimental chapters of the study (Figure 3-1, p.51). It identifies the stages of the study; setting and timescale; criteria for selection of participants; specific measurements; and a brief study procedure.

Primary objective 1: The relationship between patient reported outcome and their quality of walking 12 months after knee replacement surgery (Chapter 4)

The work in this chapter tests the hypothesis that a correlation exists between the patients' reported satisfaction 12 months after TKA and their gait quality. To examine the relationship between patient satisfaction and gait quality, patient satisfaction with function 12 months after TKA was measured in 76 patients (male/female ratio = 30/46, mean age = 64.5 ± 8.8 years, BMI = 30.3 ± 5.4) using the OKS, and their gait kinematics were measured using IMUs (GaitSmart).

Primary objectives 2, 3, and 4: Efficacy of task-orientated rehabilitation in improving knee function and satisfaction in patients 12 months after knee replacement surgery for osteoarthritis (Chapter 5)

The work in this chapter tests the hypothesis that the outcome of TKA may be enhanced by specific task-orientated rehabilitation (TOR) directed towards improving gait at 12 months after surgery. In order to assess the effect of TOR a subset of 21 patients from the 76 (male/female ratio = 9/12, mean age = 65.9 ± 8.5

years, BMI = 31.7 ± 6.5) exhibiting abnormal gait (knee flexion in stance below 12 degrees) entered a novel 4-week TOR programme, based on daily walking and stair climbing. Patients were then re-assessed with OKS and IMUs. To determine whether there was a relationship between an increase in patients' mobility and changes in patients' gait and OKS, gait quantity (i.e. mobility) was compared pre- and post-intervention using pedometers (Fitbit One). The pedometers were validated prior to their use in the rehabilitation programme.

Secondary objective 1: Effect of speed and slope on walking performance in the healthy and in those 12 months after TKA (Chapter 6)

The work in this chapter tests the hypothesis that the kinetic and kinematic responses of healthy participants to different treadmill speeds would differ from that of patients 12 months after TKA (before the TOR), and that these measurements would be significantly affected by walking on an incline. The instrumented treadmill (GRAIL) was used to explore the effect of speed and slope on 3-dimensional kinetic parameters – hip, knee and ankle joint moments of 5 healthy participants (male/female ratio = 2/3, mean age = 61.2 ± 7.2 years, BMI = 23.6 ± 3.1) and of 4 patients (male/female ratio = 2/2, mean age = 60.3 ± 8.7 years, BMI = 31.7 ± 2.6) 12 months after TKA (before the TOR). Their 2-dimensional gait kinematics (knee stance flexion, sagittal knee, hip and pelvic RoM, and coronal pelvic, thigh and calf RoM) for the same speed and slope conditions were explored with IMUs (GaitSmart). The tested conditions were treadmill level walking at speeds of 1.0, 1.2, and 1.4 m/sec; and treadmill inclined walking at 5 degrees at a speed of 1.2 m/sec.

Secondary objective 2: The effect of the TOR programme on treadmill walking in TKA patients 12 months after surgery (Chapter 7)

The work in this chapter tests the hypothesis that there would be positive changes to different treadmill speeds, and to walking on an incline in the kinetic and kinematic gait responses of 4 patients (the same patients as in Chapter 6) 12 months after TKA, before and after their TOR programmes. In order to assess the changes in kinetic and kinematic gait variables (the same gait variables as in Chapter 6) resulting from TOR, patients were tested before (in Chapter 6) and after their rehabilitation programmes with the instrumented treadmill (GRAIL) and IMUs (GaitSmart) (the treadmill conditions were the same as in Chapter 6).

Chapter 3 General methods

3.1 Overall design of the experimental chapters of the study

The general method outlines the relationship between the four experimental chapters of the study. It identifies the stages of the study; setting and timescale; criteria for selection of participants; specific measurements; and a brief study procedure. The detailed protocols are presented in these subsequent experimental chapters.

The study design was an interventional cohort study with patients 12 month after TKA surgery to investigate the relationship between gait pattern, functional assessment and activity, and to assess the efficacy of a task-orientated rehabilitation (TOR) programme. Quantitative data were collected using a questionnaire and gait analysis systems.

The study was composed of two stages as presented in Figure 3-1:

Stage 1 – Patients 12 months post TKA (n = 76), were investigated for the relationship between gait pattern (using IMUs), and functional outcome (using OKS). Chapter 4 describes this part of the study.

From these 76 patients, 4 patients, who were under 71 years of age, and had recorded a poor outcome (knee flexion below 12 degrees, as assessed by IMUs) received an additional and more detailed gait assessment, at different speeds and inclines, on the instrumented treadmill using GRAIL and IMUs. Data collected on the treadmill were compared with the data collected from 5 age-matched healthy controls. Chapter 6 presents this part of the study.

Stage 2 – 21 patients with a poor outcome (knee flexion below 12 degrees, as assessed by IMUs), including the 4 patients who received an additional gait assessment on the treadmill, were chosen from the cohort of 76 patients in Stage 1. These 21 patients took part in a 4 week TOR programme. Prior to commencing the 4-week rehabilitation exercises, consisting of walking on the flat and uphill, and climbing stairs, participants' baseline activity levels were monitored for 3 days with a pedometer device (Fitbit One). After 4 weeks the patients were re-assessed by OKS and IMUs. In addition, ten patients were re-assessed 11 weeks after the completion of their TOR programmes to explore whether any obtained progress could be sustained in the absence of the monitoring devices. Chapter 5 describes this part of the study.

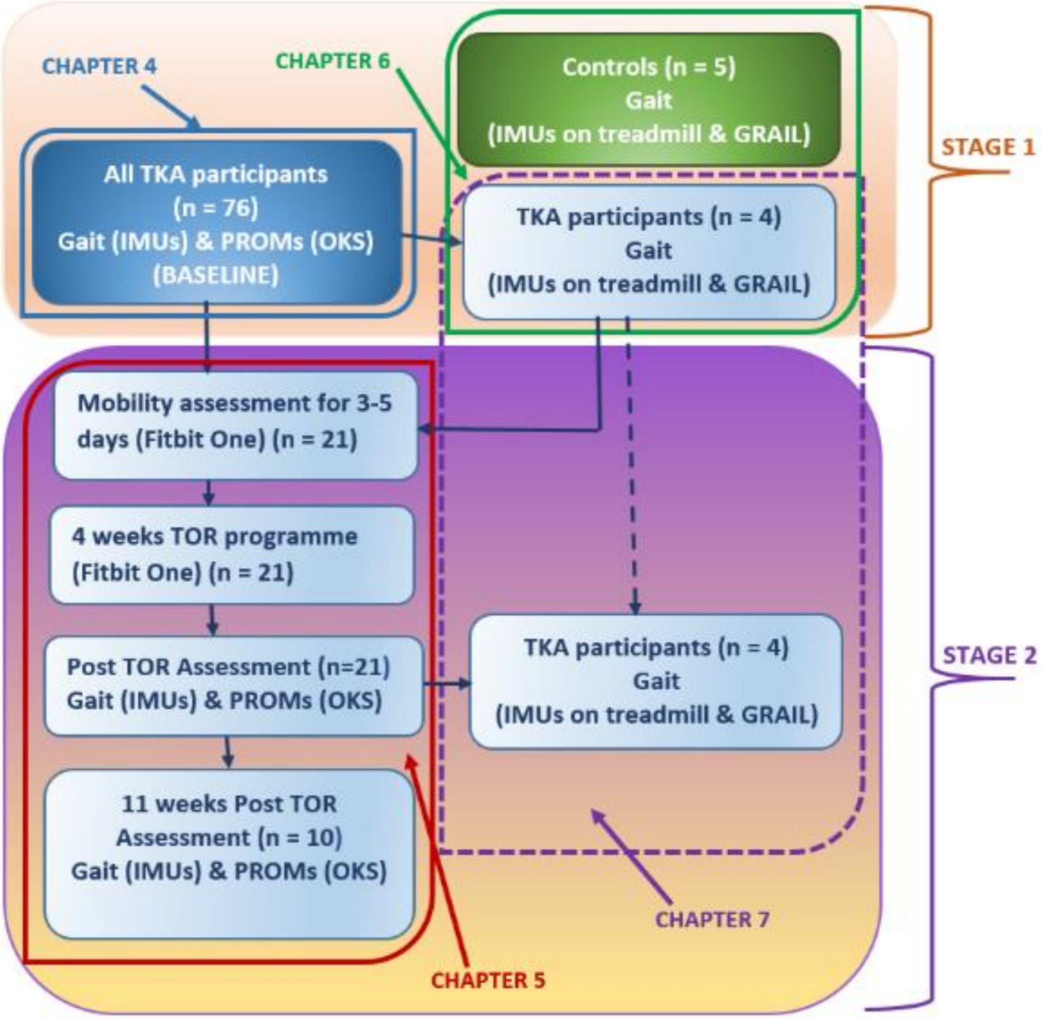


Figure 3-1: Flow chart of the whole study

The 4 patients who had a detailed gait assessment on the instrumented treadmill in Stage 1 were, in addition, re-assessed on the treadmill in the same way. Their baseline results were compared to those after the TOR programme. Chapter 7 describes this part of the study.

3.2 Ethical approval

The study was approved by London-Stanmore Research Ethics Committee (REC reference: 15/LO/0164) (see Appendix I: Ethics Approval).

3.3 Setting and timescale

The study was conducted at the Royal National Orthopaedic Hospital (RNOH), Stanmore. Assessments were performed in the out-patient clinic. The testing of four patients and five healthy controls on the instrumented treadmill took place in the Motor Learning Laboratory, which is a part of the out-patient clinic building of the RNOH. The pedometer measurements and task-orientated rehabilitation programme were home-based.

The timescale of the participation in the two stages of the study for each patient is presented in Table 3-1 below. The patients who were re-assessed 11 weeks after TOR participated in the study for 110 days.

Table 3-1: The timescale of the study for each patient

DAY 1	DAY 2 – 4	DAY 5 – 32	DAY 33
1st routine out-patient appointment: -Seeking consent -OKS -IMU gait analysis -Gait assessment with the treadmill	Monitoring of activity level (walking and climbing stairs) for 3 days using a pedometer device	Task-orientated rehabilitation programme (walking and climbing stairs) for 4 weeks (28 days) with pedometer	Re-assessment: -OKS -IMU gait -Treadmill

3.4 Recruitment process

An invitation to participate in the study was sent to each patient who met the inclusion and exclusion criteria (see sections 3.7.2 and 3.7.3) together with the participant information sheet and a consent form before their 12 months post TKA routine appointment. On the day of the appointment it was explained that the study had 2 stages and that the patients had the choice to consent to the first part only (5 minutes walking test) or both stages of the study (optional treadmill assessment and TOR and a return appointment for re-assessment). Therefore, there were three different levels of consent available:

1. Walking test alone
2. Walking test and TOR
3. Walking test and TOR with treadmill assessment.

Five age-matched healthy participants acting as controls were approached in person to discuss the project. There was a different participant information sheet and consent form for the age-matched healthy participants (controls).

3.5 Specific measurements

The Oxford Knee Score (OKS) questionnaire. The OKS is a Patient Reported Outcome Measures (PROMs) questionnaire that was developed specifically to assess the patient's perspective of outcome following Total Knee Arthroplasty. The OKS consists of twelve questions covering function and pain associated with the knee (see Appendix II: Oxford Knee Score Questionnaire).

Gait analysis using Inertial Measurement Units (IMUs) (GaitSmart, ETB, Codicote, UK). IMUs are based on accelerometers and gyroscopes and allow determination of some aspects of gait kinematics in a portable package that can be used either out in the community or in a busy out-patient clinic (see Figure 3-2).

Figure 3-2: Volunteer walking with the IMUs strapped to the thigh and shank (adapted from McCarthy et al., 2013)

Gait assessment using the instrumented treadmill (GRAIL system, Motek Medical) at the Motor Learning Laboratory, RNOH. The GRAIL system allows measurement of ground reaction force for each step and limb position and joint angle measurement by tracking small reflective markers attached to the limbs using 10 cameras around the room. The lab also includes a 180° surround screen onto which an environment is projected while the patient walks. This gives an interactive feel to the gait analysis session (see Figure 3-3).

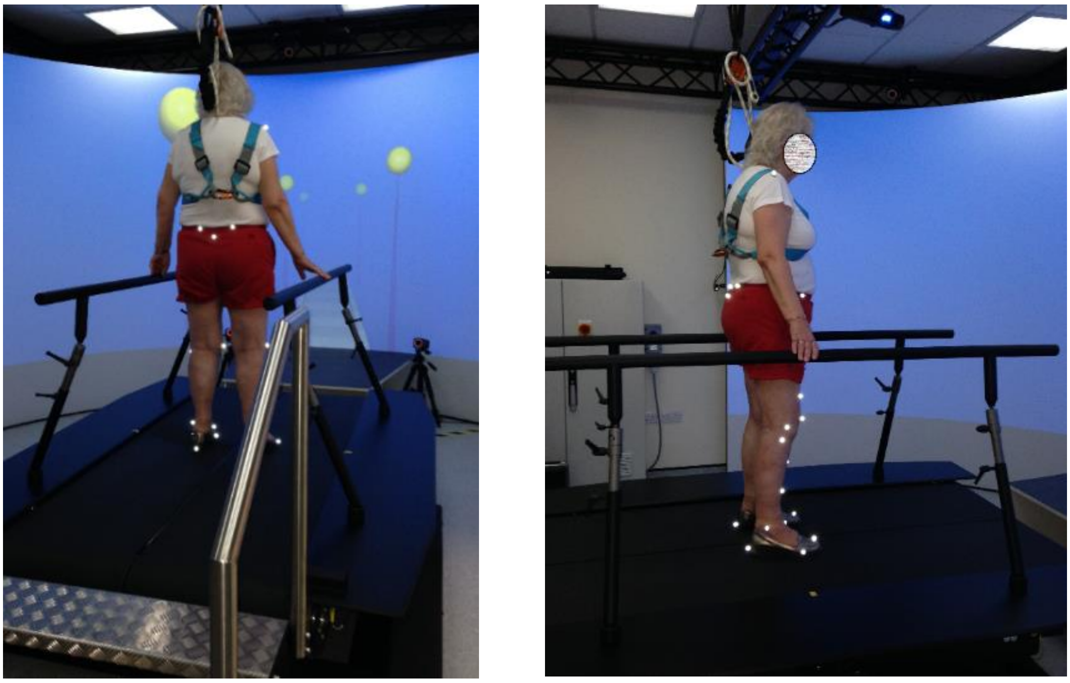


Figure 3-3: Gait assessment using the instrumented treadmill

A pedometer Fitbit One (Fitbit Inc., San Francisco, California, USA) was used to record daily activity levels (see Figure 3-4). Fitbit One trackers are portable devices, equipped with a triaxial accelerometer, which measures the motions in any way that the wearer of the device moves, by converting acceleration into digital measurements (data). They are worn on the waist, and record the number of steps taken and the number of floors climbed per day.

Figure 3-4: Activity tracker Fitbit One

3.6 Outline of study procedure

- 76 TKA patients completed their OKS questionnaires as a part of their routine 12 months follow-up assessment.

- Gait analysis using IMUs (5 minute walking test) was carried out at the same appointment, unless the patient asked for it to be carried out on a different day. Three IMUs were Velcro-strapped to each leg over the patient's clothes to the sides of the patient's pelvis, thigh and calf (for sensor placement see Figure 4-2). They then walked at their own pace on a flat surface 15 metres forward, and then back to the starting point. At the end of the walk the IMUs were removed and the data of the kinematic gait parameters for the sagittal and coronal planes were analysed.
- Based on the IMU data (knee flexion angle less than 12 degrees) the first 4 patients under 71 years of age giving consent for Level 3 participation received additional gait assessment at the Motor Learning Laboratory, RNOH, using the instrumented treadmill. The participants had reflective markers attached to their trunks and legs (for placement of reflective markers see Figure 6-1), and they walked for 60 seconds on the instrumented treadmill at 3 different speeds (1.0, 1.2, and 1.4 m/sec) on 0 degrees incline, and on 5 degrees incline at a speed of 1.2 m/sec. The same test protocol was repeated using IMUs.

- 21 eligible patients, who had given appropriate consent, were given an activity tracker, Fitbit One. Before commencing a 4-week TOR programme, consisting of walking and climbing stairs, the baseline activity of the 21 participants was monitored for 3 days with the use of the pedometers (Fitbit One). The baseline and anticipated weekly rate of progression for each participant was thus established, and the participants learned the use of the pedometers. Each one was given a Schedule of Daily Activities (see Appendix VI: Schedule of Daily Activities), in order to record their activity levels.

- The above 21 patients were re-tested following their 4 week TOR programme with OKS questionnaires and their gaits with IMUs. Ten of the 21 patients were re-assessed 11 weeks after the completion of their rehabilitation programmes with the same protocols, using OKSs and IMUs.

- The 4 patients identified as above, repeated their additional gait assessment at the Motor Learning Laboratory, RNOH, using the instrumented treadmill and IMUs as described above following their 4 week TOR programme.

3.7 Participants

Only patients who gave their written informed consent were recruited. The study was approved by London-Stanmore Research Ethics Committee (REC reference: 15/LO/0164) (see Appendix I: Ethics Approval).

3.7.1 Sample

The sample for investigation of the relationship between gait pattern and patients' satisfaction with their functions was 76 patients.

The sample for task-orientated rehabilitation consisted of 21 participants. Twenty participants were needed to meet the requirements of the power of statistical analysis. (For sample size calculation see Appendix V: Statisticians Report.) A sample size of 5 per group was chosen for the instrumented treadmill gait analysis. However, for the TKA group only 4 participants were able to participate in this part of the study.

3.7.2 Inclusion criteria

<u>Inclusion criteria for Stage 1:</u>

- TKA 12 months previously
- Implant type – Genesis II (Smith & Nephew plc.), Striker Triathlon System (Stryker Howmedica Osteonics Corp.), PFC (Press-Fit Condylar (DePuy Synthes Inc.), or Medacta (Medacta International SA)
- Age between 40 and 80 years
- Reasonable command of the English language.

Additional inclusion criteria for Stage 2:

- Knee flexion in stance on operated knee below 12 degrees
- Age between 40 and 70 years for instrumented treadmill gait analysis.

3.7.3 Exclusion criteria for Stages 1 and 2

- Previous surgery on the lower limb prior to TKA
- Lower limb joint fusion
- Co-morbidities that may affect gait (e.g. Parkinson's disease, stroke, low back pain, et al.).

Chapter 4 The relationship between patient reported outcome and their quality of walking 12 months after knee replacement surgery

4.1 Introduction

It has become increasingly relevant in the light of the evidence that patient satisfaction is much less for TKA than for THA. Based on current accepted scoring systems, it was documented that there was 81% satisfaction in patients 12 months after TKA (Bourne et al., 2010, Hamilton et al., 2012), as compared to 89% (Bourne et al., 2010) and 91% (Hamilton et al., 2012) after hip replacements. Taking into account that patients assessed prior to their knee replacement and 2 years after showed more dissatisfaction in 2002-2005 as compared to 1993-1995 (Singh and Lewallen, 2014), with the growing size and age of the population, the number of knee replacement operations will steadily rise, inevitably increasing the number of patients reporting poor functional outcome.

It has been documented that even though expectations in reduction of pain were reasonably fulfilled one year after patients' surgery, their expectations in regard to demanding physical activity at the same time point were not met to the same degree. Interestingly, none of the PROMs cover the activities that a younger group of patients rate as important (Witjes et al., 2017, Nilsdotter et al., 2009). The deficiencies of the PROMs highlights the need for a quick, portable, objective functional assessment which could be routinely employed at the currently established follow-up time points.

A way of assessing the functional outcome after TKA, which is commonly used in research, but is not currently a part of routine assessment in hospitals, is the testing of patients' gait, with the aim of identifying the common changes in their gait pattern as the recovery of patients after their surgery progresses. This type of assessment might offer a more realistic, objective outcome, in regard to patients' expectations. It could also reveal whether the patients' poor functional outcomes can be related to their existing gait abnormalities, especially as it has been documented in numerous studies that there is a deviation from the normal gait pre- and post- operatively, as well as at different points of recovery after the knee replacement surgery, with characteristic gait patterns, presented by altered knee flexion and extension moments (Kaufman et al., 2001, Smith et al., 2004, Andriacchi and Hurwitz, 1997). Altered knee flexor moment pattern observed in TKA patients at 4 months after their surgery is likely to become permanent (Levinger et al., 2012b). The other most consistently observed changes are decrease in knee total RoM, and reduced range of knee flexion during stance (McClelland et al., 2007, Milner, 2009).

As earlier presented in section 1.5 Chapter 1, the lengthy and costly process of traditional gait analysis makes it unsuitable for routine clinical assessment of patients with knee osteoarthritis. Whereas the use of IMUs to assess lower limb kinematics has made objective functional assessment of patients available in the clinic, and in communities. It has been demonstrated that gait analysis using IMUs can identify abnormalities of gait in patients about to undergo knee replacement surgery, and at different time points of recovery after surgery (McCarthy et al., 2013, Monda et al., 2015, Rahman et al., 2015). The findings of these studies, where measurements were taken with IMUs, are in agreement with those presented earlier in this section, where gait kinematic parameters were measured in specially designated laboratories, equipped with much more expensive and elaborate equipment. Therefore, this made use of IMUs for this part of the study highly appropriate for measuring the objective functions of TKA patients, namely, the quality of their walking.

Since the OKS is measuring patients’ perception of their functions, it is important to understand how patients’ actual objective functions (the quality of their walking) change in concert with changes in their perception of their functions (their OKS). Therefore the specific aim of this study was to identify whether there is a correlation between gait pattern and patient perception of outcome.

Hypothesis.

Patients reported functional outcome using the OKS 12 months after TKA correlates with measures of gait quality.

Objectives.

1. Quantify patient perception of outcome 12 months after TKA using the OKS.
2. Evaluate gait 12 months after TKA using IMUs (GaitSmart).
3. Examine the relationship between OKS and gait quality.

4.2 Methods

4.2.1 Study design

The study design was a non-interventional cohort study with human patients selected from the clinic at 12-month follow-up at the RNOH following TKA surgery. Quantitative data were collected using a questionnaire and gait analysis system.

Participants

Patients one-year after TKA (n = 76, male/female ratio = 30/46, mean age = 64.5 ± 8.8 years, BMI = 30.3 ± 5.4) were recruited from the RNOH outpatient clinic when they were booked for their 1-year follow up appointment by their arthroplasty practitioner. Only patients who gave their written informed consent were recruited. The study was approved by London-Stanmore Research Ethics Committee (REC reference: 15/LO/0164 (see Appendix I: Ethics Approval).

Inclusion criteria were: TKA 12 months previously, and ability to walk unaided; implant types – Genesis II, Triathlon, PFC and Medacta; age of patients between 40 and 80, with a reasonable command of the English language, and ability to sign informed consent.

Exclusion criteria were: previous joint replacements on any other than the knee on the same, and/or contralateral leg; lower limb joint fusion; co-morbidities that may affect gait (e.g. Parkinson’s disease, stroke, low back pain, et al.).

The right leg was operated on in 36 patients, and the left in 40 patients, 30 out of 76 patients had previous TKA on the contralateral knee. Surgery was performed by six different orthopaedic surgeons, each with more than 10 years of experience. All patients underwent a TKA by a medial para-patellar approach. Types of implant used were Genesis II, Stryker Triathlon System, Medacta and PFC. A cruciate-retaining (CR) TKA was used in 74 patients. 30 out of 76 patients had the patella resurfaced (see Figure 4-1). All patients received physiotherapy for early mobilisation from day one post-operatively, and were discharged at day four or five post-operatively. After discharge from the hospital, all patients went through the same out-patients rehabilitation protocol for knee replacement surgery with the hospital physiotherapists.

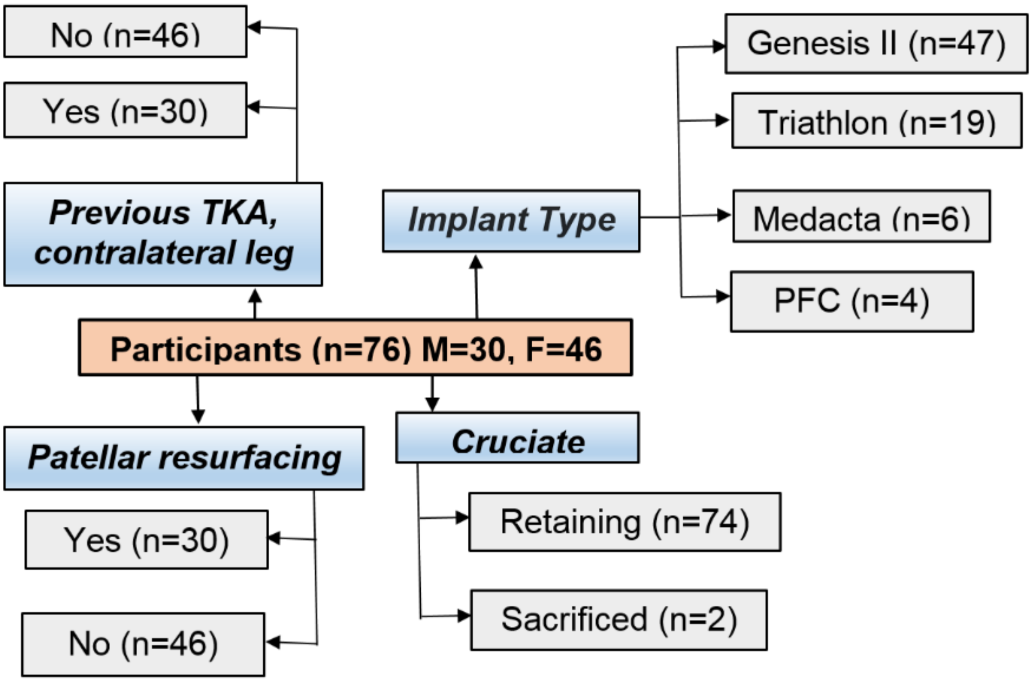


Figure 4-1: Summary of groups of patients' knee replacement surgeries

4.2.2 Procedure

PROMs

OKS questionnaires were completed by recruited patients as a part of their routine 12 month follow-up assessment. The OKS is the preferred measurement outcome used by the RNOH NHS Trust for TKA. The paper questionnaire was filled in by each patient before performing the walking test. Patients' responses were transferred to Orthopaedic Knee Score – Orthopaedic Scores online calculator of OKS, where each questionnaire score was calculated (Kurer and Gooding, 2005). This method of calculation made it possible to collect the scores for the patients who were tested at their homes, or at the Bolsover street branch of the RNOH. OKSs were recorded in the Excel spreadsheet for further statistical analysis.

The Likert scale with values from 0 to 4 for each question gives an overall OKS ranging from 0 to 48. An overall score of 0 – 19 corresponds to severe OA, 20 – 29 severe to moderate OA and 30 – 39 moderate to mild OA. A score of 40 – 48 may indicate satisfactory joint function (Dawson et al., 1998, Kurer and Gooding, 2005, Murray et al., 2007). For the purpose of this study, patients were considered to have a poor outcome if their OKS was below 30.

Gait analysis

Gait assessment was performed using inertial motion sensors (GaitSmart, ETB, Codicote, UK) mounted on the patients' pelvis and lower limbs (Figure 4-2), and associated analysis software (GaitSmart_rel_8_1_6) was used for analysis of the data. Gait assessment (5 minute walking test on a flat surface) for analysis of patients' lower limb and pelvic movement in the sagittal and coronal planes was carried out at the routine 12 month hospital appointment, except for those patients who asked for it to be carried out on a different day, or to be tested at their homes. A designated changing room was available during the clinic, in order to provide privacy for the patients and to avoid delay in the clinic. Three IMUs were Velcro-strapped to each leg over the patient's clothes to the sides of the patient's pelvis, thigh and calf (as shown in Figure 4-2). To determine orientation, each sensor contains three tri-axial gyroscopes and three tri-axial accelerometers, which correct for drift on the gyroscope in the sagittal and coronal planes, as was used in the study on joint angles by Cooper et al. (Cooper et al., 2009). The sensors also contain a precision clock and a memory storage device card (micro SD card). Typical accuracy for all segments and joint angles at walk is ±1 Degrees (European Technology for Business Ltd, 2013).

Figure 4-2: Positioning of the sensors on pelvis, thighs and calves

All six sensors were synchronised using GaitSmart_rel_8_1_6 software on the laptop, and switched on prior to attaching to the patients and inserting into the pockets in the Velcro straps. The thigh sensors, one on each side, were attached to the lateral aspect of the thigh along an imaginary line from the greater trochanter to the lateral condyle of the femur, half way between the hip and the knee. The calf sensors were attached over the widest part of the calf muscle and aligned along an imaginary line drawn between the head of the fibula and the lateral malleolus. The pelvic sensors were attached to the lateral aspects of the pelvis, in line with the anterior superior iliac spines and the thigh sensors. Patients were asked to stand still for 10 seconds to allow the sensors to calibrate, following which the patients walked at their own comfortable pace on a flat surface 15 metres forward, and then back to the starting point. On completion of their walking test the sensors were removed from the pockets, switched off while still in the vertical position, and connected to the computer with GaitSmart software for downloading the data from the sensors' SD cards at 102.4 Hz, and analysing of the recorded kinematic gait parameters for the sagittal and coronal planes.

The following kinematic gait parameters were calculated: pelvis, hip, thigh and calf sagittal and coronal angles, knee sagittal angles, and temporal descriptors of gait, stride duration, swing flexion time, and the difference in timing between the two peaks of thigh sagittal angle (time between maximum hip flexion before heel strike and maximum hip flexion on load).

4.2.3 Data analysis for gait measurements

The analysis of the data was done using the GaitSmart software (rel_8_1_6), which calculates the joint and segment angles for the entire walking test. Two sections, one when the participant was walking away from the starting point, and the other when returning, were chosen for analysis. Sections were chosen where the participant was walking steadily for at least 8 strides, which is approximately 9 metres. The typical strides for each section were then calculated by the software. The stride with the lowest error was shown as the darkest fragment on the plot in Figure 4-3. The analysis of the typical stride was considered valid, as a previous study had demonstrated low stride-to-stride variability during walking (Lewek et al., 2006).

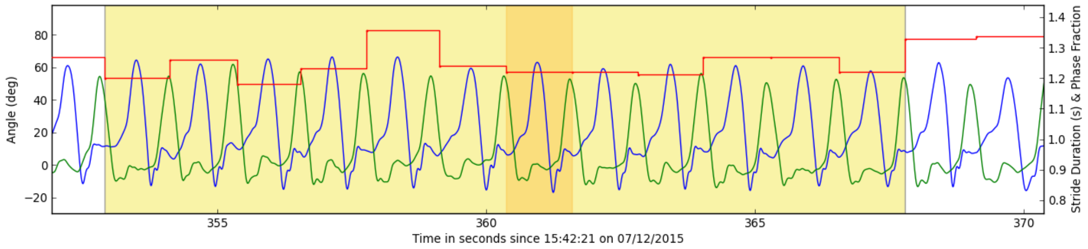


Figure 4-3: Typical knee angle profile obtained during the test procedure. The most typical stride during the test, which is used for subsequent analysis, is presented as a darker area

An example of the GaitSmart analysis report generated automatically by the software for one participant, showing temporal gait events, and the gait parameters calculated for the typical stride is presented in Appendix III: An example of GaitSmart gait analysis report for one participant. These gait parameters were then calculated as averages of the two walking sections analysed, and these averages (23 parameters) were taken for further statistical analysis.

4.2.4 Statistical analysis

The strength of relationship between gait pattern (using IMUs), and patient related outcome (using OKS) in 76 patients 12 months post TKA was evaluated using SPSS Statistics for Windows (version 22). As the number of participants was relatively small, and the number of gait variables was large, and in the presence of a strong correlation between the predictors (the Pearson's product-moment correlation was used to determine the strength and direction of a linear relationship between continuous variables), it was decided to use a Factor Analysis (Unweighted Least Squares (ULS) extraction with Oblimin rotation) to reduce the number of predictors. An oblimin rotation provided the best defined factor structure. "Data reduction" was done to reduce redundancy in the dataset, and bring out the underlying patterns. Fewer variables reduced the possibility of Type I errors, and by reducing collinearity, the regression analysis was made possible.

To identify whether each of these factors can make an acceptable measurement scale, scale reliabilities were computed. Internal consistency for each of the scales was examined using Cronbach's alpha, α. Correlation between the subjective functional outcome scores of PROM (OKS) and objective gait parameters, presented as scale reliabilities with alpha greater than 0.6 and individual variables of factors that had alpha below 0.6, were calculated with the parametric Pearson correlation coefficient. Composite scores (z-scores) for scales were calculated prior to running a Pearson correlation.

A one-way ANOVA was exploring whether there were any relations between OKS and categorical demographics (sex, type of implant, cruciate retaining/sacrificed, patellar resurfacing and previous TKA on the opposite leg).

To identify the value of all variables that had significant relationship with OKS they were entered into a Regression Analysis. The trimmed model, which was obtained as a result of stepwise elimination procedure, was re-entered into a Regression Analysis.

Finally, Path Analysis (or Structural equation modelling) was carried out to construct the path model to gain additional insight into causal model reflecting relationship between OKS and the gait scales and stride duration. Path coefficients were estimated using the maximum likelihood method in SPSS AMOS 23. Final model was produced by elimination of non-significant paths.

4.3 Results

4.3.1 Oxford Knee Score

Participants' OKSs, age, gender and BMI are presented in Table 4-1.

Table 4-1: Descriptive statistics of other than gait variables taken for analysis

		Number	M ±SD (range)
OKS		76	34.34 ± 10.05 (8 - 48)
	OKS for men	30	37.20 ± 8.91 (14 – 48)
	OKS for women	46	32.48 ± 10.39 (8 – 47)
Age		76	64.5 ± 8.8 (44.0 - 80.0)
	Age for men	30	65.0 ± 8.0 (48.0 - 79.0)
	Age for women	46	64.2 ± 9.4 (44.0 - 80.0)
BMI		76	30.3 ± 5.4 (21.3 - 48.0)
	BMI for men	30	30.2 ± 5.8 (22.0 - 48.0)
	BMI for women	46	30.4 ± 5.2 (21.3 - 43.8)

Out of 76 participants (male/female ratio = 30/46, mean age = 64.5 ± 8.8 years, BMI = 30.3 ± 5.4), 68.4% (52 participants, 29 females and 23 males) had an OKS above 30, indicating that they had a good outcome of their surgery 12 months after TKA. Twenty-four participants (17 females and 7 males), or 31.6%, had an OKS below 30 indicating that they had a poor outcome.

Relationships between OKS and the categorical demographics sex, type of implant, cruciate retaining/sacrificed, patellar resurfacing and previous TKA on the opposite leg (see Table 4-1 and Figure 4-1 for groups of categorical demographics) were examined using one-way ANOVA. The only significant attribute was Sex, F (1, 74) = 4.18, p = 0.044, which indicated that females were more likely to report a lower OKS than males. There was no significant correlation between OKS and age, (r = 0.13, p = 0.26), but there was a significant correlation with BMI (r = -0.33, p = 0.003) indicating that patients with a high BMI reported a lower functional outcome.

4.3.2 Gait analysis

Participants' measured gait parameters are presented in Table 4-2 below.

Table 4-2: Gait parameters of 76 participants measured with IMUs

Gait parameters	Mean ± SD (range)
Operated Limb Knee flexion in stance (°)	14.22 ± 4.75 (4.42 - 29.20)
Non-operated limb Knee flexion in stance (°)	16.02 ± 5.91 (2.23 - 34.81)
Operated Limb Swing flexion time (%)	49.20 ± 1.38 (46.00 - 55.00)
Non-operated Limb Swing flexion time (%)	48.75 ± 1.34 (46.00 - 53.00)
Operated Limb Knee Sagittal RoM (°)	61.28 ± 7.57 (36.26 - 75.39)
Non-operated Limb Knee Sagittal RoM (°)	62.44 ± 8.15 (38.22 - 80.70)
Operated Limb Pelvis Sagittal RoM (°)	7.20 ± 2.32 (2.64 - 14.98)
Non-operated Limb Pelvis Sagittal RoM (°)	7.66 ± 2.74 (3.20 - 18.16)
Operated Limb Hip Sagittal RoM (°)	33.63 ± 6.61 (18.34 - 54.76)
Non-operated Limb Hip Sagittal RoM (°)	33.08 ± 7.39 (12.97 - 50.09)
Operated Limb Thigh Sagittal RoM (°)	37.28 ± 6.49 (21.04 - 56.05)
Non-operated Limb Thigh Sagittal RoM (°)	37.01 ± 7.08 (18.00 - 52.30)
Operated Limb Calf Sagittal RoM (°)	72.78 ± 7.43 (52.62 - 89.15)
Non-op Limb Calf Sagittal RoM (°)	72.38 ± 7.44 (52.28 - 85.53)
Operated Limb Pelvis Coronal RoM (°)	7.48 ± 2.66 (3.50 - 15.91)
Non-operated Limb Pelvis Coronal RoM (°)	7.70 ± 2.66 (2.70 - 17.99)
Operated Limb Thigh Coronal RoM (°)	13.69 ± 4.85 (4.74 - 27.79)
Non-operated Limb Thigh Coronal RoM (°)	13.54 ± 4.37 (5.31 - 25.05)
Operated Limb Calf Coronal RoM (°)	12.59 ± 5.02 (4.59 - 26.46)
Non-operated Limb Calf Coronal RoM (°)	13.05 ± 5.85 (4.92 - 38.79)
Operated limb Difference between 2 peaks of thigh sagittal angle (%)	15.39 ± 4.49 (2.00 - 27.00)
Non-operated Limb Difference between 2 peaks of thigh sagittal angle (%)	15.48 ± 4.68 (2.00 - 27.00)
Stride duration (sec)	1.11 ± 0.14 (0.89 - 1.54)

Fifty patients (31 females and 19 males), or 65.8% demonstrated normal knee flexion in stance for the operated leg. Twenty-six patients (15 females and 11 males), or 34.2%, however, demonstrated abnormal knee flexion in stance, nine of whom (5 females and 4 males), had their OKS below 30.

4.3.3 Relationship between OKS and gait parameters

OKS showed a significant correlation with a number of gait parameters (Table 4-3).

Table 4-3: Pearson correlations between gait variables and OKS scores

Gait variable	r
Op Limb Knee flexion in stance (°)	.212
Non-op/op earlier limb KFS (°)	.336**
Op Limb Swing flexion time (%)	.208
Non-op/op earlier Limb SFT (%)	.231*
Op Limb Knee Sag ROM (°)	.404**
Non-op/op earlier Limb Knee Sag RoM (°)	.416**
Op Limb Pelvis Sag RoM (°)	.152
Non-op/op earlier Limb Pelvis Sag RoM (°)	.194
Op Limb Hip Sag ROM (°)	.280*
Non-op/op earlier Limb Hip Sag RoM (°)	.340**
Op Limb Thigh Sag RoM (°)	.367**
Non-op/op earlier Limb Thigh Sag RoM (°)	.420**
Op Limb Calf Sag RoM (°)	.465**
Non-op/op earlier Limb Calf Sag RoM (°)	.475**
Op Limb Pelvis Cor RoM (°)	.013
Non-op/op earlier LimbPelvis Cor RoM (°)	.154
Op Limb Thigh Cor RoM (°)	.125
Non-op/op earlier Limb Thigh Cor RoM (°)	.04
Op Limb Calf Cor RoM (°)	.025
Non-op/op earlier Limb Calf Cor RoM (°)	-.033
Op limb Difference between 2 peaks of thigh sag angle (%)	.065
Non-op/op earlier Limb Difference between 2 peaks of thigh sag angle (%)	.178
Stride duration (sec)	-.620**

** Correlation is significant at the 0.01 level (2-tailed).
* Correlation is significant at the 0.05 level (2-tailed).

Eleven of the 23 gait variables correlated significantly with OKS; in general, larger ranges of motion, and a decreased stride duration were associated with higher OKS.

To quantify the overall degree of association between gait and outcome it was decided to conduct a multiple regression analysis. The results of such an analysis would indicate how much of the observed variation in outcome could be attributed to different aspects of gait. However, a sample size of 76 was too small to support a stable regression analysis with 23 predictor variables; in addition, the substantial correlations between the gait predictors (see Appendix IV: Correlation matrix for the

23 gait variables) would lead to multicollinearity, which means that the regression coefficients would vary considerably depending on which predictors were included in the regression model, thereby limiting the conclusions that could be drawn.

To reduce the number of predictors and degree of multicollinearity, the gait variables were factor analysed. Factor analysis is a procedure for replacing a large number of correlated variables with a smaller number of “derived” variables, which still represent most of the original information. These new variables can then be used in statistical procedures.

4.3.4 Factor Analysis

The first step was to examine the factorability of the 23 gait variables according to a number of commonly used criteria. First, 21 of the 23 variables correlated with at least one other gait variable at $r \geq 0.3$ or greater (see Appendix IV: Correlation matrix for the 23 gait variables), suggesting reasonable factorability (Tabachnick and Fidell, 2001). Secondly, the Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy (a measure of how suited the data is for factor analysis) was 0.66 (Middling), above the commonly recommended value of 0.6 (Tabachnick and Fidell, 2001). Thirdly, Bartlett’s test of sphericity was significant (χ^2 (253) = 1463.84, $p < 0.0005$), indicating that the correlation matrix was significantly different to an identity matrix. Finally, all the gait variables had communalities above 0.3, further confirming that each variable shared some common variance with the others. Given these overall indications, it was concluded that the gait variable correlation matrix could be factor analysed.

Preliminary analyses indicated that the simplest and most interpretable factor structure was obtained with Unweighted Least Squares extraction and Oblimin rotation. Six factors emerged with initial eigenvalues greater than 1, and explaining respectively 32%, 12%, 9%, 8%, 6%, and 5% of the total variance. However, the sixth factor (which consisted of low knee flexion and a high range of calf coronal motion in the operated leg) had no obvious interpretation. Therefore, five factors were extracted (see Table 4-4): **Hip Thigh Calf SAG** (hip, thigh, and calf sagittal RoM for both legs); **Knee SAG Flex TP Diff** (knee sagittal RoM, knee flexion in stance, and the difference between 2 peaks of thigh sagittal angle for both legs); **Pelvis Cor Sag** (pelvis coronal and sagittal RoM for both legs); **Limb SFT** (limb swing flexion time for both legs); and **Thigh Cor** (thigh coronal RoM for both legs). The five-factor solution explained 68% of the total variance. Factor loadings and communalities of the rotated solution are presented in Table 4-4.

Table 4-4: Factor loadings and communalities based on a factor analysis (Unweighted Least Squares extraction with Oblimin rotation) for 23 gait parameters as measured by IMUs (n = 76)

		Factor					Communality
		1	2	3	4	5	
Hip Thigh Calf SAG	Op Limb Thigh Sag RoM (°)	.934					.975
	Op Limb Hip Sag RoM (°)	.929					.955
	Non-op/op earlier Limb Hip Sag RoM (°)	.893					.956
	Non-op/op earlier Limb Thigh Sag RoM (°)	.861					.969
	Op Limb Calf Sag RoM (°)	.716	.361				.952
	Non-op/op earlier Limb Calf Sag RoM (°)	.687	.412				.960
	Stride duration (sec)	-.439			-.428		.572
Knee SAG Flex TP Diff	Non-op/op earlier Limb Knee Sag RoM (°)	.378	.679				.894
	Non-op/op earlier LimbDif b/w 2 peaks of thigh sag angle (%)		.670				.695
	Op Limb Knee Sag RoM (°)	.400	.662				.893
	Op limb Dif b/w 2 peaks of thigh sag angle (%)		.655				.655
	Op Limb Knee flexion in stance (°)		.589				.692
	Non-op/op earlier limb KFS (°)		.525				.704
Pelvis Cor Sag	Non-op/op earlier Limb Pelvis Sag RoM (°)			.768			.819
	Op Limb Pelvis Cor RoM (°)			.743			.663
	Non-op/op earlier LimbPelvis Cor RoM (°)			.715			.641
	Op Limb Pelvis Sag RoM (°)			.638			.798
Limb SFT	Op Limb Swing flexion time (%)				.811		.688
	Non-op/op earlier Limb SFT (%)				.713		.658
Thigh Cor	Non-op/op earlier Limb Thigh Cor RoM (°)					.699	.403
	Op Limb Thigh Cor RoM (°)					.573	.373
	Non-op/op earlier Limb Calf Cor RoM (°)						.368
	Op Limb Calf Cor RoM (°)						.370

Note: Loadings smaller than ± 0.3 not shown.

4.3.5 Scale Construction

The next step was to examine whether each of the 5 factors could make an acceptable summated rating scale. The internal consistency reliability of the five potential scales was examined using Cronbach's alpha, α (see Table 4-5). Alpha takes values between 0 and 1, and values above 0.7 are considered acceptable for practical purposes, and values above 0.6 acceptable for research purposes (Nunnally, 1978, Flynn et al., 1990, Horne et al., 2001).

Table 4-5: Scale Reliabilities (Internal consistency) as assessed using Cronbach's Alpha (α)

Scale	No of items	Standardized Item Alpha
Hip Thigh Calf SAG	6	0.95
Knee Sag Flex TP Diff	6	0.84
Pelvis Cor Sag	4	0.80
Thigh Cor	2	0.56
Limb SFT	2	0.73

Table 4-5 shows that four of the five scales have acceptable reliability. The reliability of the **Thigh Cor** scale (thigh coronal RoM for both legs) was below the acceptable level of 0.6.

Because the gait variables were measured on different scales, they were converted to z-scores for the purposes of scale construction (z-scores have a mean of zero and a standard deviation of 1). Each gait variable was converted to a z-score by subtracting the mean and dividing by the standard deviation. Participant scores for each of the four scales were then calculated by computing the average z-score of its constituent variables.

Descriptive statistics for the scales are shown in Table 4-6. The low values of Skewness and Kurtosis indicated that they were reasonably normally distributed.

Table 4-6: Descriptive statistics for the five Scale factors (n = 76)

Scale factors	No of items	M ±SD (range)	Skewness	Kurtosis
Hip Thigh Calf SAG	6	0.00 ± 0.90 (-2.50 - 2.20)	-0.371	0.208
Knee Sag Flex TP Diff	6	0.00 ± 0.74 (-2.21 - 2.18)	-0.178	1.511
Pelvis Cor Sag	4	0.00 ± 0.79 (-1.31 - 2.90)	0.798	1.433
Thigh Cor	2	0.00 ± 0.83 (-1.58 - 2.36)	0.562	0.092
Limb SFT	2	0.00 ± 0.89 (-2.19 -3.32)	0.536	1.651

Overall, the factor analysis suggested that five distinct factors underlaid the gait patterns in patients 12 months after knee replacement surgery. However, the **Thigh Cor** scale was excluded from further analysis due to its reliability being below the acceptable level of 0.6.

From an analysis viewpoint, the factor analysis achieved a considerable simplification in the data structure, enabling eighteen of the original gait variables to be replaced by four scales.

Table 4-7 shows the correlation between OKS and the four gait scales.

Table 4-7: Correlation between OKS and Gait Scales

Gait Scales	***r***	***p***
Hip Thigh Calf SAG	0.433**	0.000
Knee Sag Flex TP Diff	0.362**	0.001
Pelvis COR SAG	0.162	0.162
Limb SFT	0.248*	0.031

Note: N=76
* = statistically significant at $p < 0.05$ level, ** = statistically significant at $p < 0.01$ level.

4.3.6 Multiple Regression analysis

The purpose of the regression analysis was to investigate the relationship between outcome of knee surgery and gait, while controlling for other patient attributes. The dependent variable was the patient's OKS score. The predictors included all the variables that had a significant correlation with OKS, as listed below in Table 4-8.

Table 4-8: Predictors for regression analysis

Gait Scales	Hip Thigh Calf SAG, Knee Sag Flex TP Diff, Limb SFT
Gait variables not included in gait scales	Stride Duration
Control variables	Sex, BMI

The regression analysis results for the initial model are shown below in Table 4-9.

Table 4-9: Regression Results, Initial Model

	B	**Std. Error**	**Beta**	**t**	**sig.**
(Constant)	90.55***	11.0		8.23	.000
Sex	-3.90*	1.8	-.191	-2.12	.037
BMI	-0.36*	0.2	-.196	-2.20	.031
Hip Thigh Calf SAG	1.21	1.3	.109	0.95	.345
Knee Sag Flex TP Diff	0.89	1.4	.066	0.64	.523
Limb SFT	0.64	1.1	.057	0.58	.565
Stride duration (sec)	-35.21***	8.4	-.477	-4.18	.000
F(6, 69) = 11.1***					
*R*² = 0.490					

* p <= .05, ** p < =.01, *** p <= .001

A stepwise elimination procedure, in which non-significant predictors were successively removed, produced the final trimmed model (see Table 4-10).

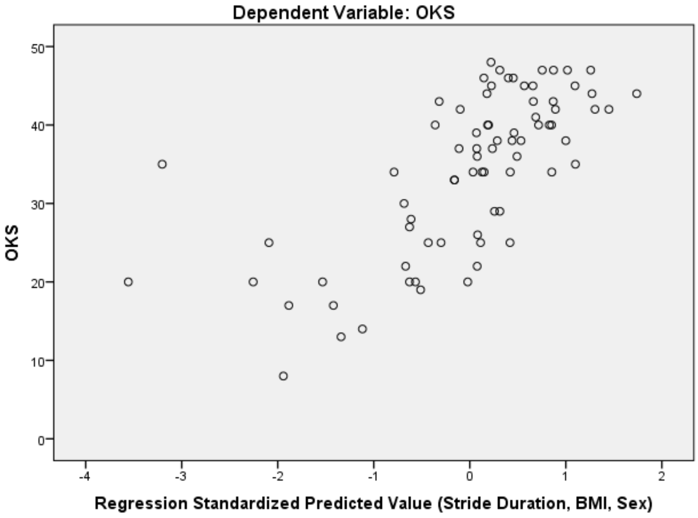
Table 4-10: Regression Results, Final Model

	B	**Std. Error**	**Beta**	**t**	**sig**
(Constant)	100.05***	8.24		12.15	.000
Stride duration (sec)	-42.37***	6.44	-.574	-6.58	.000
Sex	-4.49*	1.74	-.220	-2.58	.012
BMI	-0.38*	0.16	-.207	-2.37	.020
F(3, 72) = 21.8***					
*R*² = 0.476					

* p <= .05, ** p < =.01, *** p <= .001

Table 4-10 and Figure 4-4 show that Stride Duration, Sex and BMI were significant predictors of OKS, and together explained about 48% of the variance in OKS scores.

Figure 4-4: Relationship between OKS and Stride Duration, BMI and Sex (N = 76)

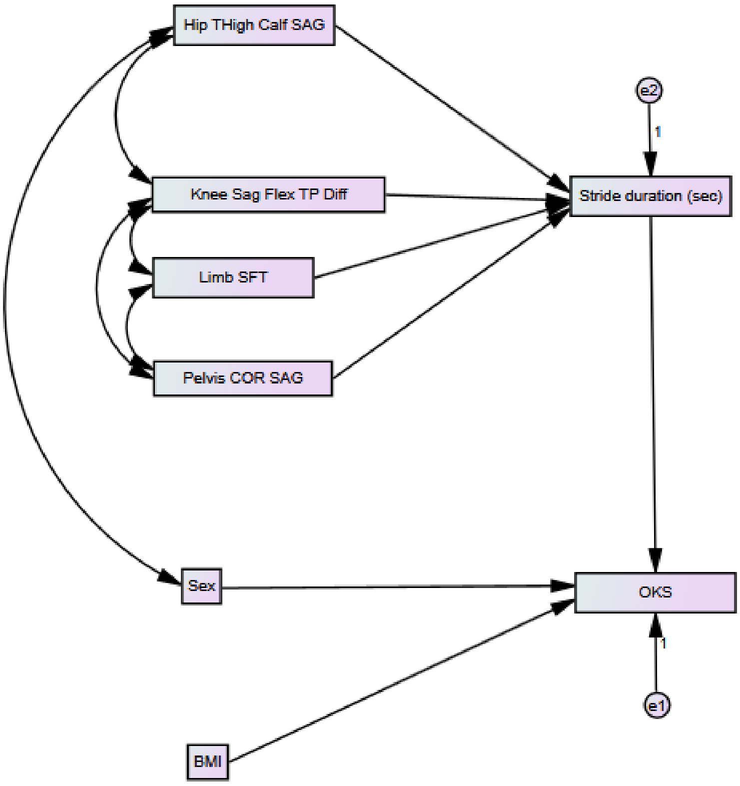


4.3.7 Path model

Although several gait variables had significant correlation with OKS, only Stride Duration was a significant predictor of OKS in the regression model. However, based on the correlations between Stride duration and the other gait scales, it was conjectured that the Stride Duration might have been playing a mediating role. In other words, patients' perception of function and pain, as measured by the OKS was primarily driven by ease of stride, which in turn depended on the gait scores. Traditional multiple regression analysis cannot reveal this type of relationship. A "path analysis" was therefore conducted. Path analysis is a method for estimating the hypothesised regression relationships between arbitrarily complex networks of variables; it is a subset of the structural equation modelling (SEM) technique, and can be conducted using SEM software.

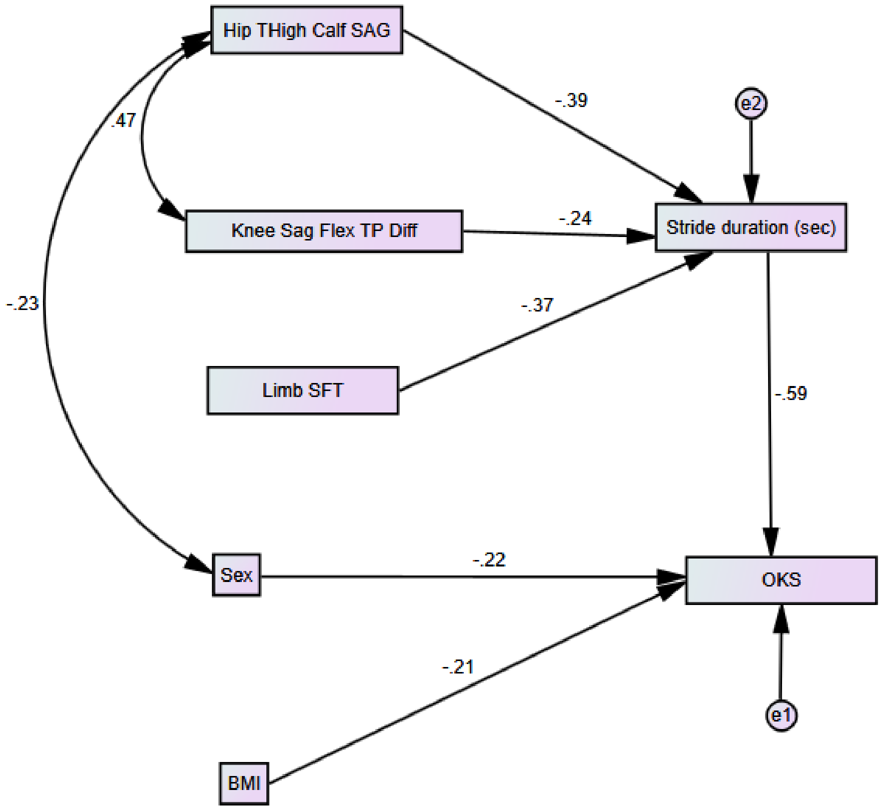
The initial path model is shown in Figure 4-5. In this figure, observed variables are represented by rectangles, regression coefficients by single-headed arrows, and correlations by double-headed arrows. The circles represent unobserved (latent) variables, in this case representing the unexplained regression (error) variance in Stride Duration and OKS respectively. Stride Duration was regressed on the four gait scales, and OKS was regressed on Stride Duration. BMI and Sex, which were previously found to have significant correlations with OKS, were included as control variables.

Figure 4-5: An initial path model of relationship between OKS and four Gait Scales, Stride Duration, BMI and Sex



Path coefficients (i.e. the magnitude of the regression and correlation coefficients in the path model) were estimated using the maximum likelihood method in SPSS AMOS 23. Non-significant paths were eliminated, producing the final model shown in Figure 4-6. In this figure, the numbers on the single-headed arrows represent standardized regression weights and the numbers on the double-headed arrows represent correlation coefficients.

Figure 4-6: Final path model of relationship between OKS and three Gait Scales, Stride Duration, BMI and Sex



Standardized and unstandardized coefficients together with standard errors and significance levels are shown in Table 4-11 below.

Table 4-11: Coefficients for Final Path Model

Regression weights	Unstandardized Regression Weight (SE)	Standardized Regression Weight	Critical Ratio	Sig. Level
Stride Duration <--- Limb SFT	-0.058 (0.014)	-0.373	-4.27	< .001
Stride Duration <--- Hip Thigh Calf SAG	-0.059 (0.015)	-0.386	-3.91	< .001
Stride Duration <--- Knee Sag Flex TP Diff	-0.044 (0.018)	-0.237	-2.40	.016
OKS <--- Stride Duration	-42.375 (6.14)	-0.587	-6.90	< .001
OKS <--- BMI	-0.384 (0.155)	-0.210	-2.48	.013
OKS <--- Sex	-4.488 (1.714)	-0.223	-2.62	.009

Covariances	Covariance	Correlation	Critical Ratio	Sig. Level
HTCSAG <--> Knee Sag Flex TP Diff	0.308 (0.082)	0.469	3.761	<.001
HTCSAG <--> Sex	-0.100 (0.046)	-0.229	-2.176	.03

Estimation of a path model also produced measures of model fit, which indicated whether or not the path model was an adequate description of the data. Fit indices for the model are shown in Table 4-12, and demonstrate that the model fits the data very well.

Table 4-12: Fit indices for the path model

Acronym	Name	Value	Cut-off Value	Type of Index	Good fit?
GFI	Goodness of Fit index	0.962	0.90-0.95	Larger is better	Yes
CFI	Comparative Fit Index	1.000	0.95	Larger is better	Yes
TLI	Tucker Lewis Index	1.03	0.95	Larger is better	Yes
RMSEA	Root Mean Square Error of Approximation	0.000	0.06	Smaller is better	Yes
CMIN	Chi-Square per df	0.85	2.0-5.0	Smaller is better	Yes

The Goodness of Fit Index was 0.962, safely above the cut-off criterion for good fit (given as 0.90 and 0.95 by various authorities (Hooper et al., 2008). The Comparative Fit Index was 1.00, and the Tucker Lewis Index was 1.03, both exceeding their common good-fit criterion of 0.95 (Hu and Bentler, 1999). Chi-square per df was below the recommended cut-off of between 2.0 and 5.0 (Hooper et al., 2008), and the Root Mean Square Error of Approximation was below the accepted limit of 0.06 (Hu and Bentler, 1999).

The negative coefficients for the three gait scales in the path model indicate that high scores on the three gait scales produce lower (i.e. faster) stride duration; similarly, the negative coefficient for stride duration indicates that high scores on stride duration (i.e. slower) produce lower (i.e. worse) scores on the OKS. Additionally, the negative coefficient for BMI indicates that patients with high BMI have depressed OKS scores. Sex was encoded as 1 = Male, and 2 = Female, so the negative coefficient for Sex indicates that females score lower than males.

4.4 Discussion

The aim of this study was to determine the relationship between patients' functions, as assessed by the quality of their gait, measured by IMUs, and the perception of their functions, as assessed by PROM score, measured by OKS.

The model produced as a result of this study demonstrated that higher OKS was observed in patients who have shorter stride duration, which was in turn a result of greater leg joints and segments RoM in the sagittal plane. In this study 65.8% of participants demonstrated a normal range of knee flexion in stance, which was two times higher than previously found. As gait parameters were measured at one time point in this study, the comparison of the individual parameters was not determined. In previous studies, slower stride duration by 25% reduced knee flexion in swing, and approximately 30% of tested patients had normal knee flexion in stance at 12 months after TKA (Rahman et al., 2015). Systematic reviews, assessing studies looking at gait analysis of patients after TKA, found consistency in decrease in knee total RoM, and reduced range of knee flexion during stance for the operated leg (McClelland et al., 2007, Milner, 2009), and also that patients tend to walk more slowly (Alnahdi et al., 2011). These studies do not show whether TKA returns patients' gait to normal and whether there is the need for additional gait rehabilitation (Sosdian et al., 2014). Furthermore, previous studies have not looked at correlation of the gait parameters with PROMs.

The results of this study show that the number of patients having a poor outcome, as assessed by their OKS, was 31.6%. It has been documented that patient dissatisfaction after TKA ranges from 8% to 25% (Hamilton et al., 2012, Robertsson et al., 2000, Choi and Ra, 2016). The assessment of satisfaction in some of these studies was measured by one question on different points in a Likert scale, which makes it not stringent enough. Moreover, the cutting point for satisfactory outcome for TKA if it is measured by PROMs is not clear. Baker et al claimed 29% of patients admitted to improvement after TKA after reviewing the National Joint Registry for England and Wales (Baker et al., 2013). Their assessment was based on symptom improvement (operative success) and the post-operative EuroQol-5 score.

The finding of lower OKS in women (Fisher et al., 2007, Bonnin et al., 2011) and in those with a higher BMI was in agreement with previous studies (Merle-Vincent et al., 2011, Fisher et al., 2007).

It is the current practice to use PROMs to evaluate the outcome of function after TKA. These provide the patient's own assessment of their function, and increasingly there is evidence that their assessment is strongly influenced by pain and that the main reporting in PROMs is of this pain, rather than of true physical function, or ability to perform normal daily tasks (Stratford and Kennedy, 2006, Hossain et al., 2013, Jacobs and Christensen, 2009). Using PROMs alone for assessing the outcome after TKA appears to provide an over-estimation of both the short- and long-term changes in physical function due to immediate relief of pain after surgery, and the patient's own high expectations (Terwee et al., 2006, Vissers et al., 2012, Hossain et al., 2013). These inbuilt problems with PROMs have resulted in assessors being more satisfied with objectively measured tests of functional outcome. Evidence showed that the patient's first post-operative month performance based tests were inferior to their pre-operative level, however their PROMs showed significant improvement. In this study it was impossible to collect pre-operative and 1 month post-operative levels of OKS, as some of the participants were operated on in different hospitals, and it is not a common practice in the hospital where research took place to record one month OKS. Similarly, at one year PROMs assessment overstated the performance-based tests results (Jacobs and Christensen, 2009, Mizner et al., 2011, Stevens-Lapsley et al., 2011). Moreover, the performance-based measures and PROMs were moderately correlated pre- and post-operatively, suggesting that both measures represent different aspects of true physical performance, and together serve the same purpose.

The fact of the polarity of the functional assessments and PROMs outcomes at different stages of recovery after surgery makes portable gait analysis using IMUs, as a functional assessment, of added value. This gait assessment would also provide prompt evaluation of the efficacy or progression of the rehabilitation received by these patients. To add to the above, the study of Genet *et al.* (2008), looking at performance-based functional changes immediately after operation and 6 months later, found no correlation between functional performance as assessed by isokinetic measures of quadriceps and hamstrings strength and overall satisfaction with surgery as assessed by PROMs (by WOMAC), despite significant improvements in physical performance (Genet et al., 2008). In this case, improved strength, as a single aspect of function, does not guarantee improved function, especially if that function is assessed by the patients themselves. This is where improved gait might make a difference in functional outcome, particularly if patients can actually see the exact changes, which can be easily understood, at different time points after their surgery. Making gait measurement a standard procedure would empower patients by the knowledge of their progress and therefore give them the opportunity to be in charge of this progress.

In this study PROMs (the OKSs) and the performance-based parameters (gait parameters: joints and segments RoM, swing flexion time, and stride duration) were moderately correlated (Pearson correlations range 0.25-0.62), suggesting that both measurements were linked in reflecting physical functions, at the same time providing distinctly different dimensions of physical performance. Both measures may need to be collected for a broader understanding of a patient's functional recovery. Despite some limitations that were documented in regard to the OKS, such as redundancies within the Score, as a result of not completing some questions when sent by post, and the ceiling effect (Whitehouse et al., 2005, Thomsen et al., 2016), it differs favourably from other PROMs in that it was designed to assess the level of, and changes with time, in pain and function of the operated knee only from the patients' point of view. Therefore it is more accurate as it is more specific, reliable, and sensitive to clinically important changes, as compared to the Knee Society Score (Insall et al., 1989), or generic health scales, such as the SF-36 (Ware and Sherbourne, 1992), the Arthritis Impact Measurement Scale (AIMS) (Meenan et al., 1980), and Health Assessment Questionnaire (HAQ), which have been criticised for their length, difficulties in completion, and poor relevance to joint replacement patients (Fitzpatrick et al., 1992).

OKS is similar to other PROMs in respect to the absence of questions that have an exact relevance to the activity that has been tested – in the case of this study, walking. Patients record more easily how they are functioning physically by reporting on how well they are able to walk, using OKS. This could be a reason for weak or poor correlation between OKSs and functional performance-based tests.

One of the limitations of this study was that the OKS was measured only once, 12 months after TKA. Even though it is a standard practice in RNOH to have completed OKS pre-operatively as part of their clinical journey, their OKS data were not utilised, as this was done before they were recruited to this research study. OKS measurement pre-, post- and 12 months later would reflect more informatively the progress, as the most significant changes occurred during the first year, no matter how good, or bad patients were pre-operatively (Lavernia et al., 2009). Their functional impairment 3 years after TKA though could be worse for those with a poorer level of functions pre-operatively, as compared to those with a better pre-operative level of functions (Lavernia et al., 2009). Additional performance-based measurements (walking test) would quantify their performance, and present a genuine functional ability, as opposed to their perception of functions (Stevens-Lapsley et al., 2011, Gandhi et al., 2009). Moreover, it was documented that performance-based tests are more sensitive in reflecting changes as compared to self-reported measures, because patients tend to report their experience while doing daily activity, rather than their true ability to do these activities (Parent and Moffet, 2002, Stratford et al., 2009, Stratford and Kennedy, 2006). As there was a correlation between both assessments, utilisation of both of them would represent a more accurate level of patient functional capability. Utilisation of more complex tasks with IMUs assessment, such as walking upstairs, or on an incline could reveal a broader outlook on patients' disabilities, and identify patients with greater demand, who are likely to cause a ceiling effect in their OKSs. It might be interesting to consider the separate scores for pain and functions, as can be identified from OKS and would demonstrate in which domain the main issue was, either pain or function, or both.

There was a further limitation in that participants did not represent a consecutive series of cases, as they were self-selected and therefore unavoidable selection bias could, to a degree, confound the outcome. The relatively small sample size could also affect the results. However, the use of portable IMUs, allowing objective functional assessment, and standardised PROM questionnaires, allowed a more insightful and complete approach and, therefore, a more realistic and comprehensive assessment, serving to monitor the recovery of the patients after TKA, which represented a strength of this study.

The strength of this method, using OKS and IMUs, is that it can be conducted in hospital settings or in communities, avoiding time constraints and usage of expensive gait analysis laboratories, which in some cases patients cannot cope with (e.g. walking on a treadmill), and more importantly these laboratories do not have the capacity to analyse the currently treated number of patients on a routine basis. It is cost effective, as apart from portable IMU equipment, and the staff who operate it, it does not encounter any additional cost. The results of both assessments (OKS and gait report) for one tested patient are ready in half an hour. Any patient who is able to walk unaided can be tested, providing two different perspectives of the functionality at different stages of the recovery after surgery. The fact that functional gait measurements are related to outcome suggests a natural progression to the hypothesis that gait training (or task-orientated rehabilitation) could be applied to improving outcome.

4.5 Conclusions

- Patients recording a low OKS showed abnormalities in their gait pattern characterised by increased stride duration.
- This increased stride duration was indicative of reduced joints' sagittal RoM in swing and stance, and swing flexion time.
- Patients with a high BMI are more likely to report poor function using the OKS.
- Female patients' OKSs were lower than those of male patients.
- Portable IMU devices provide a convenient and affordable method for measuring the progress of patients' functional capability, as assessed by their gait following TKA.

Chapter 5 Efficacy of task-orientated rehabilitation in improving knee function and satisfaction in patients 12 months after knee replacement surgery for osteoarthritis

5.1 Introduction

The findings of Chapter 4, which supported the hypothesis that there is an association between an inferior OKS in patients who have shown abnormalities in their gait pattern 12 months after their knee replacement surgery, imply that it would be possible to change for the better the way these patients walk, and that their reported functional outcomes could be improved. That being the case, the presence of lower patient satisfaction (Bourne et al., 2010, Hamilton et al., 2012, Nilsdotter et al., 2009, Dunbar et al., 2013, Hamilton et al., 2013), and abnormalities in the gait biomechanics of TKA patients 12 months after their surgery (McClelland et al., 2007, Milner, 2009, Walsh et al., 1998), suggest that improving the gait of these patients may lead to greater satisfaction, as the persistence of pronounced physical impairments and inadequate gait (Walsh et al., 1998) will lead to poor functional performance (walking, stair climbing, etc.).

Abnormal gait also affects other joints of the operated and, in particular, the contralateral leg by putting greater load on them (Alnahdi et al., 2011, Yoshida et al., 2012, Farquhar and Snyder-Mackler, 2010, Shakoor et al., 2002). This precipitates their degeneration and the likelihood of further joint replacements. Further joint replacements have been recorded in around 40% of patients (Mont et al., 1995, Ritter et al., 1994), however, if at the time of TKA no contralateral arthritis is diagnosed, the likelihood of contralateral TKA is approximately 9%. In the case of the presence of moderate or severe arthritis, the chances of a contralateral TKA increases to up to 93% within a 5 year follow up (Mont et al., 1995). It was documented that 3 years after TKA, patients were weaker, walked more slowly, experienced more pain in their non-operated limb, and recorded lower self-reported outcome measures as compared to age-matched controls (Farquhar and Snyder-Mackler, 2010). The fact that every TKA patient had standard rehabilitation following their surgery shows that this rehabilitation neither achieved a complete recovery of these patients' gaits, nor had a long lasting effect, suggesting that the approach to rehabilitation for these patients should be reconsidered.

Typical prescribed rehabilitation exercises (Mintken et al., 2007, Bade et al., 2010, Levine et al., 2013, Schache et al., 2016) have an internal focus on, for example, a specific muscle, e.g. quadriceps strengthening or hamstrings stretching for increasing knee range of movement, which are intended to improve patients' ambulation. However, these types of exercises focus on a small part of an intricate movement only, and represent isolated tasks (e.g. increasing power and range of knee extension), and therefore may have a limited influence on improving economy of walking (Godges et al., 1993), or carrying out everyday activities. Movement is a complex process driven by coordinated interaction between different muscles and the peripheral and central nervous systems, suggesting that practising activities that form part of everyday life (task-orientated rehabilitation) may have the potential to offer improvement of gait quality for patients from 12 months after TKA.

The majority of patients recover naturally, but task-orientated rehabilitation may have the potential to improve normal walking patterns in patients who do less well with the standard rehabilitation approach. For this to occur, one needs to imply the plasticity of the motor system (Kidd, 1992, DeFeudis and DeFeudis, 1977, Rose, 1992), the neurophysiological processes associated with learning and sensory-motor adaptation (McComas, 1994), the quality that is able to adapt to new experiences, and the essence which makes this recovery of movement possible (Kaneko et al., 2003, Pascual-Leone et al., 1992). It has been shown, using brain imaging, that changes in the cortex occur within 3 weeks of practising a novel task (Karni et al., 1998), followed by changes in the cerebellum, striatum and related cortical areas which were evident a few days later (Ungerleider et al., 2002). Rehabilitation may be more effective when encompassing facilitation of cognitive-sensory-motor processes in a stimulating and variation-rich environment, rather than just doing prescribed exercises. This is more likely to be effective in recovery of physical losses (e.g. RoMs, muscle strengths) and motor reorganisation, and to sustain the achieved changes, as a result of adaptation and acquired behaviour. As stated in Chapter 1, this type of rehabilitation of RoM is referred to as "managed recovery behaviour", on the basis that the patients are self-sufficient and compliant with their rehabilitation programme (Lederman, 2013).

There are three identifiable features in such behaviour that benefit the process of improving deficiencies in movement, which encompass restoring of muscle strength, range of movement loss, and movement biomechanics simultaneously. The movement ought to have maximum resemblance to the functional task performed by the affected part of the body on an everyday basis, and exercised as often as possible throughout the day, gradually increasing the physical demand on this affected body part by requiring progressively exaggerated movements. These essential components resemble, first, specificity – the bigger the gap in similarity of movements the less likely for impaired movement to be transferred to better movement. Second, overloading – e.g. challenging yourself by attempting greater RoM and more difficult conditions for executing this new RoM. Third, repetition – progressing daily with a greater number of repetitions of the movement that requires restoration. These are also the principles employed to enhance sports performance.

A movement rehabilitation programme can be formulated for TKA patients that includes these three elements. Applying this programme to our patients with reduced knee movement 12 months after knee replacement surgery, requires them to carry out walking exercises, which represents the first element (specificity); to attempt to increase their stride length, and walking more upstairs and uphill (overloading); and to tackle their walking exercises as many times as possible during each day (repetition). The patients' end-range is achieved while they are engaged in daily functional activities, executing specific tasks, by utilising appropriate diverse movements. Therefore task-orientated (functional) rehabilitation is managed recovery behaviour aimed at returning impaired movement to normal function.

Hypothesis.

Patient reported functional outcome of TKA using the OKS is enhanced by specific task-orientated rehabilitation directed towards improving gait at 12 months after surgery.

Objectives.

1. Validate pedometer devices (Fitbit One) for further use for monitoring the level of daily activity (steps and floors) in participating TKA patients.

2. Quantify patient reported functional outcome (21 patients) 12 months after TKA (Baseline) and post TOR programme, using the OKS.
3. Evaluate gait (21 patients) 12 months after TKA (Baseline) and post TOR programme, using IMUs (GaitSmart).
4. Quantify patient mobility (21 patients) 12 months after TKA (Baseline) and post TOR programme, using Fitbit One data (steps and floors).
5. Quantify patient reported functional outcome (10 patients) 11 weeks post TOR programme, using the OKS.
6. Evaluate gait (10 patients) 11 weeks post TOR programme, using IMUs (GaitSmart).

5.2 Method

5.2.1 Participants

Participants for this part of the study (Stage 2), who showed abnormal knee flexion, were selected from the cohort of 76 participants in Stage 1 (see Chapter 4). Data were collected from 21 patients (male/female ratio = 9/12, mean age = 65.9 ±8.5 years, BMI = 31.7 ± 6.5) 12 months after TKA. These patients, who exhibited abnormal gait (knee flexion in stance below 12 degrees, as assessed by IMUs) were assessed over two sessions, prior to and after their 4-week TOR programme (see Table 5-1). Sample size calculations based on 0.95% power, a two-tailed significance level of 0.05, and a Cohens d of 0.7 indicated 20 participants would be required. (For sample size calculation see Appendix V: Statisticians Report.) Only patients who gave their written informed consent to take part in the walking test and TOR were recruited.

Ten patients (male/female ratio = 6/4, mean age = 66.2 ±6.9 years, BMI = 31.0 ± 4.5) from the above cohort of 21 were additionally re-assessed at a third session, 11 weeks after the completion of their TOR programme (see Table 5-1).

Inclusion criterion for this part of Stage 2 was: knee flexion in stance on the operated knee below 12 degrees.

Exclusion criteria were as for Stage 1 (See Chapter 4).

The right leg was operated on in 13 patients, and the left in 8 patients, 10 out of 21 patients had previous TKA on the contralateral knee. Types of implant used were Genesis II (Smith & Nephew plc), Stryker Triathlon System, Medacta and PFC. A cruciate-retaining (CR) TKA was used in 20 patients. 10 out of 21 patients had the patella resurfaced (see Figure 5-1).

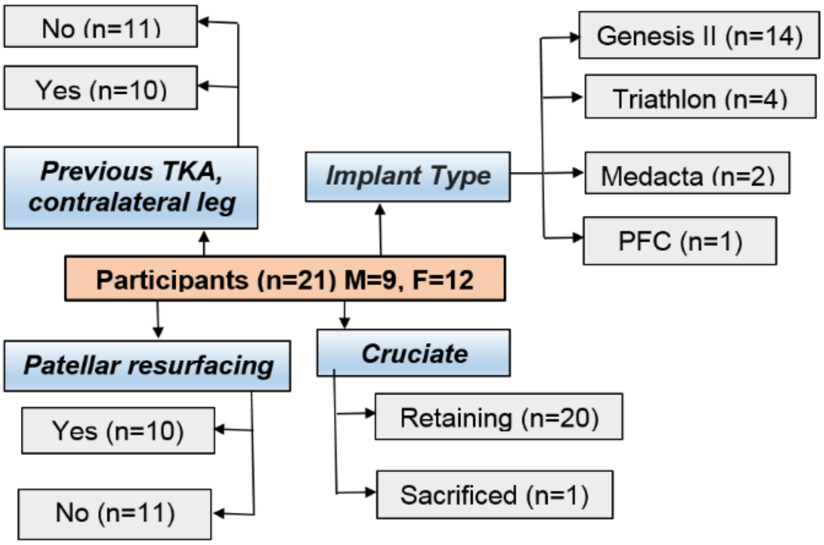


Figure 5-1: Summary of groups of knee replacement surgeries for patients recruited for task-orientated rehabilitation (TOR) programme

5.2.2 Procedure

The whole protocol of this part of the study (Stage 2) is presented in Table 5-1.

Table 5-1: Study protocol exploring the efficacy of a task-orientated rehabilitation (TOR) programme in TKA patients 12 months after their surgery

DAY 1	**DAYS 2 – 4**	**DAYS 5 – 32**	**DAY 33**	**DAY 110**
Testing Session 1 (Baseline, Prior to TOR)	**No testing (Establishing baseline activity level)**	**No testing (4-week TOR programme)**	**Testing Session 2 (Post 4-week TOR programme)**	**Testing Session 3 (11 weeks after completion of TOR programme)**
TKA patients (n=21, male/female=9/12)	*TKA patients (same as in Testing Session 1)*	*TKA patients (same as in Testing Session 1)*	*TKA patients (same as in Testing Session 1)*	*TKA patients (n=10, male/female=6/4)*
Baseline assessment at the first routine out-patient appointment: - Seeking consent; - OKS; - IMU gait analysis (gate kinematic).	***Monitoring of activity level*** (walking and climbing stairs) for 3 days using a pedometer device	***TOR programme*** (daily walking and stair and/or uphill climbing) for 4 weeks (28 days) with pedometer, gradually increasing number of steps and stairs.	***Re-assessment:*** - OKS; - IMU gait analysis (gate kinematic). Retrieval of 4-week pedometer's recordings (steps and floors).	***Re-testing:*** - OKS; - IMU gait analysis (gate kinematic).

The preliminary stage of testing the efficacy of TOR was the validation of pedometer devices used for monitoring daily activities (see below).

The testing routine of the first testing session, where patients were giving their consent to be tested and to participate in TOR, was identical to that discussed in Chapter 4. This was followed by the monitoring of the baseline activity level of participants for three days, using the pedometers, and the recording of the number of steps walked and the flights of stairs climbed at the end of each day onto paper copies of a Schedule of Daily Activities (Appendix VI: Schedule of Daily Activities), which was given them at their first testing session. At this stage patients learned how to handle and charge their activity trackers, and to ask the investigator any questions resulting from this.

Task-orientated rehabilitation guidelines: TOR began on day five, and continued for four weeks (28 days). The main guidelines were on walking techniques for improving patients' RoM (to walk taking longer strides – at least one foot distance between the steps – on a flat surface, but with the main emphasis on walking uphill and upstairs, consciously increasing the number of stairs ascended). To make this newly acquired RoM their habitual one by a gradual increase every consecutive week of their level of activity by up to 20%, or however their general wellbeing allowed. As the level of fitness of the majority of the participants was poor, the main purpose was to keep consistency, i.e. to do their activity level daily, and at the level achieved, avoiding reducing it. The steps walked and floors climbed were recorded in each patient's personal Schedule of Daily Activities (Appendix VI: Schedule of Daily Activities).

The assessment of the TOR programme for the participating 21 patients took place the day after its completion at testing session 2 (see Table 5-1). Testing procedures were the same as those at the initial routine out-patient appointment (testing session 1, see Table 5-1). After completing the OKS questionnaire, patients undertook the walking test using inertial motion sensors (IMUs) (GaitSmart, ETB, Codicote, UK). Walking tests were performed either at the out-patients department of the RNOH, or at patients' homes. The completed schedules of daily activities together with the pedometer devices – FitbitOne activity trackers – were collected at testing session 2.

Those participants who agreed to be tested 11 weeks after the completion of their TOR were re-assessed at testing session 3 (see Table 5-1), following the same routine, as was used previously for testing sessions 1 and 2 (see Table 5-1). The purpose of this re-assessment was to check whether the progress or regression observed in their testing session 2, immediately after the TOR, was sustained, and whether patients were still using the routine acquired during their 4-week TOR or not, even when they were not monitoring their activity with pedometer devices.

Validation of pedometer devices

The choice of the activity tracker was driven by the need to monitor the number of steps walked, and the number of floors climbed. At the time of the experiment there were two activity trackers Fitbit One (waist attached), and Fitbit Charge HR (wrist-based device) (Fitbit Inc., San Francisco, California, USA) able to monitor steps and floors climbed. However, due to the more complicated charging process and the considerably greater cost of the Fitbit Charge, the Fitbit One (see Figure 5-2) was chosen for further validity testing.

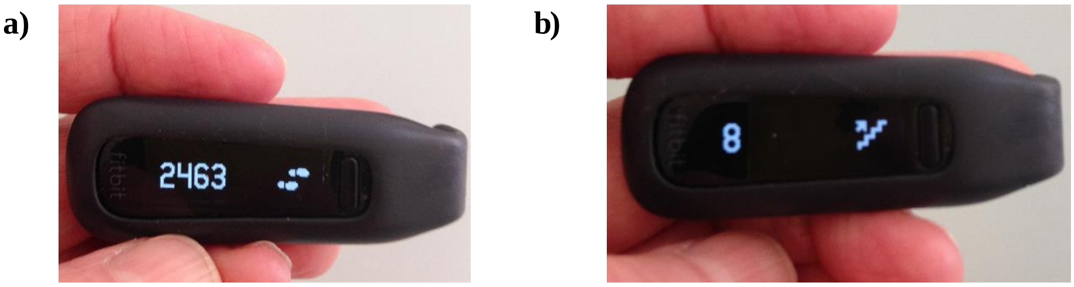


Figure 5-2: The pedometer Fitbit One (Fitbit Inc., San Francisco, California, USA) used for monitoring daily activities – number of steps walked (a) and flights of stairs climbed (b)

Unlike older single-axis pedometers, all Fitbit trackers are equipped with a triaxial accelerometer, which measures the motions in any way that the wearer of the device moves, by converting acceleration into digital measurements (data). An in-built algorithm and a predetermined threshold of the motion and its acceleration utilises these data for step counting. However, as this algorithm is tailored to the motion patterns indicative of average walking, wearing them while riding or cycling can result in under or over counting of steps, and this is acknowledged by the manufacturer (Fitbit Inc., 2017b).

For counting the number of floors climbed, Fitbit trackers are equipped with an altimeter sensor, which measures changes in barometric pressure, and registers one floor when the wearer climbs not less than ten feet in one ascent. Walking down stairs, or on an inclined treadmill, or when the wearer uses a StairMaster or an escalator does not register the floors (Fitbit Inc., 2017a).

The Fitbit One (Fitbit. Inc., San Francisco, California, USA) is a waist-worn, triaxial, accelerometry-based physical activity device that can measure steps taken, flights of stairs climbed, distance travelled, calories burned, and sleep (quantity and quality). For this study only information on steps taken and floors climbed was utilised. This monitor is a small (48.0 x 19.3 x 9.6 mm), light-weight (12 g) instrument. The Fitbit One has a five to ten days rechargeable battery life, and an internal memory that can store data for up to 24 days. It uses an Internet connection or Bluetooth to transmit its data to a computer or a smartphone device, and data can be uploaded to the Fitbit Connect Application. Its display screen provides real-time tracking information for the variables assessed.

It was documented previously that among others the Fitbit One activity tracker had comparable accuracy with the research-grade accelerometer ActiGraph for tracking physical activity (Imboden et al., 2017). The precision of all Fitbit One pedometers used in this part of the study was assessed prior to their usage by participants, in order that the data would be reliable.

To validate the Fitbit One pedometers the information from seven activity trackers, FitbitOne (Fitbit. Inc., San Francisco, California, USA) was collected over 16 consecutive days. These activity trackers were attached to the waist of the investigator in order to monitor the number of steps walked and the number of floors climbed from first thing in the morning till the end of the day. At the end of the 16 days, the information was retrieved for analysing the internal consistency of the devices.

PROMs

Patients completed the OKS questionnaire at least twice: once at their first testing session, as part of their routine 12 month follow-up assessment before performing their walking test (as described in Chapter 4), and then at their second testing session, the day after the completion of the 4-week TOR programme (see Table 5-1). Calculation of the OKS scores is described in Chapter 4.

Patients who were re-assessed at the third session, 11 weeks after the completion of their TOR programme, also completed a third OKS questionnaire (see Table 5-1).

Gait analysis

Gait assessment was performed using inertial motion sensors (GaitSmart, ETB, Codicote, UK) over two sessions, as described in Chapter 4. The first (Baseline) assessment occurred before the 4-week TOR programme. The second assessment was done on the day after the completion of the 4-week TOR programme (see Table 5-1 and Figure 5-3).

Figure 5-3: Gait assessment of a participant using IMUs: (a) prior to TOR (patient looking down, slumped posture, arms not swinging); (b) post 4-week TOR programme (confident gait – looking ahead, upright posture, arms swinging)

An additional third gait assessment of 10 patients was done at the testing session 3, eleven weeks after the completion of their TOR programme following the routine described in Chapter 4.

The following kinematic gait parameters, as described in Chapter 4, were calculated: pelvis, hip, thigh and calf sagittal and coronal angles, knee sagittal angles, and temporal descriptors of gait, stride duration, swing flexion time, and the difference in timing between the two peaks of thigh sagittal angle (time between maximum hip flexion before heel strike and maximum hip flexion on load).

5.2.3 Data analysis for gait measurements

IMUs' kinematic data were obtained and managed in the identical manner to those, applied in Chapter 4.

5.2.4 Statistical analysis

Validation of seven pedometer devices (Fitbit One), and comparison of pedometer devices' data (steps and floors), PROMs scores (OKSs) and IMUs kinematic data (pelvis, hip, thigh and calf sagittal, and pelvis coronal angles, knee sagittal angles, and temporal descriptors of gait, stride duration, swing flexion time, and the difference in timing between the two peaks of thigh sagittal angle) for 21 participants 12 months after TKA, pre and post their task-orientated rehabilitation (TOR) programme, were conducted using SPSS Statistics for Windows (version 22).

A reliability analysis procedure, using a two-way mixed effects model Intraclass Correlation Coefficient, was performed to explore the internal consistency of the measurements of steps and floors for seven Fitbit One pedometer devices.

The effectiveness of the TOR programme was assessed by conducting a series of Doubly Multivariate Repeated MANOVA tests, and follow-up Univariate ANOVAs. The MANOVA procedure allows multiple variables to be grouped together in 'factors' and tested simultaneously. MANOVA tests were performed on the four scale factors identified in Chapter 4 – **Hip Thigh Calf SAG** (hip, thigh, and calf sagittal RoM for both legs), **Knee Sag Flex TP Diff** (knee sagittal RoM, knee flexion in stance, and the difference between 2 peaks of thigh sagittal angle for both legs), **Pelvis Cor Sag** (pelvis coronal and sagittal RoM for both legs), **Limb SFT** (limb swing flexion time for both legs). Each MANOVA factor has two levels (pre and post TOR testing), therefore sphericity was irrelevant, and did not need to be considered. When the overall MANOVA for a factor was significant, a random effects univariate ANOVA test was conducted for each individual item. Univariate ANOVAs were also conducted to determine whether there were any changes in the Stride duration and the OKSs following the rehabilitation programme. A Simple Within-Subject Contrast test was used to determine whether differences existed between pre and post 4-week TOR programme groups' measured variables. The TOR programme was considered to be making a difference if the group measure effect (Baseline and Post TOR) was significant at the 5% level.

To find whether patients increased their activity during the TOR programme, a MANOVA factor called **Mobility** was constructed. The two items in the factor were the number of steps walked and the number of floors climbed. Following the MANOVA, paired-samples-t-tests were conducted for mean differences between the steps and floors measurements, and proportional differences in mobility, made at the baseline (prior to TOR), and at the end of the TOR programme. The proportional change in **Mobility** was calculated as follows:

$$Proportional\ change\ steps = \frac{No.steps\ post\ rehab - No.steps\ pre\ rehab}{No.steps\ pre\ rehab}$$

$$Proportional\ change\ floors = \frac{No.floors\ post\ rehab - No.floors\ pre\ rehab}{No.floors\ pre\ rehab}$$

$$Proportional\ change\ in\ Mobility = \frac{Proportional\ change\ steps + Proportional\ change\ floors}{2}$$

Finally, Pearson's correlation was run to determine whether OKS and gait quality improved/decreased relative to their increase/decrease in activity level after their 4-week TOR programme as compared to their baseline (pre-rehabilitation) levels. For the OKSs the raw difference between baseline and post-rehabilitation scores was used. For four scale factors, and for steps and floors the Proportional change was used for analysis.

To explore whether the obtained progress could be sustained, the post TOR programme gait variables, and the scale factors of the gait variables, where significant changes were recorded, and the OKSs of 10 out of 21 of the above participants were compared to those obtained 11 weeks after the completion of the programme, using a random effects univariate ANOVA.

5.3 Results.

5.3.1 Validation of pedometer devices (Fitbit One)

The Fitbit One devices demonstrated a high level of consistency (recommended values are 0.7 or higher (DeVellis, 2003, Kline, 2005)), as determined by their Cronbach's alpha of 1.000 for steps, and 0.998 for floors respectively. For the graphic representation of the data see Figure 5-4 and Figure 5-5.

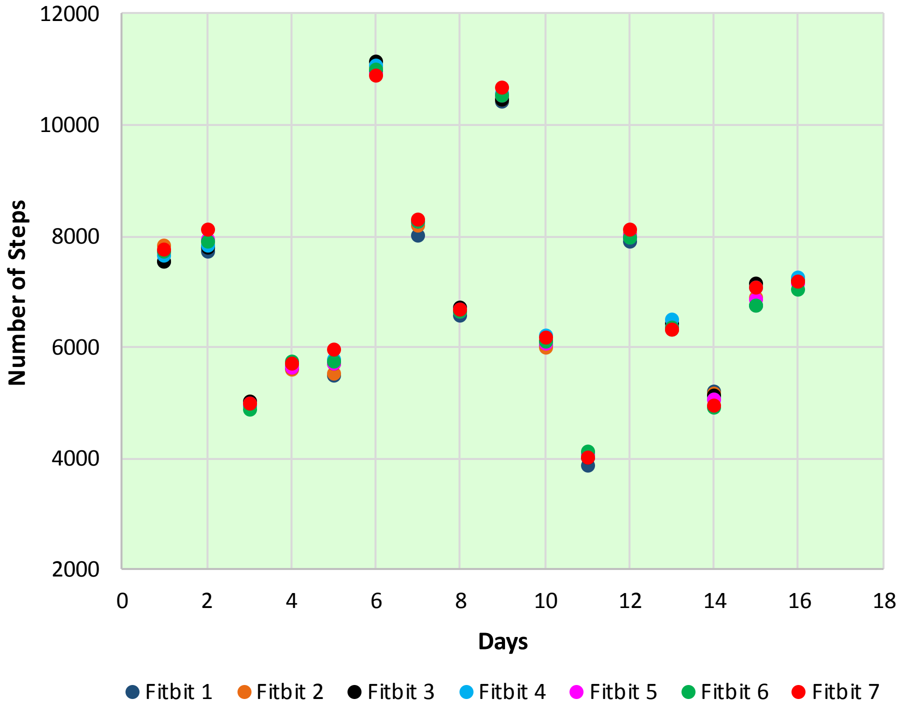


Figure 5-4: Fitbit One (n=7) steps data for 16 consecutive testing days on one individual

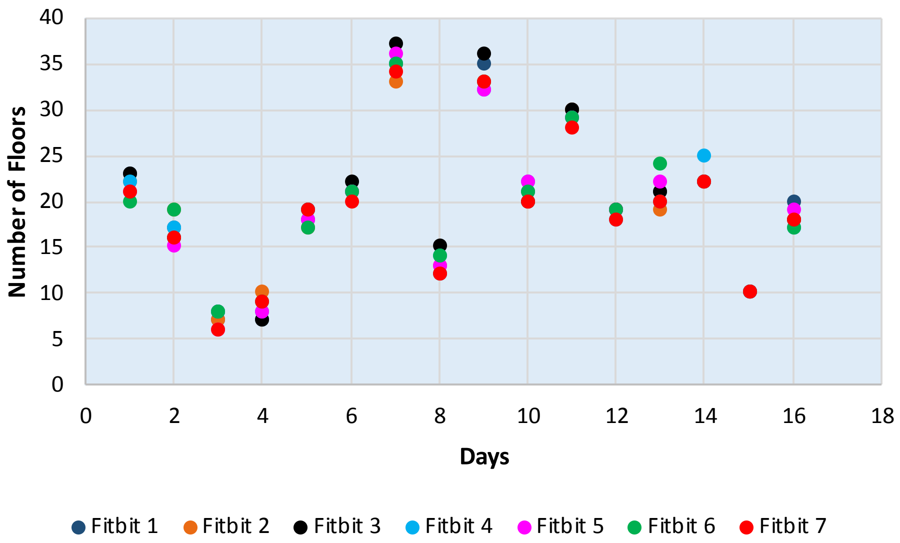


Figure 5-5: Fitbit One (n=7) floors data for 16 consecutive testing days on one individual

5.3.2 Efficacy of TOR programme

5.3.2.1 PROMs

There was a significant difference of 3.6 points in participants' OKS. Participants demonstrated a significantly higher OKS after their TOR (38.1 ± 5.7) as compared to their baseline OKS (34.5 ± 8.7), F (1, 20) = 15.745, ρ = 0.001. For participants' individual OKSs pre and post TOR see Figure 5-6.

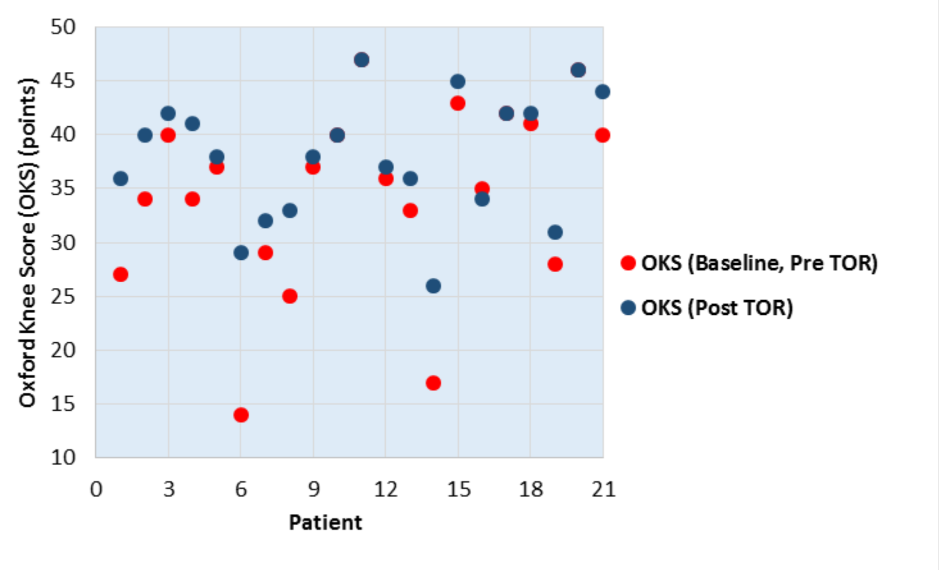


Figure 5-6: Individual OKSs of participants (n=21) pre and post their TOR programme

5.3.2.2 Kinematic variables

MANOVA for the four scale factors of kinematic gait variables prior to and post TOR programme showed significant differences in **Hip Thigh Calf SAG** (hip, thigh, and calf sagittal RoM for both legs), (F = 10.681, ρ= 0.004), and **Knee Sag Flex TP Diff** (knee sagittal RoM, knee flexion in stance, and the difference between 2 peaks of thigh sagittal angle for both legs), (F = 27.204, ρ = 0.000).

No significant differences were found for **Pelvis Cor Sag** (pelvis coronal and sagittal RoM for both legs), (F = 0.041, ρ = 0.842), and **Limb SFT** (limb swing flexion time for both legs), (F = 0.310, ρ = 0.584). The items in these factors were therefore excluded from further analysis. This left 15 of the 21 gait variables, which were then analysed with a random effect univariate ANOVA test. The results for these 15 gait parameters are presented in Table 5-2. A significant difference was observed for 9 gait variables, where 7 variables were RoMs of joints and segments (degrees) (see Table 5-2 and Figure 5-7), the eighth parameter was the difference between two peaks of thigh sagittal angle for the non-operated leg (percentages) (see Table 5-2), and the ninth was stride duration (seconds) (see Table 5-2 and Figure 5-8).

Table 5-2: The ANOVA results of TOR programme's 15 gait parameters testing (Pre (Baseline) and Post TOR) for 21 participants

Gait parameters (n=17)	Mean difference (Post TOR – Baseline)	95% CI for Mean Difference		F test (F)	Significance (ρ)
		Lower Bound	Upper Bound		
Operated Limb Knee flexion in stance (°)	4.884*	3.181	6.586	35.811	0.000
Non-operated limb Knee flexion in stance (°)	3.018*	1.219	4.816	12.251	0.002
Operated Limb Knee Sagittal RoM (°)	3.376*	0.926	5.826	8.263	0.009
Non-operated Limb Knee Sagittal RoM (°)	1.077	-1.667	3.822	0.671	0.422
Operated Limb Hip Sagittal RoM (°)	1.593	-1.079	4.265	1.547	0.228
Non-operated Limb Hip Sagittal RoM (°)	3.060	-0.306	6.427	3.596	0.072
Operated Limb Thigh Sagittal RoM (°)	2.566*	0.872	4.261	9.978	0.005
Non-operated Limb Thigh Sagittal RoM (°)	3.259*	1.153	5.364	10.419	0.004
Operated Limb Calf Sagittal RoM (°)	3.957*	2.080	5.835	19.328	0.000
Non-op Limb Calf Sagittal RoM (°)	3.442*	0.744	6.141	7.079	0.015
Operated Limb Calf Coronal RoM (°)	-1.961	-5.045	1.124	1.758	0.200
Non-operated Limb Calf Coronal RoM (°)	-0.110	-1.978	1.758	0.015	0.904
Operated limb Difference between 2 peaks of thigh sagittal angle (%)	0.667	-0.775	2.109	0.930	0.346
Non-operated Limb Difference between 2 peaks of thigh sagittal angle (%)	1.810*	0.109	3.510	4.925	0.038
Stride duration (sec)	-0.063*	-0.101	-0.025	12.096	0.002

* The mean difference is significant at the 0.05 level.

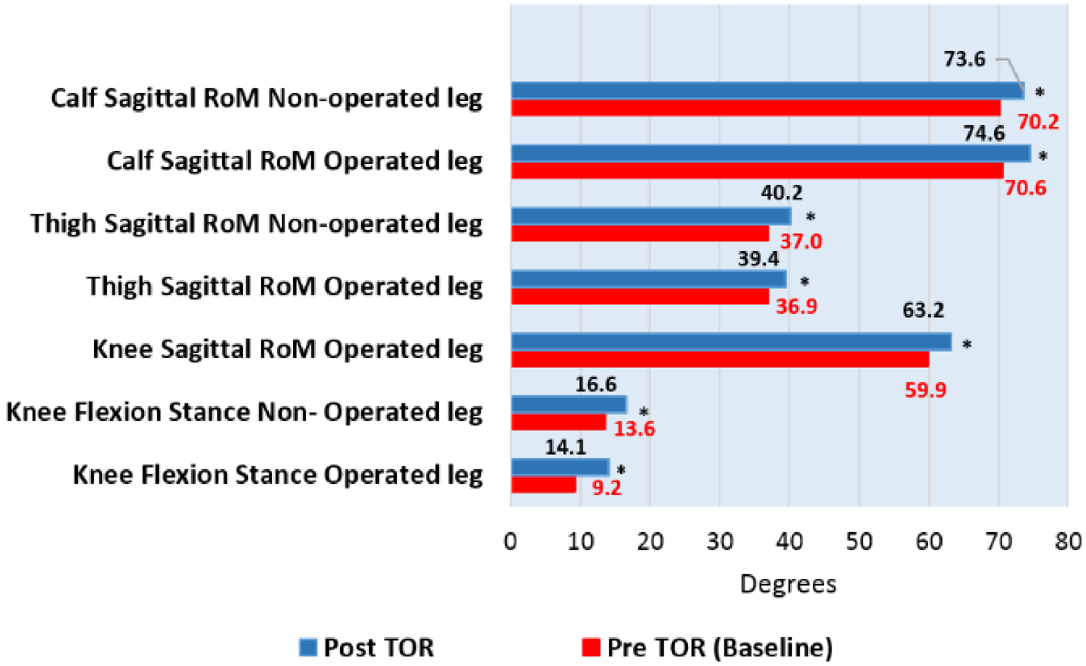


Figure 5-7: RoMs of joints and segments that exhibited a significant difference post TOR programme. Data are shown as average (n=21 participants)

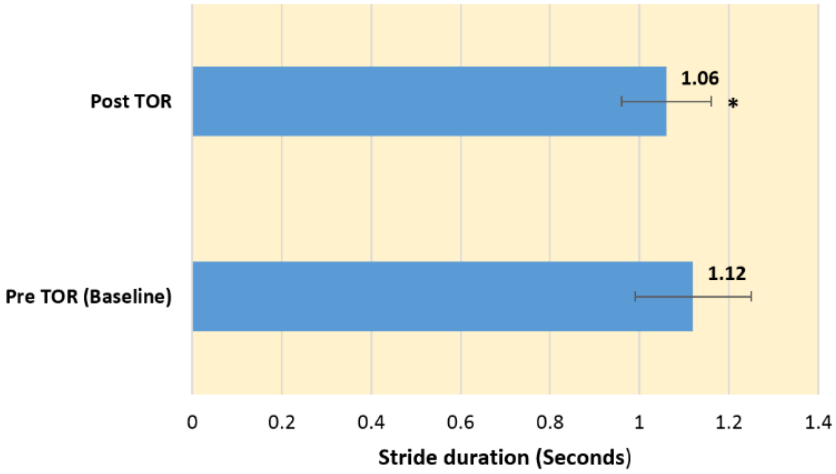


Figure 5-8: Stride Duration pre and post TOR programme (n= 21 participants), F (1, 20) = 12.096, ρ = 0.002

5.3.3 Mobility (steps and floors) assessment

MANOVA results confirmed that **Mobility**, which was a combination of Steps and Floors, post the TOR programme was significantly different from **Mobility** prior to the TOR programme (F = 9.429.198, ρ= 0.006). There was a significant increase of 6.4 points (*p* = 0.029, 95% CI from 0.7 to 12.0 points) in proportional difference in Mobility, with its mean value of 39.7 points (95% CI from 30.0 to 50.0) on completion of the TOR programme, as compared to 33.3 points (95% CI from 23.1 to 43.3 points) prior to their rehabilitation.

A significant increase of 992.8 in participants' number of steps walked was observed by the end of their 4-week rehabilitation programme (*p* = 0.006, 95% CI from 318.4 to 1667.2 steps). The mean value of the number of steps on completion of the rehabilitation programme was 5666.8 (95% CI from 4722.7 to 6661.54), as compared to 4674 (95% CI from 3667.2 to 5836.7) pre rehabilitation (see Figure 5-9).

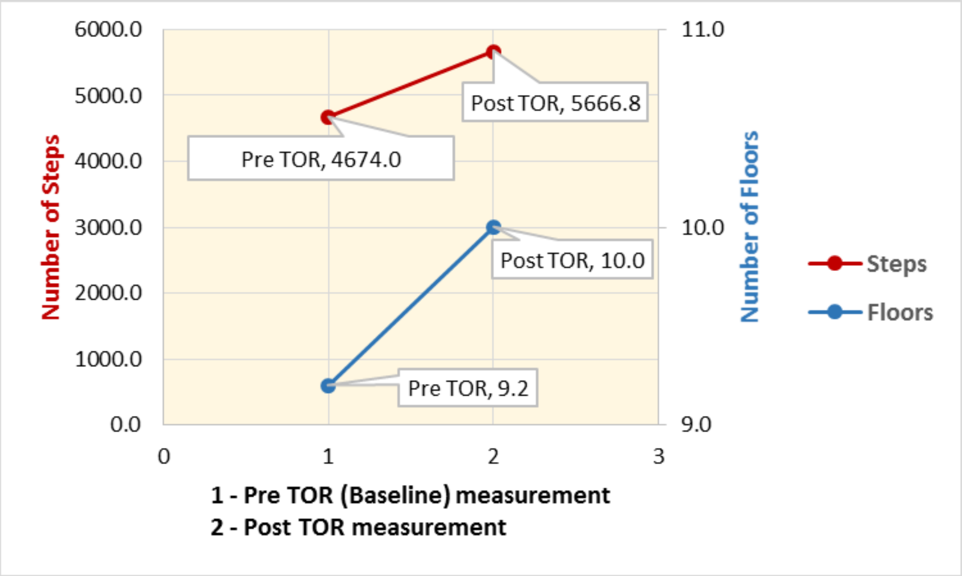


Figure 5-9: Mean values of number of steps and floors for all participants (n=21) pre and post TOR programme

The mean value of the number of floors climbed by the end of 4 weeks of the rehabilitation programme was higher (10 floors, 95% CI from 7.7 to 12.4 floors), as compared to its mean value prior to commencing the TOR programme (9.2 floors, 95% CI from 6.9 to 11.4 floors) (see Figure 5-9). However, the difference of 0.8 floors was not significant (*p* = 0.260).

Although both gait and mobility improved after the TOR programme, there were no significant correlations between changes in mobility and changes in the gait factor scores (see Table 5-3). However, changes in OKS were positively and significantly correlated (*r* = 0.546, *p* = 0.010) with the proportional difference score in floors (see Table 5-3). This indicates that the patients who increased their floor climbing activity more reported greater increase in function in their OKSs.

Table 5-3: Pearson correlations (*r*) between changes in mobility and OKS, and the five gait factor scores and the stride duration of 21 participants

		dOKS	dHTCSAG	dKSagFlexTPDiff	dPelvisCorSag	dThighCor	dLimbSFT	dStrideduration
dsteps	***r***	-.030	.060	.293	.387	-.251	.070	.229
	p	.897	.795	.198	.083	.272	.763	.317
dfloors	***r***	.546*	.205	-.159	-.104	-.193	-.028	.134
	p	.010	.372	.490	.654	.401	.905	.563
dMOBILITY	***r***	.228	.135	.127	.217	-.260	.035	.218
	p	.321	.561	.582	.344	.256	.879	.343
dOKS	***r***	1.000**	.215	-.152	-.226	.221	-.067	-.162
	p	0.000	.349	.512	.325	.335	.774	.483

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

Note: dsteps = proportional difference score in steps; dfloors = proportional difference score in floors; dMOBILITY = proportional difference score in mobility = (dsteps + dfloors)/2; dOKS = raw change in OKS = (OKS post TOR – OKS prior to TOR); dHTCSAG = proportional difference in Hip Thigh Calf SAG score; dKSagFlexTPDiff = proportional difference in Knee Sag Flex TP Diff score; dPelvisCorSag = proportional difference in Pelvis Cor Sag score; dThighCor = proportional difference in Thigh Cor score; dLimbSFT = proportional difference in Limb SFT score; dStrideduration = proportional difference in Stride duration score.

5.3.4 Sustained improvements following TOR

To test for sustained improvements, gait variables and OKSs were examined at three time points (Baseline, Post Rehab, and 11 Weeks Post Rehab). A random effect ANOVA was conducted on each gait variable, OKS, and two scale factors. The results are shown in Table 5-4.

Table 5-4: Sustained improvement in Gait and OKS for 10 patients

Gait variable, OKS, scale factor	**Mean at Baseline**	**Mean at Post Rehab**	**Mean at 11 Weeks Post Rehab**	**Improvement sustained**
Operated Limb Knee flexion in stance (°)	8.4	14.6***	16.6***	Yes
Non-operated limb Knee flexion in stance (°)	13.7	17.6*	17.0*	Yes
Operated Limb Knee Sagittal RoM (°)	63.6	63.7	66.2	N/A
Non-operated Limb Knee Sagittal RoM (°)	65.2	66.1	66.0	N/A
Operated Limb Hip Sagittal RoM (°)	33.9	36.5	36.6	N/A
Non-operated Limb Hip Sagittal RoM (°)	33.7	38.4	37.8	N/A
Operated Limb Thigh Sagittal RoM (°)	38.6	41.6	41.9*	Yes
Non-operated Limb Thigh Sagittal RoM (°)	38.8	42.3	42.4	N/A
Operated Limb Calf Sagittal RoM (°)	72.8	76.3*	78.3**	Yes
Non-op Limb Calf Sagittal RoM (°)	72.1	77.1*	77.7*	Yes
Operated Limb Calf Coronal RoM (°)	14.6	10.8	14.2	N/A
Non-operated Limb Calf Coronal RoM (°)	12.5	11.2	14.7	N/A
Operated limb Difference between 2 peaks of thigh sagittal angle (%)	15.1	14.4	14.1	N/A
Non-operated Limb Difference between 2 peaks of thigh sagittal angle (%)	16.0	16.4	16.3	N/A
Stride duration (sec)	1.07	1.04	1.00*	Yes
OKS	38.3	40.6*	43.4***	Yes
Hip Thigh Calf SAG	0.093	0.614*	0.660*	Yes
Knee Sag Flex TP Diff	-0.155	0.181*	0.275**	Yes

Note: n = 10. N/A = not applicable. * Significantly different from Baseline at $\rho <= 0.05$; ** significantly different from Baseline at $\rho <= 0.01$; *** significantly different from Baseline at $\rho <= 0.001$.

The significance levels reported in Table 5-4 indicate differences from Baseline. “Sustained improvement” was deemed to have occurred if the patient response Post Rehab was significantly better than Baseline, and the patient response at 11 Weeks Post Rehab was significantly better than Baseline.

Table 5-4 shows sustained improvement in six of the gait variables, two scale factors of the gait variables, and OKS. This means that these ten patients were able to sustain their achieved progress in gait 11 weeks after completing their TOR, although they were no longer monitoring their daily activities. Moreover, there was a further significant improvement of 2.8 points in patients reported functional outcome, as measured by OKS ($\rho = 0.019$), as compared to their post TOR’s OKS, or 5.1 points as compared to their baseline OKS ($\rho <= 0.001$).

5.3.5 Patient feedback

Although requesting feedback from patients was not part of the study design, when the first three patients sent their comments about their experience of the TOR programme spontaneously by e-mail, it was decided to ask all the remaining participants to put in their own words what value, if any, they had received from the TOR programme.

The method of conceptual analysis (Busch et al., 1994-2012, Cook, 2010) was applied to analyse their written responses. The level of analysis for sets of words or phrases was chosen by two coders for rigour, investigator and statistician. It was decided to code for fourteen concepts, based on the frequency of their occurrence in the participants' feedback. A choice was made that similar concepts worded slightly differently such as "decreased pain" and "less pain" would be better represented under one category, "decreased/less pain". Consistency of the coding was applied throughout. Irrelevant information was disregarded. The text was coded by hand, by reading through the text four times and concept occurrences were manually noted, in order to facilitate the recognition and exclusion of errors. The manually collated qualitative data was then grouped into three themes – Pain and well-being, Mobility, and Quality of life (Table 5-5). The data were entered and analysed in Excel.

The Pain and well-being theme consisted of the following categories: decreased/less pain, pain free, better health.

The Mobility theme consisted of the following categories: walking further/longer, easier stair climbing, knees/walking improved, walking faster, longer strides/steps, correct walking, improved mobility.

The Quality of life theme consisted of the following categories: enjoy walking, increased confidence/self-confidence, increased motivation, and increased inspiration/incentive.

Table 5-5: Patient feedback on impact of participation in the TOR programme (n = 19)

Theme	*Category*	*Frequency*	*%*
Pain and well being	Decreased/less pain	14	60.9
	Pain free	4	17.4
	Better health	5	21.7
Subtotal		23	100.0
Mobility	Walking further/longer	9	20.0
	Easier stair climbing	6	13.3
	Knees/walking improved	6	13.3
	Walking faster	2	4.4
	Longer strides/steps	14	31.1
	Correct walking	4	8.9
	Improved mobility	4	8.9
Subtotal		45	100.0
Quality of life	Enjoy walking	9	18.4
	Increased confidence/self-confidence	11	22.4
	Increased motivation	13	26.5
	Increased inspiration/incentive	16	32.7
Subtotal		49	100.0

Of the twenty-one patients taking part in the programme, responses were received from nineteen (Appendix VII: Patients' feedbacks). Decreased or no pain was reported by 18 patients (78.3%). All nineteen participants stated that they had achieved improved mobility (i.e. walking faster and for longer distances, easier stair climbing, etc.) and better quality of life (i.e. enjoying walking, increased confidence, etc.).

5.4 Discussion

These findings are consistent with the study hypothesis, which suggested that the outcome of TKA may be enhanced by specific task-orientated rehabilitation directed towards improving gait at 12 months after surgery.

The results of this study show that the prescribed TOR programme improved the gait quality of participants at 12 months after surgery. The improved gait quality manifested itself in greater RoMs of joints (hip and knee) and segments (thigh and calf) involved in walking, in the direction of walking (i.e. sagittal plane); and consequently smoother, less laboured walking as a result of shorter stride duration.

There is a lack of research on rehabilitation of TKA patients from 1 year after their surgery, as the rehabilitation of these patients was as a rule completed by this time. Additionally, the majority of the research looking at this group of patients investigated the changes in their gait kinetic and kinematic at a later stage (12 months onwards) TKA, rather than exploring rehabilitations for tackling gait kinetic and kinematic deficiencies. Therefore, the results of studies investigating gait performance for older groups of adults, following different types of rehabilitation, and those investigating the effects of different rehabilitation of TKA patients at the earlier than 1 year stage of recovery, were taken for comparison with the results of this study.

Harikesavan *et al.*, in their study of 10 patients assessing the efficacy of hip abductor strengthening in addition to standard rehabilitation on functional outcome 3, 6, 12 months after TKA, found significant improvements over 10 controls, who undertook standard rehabilitation alone, in hip abductor strength, single operated leg stance test and six minute walk test (Harikesavan et al., 2017). The exercise programme was carried out 2-3 sessions per week and lasted 40-45 minutes. Even though our study did not carry out the same assessments, it found the mobility of the participants was significantly higher on the completion of their rehabilitation programme. However, Harikesavan *et al.*'s study did not have a sufficient number of participants to draw strong conclusions. The patients were compared at the earlier stages of their recovery (1 month, 3 months) and the stage where recovery had completed (1 year), so the element of natural progression inevitably existed. Additionally, knee strength in the abductor strengthening group just failed to reach statistical significance (ρ = 0.062) in being worse as compared to the controls. It would be more informative if the test would be performed at a later stage, e.g. 18 months onwards.

A meta-analysis examining the effects of different types or combinations of exercise interventions using randomised controlled trials, looking at improvement in preferred gait speed, concluded that the most effective type of exercise was progressive resistance training with high intensities (Van Abbema et al., 2015). In our study, walking uphill could be considered as progressive resistance training, as participants were increasing uphill walking day by day, and the result of it was reduced stride duration with greater RoM. It has been found that a beneficial adaptation after resistance exercise diminishes within 6 weeks of detraining, confirming that older adults should carry out a lifelong systematic routine for improving and maintaining their physical functions (Kalapotharakos et al., 2010). In our study 10 out of 21 participants, who were re-assessed 11 weeks after the completion of their TOR programme, demonstrated that their gait parameters had not changed, moreover, they kept improving. Of course, it could be argued that not all the participants were tested at this time point, and the tested participants were self-selected volunteers. Although they did not have activity trackers monitoring their daily progress, they had acquired the learned routine, and they could estimate the distances they needed to walk, as they had walked them so many times during their rehabilitation programme, thus avoiding detraining.

A study on the gait performance of healthy older adults (66 – 91 years) investigating the additional effects of foot gymnastic exercises (aimed at strengthening of the muscles of the feet and increasing the ankle joint RoM) combined with more traditional exercises for improvement of strength and flexibility in the lower extremity, concluded that even though there was significant improvement in gait performance and muscle power after the training period in both groups, no additional effect on physical and walking performance, as measured by their spatio-temporal gait parameters (walking speed, cadence and step duration), was observed post training in the foot gymnastic exercises group. The foot gymnastic group though showed a significant improvement of ankle RoM after their training programme as compared to only traditional exercise. Fifty-six subjects were randomly assigned to either the foot gymnastic group (traditional exercise plus foot gymnastics), or to the traditional exercises group only, these both performed twice weekly for 12 weeks (Hartmann et al., 2009). Addition of foot gymnastics, aimed at RoM improvement and foot muscle strength, achieved these aims. However, this addition did not specifically improve walking, as the gymnastics were not task-specific or functional for improving walking, therefore failing to transfer achieved gains to walking performance, despite being exercised for 12 weeks, while the adaptations could be noticed after training a specific task for 3 weeks (Karni et al., 1998).

A similar study examining the effect on gait performance of 8 week twice daily hip and ankle stretching in older people found a moderate increase in RoM in the above joints, but no change in stride length (Christiansen, 2008). The study looking at the effect of stretching and strengthening of leg and abdominal muscles of 27 postmenopausal women twice weekly for three months found no effect on their walking performance, confirming lack of transfer between tasks (Reis et al., 2012). The findings were similar to other studies where no transfer of gains to sports performance was found (Ingraham, 2003, Magnusson and Renström, 2006).

On the contrary, the study comparing the immediate and long-term effects of a 6-8 week walking-skill programme with conventional physiotherapy started 6 weeks after TKA, found that the six minutes walking test results of the walking-skill programme group were superior to the conventional physiotherapy group results immediately after the completion of the programme and 9 months after its completion. This suggests that the walking-skill programme was more effective for improving walking than conventional physiotherapy (Bruun-Olsen et al., 2013). No difference in stair climbing between the groups was observed. The author suggested that the lack of improvement was due firstly to the fact that stair climbing was considered to be a difficult task at an early stage of recovery, as the pain still persisted (Heiberg et al., 2010), and secondly, because the stair climbing task was not practiced with the same intensity as walking. This programme utilised the principles of motor control and learning (Schmidt and Lee, 2005, Shumway-Cook and Woollacott, 2007), in that the improvement of motor control could be achieved through continuous practice of daily walking tasks in wide varieties, keeping the main emphasis on “learning by doing” with regard to walking and transfer activity training (Bruun-Olsen et al., 2013). The six minutes results of a similar study (Moffet et al., 2004), that used functional task-orientated exercises as part of their intensive rehabilitation, were comparable to Bruun-Olsen *et al.*’s. Although, at 12 months the six minutes walking results of Bruun-Olsen et al.’s study were superior to Moffet *et al.*’s, which could be explained by the former study using more walking load. Moreover, no complications were caused by intervention, and excellent compliance in both studies was recorded. Finally, no difference in PROMs in either study was noted at 12 months (Moffet et al., 2004, Bruun-Olsen et al., 2013).

The same approach was used in our study, and even though the measures of performance were different, significant improvement in patients’ gait was observed consistent with the findings of Bruun-Olsen *et al.* and Moffet *et al.* studies. We did not do the six minutes walking test, but the fact that participants covered longer distances, climbed more flights of stairs, and their stride duration decreased on the completion of their programme, could be a good basis on which to think that they could be more successful in six minutes walking as well. The participants of our study were doing their TOR programme themselves from the first day to the last, unlike Moffet *et al.*'s and Bruun-Olsen *et al.*'s patients who attended 12 supervised physiotherapy sessions lasting around 70 minutes each over their rehabilitation period. As in both of the above studies no complications were caused by the TOR programme, and good compliance was found.

Unlike the analysed studies above, the results of PROMs, as assessed by OKSs of the participants, were significantly improved at the completion of the TOR programme, and moreover, the rise of the OKSs was observed 11 weeks post the TOR programme. There could be several reasons for the observed significant improvement. The first one is that patients participating in this study were much further into their recovery, when the recovery process was generally considered completed by then. Therefore their functions and pain level were most likely better at the baseline, as compared to the above studies, and the participants were looking forward to even bigger improvements. The second is that patients were motivated by their own progress, therefore motivation persisted and got even higher as they progressed with their programme over time. They were empowered by the fact that they were in control of their further future improvements. It was also evident that those who put more efforts into their stair climbing produced higher scores. Their significantly higher OKSs following completion of the TOR programme indicated their greater satisfaction with more efficient function.

The strength of our study was in that mobility outcome was measured by actual everyday mobility (number of steps walked and floors climbed), as compared to studies where muscle strength and power, or timed get up and go, or chair-raise test, was presented as outcome of function, which might have a relatively weak transfer to actual mobility. The fact that rehabilitation was taken to participants' homes and community made it more cost-effective, as no additional NHS staff or specialised equipment were required. Moreover, this approach to rehabilitation confirmed that older adults of this group of the population, post TKA, were able independently to apply the programme, and were motivated consistently to continue it, as no more additional skills than those that they already had were required.

The limitation of our study, though, was the absence of control groups (no rehabilitation) or comparison groups, for which other accepted types of rehabilitation could have been used. A bigger population sample size would make the study more powerful for assessing the efficacy of the intervention, and its further implications. The analysis of other co-morbidities of participants could give a bigger picture of limitations or lack of it for implication of the programme. Previous studies found that the reliability and validity of consumer activity trackers was dependent on the walking speed of the tested individuals, age group 65-84 years, tending to undercount steps in those who were walking with lower speeds (Fokkema et al., 2017, Modave et al., 2017). Taking into account that the mean age of the participants was 65.9 ±8.5 years, this could be another limitation of our study in respect to step counting.

To conclude, these studies demonstrated the importance of specificity and transfer in training, where rehabilitation involves the utilisation of the movement that needs restoration. The movement challenge should be within task or function rather than extra-functional, as transfer of skills within different tasks is negligible or entirely absent (Schmidt and Lee, 2005, Healy et al., 2006). The principle of specificity and lack of transfer in learning new tasks was demonstrated in young children (Haga et al., 2008), as well as being shown in adults (Schmidt and Lee, 2005, Fleishman, 1958).

The rehabilitation of TKA patients in the presented study used a task specific approach, i.e. the participants were given very specific tasks – they were asked to walk on the flat and uphill, and to climb stairs in their real environment, so that their position, dynamic of movement and the surrounding environment was natural to their real world, while leading their normal lives. Moreover, their gait rehabilitation was a part of their everyday life, and it was they themselves who would make it happen. They would know their limitations as they were explained to them, and each participant was given their own baseline report highlighting their weaknesses, and how to execute the movement, so that changes might happen. They were thinking about movements they were intending to execute, thereby facilitating their motor adaptation by mental practice (Jeannerod, 2001, Schmidt and Lee, 2005). They were thus empowered by the knowledge of how to help themselves, i.e. why they should do what they did. Finally, they were not entirely on their own, as they had their own activity trackers, the precision of which was reliable enough to use in a clinical setting, to show them their daily achieved progress, encouraging them to keep it up, and beat their "own record" every following day. This logical process of rehabilitation made a natural progression based on results achieved. Therefore, the quality of their gait significantly improved after the TOR, as measured by their kinematic gait parameters, which in turn improved their mobility and function, and most importantly their satisfaction, as stated in their voluntary and enthusiastic feedbacks (see Appendix VII: Patients' feedbacks).

Comments made by the participants, who had unsatisfactory walking patterns 12 months after their TKA, underpinned the view, on completion of their TOR programmes, that the TOR approach to rehabilitation had a positive effect on the major reasons for which they had desired joint replacement surgery in the first place, i.e. pain and its impact on their well-being; reduced mobility, and the effect of it on their quality of life. Out of nineteen feedbacks from the 21 patients, who completed the TOR programme, eighteen participants reported a reduction in pain and improved well-being. All feedbacks proclaimed improved mobility (e.g. walking faster and for longer distances, easier stair climbing, etc.) and superior quality of life (e.g. enjoying walking, increased confidence, etc.).

5.5 Conclusions

- The 4-week TOR programme improved the gait quality of the 21 patients taking part in the rehabilitation.
- The rehabilitation programme resulted in a greater RoM of joints and segments involved in walking and a shorter stride duration.
- Participants recorded significantly higher OKSs following the rehabilitation programme, demonstrating improved perceived functional outcome and suggesting greater satisfaction.

- There is evidence that the increases in OKSs are higher in patients who show a greater increase in their climbing activity (steps and stairs).
- Improvements gained immediately following the rehabilitation programme were maintained in the longer term.
- Validation of pedometer devices' (Fitbit One) measurements demonstrated a high level of internal consistency, allowing reliable utilisation of them for this experiment.

Chapter 6 Effect of speed and slope on walking performance in the healthy and in those 12 months after TKA

6.1 Introduction

It has been found previously that limitations in executing daily tasks, e.g. walking and stair climbing (Walsh et al., 1998, Mizner et al., 2005, Meier et al., 2008), and abnormal gait patterns remain long after surgery (Andriacchi et al., 1982, McClelland et al., 2011, Ouellet and Moffet, 2002). In Chapter 5 we established that the patients who increased their floor climbing activity reported a greater increase in function in their OKSs, suggesting that stair climbing activity was a major determinant of patient reported functional outcome improvement. This finding naturally led to the need to investigate participants' gait in more challenging environments.

In order to create differing controlled conditions in relation to speed and gradient, which allow stressing of the participants gait deficiencies more profoundly, and therefore to reveal any changes in gait kinematic and gait kinetic variables, which were not available from the GaitSmart system, the instrumented treadmill (a clinic based tool) was used to test the participants. Additionally, as GaitSmart did not provide kinetic gait data, the kinetic data obtained from the treadmill could supply an insight for interpretation of the findings in previous experimental chapters.

Gait assessment following knee replacement surgery is necessary for a number of reasons. Firstly, tibial component fixation is influenced by gait patterns and subsequent joint loading. Second, changes in gait are predictive of component migration and aseptic prosthetic loosening (Hilding et al., 1996, Hilding et al., 1999, Astephen Wilson et al., 2010), which after infection is the major reason for knee revision surgery (Le et al., 2014, National Joint Registry, 2016). Third, development or retention of abnormal gait patterns following TKA could lead to progression of OA in other joints of the operated leg, or the joints in the non-operated leg (Shakoor et al., 2002). Altered loading of the joints of the operated and non-operated leg are biomechanical factors greatly contributing to speedy progression of the disease. Therefore, establishment of the contributing factors to abnormal gait biomechanics, especially when the patients are subjected to different walking load conditions, as in real life, could have an effect on the long-term outcome after knee replacement surgery. Utilising the instrumented treadmill for creating these different conditions, and obtaining additional data from these assessments could provide complementary aspects of the gait pattern of such patients.

A more comprehensive analysis of the differences of knee joint biomechanics after TKA as compared to healthy controls has been achieved in other studies by three dimensional motion analysis (Andriacchi et al., 1982, Bolanos et al., 1998, Lee et al., 1999, Otsuki et al., 1999, Saari et al., 2005, Fenner et al., 2017). The most common findings were reduced stance knee flexion and abnormal patterns of external flexion/extension moment of the knee (Andriacchi et al., 1982, Milner, 2009, McClelland et al., 2011, Levinger et al., 2012b). Reduced walking speed, shorter stride length, decreased range of motion in the sagittal plane, different moments in the joints of the lower limbs, quadriceps weakness, and the presence of compensatory patterns in non-operated joints were also observed after TKA (Benedetti et al., 2003, Saari et al., 2004, Saari et al., 2005, Levinger et al., 2013).

Gait abnormalities while walking on the flat at a self-selected speed, or stair climbing were equally found in patients with different types of implant design. However, the impact of the type of TKA implant design with level walking or stair climbing, is controversial. Some authors found that the type of implant had no significant effect on altered gait of TKA patients (Hilding et al., 1996, Bolanos et al., 1998, Saari et al., 2005, Hajduk et al., 2016), nor did the presence or absence of patellar resurfacing (Smith et al., 2006). Others documented greater deviations from normal with a sacrificed posterior cruciate ligament (PCL). It was reported that patients with retaining PCL had more normal gait with greater knee flexion during stair walking as compared to a sacrificed PCL (Andriacchi et al., 1982, Cloutier, 1983, Kramers-de Quervain et al., 1997). Conversely, greater knee flexion and increased flexion and adduction moments during loading were found in patients with PCL sacrificed (Dorr et al., 1988).

The majority of research studying gait kinetics and kinematics of patients after TKA utilised level walking at a comfortable self-selected speed. Being able to change the speed of walking, either more quickly or more slowly, is an integral part of everyday life. Walking at a faster speed in a healthy population has been associated with greater knee flexion (Kirtley et al., 1985), whereas in people with knee OA with lesser knee and greater pelvic motion (Bejek et al., 2006). Patients after TKA walking faster had shorter step length and higher cadence than healthy people, the differences in both parameters diminished by 6 months post-operatively (Andriacchi et al., 1977). McClelland *et al.* compared TKA patients 12 months post-operatively to healthy controls walking at comfortable and fast speeds, and found that despite showing deficiency in their gait parameters there was a similar response in both groups in velocity, cadence and stride length, and knee RoM, with increased speed (McClelland et al., 2011).

It was shown by Riener *et al.*, on healthy subjects, that there was a distinct difference in the kinetic and kinematics in joint angles and moments from level walking to stair climbing, which was significantly related to incline. The produced energy required to ascend (concentric muscle work), or absorbed to descend (eccentric muscle work) was greater than in level walking and also considerably depends on the gradient (Riener et al., 2002).

Examining the walking patterns of patients 12 months after TKA at variable speeds, i.e. slower and faster than normal, and walking on an incline, apart from being more representative of normal activities, could reveal a wider spectrum of deficiencies, or lack of them. Comparing TKA patients with unimpaired counterparts' walking patterns would additionally provide the information about whether their responses to different conditions had the same or different tendencies.

Additionally, walking on an incline provided knee flexion in stance data in comparison to the same data from level walking at different speeds. Increased knee flexion in stance while walking on an incline would confirm or deny the rationale which was used for the proposed TOR programme, which was previously tested in Chapter 5 of our study. The fact that walking on an incline would increase the knee angle would provide a logical link to the proposed rehabilitation approach.

The purpose of this chapter was to collate additional kinetic gait measurements, at differing speeds and incline, of patients 12 months after TKA, not available with

IMU’s assessment, and compare them with age-matched controls. This allowed a more appropriate assessment to be designed for future studies.

Hypothesis.

The kinetic and kinematic response of healthy participants and patients 12 months after TKA differs at different treadmill speeds and by walking on an incline.

Objectives.

1. To explore the effect of speed on hip, knee and ankle joint kinetics and kinematics in healthy participants.
2. To determine whether the gait of TKA patients responds in the same way as healthy participants to variations in speed.
3. To determine whether walking on an incline induces greater knee flexion in stance in TKA patients, supporting the use of incline walking in the rehabilitation programme.

6.2 Method

6.2.1 Participants

Data were collected from 9 participants, 5 of whom (2 male and 3 female) were in the control group, and 4 (2 male and 2 female) were TKA patients prior to their TOR programme. Mean age of participants in the control group was 61.2 ± 7.2 years, and their BMI was 23.6 ± 3.1. Mean age of TKA participants was 60.3 ± 8.7 years, and their BMI was 31.7 ± 2.6. Only participants who gave their written informed consent to take part in the walking test and treadmill assessment were recruited for this part of the study.

Inclusion criteria (in addition to those in Chapter 4):

- Age of participants between 40 and 70
- Knee flexion in stance on operated knee below 12 degrees (TKA participants)

Exclusion criteria were as for Stage 1 (See Chapter 4).

6.2.2 Procedure

Assessments were carried out at the Motor Learning Lab of The RNOH, Stanmore. Each participant, either control or TKA patient, was assessed on one occasion, see Table 6-1. Heights and weights of the participants were measured prior to any gait assessment procedures.

Table 6-1: Study protocol exploring the effect of speed and slope on gait pattern of healthy controls, and those 12 months after TKA, prior to their rehabilitation

Controls (n=5, m/f=2/3)	**TKA patients** (n=4, m/f=2/2)
Tests performed at GRAIL (MOTEK): - Instrumented treadmill walking - 0° incline, at 1.0, 1.2, and 1.4 m/sec (3-dimensional kinetic parameters - knee, hip and ankle moments).	***Tests performed at GRAIL (MOTEK):*** - Instrumented treadmill walking - 0° incline, at 1.0, 1.2, and 1.4 m/sec; and 5° incline, at 1.2 m/sec (3-dimensional kinetic parameters - knee, hip and ankle moments)
Tests performed with IMUs (GaitSmart): - Treadmill walking - 0° incline, at 1.0, 1.2, and 1.4 m/sec (kinematic parameters – knee stance flexion, sagittal knee, hip and pelvic RoM, and coronal pelvic, thigh and calf RoM).	***Tests performed with IMUs (GaitSmart):*** - Treadmill walking - 0° incline, at 1.0, 1.2, and 1.4 m/sec; and 5° incline, at 1.2 m/sec (kinematic parameters - knee stance flexion, sagittal knee, hip and pelvic RoM, and coronal pelvic, thigh and calf RoM).

As the number of tested participants in each group was small (five participants in the control, and four in TKA patients groups), the choice of kinetic and kinematic parameters presented in Table 6-1 was defined by having a sufficient, but not overwhelming number of parameters allowing the carrying out of a comprehensive lower limb biomechanics analysis, comparing these two groups of participants walking on the treadmill.

6.2.2.1 Data acquisition

Gait analysis was performed using a 3D, 10-camera motion capture system (GRAIL, Motec Medical B.V., Amsterdam, The Netherlands) synchronized with two force plates, which are an integral part of the GRAIL system. Fourteen-millimetre spherical retro-reflective markers were placed on the sacrum and bilaterally on the anterior and posterior superior iliac spines to track pelvic motion; bilaterally on the anterior thigh, the medial and lateral condyles, and the patella to track thighs motion; bilaterally on the fibular head, the proximal and distal shins, the medial and lateral malleoli to track shanks motion; bilaterally on the first, second and fifth metatarsal heads, and the inferior calcaneus to track feet motion; bilaterally on the acromion to identify the centre of mass (Figure 6-1). The position and optimal number of the markers for this study were chosen during a preliminary trial using The RNOH Motor Learning Lab current testing protocol (Thornton, personal communication). Marker data were sampled at 100 Hz, the force platforms data were collected at 1000 Hz. Data collection was carried out using Vicon Nexus 1.8.5 software, commencing with standing calibration for identifying the joint centres, and creation of a coordinate system. Before recording the walking data, subjects practised walking at the predetermined speed, until they felt comfortable with it, informing the operator that they are ready to be tested. The participants were tested wearing their own comfortable shoes. The walking test at each speed lasted for approximately 60 seconds, progressed from the slowest to the fastest speeds (1.0 m/sec, 1.2 m/sec, 1.4 m/sec). The TKA patients, additionally, completed by testing their walk on the 5 degrees incline, at a speed of 1.2 m/sec.

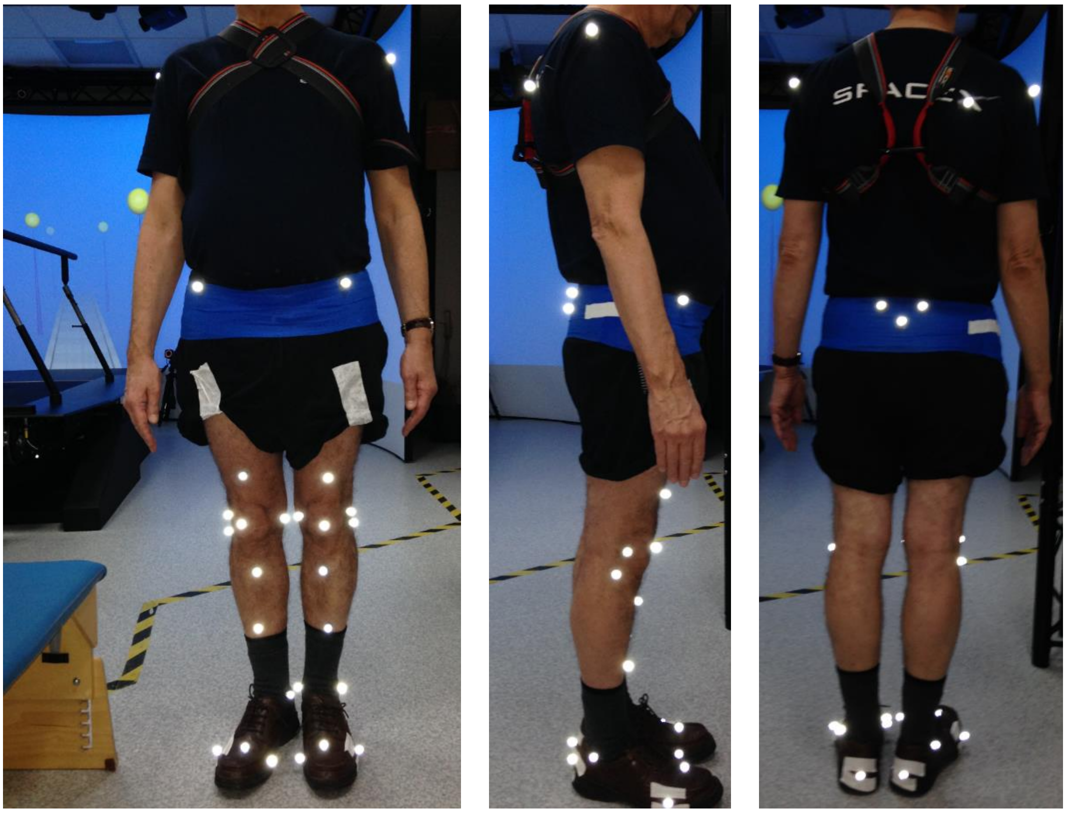


Figure 6-1: Placement of the reflective markers on a participant for testing on an instrumented treadmill

Kinematic data acquisition was made using IMUs, carrying out the same treadmill protocol. The placement of sensors was identical to those applied in Chapter 4.

6.2.2.2 Data management

Marker trajectories were low pass filtered at 6 Hz. For each force platform the analogue channel was converted into three forces and three moments. Hip and knee joint angles were calculated using Euler X-Y-Z sequence corresponding to flexion/extension, abduction/adduction, and rotation sequences. For ankle joint the sequence was X-Z-Y, corresponding to dorsiflexion/plantarflexion, abduction/adduction, and inversion/eversion. Joint moments were calculated using three-dimensional inverse dynamics and were expressed as external moments normalized to body mass and height. Kinematic and kinetic calculations were done using software Visual3D Motion Capture Analysis Application version 6 x 64 (C-motion, Inc., Germantown, MD). Kinetic data - hip, knee and ankle moments - were taken further for analysis. For an example of a graphic representation of these data see Figure 6-2 and Figure 6-3 (the scale for knee moment is different for controls and TKA patients). In these figures the hip and ankle moments are comparable for both the healthy and the TKA participants' legs, unlike the knee moments, which on the contrary differ notably.

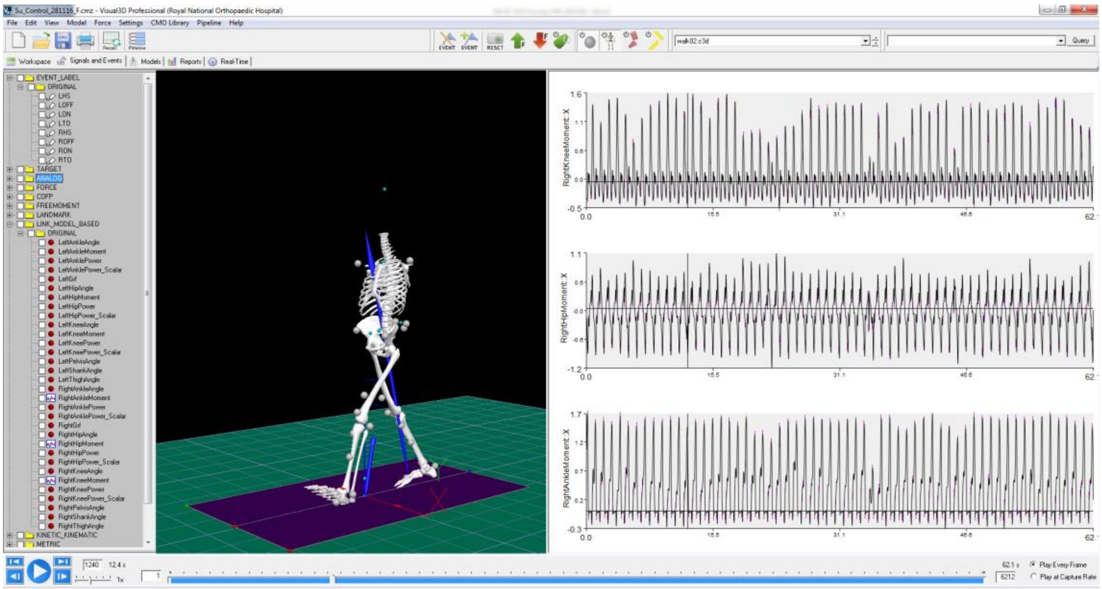


Figure 6-2: Example of control female participant's data for the right knee (top), hip (middle) flexion/extension, and ankle (bottom) dorsi-/plantarflexion moments data (speed 1.4 m/sec, incline 0°)

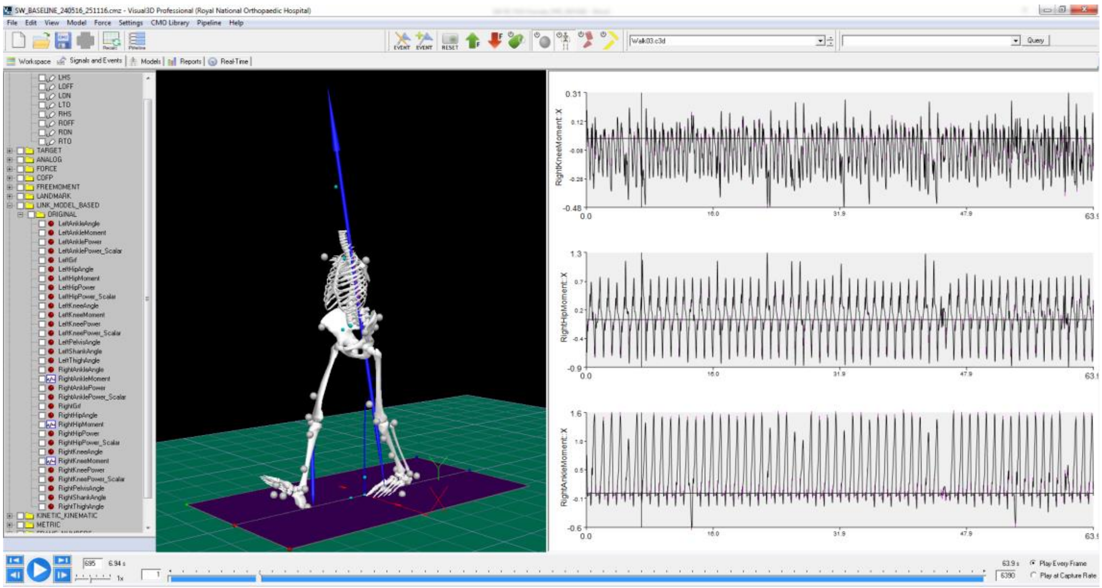


Figure 6-3: Example of female TKA participant's data for the operated (right) knee (top), hip (middle) flexion/extension, and ankle (bottom) dorsi-/plantarflexion moments data (speed 1.4 m/sec, incline 0°)

Dependent variables were the peak hip, knee and ankle moments during stance, i.e. between heel strike (RHS or LHS) and toe off (RTO or LTO) events. These events for kinetic data correspond to Right On (RON) or Left On (LON) and Right Off (ROFF) or Left Off (LOFF) events, which were only created when contact with a force platform was made, therefore for joint moments was able to have meaningful data when the foot was in contact with the ground, but no ground reaction forces were measured (C-Motion, 2015). The mean of these cycles for each subject, for each treadmill condition was taken for further analysis.

IMUs' kinematic data were obtained and managed in an identical manner to those applied in Chapter 4.

6.2.3 Statistical analysis

Comparison of kinetic (three dimensional hip, knee and ankle moments), and kinematic (knee flexion in stance, sagittal knee, hip and pelvic RoM, and coronal pelvic, thigh and calf RoM) data for 5 control participants, and for 4 participants 12 months after TKA, prior to their rehabilitation programme, were evaluated using SPSS Statistics for Windows (version 22). To explore the effect of the treadmill and the effect of the participant's leg, a univariate one-way ANOVA on each of the moment variables was used. There were three treadmill conditions for all participants

– walking on 0 degree of incline at a speed of 1.0 (S1.0), 1.2 (S1.2), and 1.4 m/sec (S1.4), and, additionally, a fourth condition for TKA participants – walking on 5 degrees of incline at a speed of 1.2 m/sec (S1.2G).

Control and TKA participants were compared using a three-level factor for “leg”. The first level denoted the operated leg of the TKA participants (Operated leg), the second level denoted the non-operated leg of the TKA participants (Non-op leg), and the third level denoted the average of both legs for the control group participants (Controls).

In an initial analysis, the main effects of leg (LEG) and treadmill condition (TREADMILL) and their interaction were examined. The LEGxTREADMILL interaction effect was non-significant for all the tested kinetic variables, indicating that the effect of TREADMILL was the same on the operated leg, the non-operated leg, and the control group legs. In the analyses reported below, the interaction effect is therefore omitted, and only the main effects of leg and treadmill are examined. The level of significance was set at $p \leq 0.05$.

6.3 Results.

The results of kinetic (three dimensional hip, knee and ankle moments), and kinematic (knee flexion in stance, sagittal knee, hip and pelvic RoM, and coronal pelvic, thigh and calf RoM) data for 9 participants (5 participants were in the control group and 4 were TKA patients prior to their TOR programme) are presented below.

6.3.1 Kinetic variables

6.3.1.1 Knee moments

Participants’ recorded knee moments at all the tested treadmill conditions are presented in Table 6-2.

Table 6-2: Descriptive statistics for the knee moments for the control (n = 5) and the TKA (n = 4) participants

Knee Moments (N m)	Treadmill conditions (speed (m/sec) & gradient (0°))			
	1.0 (0°)	1.2 (0°)	1.4 (0°)	1.2 (5°)
K_MMx (N m)				
Control	0.68±0.11	0.85±0.15	0.98±0.13	n/a
Operated	0.28±0.26	0.29±0.23	0.56±0.38	-0.47±0.26
Non-op	0.31±0.15	0.37±0.18	0.53±0.16	-0.64±0.11
K_MMy (N m)				
Control	0.30±0.13	0.31±0.14	0.33±0.14	n/a
Operated	0.45±0.04	0.47±0.04	0.47±0.10	0.53±0.09
Non-op	0.34±0.11	0.36±0.12	0.38±0.13	0.39±0.12
K_MMz (N m)				
Control	0.06±0.03	0.08±0.03	0.10±0.03	n/a
Operated	0.10±0.04	0.10±0.02	0.13±0.03	0.42±0.06
Non-op	0.06±0.03	0.07±0.03	0.09±0.06	0.41±0.07

Note: K_MMx = Knee flexion moment, K_MMy = Knee adduction moment, K_MMz = Knee internal rotation moment. Data are presented as mean ± s.d.

6.3.1.1.1 Knee flexion moment (K_MMx)

Knee flexion moments for all tested participants are presented in Figure 6-4.

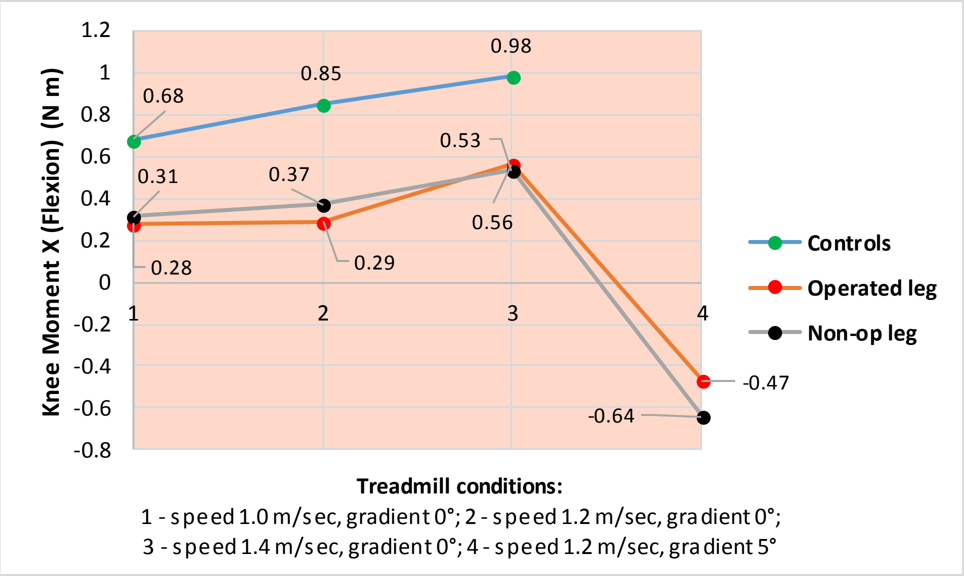


Figure 6-4: Knee flexion moments (N m) for control (n=5), operated (n=4), and non-operated (n=4) legs

Both LEG (F (2, 41) = 24.290, p < 0.0001) and TREADMILL (F (3, 41) = 50.415, p < 0.0001) had significant effects on knee flexion moment (K_MMx).

The mean values of knee flexion moments (K_MMx) were significantly lower for both legs, operated and non-operated (0.165 (N m), 95% CI from 0.066 to 0.265 (N m), and 0.143 (N m), 95% CI from 0.044 to 0.242 (N m) respectively) in TKA participants, as compared to the mean value of this moment for the average leg of the participants from the control group (0.605 (N m), 95% CI from 0.495 to 0.715 (N m)). The differences between control and operated legs (0.440 N m), and control and non-operated legs (0.462 N m) were both strongly significant ($p < 0.0001$). The difference of 0.022 (N m) between the operated and non-operated legs in TKA patients 12 months after their surgery was not significant ($p = 0.750$).

The overall mean values of knee flexion moments are presented in Table 6-3 . The highest value of knee flexion moment was observed at a speed of 1.4 m/sec at a 0°gradient, and the lowest value at a speed of 1.2 m/sec at a 5°gradient.

Table 6-3: Mean estimates of knee flexion moment (K_MMx, N m) for the tested treadmill conditions

			95% Confidence Interval	
Treadmill	Mean	Std. Error	Lower Bound	Upper Bound
S1.0	.422	.055	.311	.532
S1.2	.510	.055	.399	.620
S1.2G	-.404	.073	-.552	-.257
S1.4	.692	.055	.581	.802

Note: S1.0 = Speed 1.0 m/sec, gradient 0°; S1.2 = Speed 1.2 m/sec, gradient 0°; S1.4 = Speed 1.4 m/sec, gradient 0°; S1.2G = Speed 1.2 m/sec, gradient 5°.

The differences in knee flexion moment between the tested treadmill conditions are presented in Table 6-4. Significant differences in the knee flexion moment were registered at gradient 0° between speed 1.4 m/sec and speeds 1.0 m/sec (0.270 (N m), $p = 0.001$), and 1.2 m/sec (0.182 (N m), $p = 0.023$); and at gradient 5°, speed 1.2 m/sec and level walking (gradient 0°) at all tested speeds, i.e. 1.0 m/sec (-0.826 (N m), $p < 0.0001$), 1.2 m/sec (-0.914 (N m), $p < 0.0001$), and 1.4 m/sec (-1.096 (N m), $p < 0.0001$).

Table 6-4: Pairwise comparison of the estimated marginal means of knee flexion moment (K_MMx, N m) for the tested treadmill conditions

					95% Confidence Interval for Difference[b]	
(I) Treadmill	(J) Treadmill	Mean Difference (I-J)	Std. Error	Sig.[b]	Lower Bound	Upper Bound
S1.0	S1.2	-.088	.077	.261	-.244	.068
	S1.2G	.826*	.092	.000	.641	1.012
	S1.4	-.270*	.077	.001	-.426	-.114
S1.2	S1.0	.088	.077	.261	-.068	.244
	S1.2G	.914*	.092	.000	.729	1.100
	S1.4	-.182*	.077	.023	-.338	-.026
S1.2G	S1.0	-.826*	.092	.000	-1.012	-.641
	S1.2	-.914*	.092	.000	-1.100	-.729
	S1.4	-1.096*	.092	.000	-1.281	-.910
S1.4	S1.0	.270*	.077	.001	.114	.426
	S1.2	.182*	.077	.023	.026	.338
	S1.2G	1.096*	.092	.000	.910	1.281

Based on estimated marginal means

*. The mean difference is significant at the .050 level.

b. Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments).

Note: S1.0 = Speed 1.0 m/sec, gradient 0°; S1.2 = Speed 1.2 m/sec, gradient 0°; S1.4 = Speed 1.4 m/sec, gradient 0°; S1.2G = Speed 1.2 m/sec, gradient 5°.

6.3.1.1.2 Knee adduction moment (K_MMy)

Knee adduction moments for all tested participants are presented in Figure 6-5.

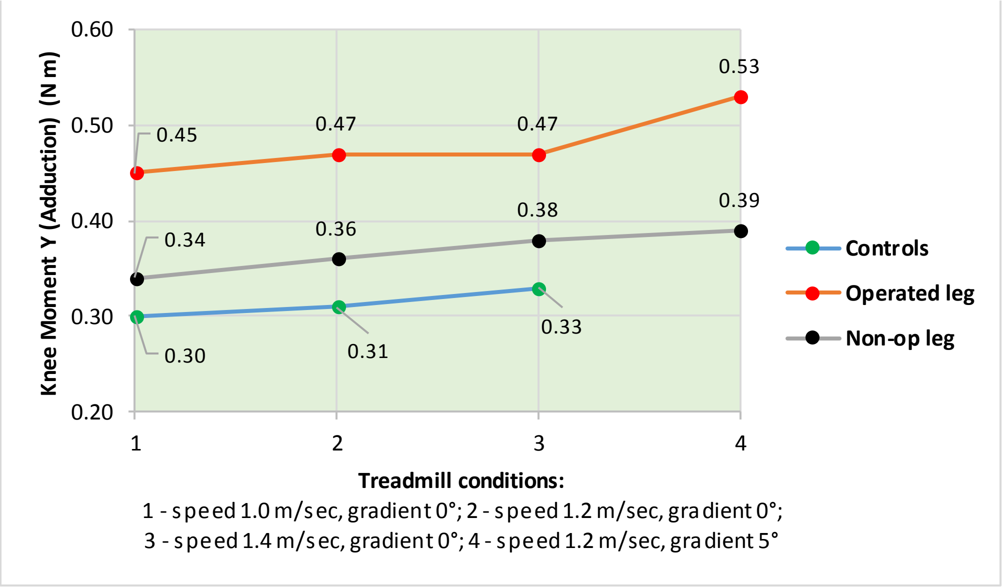


Figure 6-5: Knee adduction moments (N m) for control (n=5), operated (n=4), and non-operated (n=4) legs

LEG (F (2, 41) = 8.241, $p = 0.001$) was a significant factor affecting knee adduction moment (K_MMy), whereas the effect of TREADMILL was not significant (F (3, 41) = 0.619, $p = 0.607$).

The mean values of the knee adduction moments (K_MMy) were higher for both legs, operated and non-operated (0.480 (N m), 95% CI from 0.425 to 0.534 (N m), and 0.368 (N m), 95% CI from 0.314 to 0.423 (N m) respectively) in TKA participants, as compared to the mean value of this moment for the average leg of the participants from the control group (0.325 (N m), 95% CI from 0.265 to 0.385 (N m)). Strongly significant differences were found between control and operated legs -0.154 (N m), $p < 0.0001$, and between operated and non-operated legs 0.111 (N m), $p = 0.005$. The difference of -0.043 (N m) between control and non-operated leg in TKA patients was not significant ($p = 0.285$).

6.3.1.1.3 Knee internal rotation moment (K_MMz)

Knee internal rotation moments for all tested participants are presented in Figure 6-6.

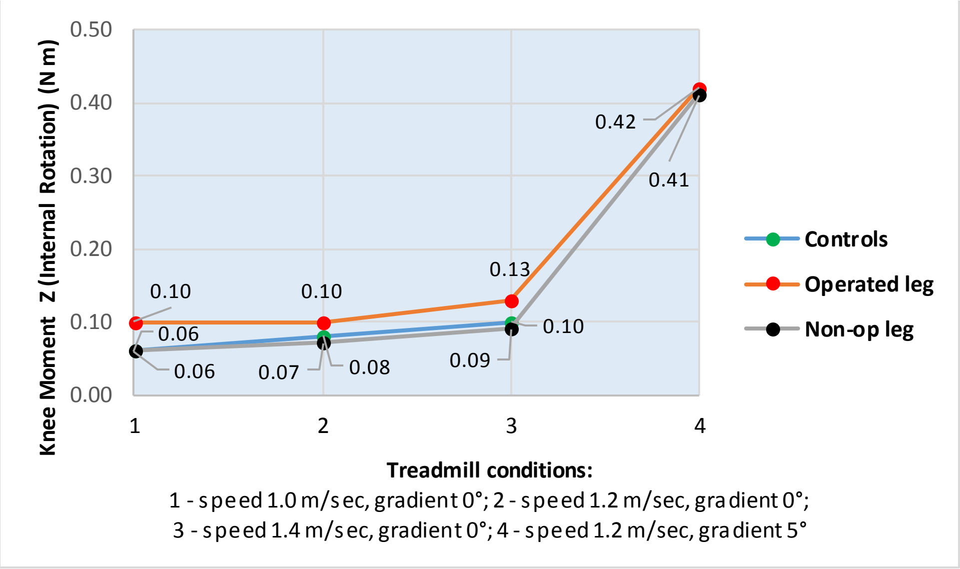


Figure 6-6: Knee internal rotation moments (N m) for control (n=5), operated (n=4), and non-operated (n=4) legs

TREADMILL had a strong significant effect on knee internal rotation moment (K_MMz), F (3, 41) = 147.040, $p < 0.0001$. The effect of LEG was not significant, F (2, 41) = 2.383, $p = 0.105$.

The overall mean values of the knee internal rotation moments are presented in Table 6-5. The highest value of knee internal rotation moment was observed at a speed of 1.2 m/sec at a 5° gradient, and the lowest value at a speed of 1.0 m/sec at a 0° gradient.

Table 6-5: Mean estimates of knee internal rotation moment (K_MMz, N m) for the tested treadmill conditions

Treadmill	Mean	Std. Error	95% Confidence Interval Lower Bound	Upper Bound
S1.0	.073	.011	.051	.094
S1.2	.083	.011	.062	.104
S1.2G	.411	.014	.383	.440
S1.4	.108	.011	.087	.129

Note: S1.0 = Speed 1.0 m/sec, gradient 0°; S1.2 = Speed 1.2 m/sec, gradient 0°; S1.4 = Speed 1.4 m/sec, gradient 0°; S1.2G = Speed 1.2 m/sec, gradient 5°.

The differences in the knee internal rotation moment between the tested treadmill conditions are presented in Table 6-6. Significant differences in knee internal rotation moment were registered at gradient 0° between speed 1.4 m/sec and speeds 1.0 m/sec (0.035 (N m), $p = 0.024$); and at gradient 5°, speed 1.2 m/sec and level walking (gradient 0°) at all tested speeds, i.e. 1.0 m/sec (0.339 (N m), $p < 0.0001$), 1.2 m/sec (0.328 (N m), $p < 0.0001$), and 1.4 m/sec (0.304 (N m), $p < 0.0001$).

Table 6-6: Pairwise comparison of the estimated marginal means of knee internal rotation moment (K_MMz, N m) for all tested treadmill conditions

(I) Treadmill	(J) Treadmill	Mean Difference (I-J)	Std. Error	Sig.^{b}	95% Confidence Interval for Difference^b Lower Bound	Upper Bound
S1.0	S1.2	-.010	.015	.500	-.040	.020
	S1.2G	-.339*	.018	.000	-.374	-.303
	S1.4	-.035*	.015	.024	-.065	-.005
S1.2	S1.0	.010	.015	.500	-.020	.040
	S1.2G	-.328*	.018	.000	-.364	-.293
	S1.4	-.025	.015	.102	-.055	.005
S1.2G	S1.0	.339*	.018	.000	.303	.374
	S1.2	.328*	.018	.000	.293	.364
	S1.4	.304*	.018	.000	.268	.339
S1.4	S1.0	.035*	.015	.024	.005	.065
	S1.2	.025	.015	.102	-.005	.055
	S1.2G	-.304*	.018	.000	-.339	-.268

Based on estimated marginal means *. The mean difference is significant at the .050 level.

b. Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments).

Note: S1.0 = Speed 1.0 m/sec, gradient 0°; S1.2 = Speed 1.2 m/sec, gradient 0°; S1.4 = Speed 1.4 m/sec, gradient 0°; S1.2G = Speed 1.2 m/sec, gradient 5°.

6.3.1.2 Hip moments

Participants' recorded hip moments at all the tested treadmill conditions are presented in Table 6-7.

Table 6-7: Descriptive statistics for the hip moments for the control (n = 5) and the TKA (n = 4) participants

Hip Moments (N m)	Treadmill conditions (speed (m/sec) & gradient (0°))			
	1.0 (0°)	1.2 (0°)	1.4 (0°)	1.2 (5°)
H_MMx (N m)				
Control	0.29±0.05	0.44±0.04	0.63±0.06	n/a
Operated	0.47±0.31	0.55±0.34	0.73±0.32	2.81±0.20
Non-op	0.54±0.14	0.64±0.19	0.78±0.28	2.82±0.41
H_Mmy (N m)				
Control	0.87±0.08	0.91±0.06	0.95±0.04	n/a
Operated	0.92±0.10	0.96±0.13	0.99±0.15	0.98±0.09
Non-op	0.86±0.16	0.90±0.15	0.93±0.20	0.74±0.10
H_MMz (N m)				
Control	0.18±0.09	0.21±0.08	0.25±0.09	n/a
Operated	0.26±0.08	0.29±0.09	0.32±0.09	0.40±0.14
Non-op	0.23±0.10	0.27±0.10	0.34±0.15	0.46±0.17

Note: H_MMx = Hip flexion moment, H_MMy = Hip abduction moment, H_MMz = Hip internal rotation moment. Data are presented as mean ± s.d.

6.3.1.2.1 Hip flexion moment (H_MMx)

Hip flexion moments for all tested participants are presented in Figure 6-7.

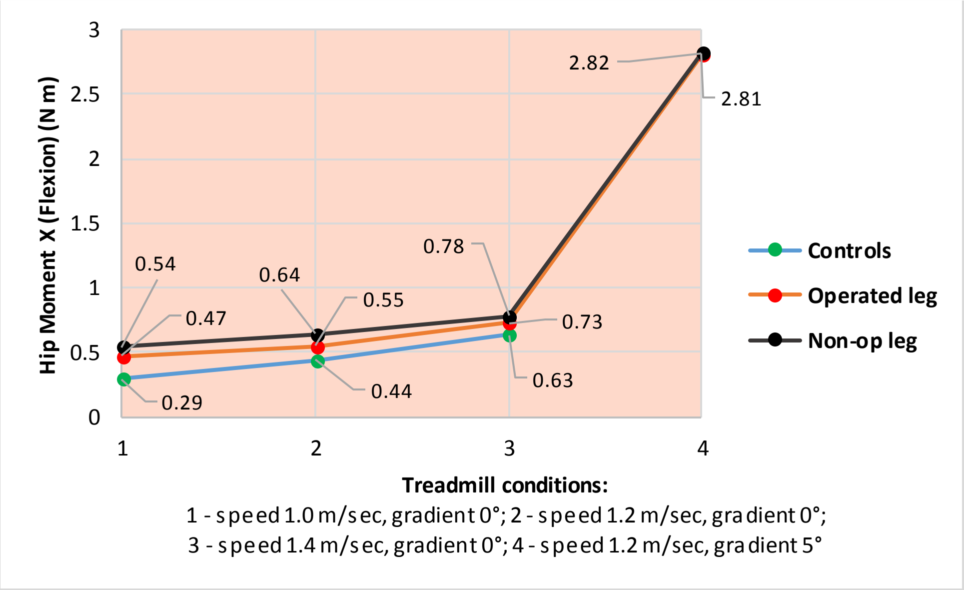


Figure 6-7: Hip flexion moments (N m) for control (n=5), operated (n=4), and non-operated (n=4) legs

TREADMILL had a strong significant effect on hip flexion moment (H_MMx), F (3, 41) = 200.329, $p < 0.0001$. The effect of LEG was not significant, F (2, 41) = 2.712, $p = 0.078$.

The overall mean values of hip flexion moments are presented in Table 6-8. The highest value of hip flexion moment was observed at a speed of 1.2 m/sec at a 5° gradient, and the lowest value at a speed of 1.0 m/sec at a 0° gradient.

Table 6-8: Mean estimates of hip flexion moment (H_MMx, N m) for the tested treadmill conditions

			95% Confidence Interval	
Treadmill	Mean	Std. Error	Lower Bound	Upper Bound
S1.0	.430	.062	.306	.554
S1.2	.543	.062	.419	.668
S1.2G	2.761	.082	2.595	2.926
S1.4	.715	.062	.591	.840

Note: S1.0 = Speed 1.0 m/sec, gradient 0°; S1.2 = Speed 1.2 m/sec, gradient 0°; S1.4 = Speed 1.4 m/sec, gradient 0°; S1.2G = Speed 1.2 m/sec, gradient 5°.

The differences in hip flexion moment between the tested treadmill conditions are presented in Table 6-9. Significant differences in hip flexion moment were registered at gradient 0° between speed 1.4 m/sec and speeds 1.0 m/sec (0.285 (N m), $p = 0.002$); and at gradient 5°, speed 1.2 m/sec and level walking (gradient 0°) at all tested speeds, i.e. 1.0 m/sec (2.331 (N m), $p < 0.0001$), 1.2 m/sec (2.217 (N m), $p < 0.0001$), and 1.4 m/sec (2.045 (N m), $p < 0.0001$).

Table 6-9: Pairwise comparisons of the marginal differences of hip flexion moment (H_MMx, N m) for the tested treadmill conditions

					95% Confidence Interval for Difference^b	
(I) Treadmill	Treadmill (J)	Mean Difference (I-J)	Std. Error	Sig.^{b}	Lower Bound	Upper Bound
S1.0	S1.2	-.113	.087	.200	-.289	.062
	S1.2G	-2.331*	.103	.000	-2.540	-2.122
	S1.4	-.285*	.087	.002	-.461	-.110
S1.2	S1.0	.113	.087	.200	-.062	.289
	S1.2G	-2.217*	.103	.000	-2.426	-2.009
	S1.4	-.172	.087	.054	-.348	.003
S1.2G	S1.0	2.331*	.103	.000	2.122	2.540
	S1.2	2.217*	.103	.000	2.009	2.426
	S1.4	2.045*	.103	.000	1.836	2.254
S1.4	S1.0	.285*	.087	.002	.110	.461
	S1.2	.172	.087	.054	-.003	.348
	S1.2G	-2.045*	.103	.000	-2.254	-1.836

Based on estimated marginal means *. The mean difference is significant at the .050 level.
b. Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments).
<u>Note</u>: S1.0 = Speed 1.0 m/sec, gradient 0°; S1.2 = Speed 1.2 m/sec, gradient 0°; S1.4 = Speed 1.4 m/sec, gradient 0°; S1.2G = Speed 1.2 m/sec, gradient 5°.

6.3.1.2.2 Hip abduction moment (H_MMy)

Hip abduction moments for all tested participants are presented in Figure 6-8.

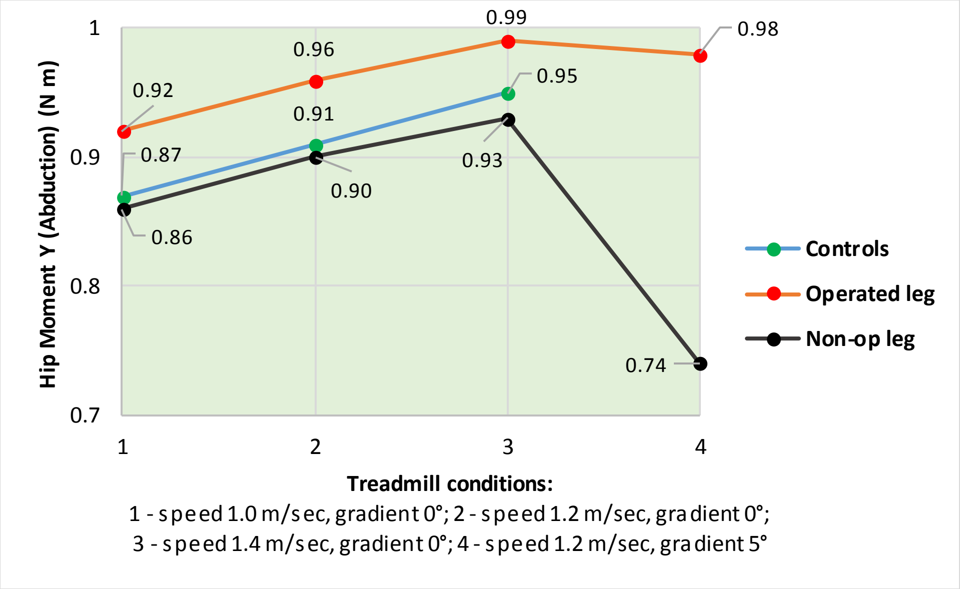


Figure 6-8: Hip abduction moments (N m) for control (n=5), operated (n=4), and non-operated (n=4) legs

LEG (F (2, 41) = 3.441, *p* = 0.042) was a significant factor affecting hip abduction moment (H_MMy), whereas the effect of TREADMILL was not significant (F (3, 41) = 1.484, *p* = 0.233).

The mean value of hip abduction moments (H_MMy) was highest for the operated leg (0.963 (N m), 95% CI from 0.904 to 1.022 (N m)), as compared to the mean values for the control (0.895 (N m), 95% CI from 0.830 to 0.961 (N m)) and non-operated (0.856 (N m), 95% CI from 0.797 to 0.915 (N m)) legs. The only significant difference was found between the operated and non-operated legs 0.107 (N m), *p* = 0.013.

6.3.1.2.3 Hip internal rotation moment (H_MMz)

Hip internal rotation moments for all tested participants are presented in Figure 6-9.

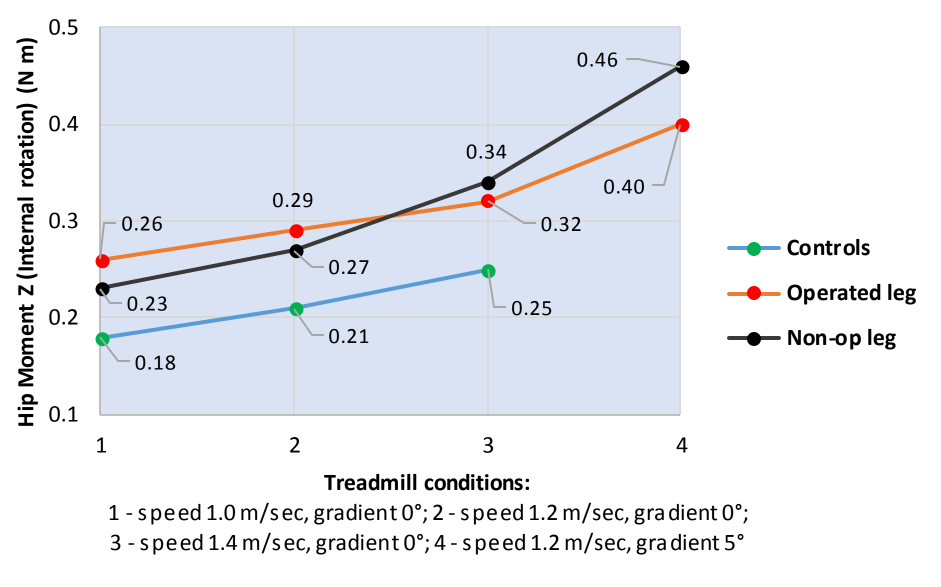


Figure 6-9: Hip internal rotation moments (N m) for control (n=5), operated (n=4), and non-operated (n=4) legs

TREADMILL had a significant effect on hip internal rotation moment (H_MMz), F (3, 41) = 5.049, *p* = 0.005. LEG did not significantly affect hip internal rotation moment, F (2, 41) = 2.357, *p* = 0.107.

The overall mean values of hip internal rotation moments are presented in Table 6-10. The highest value of hip internal rotation moment was observed at a speed of 1.2 m/sec at a 5° gradient, and the lowest value at a speed of 1.0 m/sec at a 0° gradient.

Table 6-10: Mean estimates of hip internal rotation moment (H_MMz, N m) for the tested treadmill conditions

Treadmill	Mean	Std. Error	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
S1.0	.223	.029	.165	.281
S1.2	.260	.029	.202	.318
S1.2G	.404	.038	.327	.482
S1.4	.300	.029	.242	.358

Note: S1.0 = Speed 1.0 m/sec, gradient 0°; S1.2 = Speed 1.2 m/sec, gradient 0°; S1.4 = Speed 1.4 m/sec, gradient 0°; S1.2G = Speed 1.2 m/sec, gradient 5°.

The differences in hip internal rotation moment between the tested treadmill conditions are presented in Table 6-11. Significant differences in hip internal rotation moment were registered at a gradient 5°, speed 1.2 m/sec, and level walking (gradient 0°) at all tested speeds, i.e. 1.0 m/sec (0.182 (N m), p = 0.001), 1.2 m/sec (0.145 (N m), p = 0.005), and 1.4 m/sec (0.104 (N m), p = 0.037).

Table 6-11: Pairwise comparison of the marginal differences of hip internal rotation moment (H_MMz, N m) for the tested treadmill conditions

(I) Treadmill	(J) Treadmill	Mean Difference (I-J)	Std. Error	Sig. ^{b}	95% Confidence Interval for Difference^{b} Lower Bound	95% Confidence Interval for Difference^{b} Upper Bound
S1.0	S1.2	-.037	.041	.366	-.119	.045
	S1.2G	-.182*	.048	.001	-.279	-.084
	S1.4	-.077	.041	.064	-.159	.005
S1.2	S1.0	.037	.041	.366	-.045	.119
	S1.2G	-.145*	.048	.005	-.242	-.047
	S1.4	-.040	.041	.328	-.122	.042
S1.2G	S1.0	.182*	.048	.001	.084	.279
	S1.2	.145*	.048	.005	.047	.242
	S1.4	.104*	.048	.037	.007	.202
S1.4	S1.0	.077	.041	.064	-.005	.159
	S1.2	.040	.041	.328	-.042	.122
	S1.2G	-.104*	.048	.037	-.202	-.007

Based on estimated marginal means

*. The mean difference is significant at the .050 level.

b. Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments).

Note: S1.0 = Speed 1.0 m/sec, gradient 0°; S1.2 = Speed 1.2 m/sec, gradient 0°; S1.4 = Speed 1.4 m/sec, gradient 0°; S1.2G = Speed 1.2 m/sec, gradient 5°.

6.3.1.3 Ankle moments

Participants' recorded ankle moments at all the tested treadmill conditions are presented in Table 6-12.

Table 6-12: Descriptive statistics for the ankle moments for the control (n = 5) and the TKA (n = 4) participants

Ankle Moments (N m)	Treadmill conditions (speed (m/sec) & gradient (0°))			
	1.0 (0°)	1.2 (0°)	1.4 (0°)	1.2 (5°)
A_MMx (N m)				
Control	1.34±0.07	1.44±0.08	1.57±0.16	n/a
Operated	1.35±0.22	1.38±0.09	1.50±0.11	1.97±0.19
Non-op	1.22±0.04	1.34±0.05	1.43±0.14	1.78±0.14
A_Mmy (N m)				
Control	0.30±0.10	0.34±0.12	0.41±0.12	n/a
Operated	0.30±0.12	0.31±0.06	0.38±0.09	0.43±0.14
Non-op	0.31±0.14	0.37±0.15	0.41±0.10	0.42±0.16
A_MMz (N m)				
Control	0.09±0.04	0.10±0.05	0.13±0.05	n/a
Operated	0.14±0.09	0.13±0.02	0.17±0.04	0.40±0.10
Non-op	0.09±0.05	0.10±0.05	0.14±0.08	0.36±0.12

Note: A_MMx = Ankle dorsiflexion moment, A_MMy = Ankle abduction moment, A_MMz = Ankle inversion moment. Data are presented as mean ± s.d.

6.3.1.3.1 Ankle dorsiflexion moment (A_MMx)

Ankle dorsiflexion moments for all tested participants are presented in Figure 6-10.

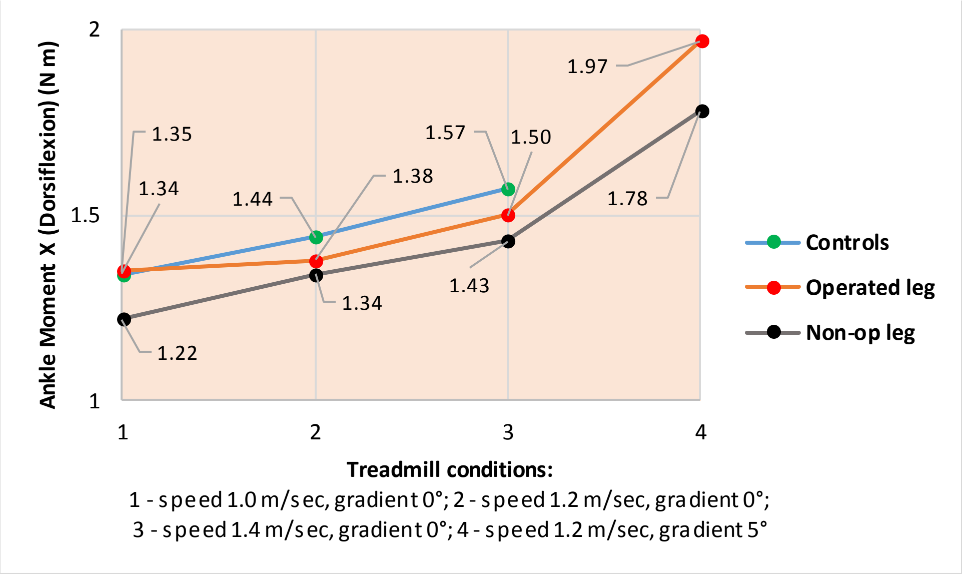


Figure 6-10: Ankle dorsiflexion moments (N m) for control (n=5), operated (n=4), and non-operated (n=4) legs

Both LEG (F (2, 41) = 4.985, $p = 0.012$) and TREADMILL (F (3, 41) = 38.939, $p < 0.0001$) had significant effects on ankle dorsiflexion moment (A_MMx).

The mean values of ankle dorsiflexion moments (A_MMx) were lower for both legs of the TKA participants, operated and non-operated (1.552 (N m), 95% CI from

1.489 to 1.614 (N m), and 1.443 (N m), 95% CI from 1.380 to 1.505 (N m) respectively), as compared to the mean value of this moment for the average leg of the participants from the control group (1.576 (N m), 95% CI from 1.507 to 1.646 (N m)). Significant differences between control and non-operated legs, and operated and non-operated legs were 0.134 (N m), $p = 0.006$ and 0.109 (N m), $p = 0.017$ respectively. The difference of 0.025 (N m) between control and operated legs was not significant ($p = 0.595$).

The overall mean values of ankle dorsiflexion moments are presented in Table 6-13. The highest value of ankle dorsiflexion moment was observed at a speed of 1.2 m/sec at a 5° gradient, and the lowest value was observed at a speed of 1.0 m/sec at a 0° gradient.

Table 6-13: Mean estimates of ankle dorsiflexion moment (A_MMx, N m) for the tested treadmill conditions

			95% Confidence Interval	
Treadmill	Mean	Std. Error	Lower Bound	Upper Bound
S1.0	1.304	.034	1.234	1.373
S1.2	1.386	.034	1.316	1.455
S1.2G	1.902	.046	1.810	1.995
S1.4	1.503	.034	1.433	1.572

Note: S1.0 = Speed 1.0 m/sec, gradient 0°; S1.2 = Speed 1.2 m/sec, gradient 0°; S1.4 = Speed 1.4 m/sec, gradient 0°; S1.2G = Speed 1.2 m/sec, gradient 5°.

The differences in ankle dorsiflexion moment between the tested treadmill conditions are presented in Table 6-14. Significant differences in ankle dorsiflexion moment were registered at gradient 0° between speed 1.4 m/sec and speeds 1.0 m/sec (0.199 (N m), $p < 0.001$), and 1.2 m/sec (0.117 (N m), $p = 0.020$); and at gradient 5°, speed 1.2 m/sec and level walking (gradient 0°) at all tested speeds, i.e. 1.0 m/sec (0.599 (N m), $p < 0.0001$), 1.2 m/sec (0.517 (N m), $p < 0.0001$), and 1.4 m/sec (0.400 (N m), $p < 0.0001$).

Table 6-14: Pairwise comparison of the marginal differences of ankle dorsiflexion moment (A_MMx, N m) for the tested treadmill conditions

(I) Treadmill	(J) Treadmill	Mean Difference (I-J)	Std. Error	Sig.[b]	95% Confidence Interval for Difference[b] Lower Bound	Upper Bound
S1.0	S1.2	-.082	.049	.099	-.180	.016
	S1.2G	-.599*	.058	.000	-.715	-.482
	S1.4	-.199*	.049	.000	-.297	-.101
S1.2	S1.0	.082	.049	.099	-.016	.180
	S1.2G	-.517*	.058	.000	-.633	-.400
	S1.4	-.117*	.049	.020	-.215	-.019
S1.2G	S1.0	.599*	.058	.000	.482	.715
	S1.2	.517*	.058	.000	.400	.633
	S1.4	.400*	.058	.000	.283	.516
S1.4	S1.0	.199*	.049	.000	.101	.297
	S1.2	.117*	.049	.020	.019	.215
	S1.2G	-.400*	.058	.000	-.516	-.283

Based on estimated marginal means

*. The mean difference is significant at the .050 level.

b. Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments).

Note: S1.0 = Speed 1.0 m/sec, gradient 0°; S1.2 = Speed 1.2 m/sec, gradient 0°; S1.4 = Speed 1.4 m/sec, gradient 0°; S1.2G = Speed 1.2 m/sec, gradient 5°.

6.3.1.3.2 Ankle abduction moment (A_MMy)

Ankle abduction moments for all tested participants are presented in Figure 6-11.

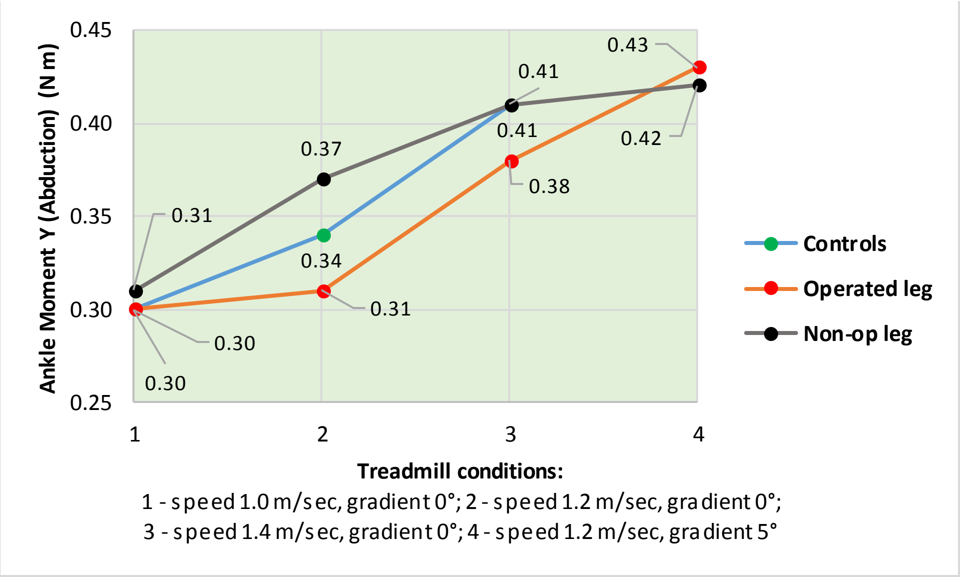


Figure 6-11: Ankle abduction moments (N m) for control (n=5), operated (n=4), and non-operated (n=4) legs

Neither TREADMILL (F (3, 41) = 2.611, *p* = 0.064), nor LEG (F (2, 41) = 0.165, *p* = 0.848) had significant effects on ankle abduction moment (A_MMy).

6.3.1.3.3 Ankle inversion moment (A_MMz)

Ankle inversion moments for all tested participants are presented in Figure 6-12.

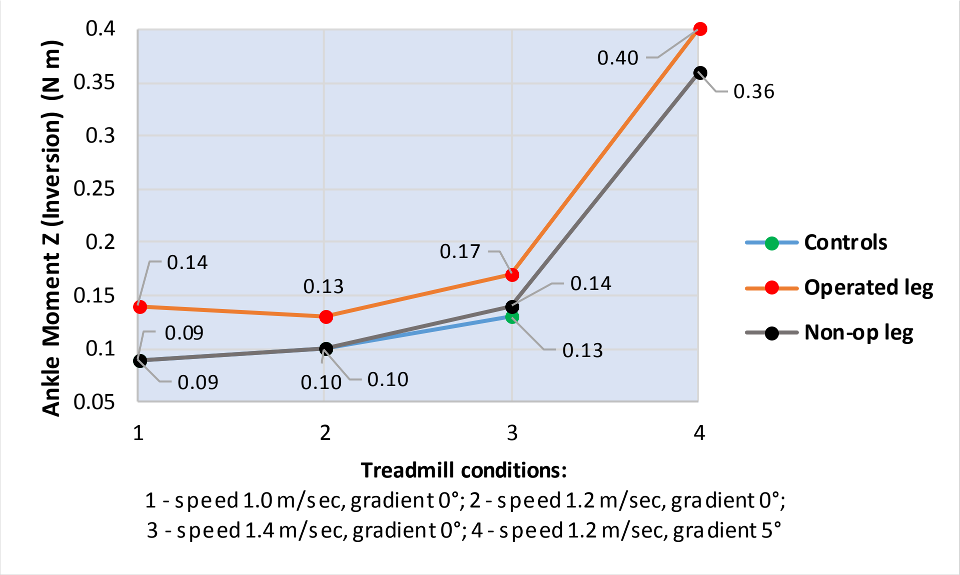


Figure 6-12: Ankle inversion moments (N m) for control (n=5), operated (n=4), and non-operated (n=4) legs

TREADMILL had a strong significant effect on ankle inversion moment (A_MMz), F (3, 41) = 30.396, $p < 0.0001$. The effect of LEG was not significant, F (2, 41) = 1.658, $p = 0.203$.

The overall mean values of ankle inversion moments are presented in Table 6-15. The highest value of ankle inversion moment was observed at a speed of 1.2 m/sec at a 5° gradient, and the lowest value at a speed of 1.0 m/sec at a 0° gradient.

Table 6-15: Mean estimates of ankle inversion moment (A_MMz, N m) for the tested treadmill conditions

			95% Confidence Interval	
Treadmill	Mean	Std. Error	Lower Bound	Upper Bound
S1.0	.104	.018	.067	.140
S1.2	.113	.018	.076	.149
S1.2G	.369	.024	.321	.418
S1.4	.147	.018	.111	.184

Note: S1.0 = Speed 1.0 m/sec, gradient 0°; S1.2 = Speed 1.2 m/sec, gradient 0°; S1.4 = Speed 1.4 m/sec, gradient 0°; S1.2G = Speed 1.2 m/sec, gradient 5°.

The differences in ankle inversion moment between the tested treadmill conditions are presented in Table 6-16. Significant differences in ankle inversion moment were registered between walking at gradient 5°, speed 1.2 m/sec and level walking (gradient 0°) at all tested speeds, i.e. 1.0 m/sec (0.266 (N m), $p < 0.0001$, 95% CI from 0.204 to 0.327 (N m)), 1.2 m/sec (0.257 (N m), $p < 0.0001$, 95% CI from 0.196 to 0.318 (N m)), and 1.4 m/sec (0.222 (N m), $p < 0.0001$, 95% CI from 0.161 to 0.283 (N m)).

Table 6-16: Pairwise comparison of the estimated marginal means of ankle inversion moment (A_MMz, N m) for all tested treadmill conditions

(I) Treadmill	(J) Treadmill	Mean Difference (I-J)	Std. Error	Sig.[b]	95% Confidence Interval for Difference[b] Lower Bound	Upper Bound
S1.0	S1.2	-.009	.025	.728	-.060	.042
	S1.2G	-.266*	.030	.000	-.327	-.204
	S1.4	-.044	.025	.092	-.095	.007
S1.2	S1.0	.009	.025	.728	-.042	.060
	S1.2G	-.257*	.030	.000	-.318	-.196
	S1.4	-.035	.025	.177	-.086	.016
S1.2G	S1.0	.266*	.030	.000	.204	.327
	S1.2	.257*	.030	.000	.196	.318
	S1.4	.222*	.030	.000	.161	.283
S1.4	S1.0	.044	.025	.092	-.007	.095
	S1.2	.035	.025	.177	-.016	.086
	S1.2G	-.222*	.030	.000	-.283	-.161

Based on estimated marginal means

*. The mean difference is significant at the .050 level.

b. Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments).

Note: S1.0 = Speed 1.0 m/sec, gradient 0°; S1.2 = Speed 1.2 m/sec, gradient 0°; S1.4 = Speed 1.4 m/sec, gradient 0°; S1.2G = Speed 1.2 m/sec, gradient 5°.

6.3.2 Kinematic variables

Participants’ recorded knee flexion in stance and sagittal knee, hip and pelvic RoM, and coronal pelvic, thigh and calf RoM at all the tested treadmill conditions are presented in Table 6-17.

Table 6-17: Descriptive statistics for kinematic variables for the control (n = 5) and the TKA (n = 4) participants

Kinematic variables	Treadmill conditions (speed (m/sec) & gradient (0°))			
	1.0 (0°)	1.2 (0°)	1.4 (0°)	1.2 (5°)
KFS (Knee flexion in stance) (°)				
Control	19.92±4.32	23.07±3.51	25.41±3.20	n/a
Operated	7.06±2.62	8.00±2.28	7.24±2.18	20.06±16.63
Non-op	8.55±1.38	11.84±5.25	12.62±4.18	15.62±8.91
KSR (Knee sagittal RoM) (°)				
Control	66.65±5.26	70.08±3.94	70.93±4.11	n/a
Operated	65.14±3.78	67.20±4.53	68.65±5.44	65.50±8.82
Non-op	61.54±2.76	64.03±1.93	66.83±3.31	60.20±7.44
HSR (Hip sagittal RoM) (°)				
Control	28.92±2.29	33.47±2.28	36.89±2.74	n/a
Operated	26.30±2.89	30.03±4.88	34.20±7.31	42.53±13.85
Non-op	28.14±3.21	31.08±4.99	36.26±3.58	40.26±4.50
PSR (Pelvic sagittal RoM) (°)				
Control	5.81±0.90	6.14±0.83	6.55±1.00	n/a
Operated	6.50±1.92	7.39±1.36	8.04±1.91	8.14±2.68
Non-op	6.70±1.22	7.00±1.21	7.35±2.05	7.40±1.57
PCR (Pelvic coronal RoM) (°)				
Control	4.67±1.30	5.31±1.33	6.22±1.92	n/a
Operated	6.86±0.33	7.12±0.72	8.07±2.90	10.35±2.29
Non-op	5.96±0.88	6.68±1.07	8.10±1.84	11.45±3.54
TCR (Thigh coronal RoM) (°)				
Control	11.99±4.10	12.46±4.24	11.28±3.03	n/a
Operated	11.57±2.64	11.04±1.74	11.33±3.04	12.50±2.32
Non-op	13.19±5.01	14.21±3.29	14.43±4.33	15.21±4.17
CCR (Calf coronal RoM) (°)				
Control	13.35±4.28	14.99±5.42	14.78±5.15	n/a
Operated	7.90±1.64	9.54±1.79	8.80±1.63	7.88±3.99
Non-op	9.90±4.45	10.67±4.59	11.31±4.98	9.96±2.94

Note: Data are presented as mean ± s.d.

6.3.2.1 Knee flexion in stance (KFS)

Knee flexion in stance for all tested participants are presented in Figure 6-13.

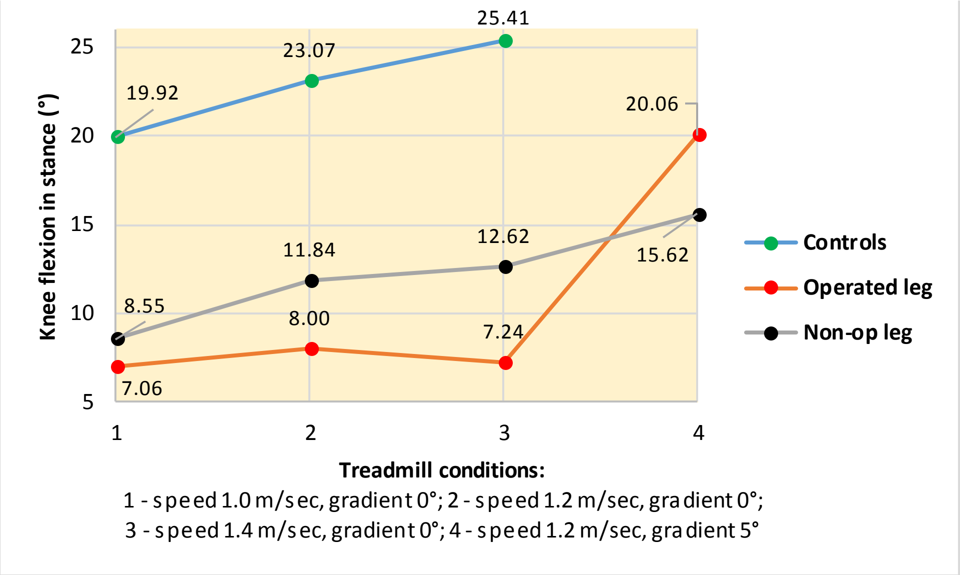


Figure 6-13: Knee flexion in stance (°) for control (n=5), operated (n=4), and non-operated (n=4) legs

Both LEG (F (2, 56) = 39.232, $p < 0.0001$) and the TREADMILL (F (3, 56) = 6.280, $p = 0.001$) had significant effects on knee flexion in stance (KFS).

The mean value of knee flexion in stance (KFS) was significantly lower for both legs, operated and non-operated (10.6°, 95% CI from 7.8° to 13.4°, and 12.2°, 95% CI from 9.3 to 15.0° respectively) in TKA participants, as compared to the mean value of this variable for the average leg of the participants from the control group (25.0°, 95% CI from 22.6° to 27.3°). The differences between control and operated legs (14.4°), and control and non-operated legs (12.8°) were both strongly significant ($p < 0.0001$). The difference of -1.6° between the operated and non-operated legs in TKA patients 12 months after their surgery was not significant ($p = 0.433$).

The overall mean values of knee flexion in stance are presented in Table 6-18. The highest value of knee flexion in stance, 22.4°, was observed in TKA participants at a speed of 1.2 m/sec at a 5° gradient.

Table 6-18: Mean estimates of knee flexion in stance (KFS, °) for the tested treadmill conditions

Treadmill	Mean	Std. Error	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
S1.0	11.518	1.368	8.777	14.259
S1.2	14.209	1.368	11.468	16.950
S1.2G	22.367	2.052	18.255	26.478
S1.4	15.509	1.368	12.769	18.250

Note: S1.0 = Speed 1.0 m/sec, gradient 0°; S1.2 = Speed 1.2 m/sec, gradient 0°; S1.4 = Speed 1.4 m/sec, gradient 0°; S1.2G = Speed 1.2 m/sec, gradient 5°.

The differences in knee flexion in stance between the tested treadmill conditions are presented in Table 6-19. Significant differences in the knee flexion in stance were registered at gradient 0° between speeds 1.4 m/sec and 1.0 m/sec (4.0°); and at gradient 5°, speed 1.2 m/sec and level walking (gradient 0°) at all tested speeds, i.e. 1.0 m/sec (10.8°, $p < 0.0001$), 1.2 m/sec (8.2°, $p = 0.002$), and 1.4 m/sec (6.9°, $p = 0.009$).

Table 6-19: Pairwise comparison of the estimated marginal means of knee flexion in stance (KFS, °) for the tested treadmill conditions

(I) Treadmill	(J) Treadmill	Mean Difference (I-J)	Std. Error	Sig.[b]	95% Confidence Interval for Difference[b] Lower Bound	95% Confidence Interval for Difference[b] Upper Bound
S1.0	S1.2	-2.691	1.873	.156	-6.444	1.062
	S1.2G	-10.849*	2.537	.000	-15.930	-5.767
	S1.4	-3.992*	1.873	.038	-7.745	-.239
S1.2	S1.0	2.691	1.873	.156	-1.062	6.444
	S1.2G	-8.158*	2.537	.002	-13.239	-3.076
	S1.4	-1.301	1.873	.490	-5.054	2.452
S1.2G	S1.0	10.849*	2.537	.000	5.767	15.930
	S1.2	8.158*	2.537	.002	3.076	13.239
	S1.4	6.857*	2.537	.009	1.776	11.939
S1.4	S1.0	3.992*	1.873	.038	.239	7.745
	S1.2	1.301	1.873	.490	-2.452	5.054
	S1.2G	-6.857*	2.537	.009	-11.939	-1.776

Based on estimated marginal means

*. The mean difference is significant at the .050 level.

b. Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments).

Note: S1.0 = Speed 1.0 m/sec, gradient 0°; S1.2 = Speed 1.2 m/sec, gradient 0°; S1.4 = Speed 1.4 m/sec, gradient 0°; S1.2G = Speed 1.2 m/sec, gradient 5°.

For only TKA (PRE-REHAB) patients, TREADMILL (F (3, 27) = 3.084, p = 0.044) was a significant factor affecting knee flexion in stance (KFS), whereas the effect of LEG was not significant (F (1, 27) = 0.387, p = 0.539). The significant mean difference in knee flexion in stance (*p* = 0.035) between level walking and walking on 5° gradient at the same speed of 1.2 m/sec was 7.9°.

6.3.2.2 Knee sagittal RoM (KSR)

Knee sagittal RoM for all tested participants are presented in Figure 6-14.

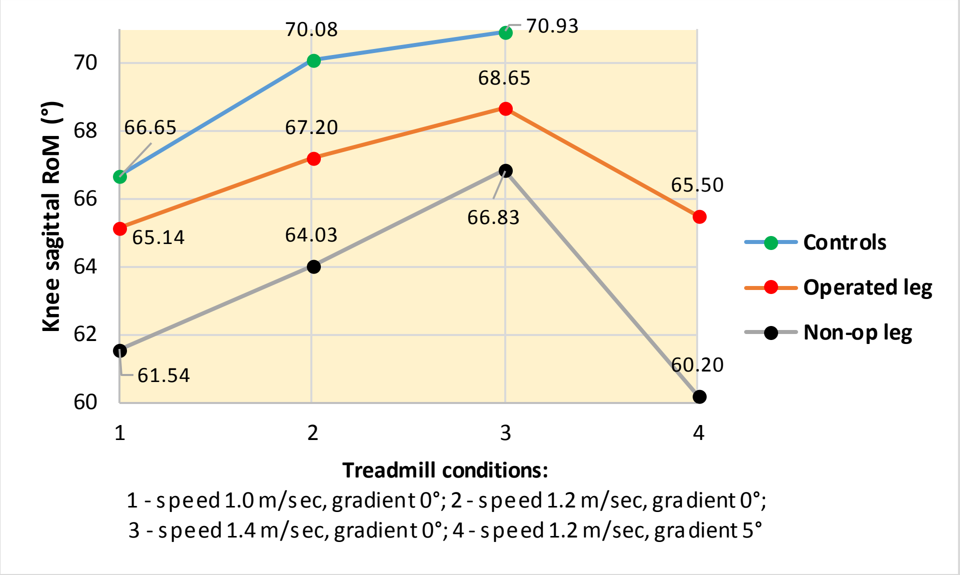


Figure 6-14: Knee sagittal RoM (°) for control (n=5), operated (n=4), and non-operated (n=4) legs

Both LEG (F (2, 56) = 6.318, *p* = 0.003) and TREADMILL (F (3, 56) = 3.377, *p* = 0.024) had significant effects on knee sagittal RoM (KSR).

The mean value of knee sagittal RoM (KSR) was lower for both legs, operated and non-operated leg (66.6°, 95% CI from 64.3°to 67.0°, and 63.1°, 95% CI from 60.8° to 65.5° respectively) in TKA participants, as compared to the mean value of this variable for the average leg of the participants from the control group (68.5°, 95% CI from 66.6° to 70.5°). The difference between control and non-operated legs (5.4°) was strongly significant (*p* = 0.001), whereas the difference between control and operated legs (1.9°) was not significant (*p* = 0.213). The significant difference in knee sagittal RoM (*p* = 0.039) between the operated and non-operated legs in TKA patients 12 months after their surgery was 3.5°

The overall mean values of knee sagittal RoM are presented in Table 6-20. The lowest value of 64.1°, was observed in TKA participants at a speed of 1.2 m/sec at a 5° gradient.

Table 6-20: Mean estimates of knee sagittal RoM (KSR, °) for the tested treadmill conditions

			95% Confidence Interval	
Treadmill	Mean	Std. Error	Lower Bound	Upper Bound
S1.0	64.365	1.135	62.092	66.637
S1.2	67.282	1.135	65.010	69.555
S1.2G	64.067	1.702	60.658	67.477
S1.4	68.699	1.135	66.426	70.972

Note: S1.0 = Speed 1.0 m/sec, gradient 0°; S1.2 = Speed 1.2 m/sec, gradient 0°; S1.4 = Speed 1.4 m/sec, gradient 0°; S1.2G = Speed 1.2 m/sec, gradient 5°.

Significant differences in the knee sagittal RoM were registered at gradient 0° between speeds 1.4 m/sec and 1.0 m/sec (4.3°, 95% CI from 1.2° to 7.4°); and at gradient 5°, speed 1.2 m/sec and level walking (gradient 0°) at speed 1.4 m/sec (-4.6°, 95% CI from -8.8° to -0.4°, *p* = 0.032).

6.3.2.3 Hip sagittal RoM (HSR)

Hip sagittal RoM for all tested participants are presented in Figure 6-15.

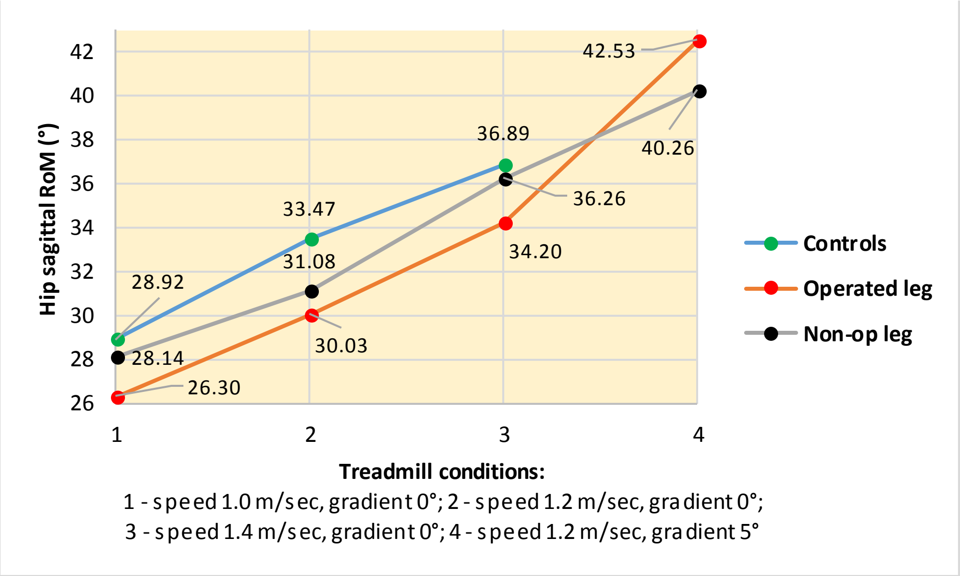


Figure 6-15: Hip sagittal RoM (°) for control (n=5), operated (n=4), and non-operated (n=4) legs

TREADMILL had a significant effect on hip sagittal RoM (HSR), F (3, 56) = 18.584, p < 0.0001. LEG did not significantly affect hip sagittal RoM, F (2, 56) = 1.412, p = 0.252.

The overall mean values of hip sagittal RoM are presented in Table 6-21. The highest value of 42.1°, was observed in TKA participants at a speed of 1.2 m/sec at a 5° gradient.

Table 6-21: Mean estimates of hip sagittal RoM (HSR, °) for the tested treadmill conditions

			95% Confidence Interval	
Treadmill	Mean	Std. Error	Lower Bound	Upper Bound
S1.0	27.701	1.140	25.419	29.984
S1.2	31.713	1.140	29.430	33.996
S1.2G	42.093	1.709	38.669	45.518
S1.4	35.685	1.140	33.402	37.968

Note: S1.0 = Speed 1.0 m/sec, gradient 0°; S1.2 = Speed 1.2 m/sec, gradient 0°; S1.4 = Speed 1.4 m/sec, gradient 0°; S1.2G = Speed 1.2 m/sec, gradient 5°.

All the differences in hip sagittal RoM between the tested treadmill conditions were significant, and are presented in Table 6-22.

Table 6-22: Pairwise comparison of the estimated marginal means of hip sagittal RoM (HSR, °) for the tested treadmill conditions

					95% Confidence Interval for Difference^b	
(I) Treadmill	(J) Treadmill	Mean Difference (I-J)	Std. Error	Sig.^{b}	Lower Bound	Upper Bound
S1.0	S1.2	-4.012*	1.560	.013	-7.138	-.886
	S1.2G	-14.392*	2.113	.000	-18.624	-10.159
	S1.4	-7.984*	1.560	.000	-11.110	-4.858
S1.2	S1.0	4.012*	1.560	.013	.886	7.138
	S1.2G	-10.380*	2.113	.000	-14.613	-6.148
	S1.4	-3.972*	1.560	.014	-7.098	-.846
S1.2G	S1.0	14.392*	2.113	.000	10.159	18.624
	S1.2	10.380*	2.113	.000	6.148	14.613
	S1.4	6.408*	2.113	.004	2.175	10.641
S1.4	S1.0	7.984*	1.560	.000	4.858	11.110
	S1.2	3.972*	1.560	.014	.846	7.098
	S1.2G	-6.408*	2.113	.004	-10.641	-2.175

Based on estimated marginal means

*. The mean difference is significant at the .050 level.

b. Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments).

Note: S1.0 = Speed 1.0 m/sec, gradient 0°; S1.2 = Speed 1.2 m/sec, gradient 0°; S1.4 = Speed 1.4 m/sec, gradient 0°; S1.2G = Speed 1.2 m/sec, gradient 5°.

6.3.2.4 Pelvic sagittal RoM (PSR)

Pelvic sagittal RoM for all tested participants are presented in Figure 6-16.

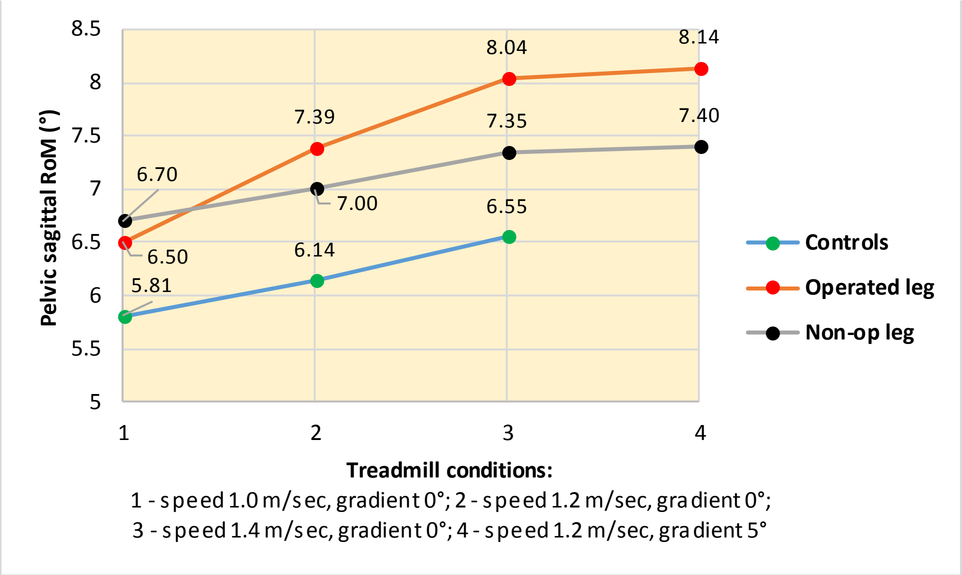


Figure 6-16: Pelvic sagittal RoM (°) for control (n=5), operated (n=4), and non-operated (n=4) legs

LEG (F (2, 56) = 4.013, *p* = 0.024) was a significant factor affecting pelvic sagittal RoM (PSR), whereas the effect of TREADMILL was not significant (F (3, 56) = 1.725, *p* = 0.172).

The mean value of pelvic sagittal RoM (PSR) was highest for the operated leg (7.5°, 95% CI from 6.8 to 8.2°), as compared to the mean values for the control (6.3°, 95% CI from 5.8 to 6.9°) and non-operated (7.1°, 95% CI from 6.4 to 7.8°) legs. The only significant difference was found between the operated and control legs 1.2°, *p* = 0.008.

6.3.2.5 Pelvic coronal RoM (PCR)

Pelvic coronal RoM for all tested participants are presented in Figure 6-17.

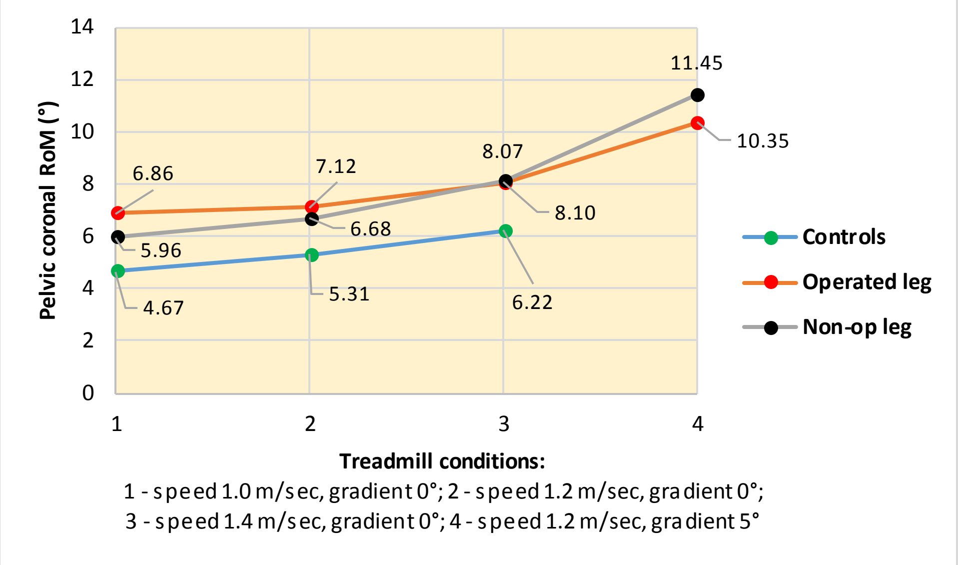


Figure 6-17: Pelvic coronal RoM (°) for control (n=5), operated (n=4), and non-operated (n=4) legs

Both TREADMILL (F (3, 56) = 12.305, *p* < 0.0001) and the LEG (F (2, 56) = 6.790, *p* = 0.002) had significant effects on pelvic coronal RoM (PCR).

The mean value of pelvic coronal RoM (PCR) was higher for both legs, operated and non-operated leg (8.1°, 95% CI from 7.2°to 9.0°, and 8.0°, 95% CI from 7.2° to 8.9° respectively) in TKA participants, as compared to the mean value of this variable for the average leg of the participants from the control group (6.3°, 95% CI from 5.6° to 7.1°). The differences between control and non-operated legs (-1.7°), and control and operated legs (-1.8°) were strongly significant (*p* = 0.004 and *p* = 0.003 respectively).

The overall mean values of pelvic coronal RoM are presented in Table 6-23 demonstrating the highest value of 10.3°, observed in TKA participants at a speed of 1.2 m/sec at a 5° gradient.

Table 6-23: Mean estimates of pelvic coronal RoM (PCR, °) for the tested treadmill conditions

			95% Confidence Interval	
Treadmill	Mean	Std. Error	Lower Bound	Upper Bound
S1.0	5.831	.418	4.994	6.669
S1.2	6.403	.418	5.565	7.240
S1.2G	10.322	.627	9.066	11.579
S1.4	7.436	.418	6.598	8.273

Note: S1.0 = Speed 1.0 m/sec, gradient 0°; S1.2 = Speed 1.2 m/sec, gradient 0°; S1.4 = Speed 1.4 m/sec, gradient 0°; S1.2G = Speed 1.2 m/sec, gradient 5°.

The differences in pelvic coronal RoM between the tested treadmill conditions are presented in Table 6-24. Significant differences in the pelvic coronal RoM were registered at gradient 0° between speeds 1.4 m/sec and 1.0 m/sec (1.6°, $p = 0.007$); and at gradient 5°, speed 1.2 m/sec and level walking (gradient 0°) at all tested speeds, i.e. 1.0 m/sec (4.5°, $p < 0.0001$), 1.2 m/sec (3.9°, $p < 0.0001$), and 1.4 m/sec (2.9°, $p < 0.0001$).

Table 6-24: Pairwise comparison of the estimated marginal means of pelvic coronal RoM (PCR, °) for the tested treadmill conditions

(I) Treadmill	(J) Treadmill	Mean Difference (I-J)	Std. Error	Sig.^{b}	95% Confidence Interval for Difference^b	
					Lower Bound	Upper Bound
S1.0	S1.2	-.572	.572	.322	-1.719	.575
	S1.2G	-4.491*	.775	.000	-6.044	-2.938
	S1.4	-1.604*	.572	.007	-2.751	-.458
S1.2	S1.0	.572	.572	.322	-.575	1.719
	S1.2G	-3.920*	.775	.000	-5.472	-2.367
	S1.4	-1.033	.572	.077	-2.180	.114
S1.2G	S1.0	4.491*	.775	.000	2.938	6.044
	S1.2	3.920*	.775	.000	2.367	5.472
	S1.4	2.887*	.775	.000	1.334	4.440
S1.4	S1.0	1.604*	.572	.007	.458	2.751
	S1.2	1.033	.572	.077	-.114	2.180
	S1.2G	-2.887*	.775	.000	-4.440	-1.334

Based on estimated marginal means

*. The mean difference is significant at the .050 level.

b. Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments).

Note: S1.0 = Speed 1.0 m/sec, gradient 0°; S1.2 = Speed 1.2 m/sec, gradient 0°; S1.4 = Speed 1.4 m/sec, gradient 0°; S1.2G = Speed 1.2 m/sec, gradient 5°.

6.3.2.6 Thigh coronal RoM (TCR)

Thigh coronal RoM for all tested participants are presented in Figure 6-18.

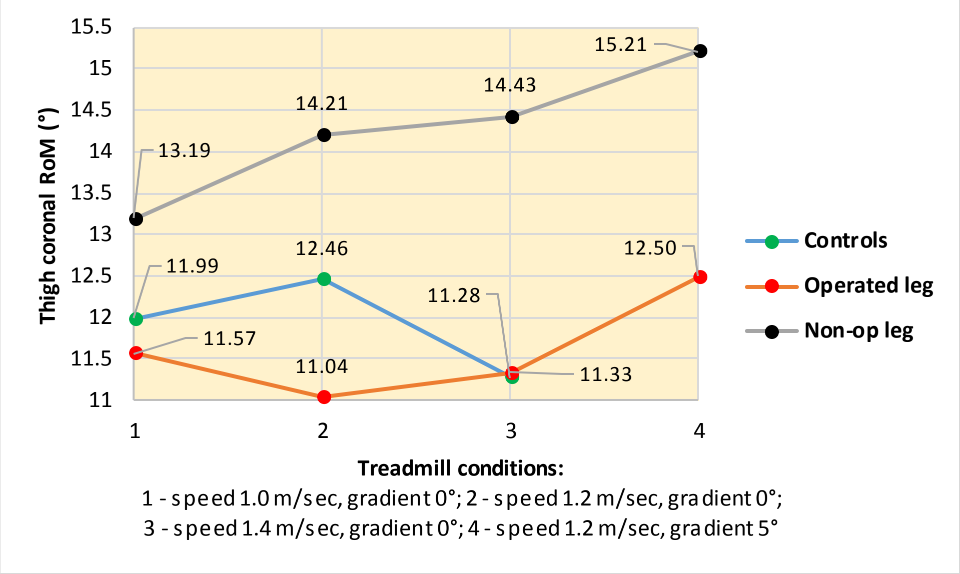


Figure 6-18: Thigh coronal RoM (°) for control (n=5), operated (n=4), and non-operated (n=4) legs

Neither TREADMILL (F (3, 56) = 0.319, *p* = 0.812), nor LEG (F (2, 56) = 2.541, *p* = 0.088) had significant effects on thigh coronal RoM (TCR).

6.3.2.7 Calf coronal RoM (CCR)

Calf coronal RoM for all tested participants are presented in Figure 6-19.

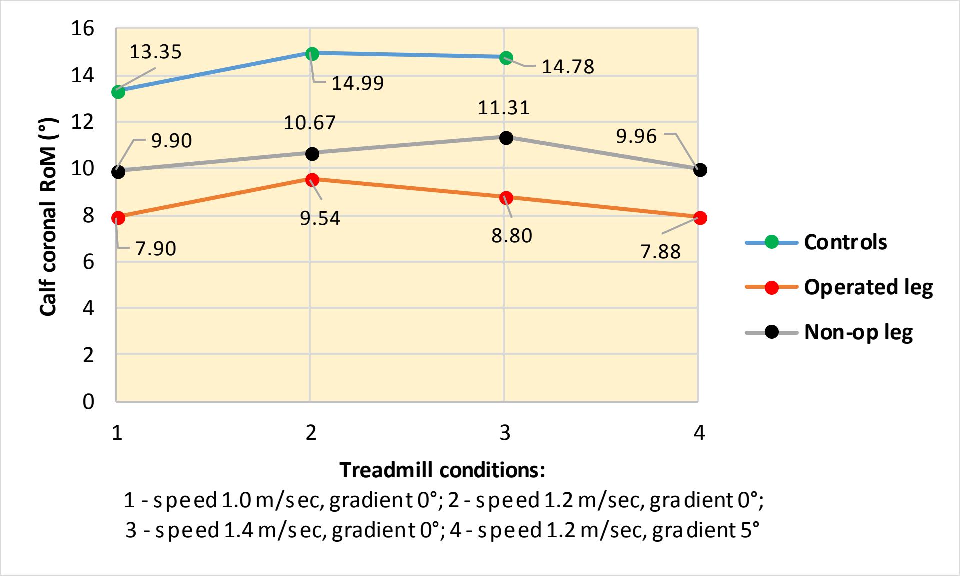


Figure 6-19: Calf coronal RoM (°) for control (n=5), operated (n=4), and non-operated (n=4) legs

LEG (F (2, 56) = 9.320, *p* < 0.0001) was a significant factor affecting calf coronal RoM (CCR), whereas the effect of TREADMILL was not significant (F (3, 56) = 0.507, *p* = 0.679).

The mean value of calf coronal RoM (CCR) was lowest for the operated leg (8.5°, 95% CI from 6.4 to 10.6°), as compared to the mean values for the control (14.2°, 95% CI from 12.4 to 15.9°) and non-operated (10.5°, 95% CI from 8.4° to 12.5°) legs. Significant differences were found between the control and the operated legs (5.6°, $p < 0.0001$), and the control and the non-operated legs (3.7°, $p = 0.008$).

6.4 Discussion.

The aim of this chapter was to determine whether the kinetic and kinematic responses of patients to different treadmill speeds 12 months after TKA would differ from that of healthy participants. In addition, the study aimed to determine whether walking on an incline would return the abnormal aspects of gait in TKA patients nearer to that of healthy participants.

Joint moments

It has previously been found that reduced magnitude of peak knee flexion was a result of avoiding pain by unloading it (Henriksen et al., 2010), similarly to the increased peak knee adduction moment, which showed a positive association with pain intensity (Thorp et al., 2007), suggesting that gait changes acquired before TKA were perpetuated long after the disappearance of pain. Initial reduction of the knee adduction moment to 85% of pre-operative values at 6 months post-operatively with an increase to 94% of pre-operative levels at 1 year after TKA was also documented (Orishimo et al., 2012). These studies did not look at the changes of moments with changes in walking speed.

In our study the kinetic gait parameters of the participants in the healthy age-matched control group and of the TKA patients (hip, knee and ankle moments) altered in a similar manner – tending to increase in response to changes from slower to faster speeds while walking on the level. For TKA patients some of these parameters were also affected by the leg factor, i.e. whether it was the operated, or the non-operated leg.

In comparison with the control group participants, TKA patients exhibited a significant deficit in their peak knee flexion moment for both legs, and their knee adduction moment was significantly greater, whereas their knee internal rotation moment was not different. The findings of lesser peak knee flexion moment at self-selected speeds on the flat in TKA patients than in controls are in agreement with previous studies (Saari et al., 2005, Smith et al., 2006), and while walking on the flat at variable speeds (Brugioni et al., 1990). It has been documented that the knee flexion moment pattern for level walking observed pre-surgery was maintained in up to 50 percent of patients following TKA (Levinger et al., 2012b).

No significant differences were found in the TKA patients' knee adduction moment than from the controls (Brugioni et al., 1990, Saari et al., 2005). Only Brugioni *et al.*'s study was investigating this kinetic variable at differing speeds. On the contrary, significantly lower adduction moments and higher abduction moments were documented in TKA patients (Benedetti et al., 2003).

In comparison with the control group participants, TKA patients exhibited comparable values and trends in their peak hip flexion and internal rotation moments for both legs. In regards to hip abduction moments, despite the trend for increased moment with faster speeds, and no significant difference in values of the abduction moment between controls and both legs of TKA patients, a significant difference in peak hip abduction moments between the operated and the non-operated legs, with highest values for the operated leg, was found. This moment for either leg was not influenced either by changes in speed, or incline. A greater hip abduction moment of the ipsilateral leg was found in patients at the mid-stage of OA progression, and this was explained by an acquired adaptive unloading mechanism which such patients tended to use during walking (Chang et al., 2005). This could be a possible explanation for the pattern that they sustained long after their knee replacement surgery. Saari *et al.* in their study of 39 TKA patients' level walking at self-selected speeds similarly reported no difference in their peak hip abduction moments, but also documented a lower peak hip extension moment for those with a posterior stabilised insert, as compared to controls (Saari et al., 2005).

TKA patients exhibited comparable values and trends in their peak abduction and inversion ankle moments for both legs, as compared to the control group participants. In regards to dorsiflexion moments, despite the trend for increased moment with faster speeds, TKA patients had lower values. A significant difference in peak ankle dorsiflexion moments was found between control and non-operated legs, with lower values for the non-operated legs. Peak ankle dorsiflexion moment was significantly different between the legs of TKA patients, with higher values for the operated legs. Decreased peak ankle dorsiflexion moment in the gait of late stage OA patients was documented previously (Astephen et al., 2008). Fenner *et al.*'s study supported our findings of the lower peak ankle dorsiflexion moments in TKA patients for both tested conditions, level walking and walking on an incline (Fenner et al., 2014). However, their study did not differentiate the legs of TKA patients. In our study, a significant difference from the controls was found in the non-operated leg, which might be a sign of altered mechanics in multiple joints of this leg, similar to the hip joint that we demonstrated above, or progression of OA in the non-operated leg.

People have to negotiate inclined surfaces in daily life, and it was suggested that this task might require different specialised neural control from that needed for level walking (Kawamura et al., 1991, Sun et al., 1996, Leroux et al., 1999, Leroux et al., 2002). Additional testing of TKA patients on an incline demonstrated that the kinetics differed considerably from that of walking on the level, suggesting a greater load on the joints involved. For example, in this study, the change in the kinetic of the knee joint in acceptance of load changed the peak knee flexion to knee extension moment, with an increase in the mean value of the knee extension moment.

Fenner *et al.* in their study found a 40% increase in this moment value for climbing stairs, as compared to a 57% increase of controls' values for this type of activity (Fenner et al., 2014). The participants of the control group in this study were not tested on an incline, therefore comparison of their response to walking on an incline was not possible. Riener *et al.* in their work studying the kinetics and kinematics of normal subjects during stair climbing at different inclinations, found an increase in the peak values of knee moment of 10.6% during ascent. The inclinations studied were much steeper, 24°, 30°, and 42° (Riener et al., 2002), as compared to our study of 5°. McIntosh *et al.* found increased knee flexion in normal subjects with increasing incline from 0° to 10° (McIntosh et al., 2006). Weakness of quadriceps muscle in TKA patients, and their lesser force generation during stair climbing were also implicated, however, a greater force generation was observed in flexor muscles, resulting in no difference in the knee extension moment between healthy participants and TKA patients 11 months and later after their surgery (Rasnick et al., 2016). This demonstrated a compensatory pattern in the gait of patients after their knee replacement surgery.

A significant increase in peak knee internal rotation, and no changes in peak adduction moments while walking on an incline were other findings of this study. A lack of changes in peak adduction moments in TKA patients during stair climbing was supported by previous literature for a fixed bearing total knee prosthesis (Catani et al., 2003, Fantozzi et al., 2003, Berti et al., 2006, Rasnick et al., 2016). Conversely, slight decreases in peak knee adduction and internal rotation on stair climbing were also found (Heinlein et al., 2009). In the level walking of TKA patients at varying speeds no changes in this variable were observed (Brugioni et al., 1990).

Hip flexion and internal rotation moments were affected by an incline, and were significantly increased. Increased hip flexion moment (Lay et al., 2006, McIntosh et al., 2006) was in agreement with our study. Changes in hip internal rotation on an incline for TKA patients were not reflected in the literature. Reduced internal rotation moment was documented in patients with lateral knee OA, which was related to the biomechanics of the hip joint (Weidow et al., 2006).

Peak ankle dorsiflexion and inversion moments of TKA patients were significantly increased by walking on an incline, whereas no significant change in peak ankle abduction moment was recorded. A similar response in ankle dorsiflexion moment to stair ascent was found in the previous study (Fenner et al., 2014). Riener *et al.* in their study on healthy subjects, on the contrary, recorded lesser ankle dorsiflexion moment during incline walking as compared to level walking, and 12.8% increase in its value with increase of incline to 42° (Riener et al., 2002). Unfortunately, no study commenting on changes in ankle inversion moment of TKA patients walking on an incline was found. In an unimpaired population it was found that peak ankle moments increase at level walking with increased walking speed (Brockett and Chapman, 2016), and with walking on an incline (Franz and Kram, 2014). The magnitude of peak ankle moments was age-related, and reduces with advancing age

(Brockett and Chapman, 2016, Franz and Kram, 2014), and compensation occurs in the hip joint (Franz and Kram, 2014).

RoMs

Knee flexion in stance and knee sagittal RoMs of TKA patients as compared to healthy controls of similar age are the most presented in the literature and have a stronger agreement between previous studies and this study than among other gait kinematic variables. Evidence from several studies demonstrated a lesser angle of knee flexion in stance and knee excursion for the operated leg in patients after knee replacement surgery at self-selected speeds during level walking on a treadmill and walking on the ground (Ishii et al., 1998, Benedetti et al., 2003, Smith et al., 2004, Smith et al., 2006, Rahman et al., 2015). These findings were taken from a wide diversity of patients, their country of origin, rehabilitation protocol, and the type of their implant. However, Simon et al.'s study (1983) reported no difference in these variables. Findings of our study confirmed the accepted lower values of these gait variables.

A significant difference of peak knee flexion in stance for both legs of TKA patients as compared to controls was found, 14.4° for the operated, and 12.8° for the non-operated legs. TKA patients responded similarly to controls to increased speed with a significant increase in the value at 1.4 m/sec as compared to 1.0m/sec. However, the increase in the knee flexion in stance with increasing speed during level walking for the operated leg of TKA patients was not so pronounced.

Knee flexion in stance while walking on level ground at a self-selected speed by both groups, as measured with GaitSmart (23.3° for controls; 8.3° for operated leg, and 12.2° for non-operated leg), was comparable with their results on the treadmill walking at 1.2m/sec (23.1° for controls; 8.0° for operated leg, and 11.8° for non-operated leg, see Figure 6-13). This showed that a pre-determined speed of 1.2m/sec was the closest to their natural speed. GaitSmart was able to calculate their knee flexion in stance with comparable precision to the treadmill measurement. However, the fact is that GaitSmart has the limitation of not providing speed measurement.

Wilson *et al.*'s study of level walking at self-selected speeds and stair climbing of both TKA patients, 4 years after their surgery, and their controls, found reduced values of knee flexion in stance, and knee sagittal RoM for level walking and stair descent, whereas there was no difference in the values of either of these variables during stair ascent (Wilson et al., 1996). The difference of peak knee flexion in stance, for TKA patients only, was more dramatic at 7.9°, suggesting that stair climbing, or walking on an incline could be beneficially incorporated into the rehabilitation of these patients, naturally encouraging them to bend their knees more.

The results of knee sagittal RoM were in agreement with those presented above for knee flexion in stance level walking. A notable difference from these studies was found in that despite both legs exhibiting lower values (66.6° for the operated leg and 63.1° for the non-operated leg) than those of the controls (68.5°), the lowest values were recorded for the non-operated leg, suggesting the possible presence of quadriceps avoidance in this leg, which might be a sign of the onset of degenerative changes in this leg. The presence of joint deterioration in the non-operated limb following TKA has been documented (Shakoor et al., 2002).

A considerable reduction of 4.6° in the peak knee sagittal RoM was found while walking on an incline as compared to level walking. Generally, the studies on healthy subjects walking on an incline recorded that the three joints of the lower limb (hip, knee and ankle) flexed more at heel strike and extended more during midstance, as compared to level walking (Lange et al., 1996, Leroux et al., 1999, Lay et al., 2006). Lange *et al.* in their study on healthy subjects found an increase of 20° for the ankle, 59° for the hip RoMs, and a decrease of 12° for the knee when walking on an incline up to 24°. Reduction in knee RoM was attributed to lesser extension of the joint (Lange et al., 1996). The presence of a quadriceps deficit might be the cause of the differences in the knee excursions of TKA patients. Another reason for the lesser value could be that of TKA patients taking a shorter step length than control subjects during stair ascending, which was recorded in Fenner *et al.*'s study (Fenner et al., 2014). Thirdly, lower peak angle values of knee flexion in stance and swing of TKA patients might have resulted in a lower knee excursion angle.

Hip sagittal RoM of TKA patients did not differ from participants of the control group both in response to speed changes, with significant increase in hip flexion with increase in speed, and in their values. These findings were in agreement with previous studies (Simon et al., 1983, Naili et al., 2016b, Komnik et al., 2015).

The increase in hip flexion angle in response to walking on an incline for TKA patients was similar to those presented in studies for healthy subjects (Lay et al., 2006), and the results of post TKA patients in comparison to healthy participants during stair climbing (Saari et al., 2004).

Calf coronal RoM, which is associated with knee adduction during swing, was not influenced either by changes in speed, nor by walking on an incline, whereas the values of this variable tested at varying speeds were significantly lower for TKA patients as compared to controls. The difference for the operated leg was 5.6°, and 3.7° for the non-operated leg. The findings suggest that TKA patients walk more rigidly as compared to control participants, subconsciously or consciously either controlling or protecting the movement of the operated leg.

Thigh coronal RoM, similar to calf coronal RoM, was not affected by changes in speed, or by walking on an incline. No difference in the values between the groups was recorded. Noticeably, as compared to controls the values of the non-operated leg were greater, whereas values of the operated leg were lesser, again suggesting compensation for limited knee movements by the contralateral hip.

Unlike knee adduction in stance, calf coronal RoM has not received considerable attention in the literature. In future studies to explore knee adduction angle in stance could provide an additional point for consideration. McClelland *et al.*’s study found lower peak knee adduction in stance angle in TKA patients 12 months post operatively as compared to controls (McClelland et al., 2011), but the difference was not significant. Similarly, lower values in knee adduction angle, but without significant difference in this variable, were reported in Saari *et al.*’s study (Saari et al., 2005). The medial offset of the centre of mass with resulting ground reaction force (GRF), and compressive forces in normal walking passes through the medial compartment of the knee, and would depend on the knee adduction angle (Johnson et al., 1980). It was documented that load during dynamic activities, such as walking, that passes through the medial compartment was substantially greater than in the static posture (Andriacchi, 1994). Furthermore, in future studies the inclusion of the pre-operative figures of this variable could provide valuable information for comparison of dynamic changes in this parameter after TKA. Interestingly, Orishimo *et al.* in their study reported that correlation between increase in both dynamic varus angle and adduction moment in TKA patients observed from 6 month to 1 year post-operatively was lost from 1 year onwards. They also observed that initial reduction in peak varus during gait at 6 months post-operatively increased by 1 year post-operatively, as well as lost improvement in knee adduction moment, concluding that the findings might be a predisposing factor for implant wear (Orishimo et al., 2012).

Pelvic sagittal RoM was not affected by changes in walking speed, or by walking on an incline. However, significantly greater values for the operated leg as compared to controls was found. Likewise, significantly greater pelvic coronal RoM for both legs of TKA patients were recorded, with significantly greater values with increasing speed and when walking on an incline. Similarly to calf and thigh coronal RoM, previous studies were analysing pelvic obliquity in the frontal plane. Liebensteiner *et al.* unexpectedly found no correlation in any gait parameters with the Knee Society Score (KSS), apart from ‘maximum pelvic obliquity stance’ in the frontal plane (Liebensteiner et al., 2008). Dropping of the pelvis at the unsupported side was commonly observed in hip joint pathology (Watelain et al., 2001), and as a compensatory mechanism in knee joint pathology (Bejek et al., 2006).

The results of our study showed, with a few exceptions, good agreement with previous reports on the level walking biomechanics of TKA patients as compared to healthy participants (Brugioni et al., 1990, Ishii et al., 1998, Saari et al., 2005, Smith et al., 2006, Orishimo et al., 2012, Fenner et al., 2014). Many fewer studies looked at the changes with changing speed. Similarly, even fewer studies examined stair ascent response in TKA patients. We also found good agreement with the findings of these studies except in the knee sagittal RoM (Catani et al., 2003, Fantozzi et al., 2003, Berti et al., 2006, Rasnick et al., 2016). Furthermore, recent studies reporting significant changes in gait kinetics, and no change in gait kinematics of TKA patients 1 year post surgery as compared to controls used Gait Deviation Index (GDI) for kinematics and GDI for kinetic for overall gait pattern deviation (Naili et al., 2016a, Naili et al., 2016b), which makes it impossible to reflect on the mechanics of individual joints.

The biomechanics of walking on an incline were largely presented by studies on healthy participants (Leroux et al., 2002, Lay et al., 2006, McIntosh et al., 2006). In the absence in our study of the control participants walking on an incline, the findings of these studies were used to compare the findings of our TKA patients, when the variables were not found in testing TKA patients in stair climbing studies. However, the incline of those stairs was higher than in our tested conditions. The difficulty in drawing definite conclusions arises from the lack of studies examining the walking biomechanics of all the joints of the lower limb, or of studies looking at all planes of motion in these joints. Furthermore, the testing conditions of the studies varied broadly. It was highlighted in a previous study (Fenner et al., 2014), and it was demonstrated in our study that the joints adjacent to the knee joint provided additional valuable information, which could be more comprehensive and holistic in choosing the type of assessment, treatment, or rehabilitation. It would help to identify compensatory patterns and mechanisms in the gait of TKA patients.

The limitation of our study, apart from the small number of participants in both groups, was the lack of control group data for walking on an incline. However, Fenner *et al.* stated that more differences were observed between TKA patients and control participants during level walking than when going upstairs (Fenner et al., 2014). Another limitation was the heterogeneity of the group of TKA participants in respect to the state of the non-operated leg, two patients had had TKA on this leg, which might have had an effect on the results. The strength of our study was in measuring a comprehensive set of variables, covering all the joints of both legs, in order to assess the difference in gait biomechanics between TKA patients 12 months after surgery and age-matched controls, and to analyse the dynamic of these differences with changes in tested speed. Additionally, the major reason for testing TKA patients on an incline was to provide evidence, and our findings confirmed this, that uphill walking, or stair climbing, could guarantee more profound knee flexion in such a group of the population, as this activity was part of our TOR programme.

Following the above, for future studies in order to obtain a whole and more comprehensive pattern of patients' gaits after their surgery, and to understand the effect of TKA on the ankle joints in a larger cohort of patients, it would be beneficial to investigate ankle kinetics and kinematics, as due to its complexity, currently this area in TKA patients is not sufficiently researched. It was found that despite no changes in static foot posture, significant changes were observed in rearfoot kinematics during walking, suggesting that the alignment of the operated knee was the cause of these changes (Levinger et al., 2012a). Additionally, inclusion of pre-operative data of TKA patients would provide more comprehensive insight of observed changes. Further, testing on a treadmill at the natural speed of TKA patients and healthy participants would show not only the difference in their natural speed, but also whether their gait mechanics differed from pre-determined speed biomechanics. Finally, measuring EMG activity in future studies during level and uphill walking could provide an understanding of the changes, or lack of them, in the motor control strategies of level and uphill walking. This knowledge could be applied to the design of prostheses, and to the rehabilitation of such patients.

Our study demonstrated the presence of deficiencies in the gait of patients 12 months after TKA, as compared to their age-matched healthy counterparts. The trend of these changes was similar in both groups with changes in speed. The altered gait was present in both legs of TKA participants, operated and non-operated. In 12 months post-operative TKA patients increased load in the adjacent hip joint of the operated leg and the knee joint of the non-operated leg, as demonstrated by their peak hip abduction and knee flexion moments, and compared to controls, may lead to the onset or accelerated progression of OA in these joints. The assessment and rehabilitation of these patients therefore requires consideration of the mechanics of all joints of both legs. The testing of TKA participants on a 5° incline demonstrated significant changes in their gait biomechanics as compared to their level walking biomechanics. This suggests that the task of uphill walking imposed a different mechanical demand on their neuromuscular system as compared to level walking at varying speeds.

6.5 Conclusions

- Kinetic and kinematic gait parameters of healthy participants tended to increase in response to changes from slower to faster speeds while walking on the level.
- The gait kinetic of TKA patients at 12 months post-surgery showed alteration in multiple gait parameters (reduced knee flexion and ankle dorsiflexion moments and increased knee adduction moment) as compared to the participants in the control group.
- The gait kinematic of TKA patients at 12 months post-surgery showed alteration in multiple gait parameters (reduced knee flexion in stance, knee sagittal RoM, and calf coronal RoM, and increased pelvic sagittal and coronal RoM) as compared to the participants in the control group.
- Kinetic and kinematic gait parameters of TKA patients showed a similar change as the healthy participants in response to change in speed.
- The observed significant changes in TKA patients' gait kinetics and kinematics, during walking up a slope suggest that the biomechanics of uphill walking differ considerably from walking on the flat, irrespective of the walking speed.
- The evidence of increased knee flexion in stance in patients 12 months after TKA while walking on a 5 degrees incline suggests that incorporating uphill walking and ascending stairs may benefit patients who experience deficiency in knee flexion in stance.

Chapter 7 The effect of the TOR programme on treadmill walking in TKA patients 12 months after surgery

7.1 Introduction

Numerous studies have shown that patients 12 months after their knee replacement surgery showed altered gait kinematics and kinetics (McClelland et al., 2007, Milner, 2009, Yoshida et al., 2012, Li et al., 2013, Sosdian et al., 2014) and these results have been confirmed by the present study. Furthermore the present study has shown that task-orientated rehabilitation can reverse some of the kinematic deficits associated with TKA resulting in a greater RoM of joints and segments involved in walking, and shorter stride duration. While the GaitSmart system provided a convenient means of measuring the kinematic properties of walking in a natural environment, this system is unable to provide data on the kinetic variables or to test gait under more controlled and variable conditions.

The forces acting on the body segments are important as these govern the pattern and efficiency of movement. An understanding of how these change in response to the TOR programme will contribute to a better overall understanding of gait modifications. In addition, testing the effect of the TOR programme in more challenging, and more controlled conditions, such as walking at variable speeds, and on an incline, provides further evidence to assess the efficacy of this type of rehabilitation. To acquire these data, four patients were additionally subjected to assessment on the instrumented treadmill after completion of their programme using conditions identical to those explored in Chapter 6.

Hypothesis.

The kinetic and kinematic characteristics of gait at different speeds and on an incline in patients 12 months after TKA are more similar to those of healthy participants following TOR.

Objectives.

1. To determine the effect of TOR on gait characteristics (kinetic and kinematic) at different walking speeds on the level and on an incline in TKA patients 12 months post-surgery.
2. To assess changes in relation to gait characteristics of healthy participants.

7.2 Method

7.2.1 Participants

Data were collected from these four participants (2 male and 2 female), 12 months after TKA prior to and after their TOR programme, mean age was 60.3±8.7 years, and their BMI was 31.7±2.6. Only participants who gave their written informed consent to take part in a walking test, and the TOR rehabilitation with treadmill assessment were recruited for this part of the study.

Inclusion and exclusion criteria were the same as for Chapter 6.

7.2.2 Procedure

Assessments were carried out at the MLL of The RNOH, Stanmore over two sessions, see Table 7-1. The first session assessment occurred before the 4-week TOR programme (i.e. baseline assessment). The second session assessment was done on the day after the completion of the 4-week TOR programme. Heights and weights of the participants were measured on the first testing day (session 1) prior to any gait assessment procedures.

Table 7-1: Study protocol exploring changes in the gait pattern on the treadmill of participants 12 months after TKA prior to and post their 4-week TOR programme

Session 1 (Baseline, Prior to TOR programme)	**4-week TOR programme**	**Session 2 (Post 4-week TOR programme)**
TKA patients (n=4, male/female=2/2	TKA patients (same as in Session 1)	TKA patients (same as in Session 1)
Tests performed at GRAIL (MOTEK): - Instrumented treadmill walking - 0° incline, at 1.0, 1.2, and 1.4 m/sec; and 5° incline, at 1.2 m/sec (3-dimensional kinetic parameters - knee, hip and ankle moments).	Daily walking and stair and/or uphill climbing	***Tests performed at GRAIL (MOTEK):*** As in Session 1.
Tests performed with IMUs (GaitSmart): - Treadmill walking - 0° incline, at 1.0, 1.2, and 1.4 m/sec; and 5° incline, at 1.2 m/sec (2-dimensional kinematic parameters - knee stance flexion, sagittal knee, hip and pelvic RoM, and coronal pelvic, thigh and calf RoM).		***Tests performed with IMUs (GaitSmart):*** As in Session 1.

7.2.2.1 Data acquisition

Kinetic data acquisition was made using a 3D, 10-camera motion capture system (GRAIL, Motec Medical B.V., Amsterdam, The Netherlands), following the same treadmill protocol as presented in Chapter 6. The placement of sensors was identical to those applied in Chapter 6.

Kinematic data acquisition was done using IMUs, carrying out the same treadmill protocol. The placement of sensors was identical to those applied in Chapter 4.

7.2.2.2 Data management

Kinetic data management and calculations were done using software Visual3D Motion Capture Analysis Application version 6 x 64 (C-motion, Inc., Germantown, MD) following the exact procedure presented in Chapter 6.

IMUs' kinematic data were obtained and managed in an identical manner to those applied in Chapter 4.

7.2.3 Statistical analysis

Comparison of kinetic data – hip, knee and ankle moments – and kinematic data – knee flexion in stance, sagittal knee, hip and pelvic RoM, and coronal pelvic, thigh and calf RoM – for four participants 12 months after TKA, prior to and post their task-orientated rehabilitation (TOR) programme, were evaluated using SPSS Statistics for Windows (version 22). To explore the effect of the TOR programme (REHABILITATION), the treadmill (walking on flat and incline) (TREADMILL), and the effect of the participant's leg (LEG) a univariate one-way ANOVA on each of the joint moments in three planes, and each of the kinematic variables was used. There were four treadmill conditions for all TKA participants prior to and post their TOR programme – walking on 0 degree of incline at a speed of 1.0 (S1.0), 1.2 (S1.2), and 1.4 m/sec (S1.4), and walking on 5 degrees of incline at a speed of 1.2 m/sec (S1.2G).

TKA participants prior to and post their rehabilitation programme, were compared using a two-level factor for "leg". The first level denoted the operated leg of the

TKA participants, the second level denoted the non-operated leg of the TKA participants.

In an initial analysis, the main effects of the rehabilitation programme (REHABILITATION), leg (LEG), and the treadmill condition (TREADMILL) and their interaction were examined. The REHABILITATIONxLEGxTREADMILL interaction effect was non-significant for all the tested kinetic and kinematic variables, indicating that the effect of TREADMILL was the same on the operated leg, and on the non-operated leg. In the analyses reported below, the interaction effect is therefore omitted, and only the main effects of rehabilitation, leg and treadmill are examined. The level of significance was set at $p \leq 0.05$.

7.3 Results.

The results of kinetic (three dimensional hip, knee and ankle moments), and kinematic (knee flexion in stance, sagittal knee, hip and pelvic RoM, and coronal pelvic, thigh and calf RoM) data for four TKA patients prior to and post their TOR programme are presented below.

7.3.1 Kinetic variables

7.3.1.1 Knee moments

Participants' recorded knee moments at all the tested treadmill conditions before and after their TOR programme are presented in Table 7-2.

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Table 7-2: Descriptive statistics for the knee moments for the TKA (n=4) participants prior to and post their TOR programme

Knee Moments (N m)	Treadmill conditions (speed (m/sec) & gradient (0°))			
	1.0 (0°)	**1.2 (0°)**	**1.4 (0°)**	**1.2 (5°)**
K_MMx (N m)				
Operated leg				
Baseline (Prior to TOR)	0.28±0.26	0.29±0.23	0.56±0.38	-0.47±0.26
Post TOR	0.38±0.32	0.50±0.44	0.68±0.61	-0.42±0.34
Non-operated leg				
Baseline (Prior to TOR)	0.31±0.15	0.37±0.18	0.53±0.16	-0.64±0.11
Post TOR	0.32±0.17	0.38±0.19	0.50±0.19	-0.69±0.19
K_MMy (N m)				
Operated leg				
Baseline (Prior to TOR)	0.45±0.04	0.47±0.04	0.47±0.10	0.53±0.09
Post TOR	0.37±0.15	0.40±0.17	0.43±0.18	0.53±0.10
Non-operated leg				
Baseline (Prior to TOR)	0.34±0.11	0.36±0.12	0.38±0.13	0.39±0.12
Post TOR	0.36±0.09	0.36±0.09	0.37±0.12	0.44±0.16
K_MMz (N m)				
Operated leg				
Baseline (Prior to TOR)	0.10±0.04	0.10±0.02	0.13±0.03	0.42±0.06
Post TOR	0.07±0.02	0.08±0.02	0.11±0.03	0.38±0.05
Non-operated leg				
Baseline (Prior to TOR)	0.06±0.03	0.07±0.03	0.09±0.06	0.41±0.07
Post TOR	0.05±0.03	0.06±0.03	0.07±0.05	0.41±0.08

Note: K_MMx = Knee flexion moment, K_MMy = Knee adduction moment, K_MMz = Knee internal rotation moment. Data are presented as mean ± s.d.

7.3.1.1.1 Knee flexion moment (K_MMx)

Mean values of knee flexion moments for all tested participants before and after their TOR programme are presented in Figure 7-1.

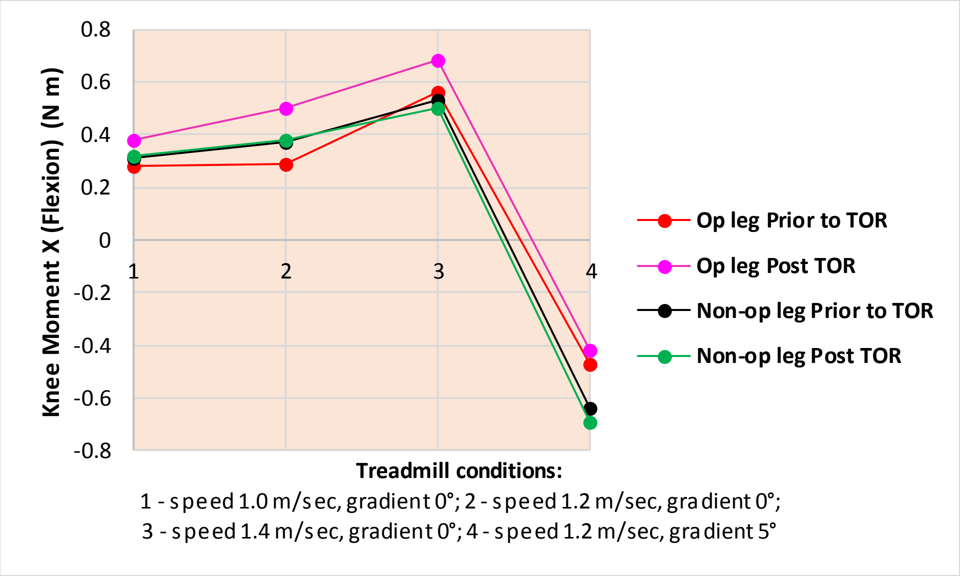

Figure 7-1: Mean values of knee flexion moments (N m) of TKA participants (n=4) prior to and post TOR programme for operated, and non-operated legs

TREADMILL (F (3, 55) = 57.530, $p < 0.0001$) was a significant factor affecting knee flexion moment (K_MMx), whereas the effect of REHABILITATION and LEG was not significant, F (1, 55) = 0.615, $p = 0.436$, and F (1, 55) = 1.893, $p = 0.174$ respectively.

Neither the increase of 0.052 (N m) in knee flexion moment after rehabilitation, nor the difference of 0.091 (N m) between the operated and the non-operated legs were significant, $p = 0.436$ and $p = 0.174$ respectively.

The overall mean values of knee flexion moments for the tested treadmill conditions are presented in Table 7-3. The highest value of knee flexion moment was observed at a speed of 1.4 m/sec at a 0°gradient, and the lowest value at a speed of 1.2 m/sec at a 5°gradient.

Table 7-3: Mean estimates of knee flexion moment (K_MMx, N m) for the tested treadmill conditions

			95% Confidence Interval	
Treadmill	Mean	Std. Error	Lower Bound	Upper Bound
S1.0	.322	.066	.190	.455
S1.2	.387	.066	.254	.519
S1.2G	-.556	.066	-.688	-.423
S1.4	.568	.066	.435	.700

Note: S1.0 = Speed 1.0 m/sec, gradient 0°; S1.2 = Speed 1.2 m/sec, gradient 0°; S1.4 = Speed 1.4 m/sec, gradient 0°; S1.2G = Speed 1.2 m/sec, gradient 5°.

The differences in knee flexion moment between the tested treadmill conditions are presented in Table 7-4. Significant differences in the knee flexion moment were registered at gradient 0° between speed 1.4 m/sec and speeds 1.0 m/sec (0.246 (N m), $p = 0.011$), and 1.2 m/sec (0.182 (N m), $p = 0.023$); and at gradient 5°, speed 1.2 m/sec and level walking (gradient 0°) at all tested speeds, i.e. 1.0 m/sec (-0.878 (N m), $p < 0.0001$), 1.2 m/sec (-0.942 (N m), $p < 0.0001$), and 1.4 m/sec (-1.124 (N m), $p < 0.0001$).

Table 7-4: Pairwise comparison of the estimated marginal means of knee flexion moment (K_MMx, N m) for the tested treadmill conditions

		Mean Difference (I-J)	Std. Error	Sig.^{b}	95% Confidence Interval for Difference^b	
(I) Treadmill	(J) Treadmill				Lower Bound	Upper Bound
S1.0	S1.2	-.064	.094	.495	-.252	.123
	S1.2G	.878*	.094	.000	.691	1.065
	S1.4	-.246*	.094	.011	-.433	-.058
S1.2	S1.0	.064	.094	.495	-.123	.252
	S1.2G	.942*	.094	.000	.755	1.130
	S1.4	-.181	.094	.058	-.369	.006
S1.2G	S1.0	-.878*	.094	.000	-1.065	-.691
	S1.2	-.942*	.094	.000	-1.130	-.755
	S1.4	-1.124*	.094	.000	-1.311	-.936
S1.4	S1.0	.246*	.094	.011	.058	.433
	S1.2	.181	.094	.058	-.006	.369
	S1.2G	1.124*	.094	.000	.936	1.311

Based on estimated marginal means

*. The mean difference is significant at the .050 level.

b. Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments).

<u>Note</u>: S1.0 = Speed 1.0 m/sec, gradient 0°; S1.2 = Speed 1.2 m/sec, gradient 0°; S1.4 = Speed 1.4 m/sec, gradient 0°; S1.2G = Speed 1.2 m/sec, gradient 5°.

7.3.1.1.2 Knee adduction moment (K_MMy)

Mean values of knee adduction moments for all tested participants before and after their TOR programme are presented in Figure 7-2.

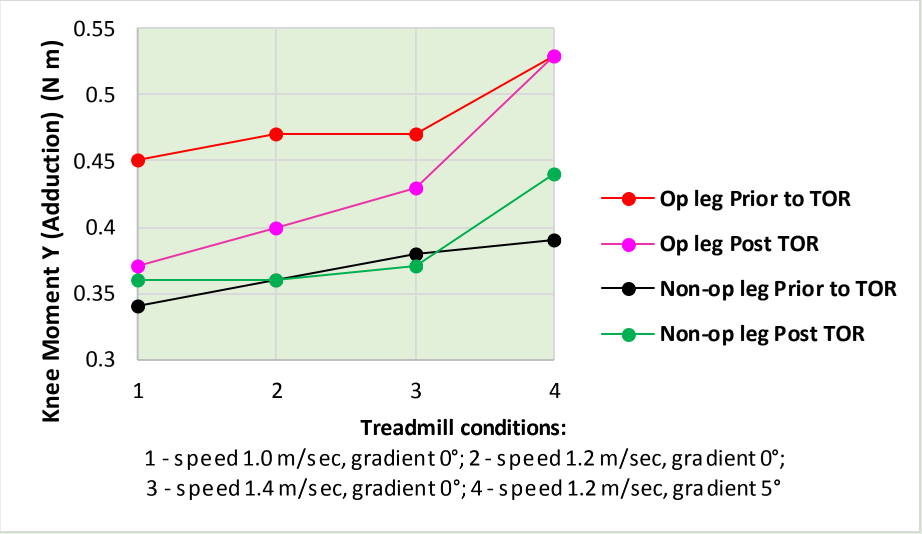

Figure 7-2: Mean values of knee adduction moments (N m) of TKA participants (n=4) prior to and post TOR programme for operated, and non-operated legs

Both LEG (F (1, 55) = 12.966, *p* = 0.001) and TREADMILL (F (3, 55) = 3.181, *p* = 0.031) had significant effects on knee adduction moment (K_MMy). The effect of

REHABILITATION, a decrease of 0.017 (N m) in knee adduction moment after the rehabilitation, was not significant, F (1, 55) = 0.584, *p* = 0.448.

A strongly significant difference of 0.082 (N m) in knee adduction moment was found between the operated and the non-operated legs *p* = 0.001.

Significant differences in the knee adduction moment were registered between walking at gradient 5°, speed 1.2 m/sec and level walking (gradient 0°) at speed 1.0 m/sec (0.093 (N m), *p* = 0.006, 95% CI from 0.028 to 0.157 (N m)), and at speed 1.2 m/sec (0.077 (N m), *p* = 0.020, 95% CI from 0.013 to 0.142 (N m)).

7.3.1.1.3 Knee internal rotation moment (K_MMz)

Mean values of knee internal rotation moments for all tested participants prior to and post their TOR programme are presented in Figure 7-3.

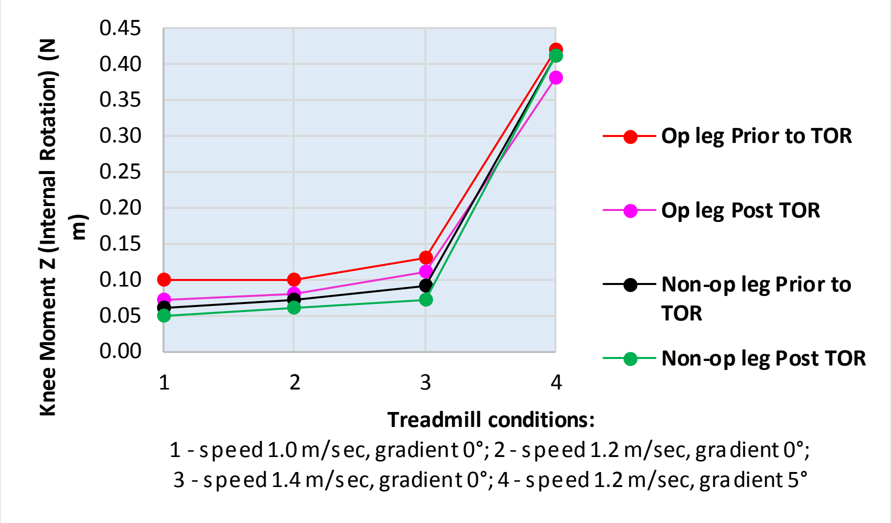

Figure 7-3: Mean values of knee internal rotation moments (N m) of TKA participants (n=4) prior to and post TOR programme for operated, and non-operated legs

TREADMILL (F (3, 55) = 291.244, *p* < 0.0001) was a significant factor affecting knee internal rotation moment (K_MMz), whereas the effect of REHABILITATION and LEG was not significant, F (1, 55) = 3.043, *p* = 0.087, and F (1, 55) = 3.804, *p* = 0.056 respectively.

The decrease of 0.017 (N m) in knee internal rotation moment after rehabilitation was not significant (*p* = 0.087). The difference of 0.018 (N m) between the operated and the non-operated legs just failed to reach a significant level (*p* = 0.056).

The highest value of knee internal rotation moment, 0.406 (N m), was observed at a speed of 1.2 m/sec at a 5° gradient, and the lowest value, 0.069 (N m), at a speed of 1.0 m/sec at a 0° gradient.

Significant differences in the knee internal rotation moment were registered at gradient 0° between speed 1.4 m/sec and speeds 1.0 m/sec (0.032 (N m), $p = 0.020$, 95% CI from 0.005 to 0.059 (N m)); and at gradient 5°, speed 1.2 m/sec and level walking (gradient 0°) at all tested speeds, i.e. 1.0 m/sec (0.337 (N m), $p < 0.0001$, 95% CI from 0.310 to 0.364 (N m)), 1.2 m/sec (0.326 (N m), $p < 0.0001$, 95% CI from 0.299 to 0.353 (N m)), and 1.4 m/sec (0.305 (N m), $p < 0.0001$, 95% CI from 0.278 to 0.332 (N m)).

7.3.1.2 Hip moments

Participants' recorded hip moments at all the tested treadmill conditions before and after their TOR programme are presented in Table 7-5.

Table 7-5: Descriptive statistics for the hip moments for the TKA (n=4) patients prior to and post their TOR programme

Hip Moments (N m)	Treadmill conditions (speed (m/sec) & gradient (0°))			
	1.0 (0°)	**1.2 (0°)**	**1.4 (0°)**	**1.2 (5°)**
H_MMx (N m)				
Operated leg				
Baseline (Prior to TOR)	0.47±0.31	0.55±0.34	0.73±0.32	2.81±0.20
Post TOR	0.53±0.20	0.61±0.20	0.72±0.23	2.84±0.26
Non-operated leg				
Baseline (Prior to TOR)	0.54±0.14	0.64±0.19	0.78±0.28	2.82±0.41
Post TOR	0.58±0.27	0.69±0.29	0.84±0.36	2.96±0.59
H_MMy (N m)				
Operated leg				
Baseline (Prior to TOR)	0.92±0.10	0.96±0.13	0.99±0.15	0.98±0.09
Post TOR	0.87±0.21	0.93±0.23	1.00±0.25	0.90±0.32
Non-operated leg				
Baseline (Prior to TOR)	0.86±0.16	0.90±0.15	0.93±0.20	0.74±0.10
Post TOR	0.89±0.10	0.91±0.09	0.97±0.12	0.82±0.18
H_MMz (N m)				
Operated leg				
Baseline (Prior to TOR)	0.26±0.08	0.29±0.09	0.32±0.09	0.40±0.14
Post TOR	0.25±0.06	0.28±0.07	0.32±0.06	0.33±0.08
Non-operated leg				
Baseline (Prior to TOR)	0.23±0.10	0.27±0.10	0.34±0.15	0.46±0.17
Post TOR	0.26±0.07	0.28±0.11	0.31±0.13	0.40±0.18

Note: H_MMx = Hip flexion moment, H_MMy = Hip abduction moment, H_MMz = Hip internal rotation moment. Data are presented as mean ± s.d.

7.3.1.2.1 Hip flexion moment (H_MMx)

Mean values of hip flexion moments for all tested participants before and after their TOR programme are presented in Figure 7-4.

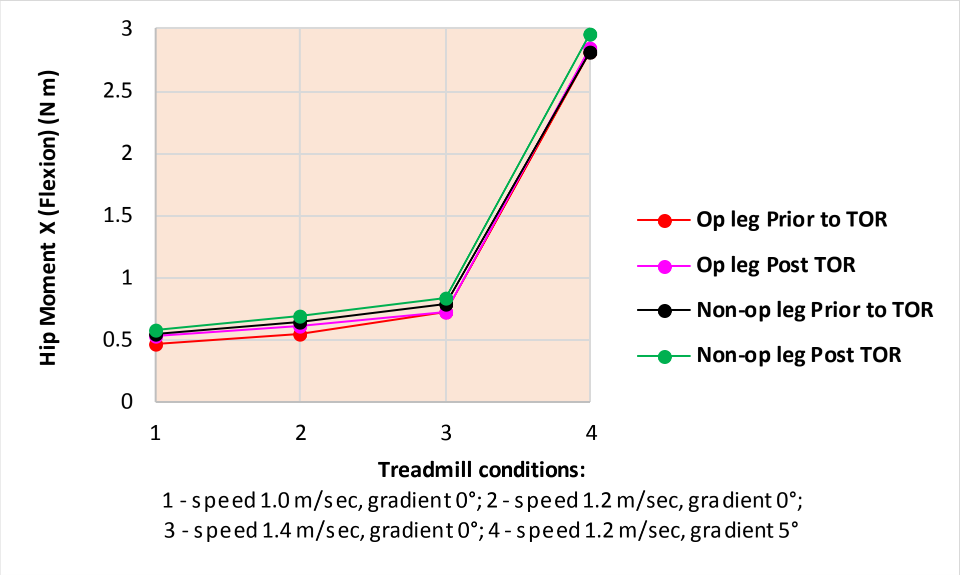

Figure 7-4: Mean values of hip flexion moments (N m) of TKA participants (n=4) prior to and post TOR programme for operated, and non-operated legs

TREADMILL had a strong significant effect on hip flexion moment (H_MMx), F (3, 55) = 403.429, p < 0.0001. The effect of REHABILITATION and LEG was not significant, F (1, 55) = 0.963, p = 0.331, and F (1, 55) = 1.800, p = 0.185 respectively.

Neither the increase of 0.054 (N m) in hip flexion moment after rehabilitation, nor the difference of -0.074 (N m) between the operated and the non-operated legs were significant, p = 0.331 and p = 0.185 respectively.

The highest value of hip flexion moment, 2.857 (N m), was observed at a speed of 1.2 m/sec at a 5° gradient, and the lowest value, 0.530 (N m), at a speed of 1.0 m/sec at a 0° gradient.

Significant differences in hip flexion moment were registered at gradient 0° between speed 1.4 m/sec and speeds 1.0 m/sec (0.238 (N m), p = 0.004, 95% CI from 0.081 to 0.395 (N m)); and at gradient 5°, speed 1.2 m/sec and level walking (gradient 0°) at all tested speeds, i.e. 1.0 m/sec (2.326 (N m), p < 0.0001, 95% CI from 2.169 to

2.484 (N m)), 1.2 m/sec (2.237 (N m), $p < 0.0001$, 95% CI from 2.080 to 2.394 (N m)), and 1.4 m/sec (2.089 (N m), $p < 0.0001$, 95% CI from 1.931 to 2.246 (N m)).

7.3.1.2.2 Hip abduction moment (H_MMy)

Mean values of hip abduction moments for all tested participants before and after their TOR programme are presented in Figure 7-5.

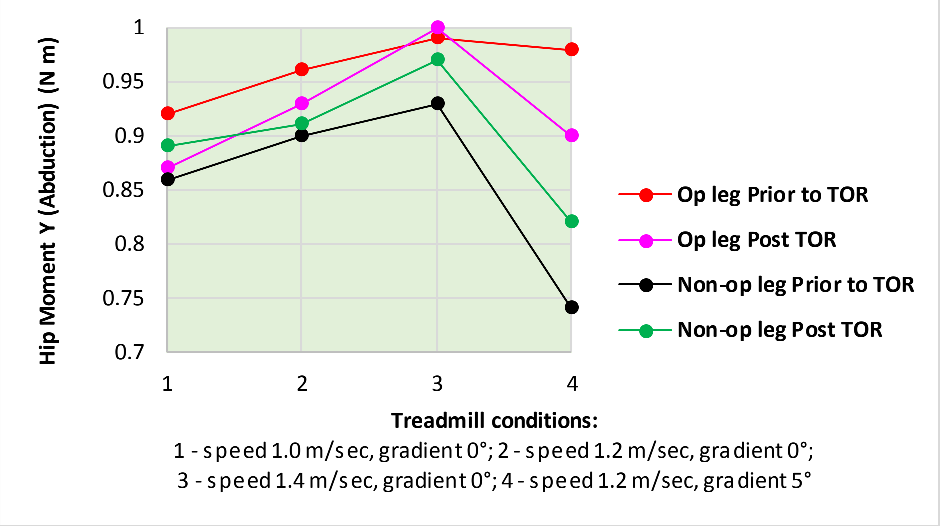

Figure 7-5: Mean values of hip abduction moments (N m) of TKA participants (n=4) prior to and post TOR programme for operated, and non-operated legs

Both LEG (F (1, 55) = 5.491, $p = 0.023$) and TREADMILL (F (3, 55) = 2.785, $p = 0.049$) had significant effects on hip abduction moment (H_MMy). The effect of REHABILITATION (an increase of 0.002 (N m) in hip abduction moment after the rehabilitation was not significant), F (1, 55) = 0.006, $p = 0.940$.

A significant difference of 0.068 (N m) was found between the operated and the non-operated legs $p = 0.023$.

The highest value of hip abduction moment, 0.971 (N m), was observed at a speed of 1.4 m/sec at a 0° gradient, and the lowest value, 0.860 (N m), at a speed of 1.2 m/sec at a 5° gradient.

Significant differences in the hip abduction moment were registered between walking at gradient 5°, speed 1.2 m/sec and level walking (gradient 0°) at speed 1.4 m/sec (-0.111 (N m), $p = 0.009$, 95% CI from -0.193 to -0.029 (N m)); and at gradient 0° between speeds 1.4 m/sec and 1.0 m/sec (0.086 (N m), *p* = 0.041), 95% CI from 0.003 to 0.168 (N m)).

7.3.1.2.3 Hip internal rotation moment (H_MMz)

Mean values of hip internal rotation moments for all tested participants before and after their TOR programme are presented in Figure 7-6.

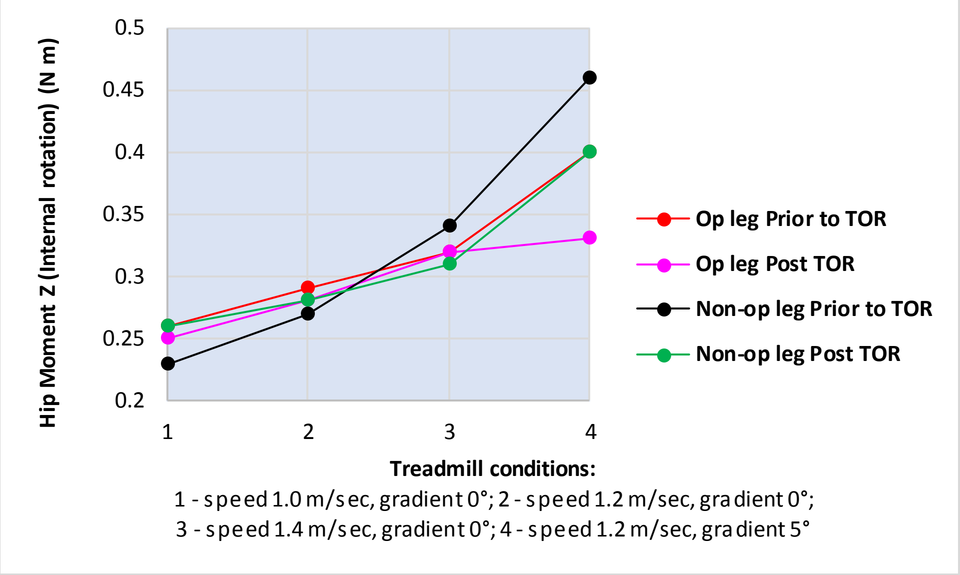

Figure 7-6: Mean values of hip internal rotation moments (N m) of TKA participants (n=4) prior to and post TOR programme for operated, and non-operated legs

TREADMILL had a strong significant effect on hip internal rotation moment (H_MMz), F (3, 55) = 9.369, *p* < 0.0001. The effect of REHABILITATION and LEG was not significant, F (1, 55) = 0.582, *p* = 0.449, and F (1, 55) = 0.411, *p* = 0.524 respectively.

The decrease of 0.016 (N m) in hip internal rotation moment after rehabilitation was not significant (*p* = 0.449). The difference of -0.013 (N m) between the operated and the non-operated legs was not significant (*p* = 0.524).

The highest value of hip internal rotation moment, 0.398 (N m), was observed at a speed of 1.2 m/sec at a 5° gradient, and the lowest value, 0.249 (N m), at a speed of 1.0 m/sec at a 0° gradient.

Significant differences in hip internal rotation moment were registered at gradient 0° between speed 1.4 m/sec and speeds 1.0 m/sec (0.075 (N m), *p* = 0.015, 95% CI from

0.015 to 0.134 (N m)); and at gradient 5°, speed 1.2 m/sec and level walking (gradient 0°) at all tested speeds, i.e. 1.0 m/sec (0.149 (N m) , $p < 0.0001$, 95% CI from 0.089 to 0.208 (N m)), 1.2 m/sec (0.115 (N m), $p < 0.0001$, 95% CI from 0.056 to 0.175 (N m)), and 1.4 m/sec (0.074 (N m), $p = 0.015$, 95% CI from 0.015 to 0.133 (N m)).

7.3.1.3 Ankle moments

Participants' recorded ankle moments at all the tested treadmill conditions before and after their TOR programme are presented in Table 7-6.

Table 7-6: Descriptive statistics for the ankle moments for the TKA (n=4) participants prior to and post their TOR programme.

Ankle Moments (N m)	**Treadmill conditions (speed (m/sec) & gradient (0°))**			
	1.0 (0°)	**1.2 (0°)**	**1.4 (0°)**	**1.2 (5°)**
A_MMx (N m)				
Operated leg				
Baseline (Prior to TOR)	1.35±0.22	1.38±0.09	1.50±0.11	1.97±0.19
Post TOR	1.27±0.15	1.35±0.16	1.46±0.16	1.93±0.12
Non-operated leg				
Baseline (Prior to TOR)	1.22±0.04	1.34±0.05	1.43±0.14	1.78±0.14
Post TOR	1.25±0.10	1.33±0.08	1.38±0.09	1.78±0.11
A_MMy (N m)				
Operated leg				
Baseline (Prior to TOR)	0.30±0.12	0.31±0.06	0.38±0.09	0.43±0.14
Post TOR	0.25±0.10	0.28±0.12	0.34±0.11	0.39±0.16
Non-operated leg				
Baseline (Prior to TOR)	0.31±0.14	0.37±0.15	0.41±0.10	0.42±0.16
Post TOR	0.34±0.04	0.37±0.03	0.41±0.04	0.44±0.08
A_MMz (N m)				
Operated leg				
Baseline (Prior to TOR)	0.14±0.09	0.13±0.02	0.17±0.04	0.40±0.10
Post TOR	0.10±0.03	0.12±0.03	0.16±0.02	0.37±0.06
Non-operated leg				
Baseline (Prior to TOR)	0.09±0.05	0.10±0.05	0.14±0.08	0.36±0.12
Post TOR	0.08±0.05	0.10±0.05	0.11±0.06	0.35±0.13

Note: A_MMx = Ankle dorsiflexion moment, A_MMy = Ankle abduction moment, A_MMz = Ankle inversion moment. Data are presented as mean ± s.d.

7.3.1.3.1 Ankle dorsiflexion moment (A_MMx)

Mean values of ankle dorsiflexion moments for all tested participants before and after their TOR programme are presented in Figure 7-7.

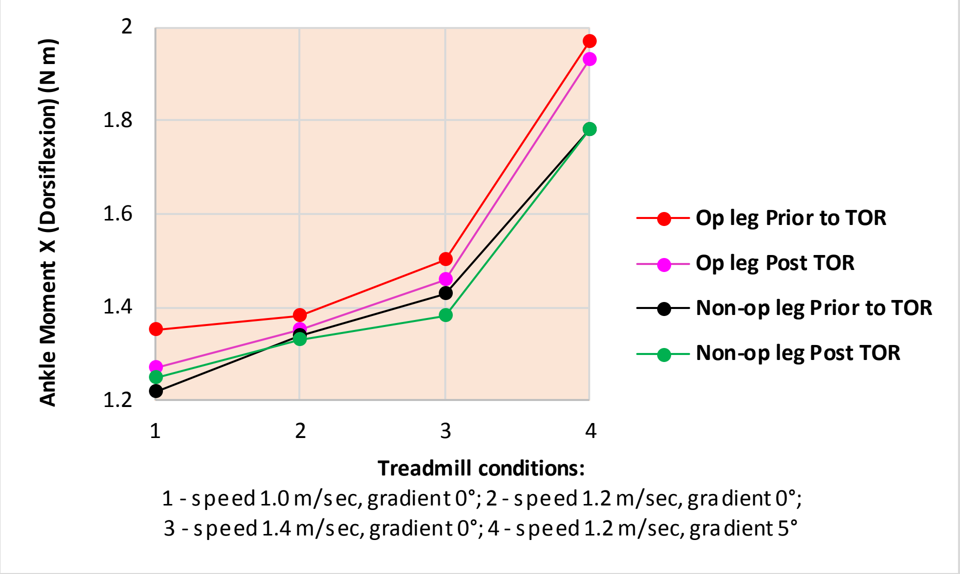

Figure 7-7: Mean values of ankle dorsiflexion moments (N m) of TKA participants (n=4) prior to and post TOR programme for operated, and non-operated legs

Both LEG (F (1, 55) = 12.309, *p* = 0.001) and TREADMILL (F (3, 55) = 108.261, *p* < 0.0001) had significant effects on ankle dorsiflexion moment (A_MMx). The effect of REHABILITATION (a decrease of 0.029 (N m) in ankle dorsiflexion moment after the rehabilitation was not significant), F (1, 55) = 1.262, *p* = 0.266.

A significant difference of 0.089 (N m) was found between the operated and the non-operated legs *p* = 0.001.

The overall mean values of ankle dorsiflexion moments for the tested treadmill conditions are presented in Table 7-7. The highest value of ankle dorsiflexion moment, 1.865 (N m), was observed at a speed of 1.2 m/sec at a 5° gradient, and the lowest value, 1.274 (N m), at a speed of 1.0 m/sec at a 0° gradient.

Table 7-7: Mean estimates of ankle dorsiflexion moment (A_MMx, N m) for the tested treadmill conditions

			95% Confidence Interval	
Treadmill	Mean	Std. Error	Lower Bound	Upper Bound
S1.0	1.274	.025	1.223	1.325
S1.2	1.350	.025	1.299	1.401
S1.2G	1.865	.025	1.814	1.916
S1.4	1.442	.025	1.391	1.493

Note: S1.0 = Speed 1.0 m/sec, gradient 0°; S1.2 = Speed 1.2 m/sec, gradient 0°; S1.4 = Speed 1.4 m/sec, gradient 0°; S1.2G = Speed 1.2 m/sec, gradient 5°.

The differences in ankle dorsiflexion moment between the tested treadmill conditions are presented in Table 7-8. Significant differences in the ankle dorsiflexion moment were registered between all the tested treadmill conditions (see Table 7-8).

Table 7-8: Pairwise comparison of the estimated marginal means of ankle dorsiflexion moment (A_MMx, N m) for the tested treadmill conditions

(I) Treadmill	(J) Treadmill	Mean Difference (I-J)	Std. Error	Sig.[b]	95% Confidence Interval for Difference[b] Lower Bound	95% Confidence Interval for Difference[b] Upper Bound
S1.0	S1.2	-.076*	.036	.040	-.148	-.004
	S1.2G	-.591*	.036	.000	-.663	-.519
	S1.4	-.168*	.036	.000	-.240	-.096
S1.2	S1.0	.076*	.036	.040	.004	.148
	S1.2G	-.516*	.036	.000	-.588	-.444
	S1.4	-.093*	.036	.013	-.164	-.021
S1.2G	S1.0	.591*	.036	.000	.519	.663
	S1.2	.516*	.036	.000	.444	.588
	S1.4	.423*	.036	.000	.351	.495
S1.4	S1.0	.168*	.036	.000	.096	.240
	S1.2	.093*	.036	.013	.021	.164
	S1.2G	-.423*	.036	.000	-.495	-.351

Based on estimated marginal means

*. The mean difference is significant at the .050 level.

b. Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments).

Note: S1.0 = Speed 1.0 m/sec, gradient 0°; S1.2 = Speed 1.2 m/sec, gradient 0°; S1.4 = Speed 1.4 m/sec, gradient 0°; S1.2G = Speed 1.2 m/sec, gradient 5°.

7.3.1.3.2 Ankle abduction moment (A_MMy)

Mean values of ankle abduction moments for all tested participants before and after their TOR programme are presented in Figure 7-8.

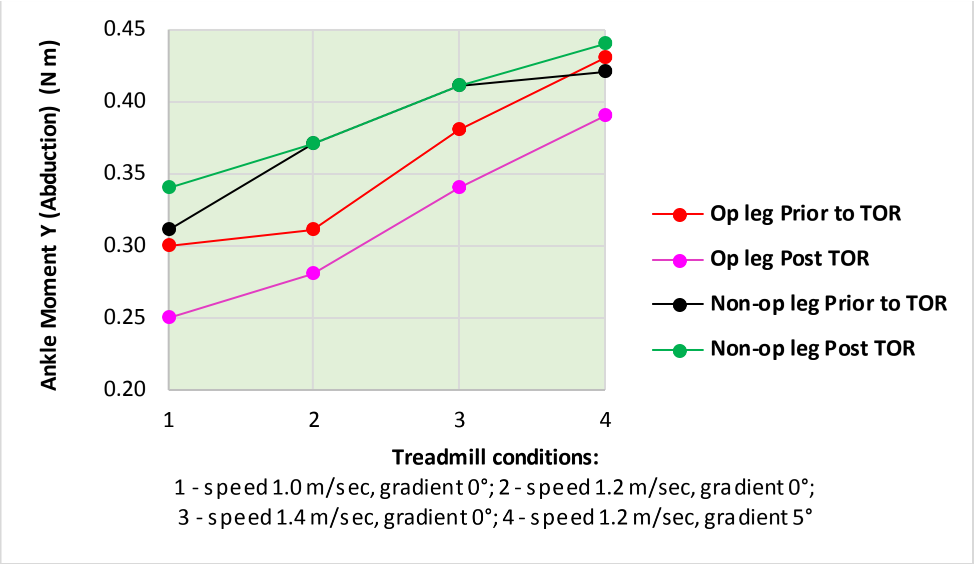

Figure 7-8: Mean values of ankle abduction moments (N m) of TKA participants (n=4) prior to and post TOR programme for operated, and non-operated legs

Both LEG (F (1, 55) = 4.322, *p* = 0.042) and TREADMILL (F (3, 55) = 5.216, *p* = 0.003) had significant effects on ankle abduction moment (A_MMy). The effect of REHABILITATION (a decrease of 0.015 (N m) in ankle abduction moment after the rehabilitation was not significant), F (1, 55) = 0.395, *p* = 0.532.

A significant difference of -0.049 (N m) in ankle abduction moment was found between the operated and the non-operated legs *p* = 0.042.

The highest value of ankle abduction moment, 0.420 (N m), was observed at a speed of 1.2 m/sec at a 5° gradient, and the lowest value, 0.299 (N m), at a speed of 1.0 m/sec at a 0° gradient.

Significant differences in ankle abduction moment were registered at gradient 0° walking between speed 1.4 m/sec and speeds 1.0 m/sec (0.087 (N m), *p* = 0.011, 95% CI from 0.020 to 0.153 (N m)); and at gradient 5°, speed 1.2 m/sec and level walking (gradient 0°) at speed 1.0 m/sec (0.121 (N m), *p* = 0.001, 95% CI from 0.054 to 0.187 (N m)), and at speed 1.2 m/sec (0.085 (N m), *p* = 0.013, 95% CI from 0.019 to 0.152 (N m)).

7.3.1.3.3 Ankle inversion moment (A_MMz)

Mean values of ankle inversion moments for all tested participants before and after their TOR programme are presented in Figure 7-9.

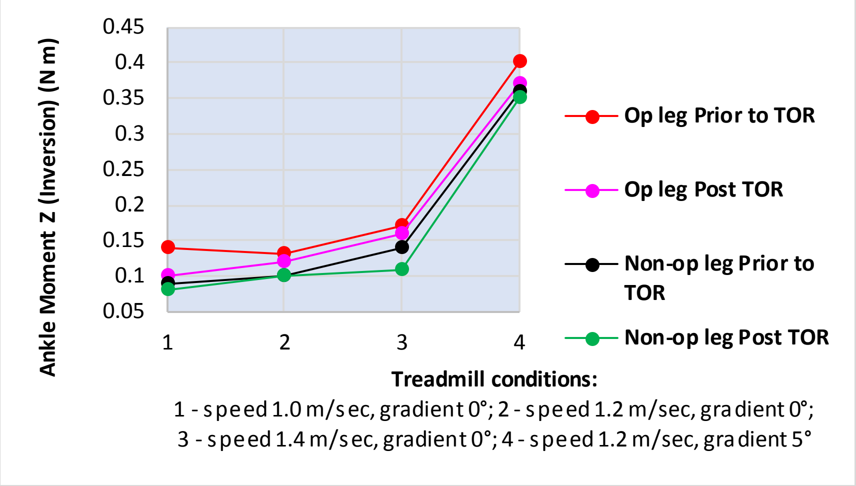

Figure 7-9: Mean values of ankle inversion moments (N m) of TKA participants (n=4) prior to and post TOR programme for operated, and non-operated legs

Both LEG (F (1, 55) = 5.535, *p* = 0.022) and TREADMILL (F (3, 55) = 78.579, *p* < 0.0001) had significant effects on ankle inversion moment (A_MMz). The effect of REHABILITATION (a decrease of 0.015 (N m) in ankle inversion moment after the rehabilitation was not significant), F (1, 55) = 1.195, *p* = 0.279.

A significant difference of 0.033 (N m) in ankle inversion moment was found between the operated and the non-operated legs *p* = 0.022.

The highest value of ankle inversion moment, 0.367 (N m), was observed at a speed of 1.2 m/sec at a 5° gradient, and the lowest value, 0.102 (N m), at a speed of 1.0 m/sec at a 0° gradient.

Significant differences in ankle inversion moment were registered at gradient 0° walking between speed 1.4 m/sec and speeds 1.0 m/sec (0.043 (N m), *p* = 0.037, 95% CI from 0.003 to 0.083 (N m)); and at gradient 5°, speed 1.2 m/sec and level walking (gradient 0°) at all tested speeds, i.e. 1.0 m/sec (0.265, *p* < 0.0001, 95% CI from 0.225 to 0.305 (N m)), 1.2 m/sec (0.255, *p* < 0.0001, 95% CI from 0.215 to 0.295 (N m)), and 1.4 m/sec (0.222, *p* < 0.0001, 95% CI from 0.182 to 0.262 (N m)).

7.3.2 Kinematic variables

Participants' recorded knee flexion in stance and sagittal knee, hip and pelvic RoM, and coronal pelvic, thigh and calf RoM at all the tested treadmill conditions before and after their TOR programme are presented in Table 7-9.

Table 7-9: Descriptive statistics for kinematic variables for the TKA (n=4) participants prior to and post their TOR programme

Knee Moments (N m)	Treadmill conditions (speed (m/sec) & gradient (0°))			
	1.0 (0°)	**1.2 (0°)**	**1.4 (0°)**	**1.2 (5°)**
KFS (Knee flexion in stance) (°)				
Operated leg				
Baseline (Prior to TOR)	7.06±2.62	8.00±2.28	7.24±2.18	20.06±16.63
Post TOR	11.94±6.31	12.91±8.36	14.66±8.68	19.01±15.30
Non-operated leg				
Baseline (Prior to TOR)	8.55±1.38	11.84±5.25	12.62±4.18	15.62±8.91
Post TOR	11.90±1.97	13.49±3.48	14.96±5.37	17.17±8.28
KSR (Knee sagittal RoM) (°)				
Operated leg				
Baseline (Prior to TOR)	65.14±3.78	67.20±4.53	68.65±5.44	65.50±8.82
Post TOR	66.40±10.00	66.87±9.81	67.02±12.33	66.12±10.49
Non-operated leg				
Baseline (Prior to TOR)	61.54±2.76	64.03±1.93	66.83±3.31	60.20±7.44
Post TOR	64.26±7.65	66.85±6.93	67.97±7.06	63.10±4.98
HSR (Hip sagittal RoM (°)				
Operated leg				
Baseline (Prior to TOR)	26.30±2.89	30.03±4.88	34.20±7.31	42.53±13.85
Post TOR	30.29±3.49	34.54±3.17	36.98±3.60	42.34±4.74
Non-operated leg				
Baseline (Prior to TOR)	28.14±3.21	31.08±4.99	36.26±3.58	40.26±4.50
Post TOR	31.53±3.46	33.86±5.30	36.79±4.96	43.81±5.20
PSR (Pelvic sagittal RoM (°)				
Operated leg				
Baseline (Prior to TOR)	6.50±1.92	7.39±1.36	8.04±1.91	8.14±2.68
Post TOR	7.43±2.36	7.26±1.95	7.60±2.11	8.31±2.14
Non-operated leg				
Baseline (Prior to TOR)	6.70±1.22	7.00±1.21	7.35±2.05	7.40±1.57
Post TOR	6.76±2.56	7.82±1.08	7.75±1.94	7.84±2.85
PCR (Pelvic coronal RoM (°)				
Operated leg				
Baseline (Prior to TOR)	6.86±0.33	7.12±0.72	8.07±2.90	10.35±2.29
Post TOR	4.44±0.82	5.34±1.38	6.74±2.12	8.36±2.83
Non-operated leg				
Baseline (Prior to TOR)	5.96±0.88	6.68±1.07	8.10±1.84	11.45±3.54
Post TOR	5.83±1.74	6.12±1.84	8.26±2.08	10.65±2.63
TCR (Thigh coronal RoM (°)				
Operated leg				
Baseline (Prior to TOR)	11.57±2.64	11.04±1.74	11.33±3.04	12.50±2.32
Post TOR	9.19±2.88	10.17±1.48	11.02±1.91	13.37±5.05
Non-operated leg				
Baseline (Prior to TOR)	13.19±5.01	14.21±3.29	14.43±4.33	15.21±4.17
Post TOR	13.50±5.30	13.52±4.89	13.85±4.73	14.78±5.00
CCR (Calf coronal RoM (°)				
Operated leg				
Baseline (Prior to TOR)	7.90±1.64	9.54±1.79	8.80±1.63	7.88±3.99
Post TOR	10.86±3.23	11.07±3.77	10.99±4.37	12.27±4.78
Non-operated leg				
Baseline (Prior to TOR)	9.90±4.45	10.67±4.59	11.31±4.98	9.96±2.94
Post TOR	10.46±4.57	11.11±5.28	12.57±5.68	10.32±4.18

Note: Data are presented as mean ± s.d.

7.3.2.1 Knee flexion in stance (KFS)

Mean values of knee flexion in stance for all tested participants before and after their TOR programme are presented in Figure 7-10.

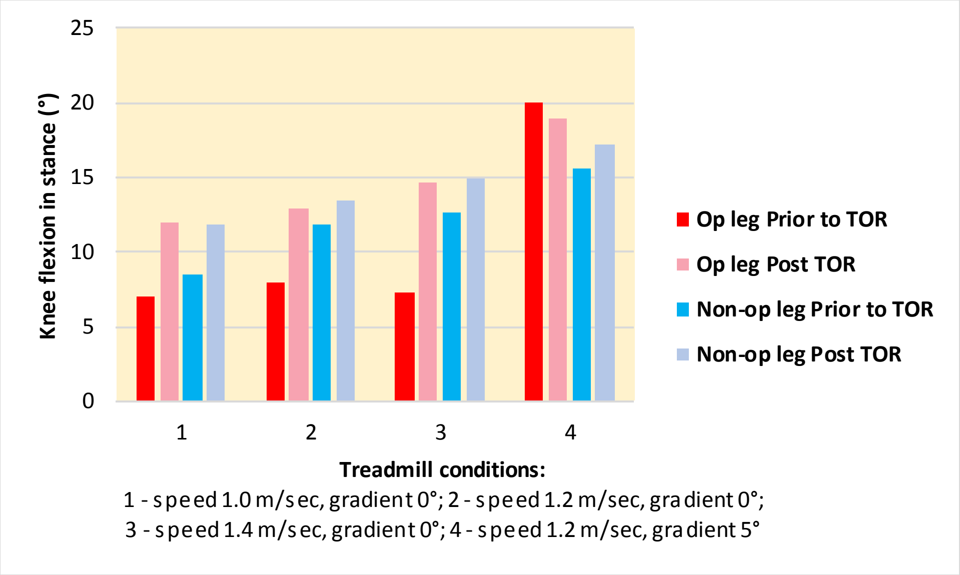

Figure 7-10: Mean values of knee flexion in stance (°) of TKA participants (n=4) prior to and post TOR programme for operated, and non-operated legs

Both REHABILITATION (F (1, 55) = 4.175, *p* = 0.046) and TREADMILL (F (3, 55) = 5.243 *p* = 0.003) had significant effects on knee flexion in stance (KFS). The effect of LEG was not significant, F (1, 55) = 0.185, *p* = 0.669.

A significant increase of 3.1° in participants' knee flexion in stance was found after their rehabilitation (*p* = 0.046, 95% CI from 0.1° to 6.2°). Their mean value of KFS after completion of their rehabilitation programme was 14.5° (95% CI from 12.3° to 16.7°), as compared to 11.4° (95% CI from 9.2° to 13.5°) before their rehabilitation.

The overall mean values of knee stance flexion for the tested treadmill conditions are presented in Table 7-10. The highest value of this variable, 17.9°, was observed at a speed of 1.2 m/sec at a 5° gradient, and the lowest value, 9.9°, at a speed of 1.0 m/sec at a 0° gradient.

Table 7-10: Mean estimates of knee flexion in stance (KFS, °) for the tested treadmill conditions.

			95% Confidence Interval	
Treadmill	Mean	Std. Error	Lower Bound	Upper Bound
S1.0	9.864	1.533	6.792	12.935
S1.2	11.560	1.533	8.488	14.632
S1.2G	17.966	1.533	14.894	21.037
S1.4	12.370	1.533	9.298	15.442

Note: S1.0 = Speed 1.0 m/sec, gradient 0°; S1.2 = Speed 1.2 m/sec, gradient 0°; S1.4 = Speed 1.4 m/sec, gradient 0°; S1.2G = Speed 1.2 m/sec, gradient 5°.

Significant differences in knee flexion in stance were registered between walking at gradient 5°, speed 1.2 m/sec and level walking (gradient 0°) at all tested speeds, i.e. 1.0 m/sec (8.1°, $p < 0.0001$, 95% CI from 3.8° to 12.4°), 1.2 m/sec (6.4°, $p = 0.005$, 95% CI from 2.1° to 10.7°), and 1.4 m/sec (5.6°, $p = 0.013$, 95% CI from 1.3° to 9.9°). No significant difference in participants' knee flexion in stance was registered between any speeds of level walking.

7.3.2.2 Knee sagittal RoM (KSR)

Mean values of knee sagittal RoM for all tested participants before and after their TOR programme are presented in Figure 7-11.

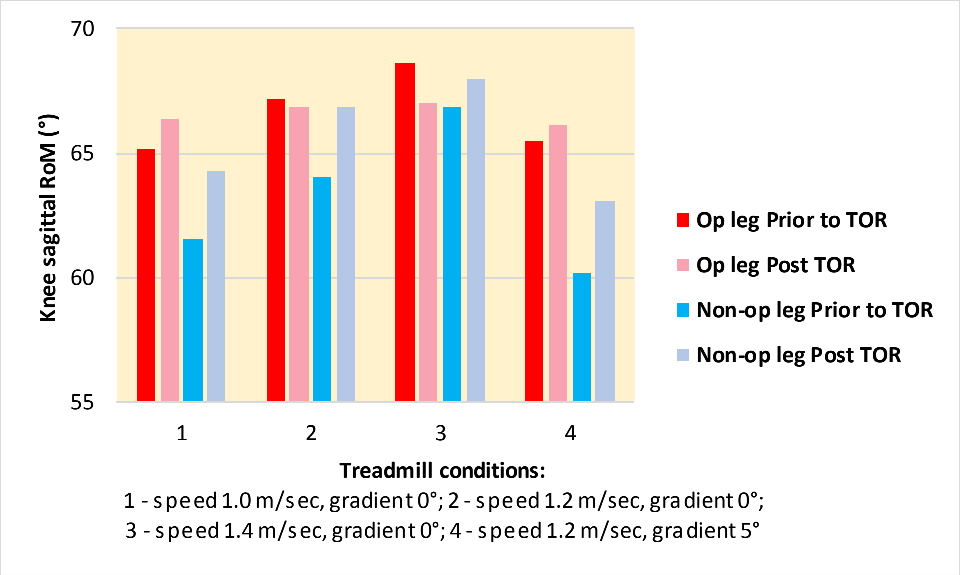

Figure 7-11: Mean values of knee sagittal RoM (°) of TKA participants (n=4) prior to and post TOR programme for operated, and non-operated legs

Neither REHABILITATION (F (1, 55) = 0.715, *p* = 0.402), nor TREADMILL (F (3, 56) = 1.610, *p* = 0.198), nor LEG (F (1, 55) = 2.605, *p* = 0.112) had significant effects on knee sagittal RoM (KSR).

7.3.2.3 Hip sagittal RoM (HSR)

Mean values of hip sagittal RoM for all tested participants before and after their TOR programme are presented in Figure 7-12.

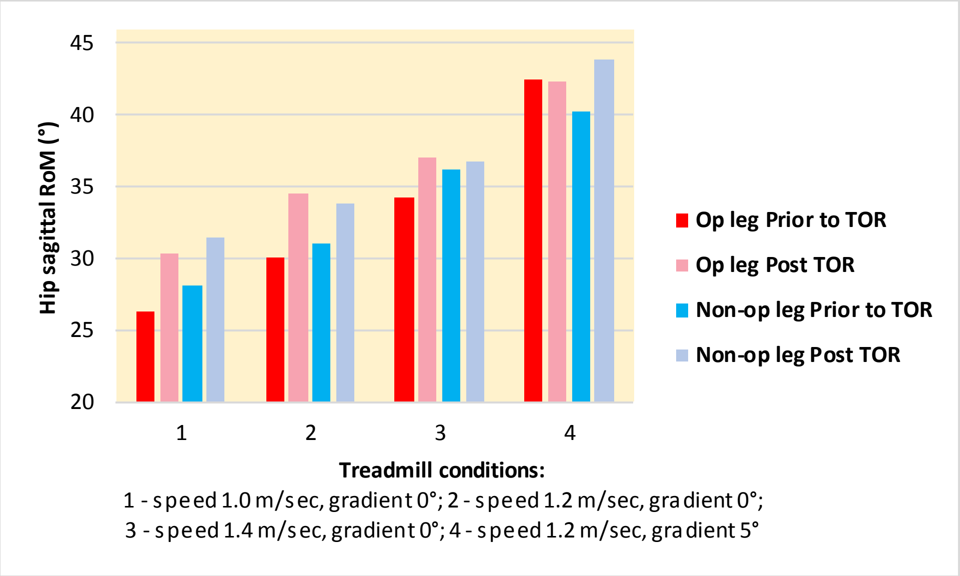

Figure 7-12: Mean values of hip sagittal RoM (°) of TKA participants (n=4) prior to and post TOR programme for operated, and non-operated legs

Both REHABILITATION (F (1, 55) = 6.963, *p* = 0.011) and TREADMILL (F (3, 55) = 31.183 *p* < 0.0001) had significant effects on hip sagittal RoM (HSR). The effect of LEG was not significant, F (1, 55) = 0.311, *p* = 0.579.

A significant increase of 2.7° in participants' hip sagittal RoM was found after their rehabilitation (*p* = 0.011, 95% CI from 0.6° to 4.7°). Their mean value of HSR was 36.3° (95% CI from 34.8° to 37.7°), as compared to 33.6° (95% CI from 32.2° to 35.0°), before their rehabilitation.

The overall mean values of hip sagittal RoM for the tested treadmill conditions are presented in Table 7-11. The highest value of this variable, 42.2°, was observed at a speed of 1.2 m/sec at a 5° gradient, and the lowest value, 29.1°, at a speed of 1.0 m/sec at a 0° gradient.

Table 7-11: Mean estimates of hip sagittal RoM (HSR, °) for the tested treadmill conditions.

Treadmill	Mean	Std. Error	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
S1.0	29.066	1.011	27.041	31.091
S1.2	32.379	1.011	30.354	34.404
S1.2G	42.236	1.011	40.210	44.261
S1.4	36.058	1.011	34.032	38.083

Note: S1.0 = Speed 1.0 m/sec, gradient 0°; S1.2 = Speed 1.2 m/sec, gradient 0°; S1.4 = Speed 1.4 m/sec, gradient 0°; S1.2G = Speed 1.2 m/sec, gradient 5°.

The differences in hip sagittal RoM between the tested treadmill conditions are presented in Table 7-12. Significant differences in hip sagittal RoM were registered between all the tested treadmill conditions (see Table 7-12).

Table 7-12: Pairwise comparison of the estimated marginal means of hip sagittal RoM (HSR, °) for the tested treadmill conditions.

(I) Treadmill	(J) Treadmill	Mean Difference (I-J)	Std. Error	Sig.^{b}	95% Confidence Interval for Difference^{b} Lower Bound	95% Confidence Interval for Difference^{b} Upper Bound
S1.0	S1.2	-3.313*	1.429	.024	-6.177	-.448
	S1.2G	-13.169*	1.429	.000	-16.033	-10.305
	S1.4	-6.991*	1.429	.000	-9.855	-4.127
S1.2	S1.0	3.313*	1.429	.024	.448	6.177
	S1.2G	-9.857*	1.429	.000	-12.721	-6.993
	S1.4	-3.679*	1.429	.013	-6.543	-.815
S1.2G	S1.0	13.169*	1.429	.000	10.305	16.033
	S1.2	9.857*	1.429	.000	6.993	12.721
	S1.4	6.178*	1.429	.000	3.314	9.042
S1.4	S1.0	6.991*	1.429	.000	4.127	9.855
	S1.2	3.679*	1.429	.013	.815	6.543
	S1.2G	-6.178*	1.429	.000	-9.042	-3.314

Based on estimated marginal means

*. The mean difference is significant at the .050 level.

b. Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments).

Note: S1.0 = Speed 1.0 m/sec, gradient 0°; S1.2 = Speed 1.2 m/sec, gradient 0°; S1.4 = Speed 1.4 m/sec, gradient 0°; S1.2G = Speed 1.2 m/sec, gradient 5°.

7.3.2.4 Pelvic sagittal RoM (PSR)

Mean values of pelvic sagittal RoM for all tested participants before and after their TOR programme are presented in Figure 7-13.

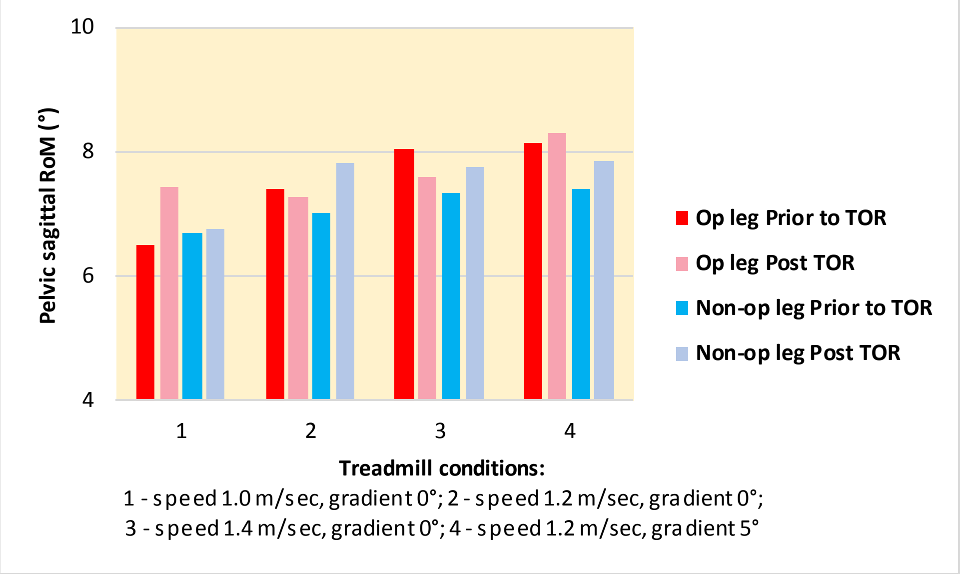

Figure 7-13: Mean values of pelvic sagittal RoM (°) of TKA participants (n=4) prior to and post TOR programme for operated, and non-operated legs

Neither REHABILITATION (F (1, 55) = 0.645, *p* = 0.425), nor TREADMILL (F (3, 56) = 1.756, *p* = 0.166), nor LEG (F (1, 55) = 0.546, *p* = 0.463) had significant effects on pelvic sagittal RoM (PSR).

7.3.2.5 Pelvic coronal RoM (PCR)

Mean values of pelvic coronal RoM for all tested participants before and after their TOR programme are presented in Figure 7-14.

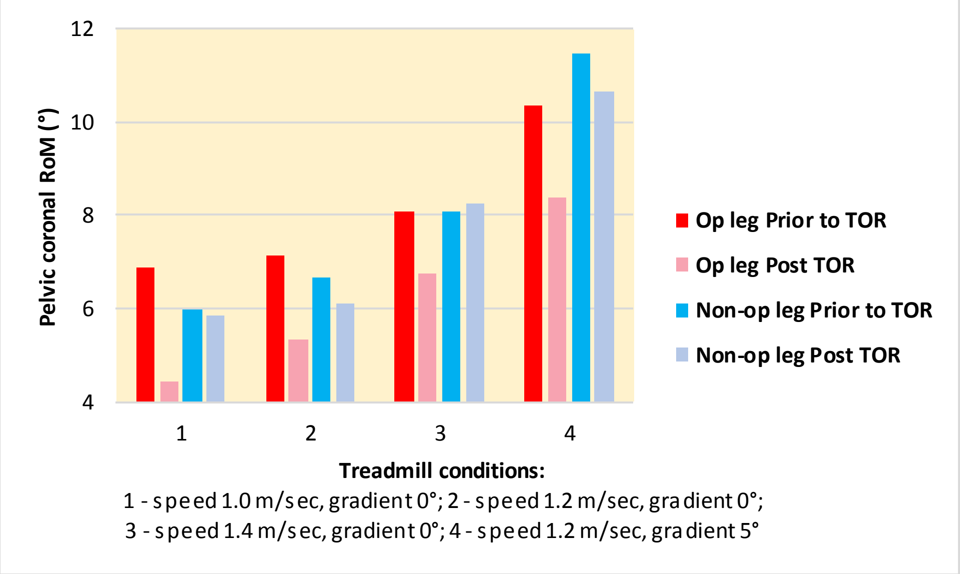

Figure 7-14: Mean values of pelvic coronal RoM (°) of TKA participants (n=4) prior to and post TOR programme for operated, and non-operated legs

Both REHABILITATION (F (1, 55) = 8.291, *p* = 0.006) and TREADMILL (F (3, 55) = 26.596 *p* < 0.0001) had significant effects on pelvic coronal RoM (PCR). The effect of LEG was not significant, F (1, 55) = 3.535, *p* = 0.065.

A significant decrease of 1.1° in participants' pelvic coronal RoM was found after their rehabilitation (*p* = 0.006, 95% CI from -1.9° to -0.3°). Their mean value of PCR was 7.0° (95% CI from 6.4° to 7.5°), as compared to 8.1° (95% CI from 7.5° to 8.6°), before their rehabilitation.

The overall mean values of pelvic coronal RoM for the tested treadmill conditions are presented in Table 7-13. The highest value of this variable, 10.2°, was observed at a speed of 1.2 m/sec at a 5° gradient, and the lowest value, 5.8°, at a speed of 1.0 m/sec at a 0° gradient.

Table 7-13: Mean estimates of pelvic coronal RoM (PCR, °) for the tested treadmill conditions.

			95% Confidence Interval	
Treadmill	Mean	Std. Error	Lower Bound	Upper Bound
S1.0	5.775	.384	5.005	6.545
S1.2	6.317	.384	5.547	7.087
S1.2G	10.204	.384	9.434	10.973
S1.4	7.795	.384	7.025	8.565

Note: S1.0 = Speed 1.0 m/sec, gradient 0°; S1.2 = Speed 1.2 m/sec, gradient 0°; S1.4 = Speed 1.4 m/sec, gradient 0°; S1.2G = Speed 1.2 m/sec, gradient 5°.

The differences in pelvic coronal RoM between the tested treadmill conditions are presented in Table 7-14. Significant differences in pelvic coronal RoM were registered between all the tested treadmill conditions, except difference between speeds 1.0 and 1.2 m/sec of level walking (see Table 7-14).

Table 7-14: Pairwise comparison of the estimated marginal means of pelvic coronal RoM (PCR, °) for the tested treadmill conditions.

(I) Treadmill	(J) Treadmill	Mean Difference (I-J)	Std. Error	Sig.[b]	95% Confidence Interval for Difference[b]	
					Lower Bound	Upper Bound
S1.0	S1.2	-.542	.543	.323	-1.630	.547
	S1.2G	-4.429*	.543	.000	-5.517	-3.340
	S1.4	-2.020*	.543	.000	-3.109	-.931
S1.2	S1.0	.542	.543	.323	-.547	1.630
	S1.2G	-3.887*	.543	.000	-4.975	-2.798
	S1.4	-1.478*	.543	.009	-2.567	-.390
S1.2G	S1.0	4.429*	.543	.000	3.340	5.517
	S1.2	3.887*	.543	.000	2.798	4.975
	S1.4	2.409*	.543	.000	1.320	3.497
S1.4	S1.0	2.020*	.543	.000	.931	3.109
	S1.2	1.478*	.543	.009	.390	2.567
	S1.2G	-2.409*	.543	.000	-3.497	-1.320

Based on estimated marginal means

*. The mean difference is significant at the .050 level.

b. Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments).

Note: S1.0 = Speed 1.0 m/sec, gradient 0°; S1.2 = Speed 1.2 m/sec, gradient 0°; S1.4 = Speed 1.4 m/sec, gradient 0°; S1.2G = Speed 1.2 m/sec, gradient 5°.

7.3.2.6 Thigh coronal RoM (TCR)

Mean values of thigh coronal RoM for all tested participants before and after their TOR programme are presented in Figure 7-15.

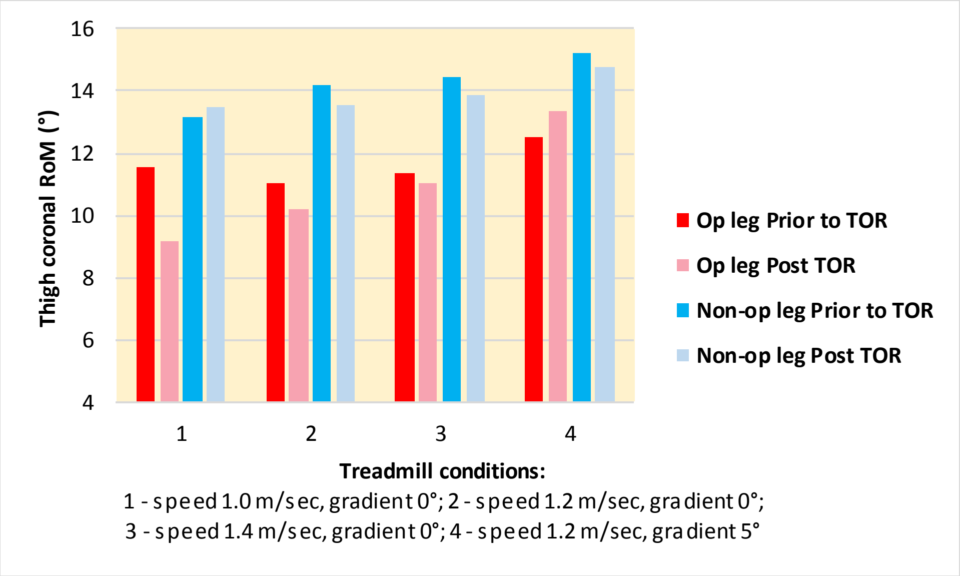

Figure 7-15: Mean values of thigh coronal RoM (°) of TKA participants (n=4) prior to and post TOR programme for operated, and non-operated legs

LEG (F (1, 55) = 12.784, *p* = 0.001) was a significant factor affecting thigh coronal RoM (TCR), whereas the effect of REHABILITATION and TREADMILL was not significant, F (1, 55) = 0.422, *p* = 0.519, and F (3, 55) = 1.360, *p* = 0.265 respectively.

The mean value of thigh coronal RoM (TCR) was lower for the operated leg (11.3°, 95% CI from 10.2° to 12.4°), as compared to the mean value for the non-operated leg (14.1°, 95% CI from 13.0 to 15.2°). The difference of 2.8° in mean values of thigh coronal RoM between non-operated and operated legs was significant (*p* = 0.001).

7.3.2.7 Calf coronal RoM (CCR)

Mean values of calf coronal RoM for all tested participants before and after their TOR programme are presented in Figure 7-16.

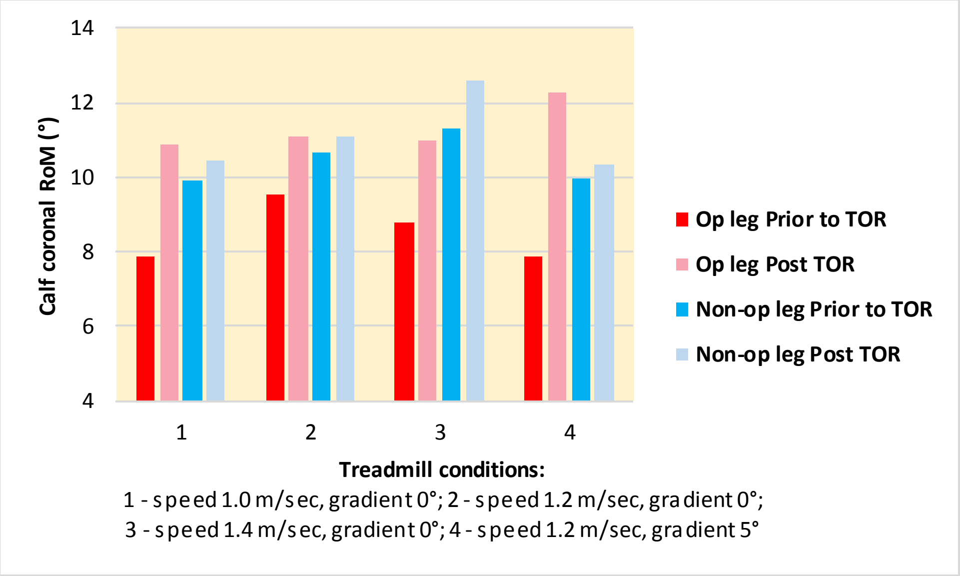

Figure 7-16: Mean values of calf coronal RoM (°) of TKA participants (n=4) prior to and post TOR programme for operated, and non-operated legs

REHABILITATION (F (1, 55) = 4.485, *p* = 0.039) was a significant factor affecting calf coronal RoM (CCR), whereas the effect of LEG and TREADMILL was not significant, F (1, 55) = 1.173, *p* = 0.284, and F (3, 55) = 0.389, *p* = 0.762 respectively.

A significant increase of 1.7° in participants' calf coronal RoM (CCR) was found after their rehabilitation (*p* = 0.039, 95% CI from 0.1° to 3.3°). The post rehabilitation mean value of CCR was 11.2° (95% CI from 10.1° to 12.4°), as compared to 9.5° (95% from 8.3° to 10.6°) to baseline, before their rehabilitation.

7.4 Discussion.

These findings are consistent with the study hypothesis, which suggested that the gait biomechanics at different walking speeds of TKA patients on the level and on an incline may be enhanced by specific task-orientated rehabilitation directed towards improving gait at 12 months after surgery.

Joint moments

Kinetic gait parameters of the TKA patients (hip, knee and ankle moments) altered in a similar manner before and after TOR – tending to increase in response to changes from slower to faster speeds while walking on the level. A further increase in the values of all moments, except knee flexion and hip abduction moments, was observed with walking on a slope. The kinetics on a five degrees incline differed considerably from that on level walking, suggesting a greater load on the joints involved, as was documented in previous literature (Lay et al., 2006, McIntosh et al., 2006, Haggerty et al., 2014). For knee flexion and hip abduction moments their values decreased during walking on a slope. Observed differences between the operated and non-operated legs of TKA patients before their rehabilitation were still present on completion of their programmes, but altered for the better, except for ankle moments, where baseline lower values of this variable as compared to the controls, were slightly further reduced after their TOR programme.

The changes resulting from task-orientated rehabilitation (TOR) of kinetic variables (hip, knee and ankle moments) for the four tested TKA patients were not significant. This can be partially explained by the insufficient number of participants. A few beneficial changes were recorded in peak leg joint moments after TOR, even though they did not show to be significant.

A significant deficit in knee flexion and higher knee adduction moments in TKA patients at their baseline (pre-rehabilitation) as compared to controls, observed in Chapter 6, were increased by 0.052 (N m) and decreased by 0.017 (N m) respectively after completion of their TOR programme. No alteration in knee internal rotation of

TKA patients as compared to the controls was observed at their baseline, equally no changes in this variable after TOR were recorded. These changes suggest that the pattern, which TKA patients use for avoiding pain and for unloading their knee joint, namely reduced peak knee flexion (Henriksen et al., 2010) and increased peak knee adduction moments (Thorp et al., 2007) started to alter following their 4-week TOR programme. The reasons for this could be increased strength of their muscles as a result of regular physical activity, improved confidence in their replaced joint, resulting in putting more load on it, and the knowledge that they will not do harm to their knee by exercising regularly, and more importantly by increasing the load of their exercise.

Baseline magnitude of peak hip flexion and internal rotation moments of TKA patients were comparable with these variables of the participants of the control group. Their values stayed unchanged after completion of the TOR programme. In regards to hip abduction moment values, which were higher for the operated leg and lower for the non-operated leg at their baselines, as compared to the controls (see Chapter 6), their values showed an overall significant difference of 0.068 (N m) (p = 0.023) between the operated and non-operated legs. There was an opposite shift in magnitude of hip abduction moment for both legs towards the values of the healthy controls, a decrease for the operated leg, and an increase for the non-operated leg. This change highlighted another beneficial trend in altering the gait of TKA patients towards normal.

No beneficial trend was found in the changes in all the ankle moments resulting from the TOR programme. There was a slightly reduced overall significant difference of 0.089 (N m), p = 0.001, between the operated and the non-operated legs, as compared to their baseline difference 0.134 (N m), p = 0.006 (see Chapter 6), which still remained below the values of the controls. This could be a cause of lower toe clearance during walking, especially uphill walking, with a subsequent hazard of falls. However, no measurements of toe clearance were made in this study. No changes in ankle abduction moments between the values in either leg were found. There was a significant overall difference -0.049 (N m) in the values of this moment between the operated and the non-operated legs (p = 0.042), with a higher load than in a healthy population for the non-operated leg. A significant difference of 0.033 (N

m) in ankle inversion moment was found between the operated and the non-operated leg p = 0.022, suggesting a greater inversion load on the operated leg. The findings for the ankle moments suggest that the ankle joint requires particular consideration in rehabilitation approaches to TKA patients, equally addressing both legs. Especially as uphill walking is a routine activity in everyday life, and the fact that this type of activity places a greater demand on the locomotor system as compared to level walking (Leroux et al., 1999, Leroux et al., 2002, Sheehan and Gottschall, 2012). Furthermore, it equally potentiates a greater risk of falls when walking up slopes, as compared to climbing stairs with similar inclinations (Sheehan and Gottschall, 2012).

Previously in Chapter 5, it was highlighted that the difficulty in comparing the findings of our study with previous research findings arises from the lack of research on the rehabilitation of TKA patients from 1 year after their surgery, as the rehabilitation of these patients was as a rule completed by this time. Existing assessments of applied rehabilitations, in general, consisted of standard tests of functions (e.g. 6 minutes walk test (6MWT), timed stair climbing, timed-stands test, etc.), tests of muscle strength and passive RoMs (Bruun-Olsen et al., 2013, Harikesavan et al., 2017, Moffet et al., 2004), and lacked testing of kinetic gait parameters. Furthermore, no studies were found that tested the efficacy of any rehabilitation programmes for rehabilitation of TKA patients using variable pre-determined speeds, and walking on an incline.

Kinematic variables

Kinematic gait parameters of the TKA patients, as assessed by their knee flexion in stance and sagittal knee, hip and pelvic RoM, and coronal pelvic, thigh and calf RoM, altered in a similar manner before and after TOR, but unlike joint moments, the individual kinematic variables did not respond uniformly to changing treadmill conditions. The observed difference of 2.8° between the legs, with lower values for the operated leg of TKA patients was only present in thigh coronal RoM, suggesting more hip swinging of the non-operated leg. No significant changes in this variable were recorded either in response to differing treadmill conditions, nor to the TOR programme.

The valuable effect of rehabilitation (TOR) for the four tested TKA patients was significant for the four out of the seven measured kinematic variables: knee flexion in stance, hip sagittal RoM, pelvic coronal RoM and calf coronal RoM. No changes after the TOR programme were observed in the knee and pelvic sagittal RoM, and there were no significant changes in their values with changing in treadmill conditions. The values for these two variables were altered in comparison to the values of the participants from the control group, lesser for the knee and greater for the pelvic sagittal RoMs for TKA patients (see Chapter 6). This could be an indication of more profoundly acquired compensatory gait patterns, which require special consideration in rehabilitation approaches.

A significant beneficial increase of 3.1° (ρ=0.046) in knee flexion in stance of TKA patients with their mean value of 14.5° post-rehabilitation, as compared to 11.4° at baseline, were comparable to and support the findings of GaitSmart, as shown in Chapter 5 of our study, where these individuals were tested at their natural speed during overground walking on the flat. A significant increase in the values of this variable were registered between walking on a slight incline of 5 degrees and all speeds of level walking. There were no significant changes in this variable with changes in speeds of level walking.

A second advantageous change following the TOR programme was a significant increase of 2.7° (ρ=0.011) in hip sagittal RoM. In contrast to knee flexion in stance, increases in the speeds and inclines of the treadmill conditions resulted in significant increases in the values of this variable.

These findings, as was shown before in Chapter 6, are in agreement with the researchers who studied the mechanics of walking on inclines in healthy subjects, where observations of increased flexion of knee, hip, and ankle at heel strike and increased extension of these joints during midstance occurred with changes from level walking to walking upslope, causing adaptation of the whole leg walking pattern to the change in the gradient (Lange et al., 1996, Leroux et al., 1999, Lay et al., 2006).

Lastly, a significant decrease of 1.1° (ρ=0.006) in pelvic coronal, and a significant increase of 1.7° (ρ=0.039) in calf coronal RoMs were two valuable changes following the TOR programme. The presence of the adverse compensatory mechanism in knee joint pathology, i.e. the dropping of the pelvis (Bejek et al., 2006) was mentioned in Chapter 6. The findings of our study suggest the possibility of changing this mechanism of compensation. Equally, the increased range of coronal calf motion might be the beginning of more natural, less stiff, movement of the calf. Unlike pelvic coronal RoM, where increase in the speeds and incline of treadmill conditions resulted in a significant increase in the value of this variable, the RoM of the calf was not affected by changes in the treadmill conditions.

The limitations of this pilot study were that a very small group of TKA patients participated in it, making it impossible to draw any conclusion from the failure to find significant changes resulting from the TOR programme. It appeared that not all participants who gave informed consent for participating in the treadmill walking test were able naturally to walk on a treadmill, despite trying out this walking for a reasonable time. It might be one of the reasons that studies on the rehabilitation of TKA patients have not used this type of assessment as they applied their rehabilitation at a much earlier stage of their recovery. Another limitation is the heterogeneity of the group, where two out of the four participants had had previous TKA for the contralateral leg. The absence in our study of a control group using current accepted rehabilitation for TKA patients who showed deficiency in their gait at 12 months after their surgery made it infeasible to make an objective comparison of the two approaches in the rehabilitation of TKA patients for improving their impaired gait. The lack of kinematic measurements for the ankle joints was the obstacle to providing the whole lower extremity biomechanics of participants in response to TOR programme, tested at varying treadmill conditions. However, this limitation arises from the limitations of GaitSmart, which currently is not equipped for the testing of ankle joints. Finally, testing these participants at a self-selected speed on a treadmill could provide truer data.

The strength of this study was in that the changes following the TOR programme intervention were measured using an instrumented treadmill, so that kinetic and kinematic measurements were utilised for analysis, resulting in a wider picture of gait mechanics than presented in previous studies assessing the effects of different types of rehabilitation of TKA patients. The results of this assessment could be applied in real life, as the similarity of the overall pattern of the biomechanics of overground and treadmill walking was shown (Lee and Hidler, 2008). Even though it was a very small cohort of participants, the findings highlighted the problem areas that, by and large, failed to receive due attention in previous studies on the rehabilitation of these patients. Among them were the analyses of the changes in the leg differences in the kinetics and the kinematics of TKA patients, following rehabilitation. An additional strength and uniqueness of our study was that rehabilitation of the TKA patients was initiated at the time of their final discharge from hospital care, i.e. 12 months after surgery, when all standard rehabilitation was completed. The observed changes after their TOR programme, in those with remaining deficiencies in their walking at the start of the programme, suggests that there is room for improvement in the aftercare of TKA patients.

A recommendation for a future study arises from the limitations of the current study. The major one is the necessity to compare the currently accepted rehabilitation of TKA patients with our novel TOR programme.

7.5 Conclusions

- A valuable significant effect of TOR was found in the gait kinematics (knee flexion in stance, hip sagittal, and pelvic and calf coronal RoMs) of TKA patients at 12 months post-surgery, when tested at different treadmill speeds and on an incline.
- The findings of the knee flexion in stance changes following TOR agreed with those observed with GaitSmart measured at natural speed.
- A beneficial trend towards normal walking, following TOR, was found in the gait kinetics (knee and hip moments) of TKA patients at 12 months post-surgery, when tested at different treadmill speeds and on an incline.
- A larger sample size than was available for this pilot study would be required to detect significant changes in kinetic variables.

Chapter 8 General discussion and conclusions

8.1 Summary of main findings

The findings from the four experimental studies (Chapters 4-7) demonstrated that knowledge of gait assessment results can be applied in the clinical practice of monitoring TKA patients' recovery and testing the efficacy of novel task-orientated rehabilitation after surgery.

The outcome of Chapter 4 confirmed this study hypothesis that a correlation exists between the patients' reported functional outcome 12 months after TKA and their gait quality. In general, larger ranges of motion, and a decreased stride duration were associated with increased PROMs scores. Although several gait variables had significant correlation with OKS, only stride duration was a significant predictor of OKS in the regression model, therefore a "path analysis" was conducted. The final Path Model showed that high scores on stride duration (i.e. slower) produced lower (i.e. worse) scores on the OKS. Similarly, high scores on the three gait scales (i.e. greater sagittal RoMs) produced lower (i.e. faster) stride duration. Similarly to previous studies (Fisher et al., 2007, Bonnin et al., 2011, Merle-Vincent et al., 2011), it was found that female patients scored a lower OKS, and that patients in general with a high BMI have had depressed OKS scores. A future study could investigate the question as to whether weight loss in patients with high BMI might lead to an improvement in their OKSs.

The findings of Chapter 5, when patients were tested at natural, self-selected speeds walking on level ground, supported this study hypothesis that the outcome of TKA may be enhanced by specific TOR directed towards improving gait at 12 months after surgery. Stride duration and three out of five scale factors of kinematic gait variables, **Hip Thigh Calf SAG**, **Knee Sag Flex TP Diff**, and **Thigh Cor**, and the majority of individual variables of which these factors consisted, exhibited significant positive changes following the TOR programme. These findings confirmed that it is possible for TOR intervention, even at 12 months after knee replacement surgery, to improve both patients reported functional outcome and their gait quality. Furthermore, tests confirmed that achieved improvements in patients' OKSs and their quality of walking were sustained two and a half months after completion of their programmes. None of the participants reported any adverse effects from the TOR programme.

The findings of Chapter 6 confirmed the presence of significant differences in the gait kinetics and kinematics of TKA patients as compared to the controls, when their walking was tested at different predetermined speeds on the treadmill.

Lastly, the findings of Chapter 7, where participants were challenged under more controlled conditions (pre-determined variable treadmill speed of walking, and walking on an incline), supported the significant beneficial kinematic changes observed in Chapter 5. A positive trend in gait kinetics of TKA participants towards the kinetic gait characteristics of the healthy participants was also found following their TOR programme.

8.2 Implications for assessment and rehabilitation of patients after TKA

The fact that the results of the study showed a correlation between PROMs and TKA patients' gait quality has an important clinical implication for the future assessment and rehabilitation of TKA patients. The employment of such an assessment in clinical settings on a daily basis could be an essential tool in the recognition of patients with poor quality of walking and, therefore, at risk of poor functional recovery. Early recognition of impaired walking patterns in such patients could lead to the adoption of enhanced post-operative rehabilitation at an early stage with a greater likelihood of improving their functional mobility, and the quality of their lives, which would lead to better patients' satisfaction.

Although TOR should be aimed primarily at patients with gait deficiencies, it could be argued that all patients would benefit post-operatively from this programme. Therefore the assessment of those requiring improvement in their walking needs to be based on objective measurements, such as their knee flexion in stance, rather than stride duration or OKS, as this can be influenced by their state of mind and other environmental factors. However, to explore these factors was not the aim of this study. Identification of such patients could be made as soon as patients begin walking unaided, and their rehabilitation could be started at this point.

Furthermore, the results presented in this study have important implications for clinical practice in several ways for different users. Firstly, for the clinician of a multidisciplinary team working with pre- and post- joint replacement surgery patients, a portable gait assessment as a standard procedure, in addition to the existing assessments, such as X-rays and PROMs, would provide them with objective information regarding walking, the most crucial function. Walking incorporates all aspects of functionality, namely physiological, behavioural, and psychological. Consequently, identified deficiencies could be addressed immediately by appropriate members of the multidisciplinary team. Such an assessment is particularly important at the pre-operative stage, so as to make those patients, whose walking is significantly affected by OA, aware that their expectations of regaining a normal walking pattern after surgery would most likely be met if they applied TOR diligently.

Making gait measurement a standard procedure at the post-operative stage would guide clinicians to help TKA patients adjust their rehabilitation according to their gait deficiencies, and monitor their own improvement. The patients, in turn, would be empowered by the knowledge of their progress and therefore would have the opportunity to be in charge of this progress. In addition different rehabilitation approaches could be investigated and objective measures taken.

Despite growing evidence of a beneficial effect of the task-orientated approach to rehabilitation, the current rehabilitation of TKA patients is based on routinely accepted protocols, where the focus is on a single factor, namely, individual muscles or joints. TOR, though, is founded on the principles of motor learning, where all aspects of movement and the plasticity of the brain are involved, securing solid, evidence based grounds for clinicians to implement this type of rehabilitation, involving daily living tasks and activities (Hubbard et al., 2009). Applying novel improved rehabilitation techniques and programmes, such as the task-orientated rehabilitation programme, comprising functional daily activities, walking and climbing stairs, holds great promise for improved outcomes for TKA patients following surgery.

8.3 Limitations of the study

One of the limitations of the study exploring the correlation between patient functional outcome and their gait quality is that OKS was measured once, 12 months after TKA. OKS measurements pre-, post- and 12 months later would reflect more informatively the progress, as the most significant changes have previously been shown to occur during the first year, no matter how good or bad patients were pre-operatively (Lavernia et al., 2009). Their functional impairment 3 years after TKA though could be worse for those with a poorer level of functions pre-operatively, as compared to those with a better pre-operative level of functions (Lavernia et al., 2009). Additional performance-based measurements (walking test) would quantify their performance, and present a genuine functional ability, as opposed to their perception of functions (Stevens-Lapsley et al., 2011, Gandhi et al., 2009). Moreover, it was documented that performance-based tests are more sensitive in reflecting changes as compared to self-reported measures, because patients tend to report their experience while doing daily activity, rather than their true ability to do these activities (Parent and Moffet, 2002, Stratford et al., 2009, Stratford and Kennedy, 2006). There was a further limitation in that participants did not represent a consecutive series of cases, as they were self-selected and therefore unavoidable selection bias could, to a degree, confound the outcome. Another factor could be that the RNOH, Stanmore, is a tertiary referral centre, therefore patients may not be representative of those seen in a district general hospital. The relatively small sample size could also affect the results.

With regards to testing TOR efficacy, the limitation was the absence of a control group (no intervention) or groups for which other accepted types of rehabilitation could have been used. The assumption made in this study was that the patients had reached a plateau in their recovery and would not have changed over the 4-week rehabilitation programme period without the intervention. The absence in our study of a control group using current accepted rehabilitation for TKA patients who showed deficiency in their gait at 12 months after their surgery made it infeasible to make an objective comparison of the two approaches in the rehabilitation of TKA patients for improving their impaired gait. The bigger population sample size would also make the study more powerful for assessing the efficacy of the intervention, and its further implications. Previous studies found that the reliability and validity of consumer activity trackers was dependent on the walking speed of the tested individuals, age group 65-84 years, tending to undercount steps in those who were walking with lower speeds (Fokkema et al., 2017, Modave et al., 2017). Taking into account that the mean age of the participants was 65.9 ±8.5 years, this could be another limitation of our study in respect to step counting.

The limitation of the treadmill walking assessment of the control and TOR participants, apart from the small number of participants in both groups, was the lack of control group (healthy participant) data for walking on an incline. However, Fenner *et al.* stated that more differences were observed between TKA patients and control participants during level walking than when going upstairs (Fenner et al., 2014).

The limitation of the treadmill walking assessment of TKA patients before and after their TOR pilot study was that a very small group of TKA patients participated in it, making it impossible to draw any conclusion from the failure to find significant changes resulting from the TOR programme. It appeared that not all participants who gave informed consent for participating in the treadmill walking test were able naturally to walk on a treadmill, despite trying out this walking for a reasonable time. It might be one of the reasons that studies on the rehabilitation of TKA patients have not used this type of assessment as they applied their rehabilitation at a much earlier stage of their recovery. Another limitation is the heterogeneity of the group, where two out of the four participants had had previous TKA for the contralateral leg. The lack of kinematic measurements for the ankle joints was the obstacle to providing the whole lower extremity biomechanics of participants in response to the TOR programme, tested at varying treadmill conditions. However, this limitation arises from the limitations of GaitSmart, which at the time of this study was not equipped for the testing of ankle joints, nor for measuring walking speed. Therefore testing these participants on a treadmill at a self-selected speed, rather than at predetermined fixed speeds, could provide more authentic real life data.

8.4 Future work

The results and limitations of the presented studies provide some directions for future research. For example, as there was a correlation between both assessments, OKS and gait analysis, utilisation of both of them would represent a more accurate level of patient functional capability. In particular, utilisation of more complex tasks with IMUs assessment, such as walking upstairs, or on an incline could reveal a broader outlook on patients' disabilities, and identify patients with greater demand, who are likely to cause a ceiling effect in their OKSs. It might be interesting to consider the separate scores for pain and functions, as can be identified from OKS and would demonstrate in which domain the main issue was, either pain or function, or both. A prospective longitudinal study with a larger cohort of patients, tested before and after their surgery, and at several points in the course of their recovery, would help identify those who are not doing well, so that therapeutic intervention could be provided at an early stage.

In future research in order to obtain a whole and more comprehensive pattern of patients' gaits, after their surgery, and to understand the effect of TKA on the ankle joints in a larger cohort of patients, it would be beneficial to investigate ankle kinetics and kinematics, as due to its complexity, currently this area in TKA patients is not sufficiently researched. It was found that despite no changes in static foot posture, significant changes were observed in rearfoot kinematics during walking, suggesting that the alignment of the operated knee was the cause of these changes (Levinger et al., 2012a). Additionally, inclusion of pre-operative data of TKA patients would provide more comprehensive insight of observed changes. Further, testing of TKA patients and healthy participants on a treadmill at a natural speed would show not only the difference in their natural speed, but also whether their gait mechanics differed from pre-determined speed biomechanics. Finally, measuring EMG activity in future studies during level and uphill walking could provide an understanding of the changes, or lack of them, in the motor control strategies of level and uphill walking. This knowledge could be applied to the design of prostheses, and to the rehabilitation of such patients.

Further work is required to test the efficacy of a TOR programme by comparing the currently accepted rehabilitation of TKA patients with our novel TOR programme. Testing a few larger sample size groups with different training approaches to rehabilitation of TKA patients 12 months after their surgery could provide stronger objective estimation of TOR efficacy. The analysis of other co-morbidities of participants could give a bigger picture of limitations or lack of them for implication of the TOR programme.

Finally, further work to advance TOR should be initiated among orthopaedic surgeons and all other health care professionals, such as physiotherapists, occupational therapists, osteopaths, GPs, etc., who will promote the benefit of this type of rehabilitation not just for TKA patients, but also for those with musculoskeletal conditions in general.

8.5 Conclusions

The work conducted for this thesis has demonstrated that:

- There is an association between how people walk and their OKSs 12 months after surgery.
- Patients recording a low OKS are likely to show abnormalities in gait pattern characterised by increased stride duration, which was indicative of reduced joints' sagittal RoM in swing and stance, and swing flexion time.
- Patients with a high BMI are more likely to report poor function using the OKS.
- There is evidence that the increases in OKSs are higher in patients who show a greater increase in their activity (steps and stairs).
- It is possible to intervene even at 12 months after surgery and to improve both OKS and how people walk.
- The TOR programme has been shown to be effective in assisting patients to improve their gait quality, mobility and functional outcome.

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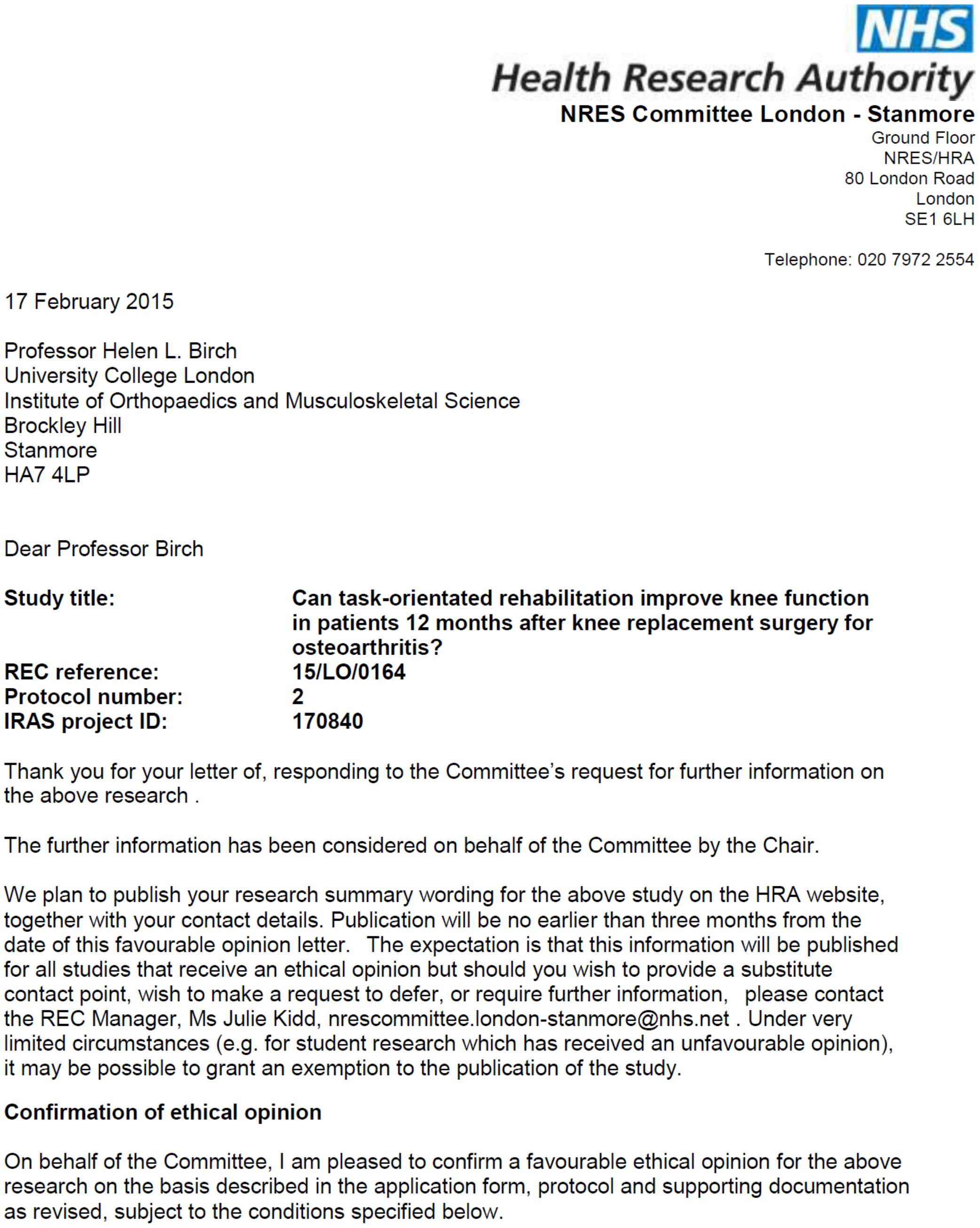
Appendices

Appendix I: Ethics Approval



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17 February 2015

Professor Helen L. Birch
University College London
Institute of Orthopaedics and Musculoskeletal Science
Brockley Hill
Stanmore
HA7 4LP

Dear Professor Birch

Study title:	**Can task-orientated rehabilitation improve knee function in patients 12 months after knee replacement surgery for osteoarthritis?**
REC reference:	**15/LO/0164**
Protocol number:	**2**
IRAS project ID:	**170840**

Thank you for your letter of, responding to the Committee's request for further information on the above research .

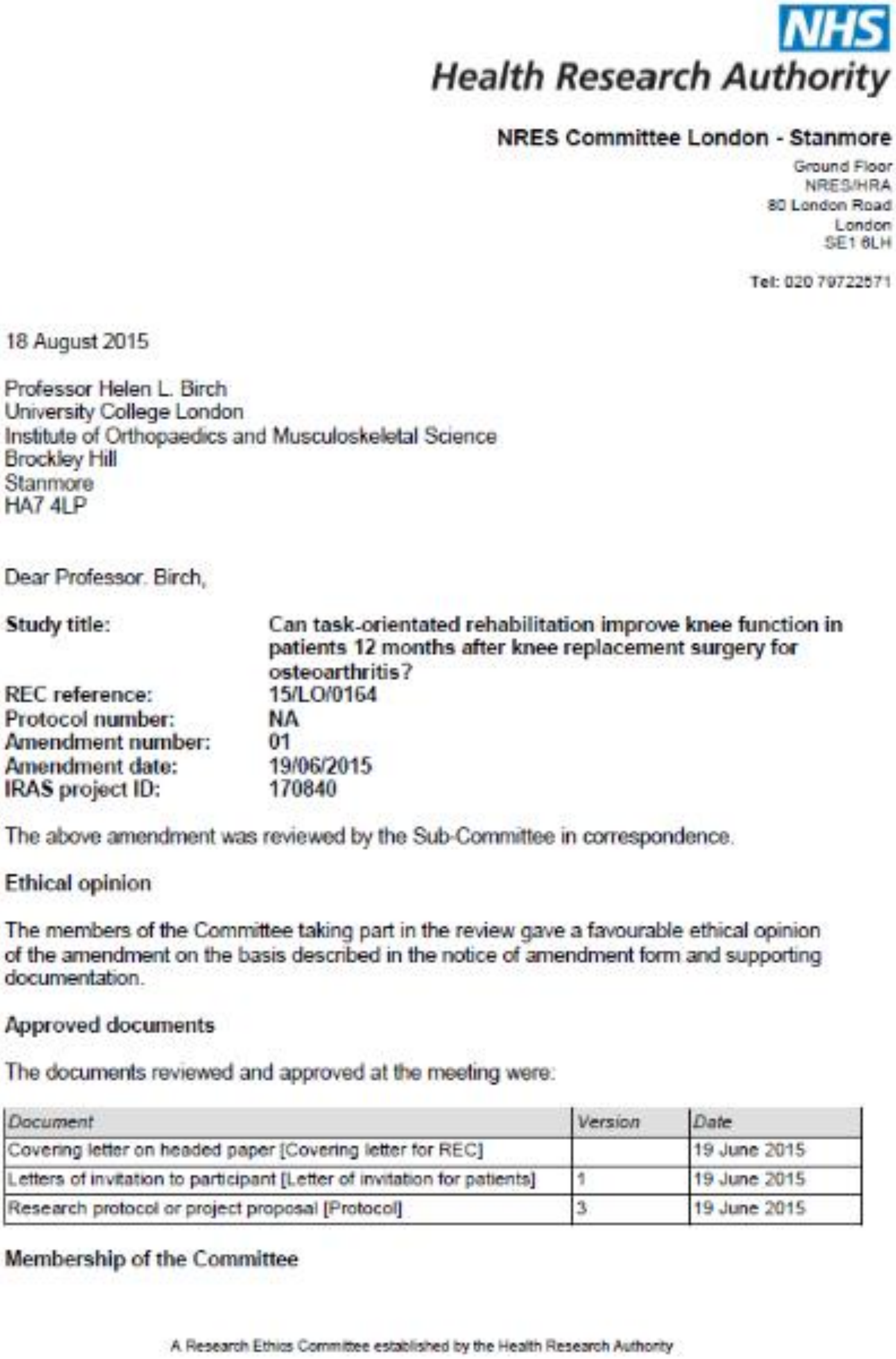
The further information has been considered on behalf of the Committee by the Chair.

We plan to publish your research summary wording for the above study on the HRA website, together with your contact details. Publication will be no earlier than three months from the date of this favourable opinion letter. The expectation is that this information will be published for all studies that receive an ethical opinion but should you wish to provide a substitute contact point, wish to make a request to defer, or require further information, please contact the REC Manager, Ms Julie Kidd, nrescommittee.london-stanmore@nhs.net . Under very limited circumstances (e.g. for student research which has received an unfavourable opinion), it may be possible to grant an exemption to the publication of the study.

Confirmation of ethical opinion

On behalf of the Committee, I am pleased to confirm a favourable ethical opinion for the above research on the basis described in the application form, protocol and supporting documentation as revised, subject to the conditions specified below.

Appendix I: Cont.



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18 August 2015

Professor Helen L. Birch
University College London
Institute of Orthopaedics and Musculoskeletal Science
Brockley Hill
Stanmore
HA7 4LP

Dear Professor. Birch,

Study title:	**Can task-orientated rehabilitation improve knee function in patients 12 months after knee replacement surgery for osteoarthritis?**
REC reference:	**15/LO/0164**
Protocol number:	**NA**
Amendment number:	**01**
Amendment date:	**19/06/2015**
IRAS project ID:	**170840**

The above amendment was reviewed by the Sub-Committee in correspondence.

Ethical opinion

The members of the Committee taking part in the review gave a favourable ethical opinion of the amendment on the basis described in the notice of amendment form and supporting documentation.

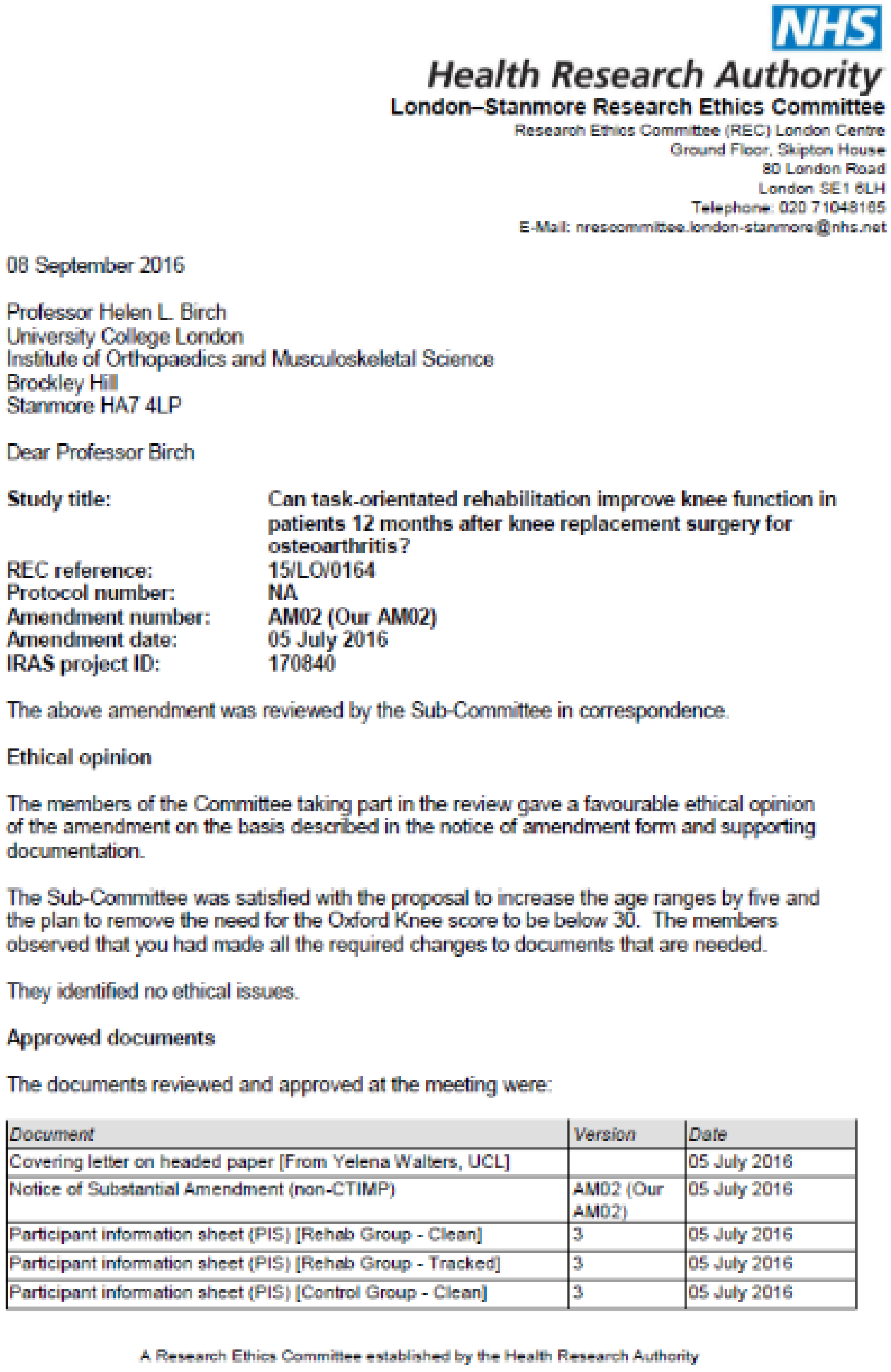
Approved documents

The documents reviewed and approved at the meeting were:

Document	*Version*	*Date*
Covering letter on headed paper [Covering letter for REC]		19 June 2015
Letters of invitation to participant [Letter of invitation for patients]	1	19 June 2015
Research protocol or project proposal [Protocol]	3	19 June 2015

Membership of the Committee

Appendix I: Cont.



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08 September 2016

Professor Helen L. Birch
University College London
Institute of Orthopaedics and Musculoskeletal Science
Brockley Hill
Stanmore HA7 4LP

Dear Professor Birch

Study title:	**Can task-orientated rehabilitation improve knee function in patients 12 months after knee replacement surgery for osteoarthritis?**
REC reference:	**15/LO/0164**
Protocol number:	**NA**
Amendment number:	**AM02 (Our AM02)**
Amendment date:	**05 July 2016**
IRAS project ID:	**170840**

The above amendment was reviewed by the Sub-Committee in correspondence.

Ethical opinion

The members of the Committee taking part in the review gave a favourable ethical opinion of the amendment on the basis described in the notice of amendment form and supporting documentation.

The Sub-Committee was satisfied with the proposal to increase the age ranges by five and the plan to remove the need for the Oxford Knee score to be below 30. The members observed that you had made all the required changes to documents that are needed.

They identified no ethical issues.

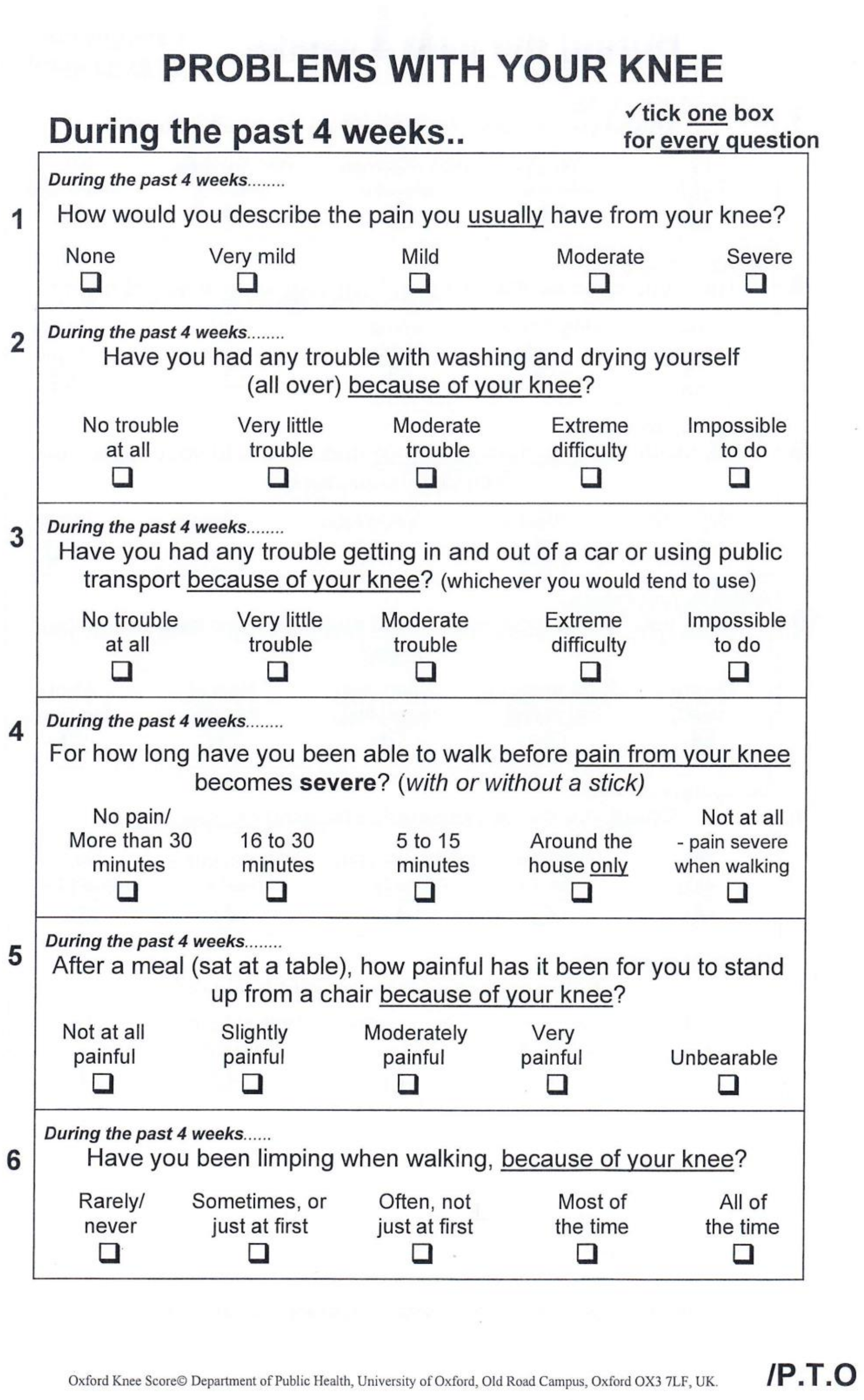
Approved documents

The documents reviewed and approved at the meeting were:

Document	*Version*	*Date*
Covering letter on headed paper [From Yelena Walters, UCL]		05 July 2016
Notice of Substantial Amendment (non-CTIMP)	AM02 (Our AM02)	05 July 2016
Participant information sheet (PIS) [Rehab Group - Clean]	3	05 July 2016
Participant information sheet (PIS) [Rehab Group - Tracked]	3	05 July 2016
Participant information sheet (PIS) [Control Group - Clean]	3	05 July 2016

A Research Ethics Committee established by the Health Research Authority

Appendix II: Oxford Knee Score Questionnaire



PROBLEMS WITH YOUR KNEE

During the past 4 weeks..

✓tick <u>one</u> box
for <u>every</u> question

1 *During the past 4 weeks........*
How would you describe the pain you <u>usually</u> have from your knee?

None	Very mild	Mild	Moderate	Severe
☐	☐	☐	☐	☐

2 *During the past 4 weeks........*
Have you had any trouble with washing and drying yourself (all over) <u>because of your knee</u>?

No trouble at all	Very little trouble	Moderate trouble	Extreme difficulty	Impossible to do
☐	☐	☐	☐	☐

3 *During the past 4 weeks........*
Have you had any trouble getting in and out of a car or using public transport <u>because of your knee</u>? (whichever you would tend to use)

No trouble at all	Very little trouble	Moderate trouble	Extreme difficulty	Impossible to do
☐	☐	☐	☐	☐

4 *During the past 4 weeks........*
For how long have you been able to walk before <u>pain from your knee</u> becomes **severe**? (*with or without a stick)*

No pain/ More than 30 minutes	16 to 30 minutes	5 to 15 minutes	Around the house <u>only</u>	Not at all - pain severe when walking
☐	☐	☐	☐	☐

5 *During the past 4 weeks........*
After a meal (sat at a table), how painful has it been for you to stand up from a chair <u>because of your knee</u>?

Not at all painful	Slightly painful	Moderately painful	Very painful	Unbearable
☐	☐	☐	☐	☐

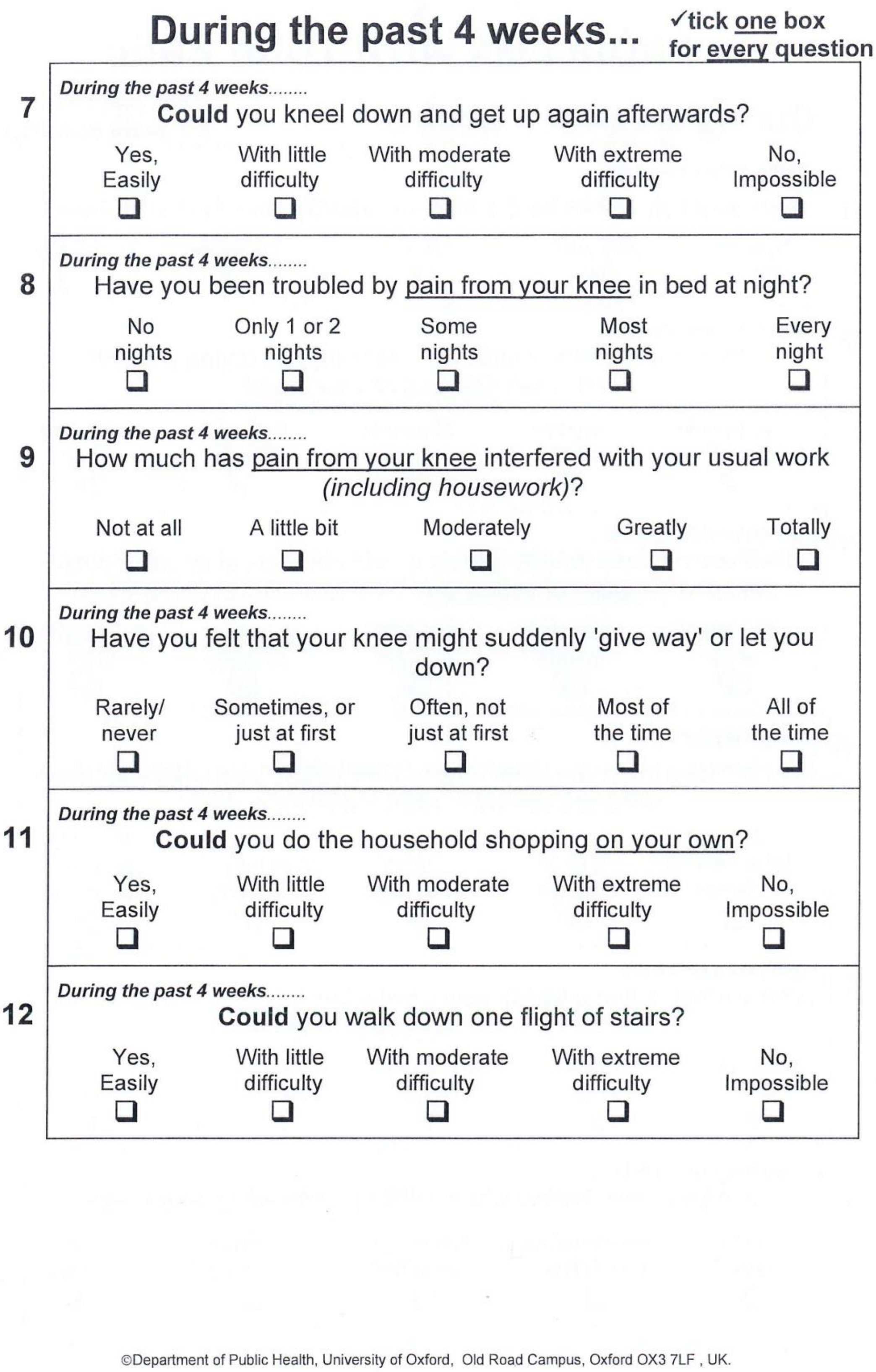
6 *During the past 4 weeks......*
Have you been limping when walking, <u>because of your knee</u>?

Rarely/ never	Sometimes, or just at first	Often, not just at first	Most of the time	All of the time
☐	☐	☐	☐	☐

Oxford Knee Score© Department of Public Health, University of Oxford, Old Road Campus, Oxford OX3 7LF, UK.

/P.T.O

Appendix II: Cont.



During the past 4 weeks...

✓tick one box for every question

7 *During the past 4 weeks........*

Could you kneel down and get up again afterwards?

Yes, Easily	With little difficulty	With moderate difficulty	With extreme difficulty	No, Impossible
☐	☐	☐	☐	☐

8 *During the past 4 weeks........*

Have you been troubled by pain from your knee in bed at night?

No nights	Only 1 or 2 nights	Some nights	Most nights	Every night
☐	☐	☐	☐	☐

9 *During the past 4 weeks........*

How much has pain from your knee interfered with your usual work *(including housework)*?

Not at all	A little bit	Moderately	Greatly	Totally
☐	☐	☐	☐	☐

10 *During the past 4 weeks........*

Have you felt that your knee might suddenly 'give way' or let you down?

Rarely/ never	Sometimes, or just at first	Often, not just at first	Most of the time	All of the time
☐	☐	☐	☐	☐

11 *During the past 4 weeks........*

Could you do the household shopping on your own?

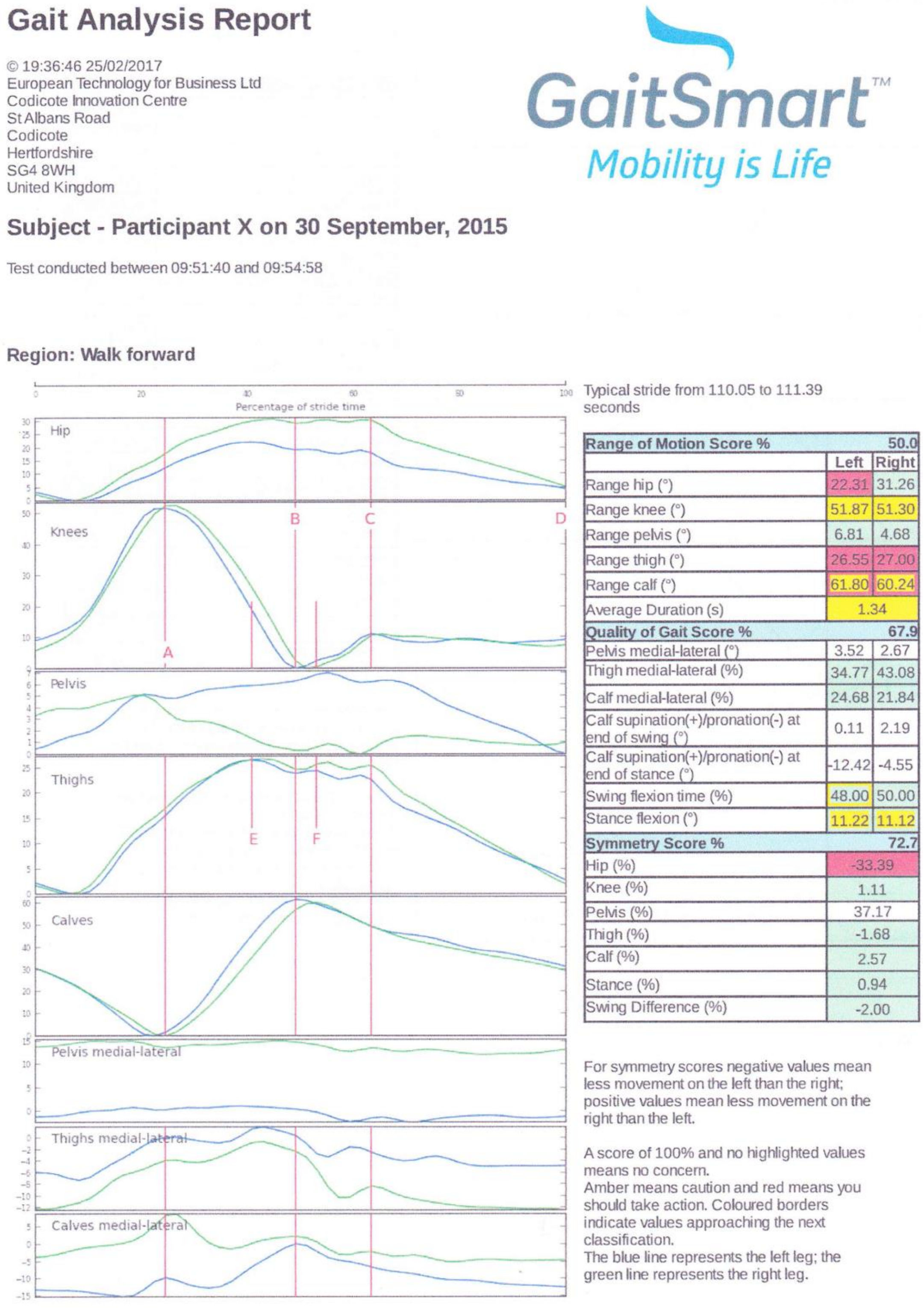
Yes, Easily	With little difficulty	With moderate difficulty	With extreme difficulty	No, Impossible
☐	☐	☐	☐	☐

12 *During the past 4 weeks........*

Could you walk down one flight of stairs?

Yes, Easily	With little difficulty	With moderate difficulty	With extreme difficulty	No, Impossible
☐	☐	☐	☐	☐

Appendix III: An example of GaitSmart gait analysis report for one participant



Gait Analysis Report

© 19:36:46 25/02/2017
European Technology for Business Ltd
Codicote Innovation Centre
St Albans Road
Codicote
Hertfordshire
SG4 8WH
United Kingdom

GaitSmart™
Mobility is Life

Subject - Participant X on 30 September, 2015

Test conducted between 09:51:40 and 09:54:58

Region: Walk forward

Typical stride from 110.05 to 111.39 seconds

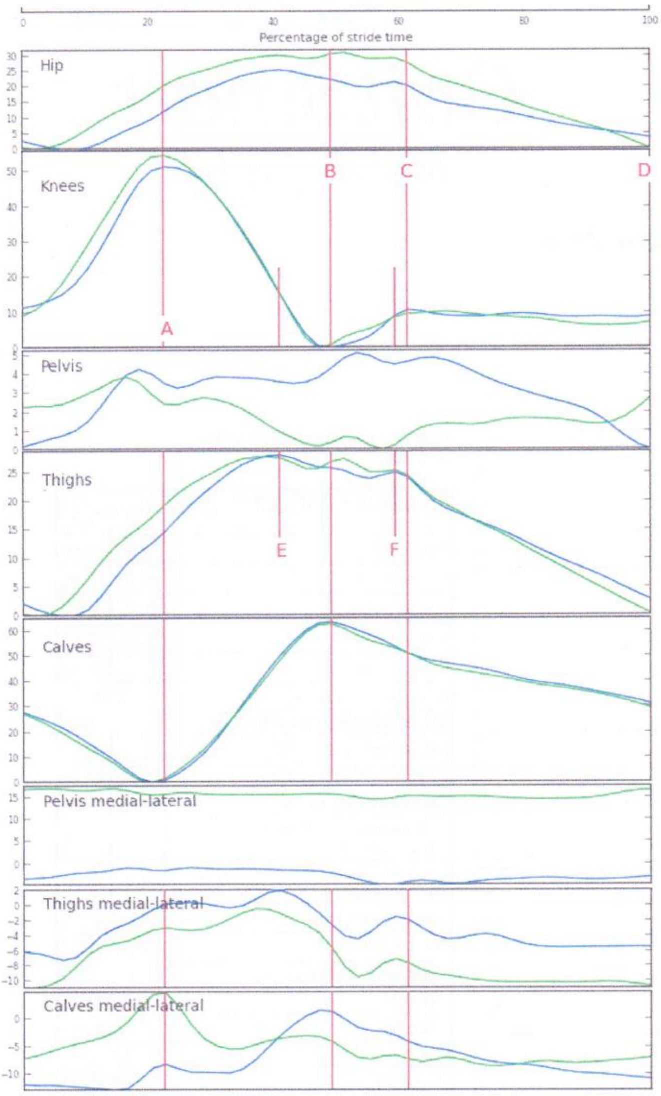
Range of Motion Score %	50.0	
	Left	Right
Range hip (°)	22.31	31.26
Range knee (°)	51.87	51.30
Range pelvis (°)	6.81	4.68
Range thigh (°)	26.55	27.00
Range calf (°)	61.80	60.24
Average Duration (s)	1.34	
Quality of Gait Score %	**67.9**	
Pelvis medial-lateral (°)	3.52	2.67
Thigh medial-lateral (%)	34.77	43.08
Calf medial-lateral (%)	24.68	21.84
Calf supination(+)/pronation(-) at end of swing (°)	0.11	2.19
Calf supination(+)/pronation(-) at end of stance (°)	-12.42	-4.55
Swing flexion time (%)	48.00	50.00
Stance flexion (°)	11.22	11.12
Symmetry Score %	**72.7**	
Hip (%)	-33.39	
Knee (%)	1.11	
Pelvis (%)	37.17	
Thigh (%)	-1.68	
Calf (%)	2.57	
Stance (%)	0.94	
Swing Difference (%)	-2.00	

For symmetry scores negative values mean less movement on the left than the right; positive values mean less movement on the right than the left.

A score of 100% and no highlighted values means no concern.
Amber means caution and red means you should take action. Coloured borders indicate values approaching the next classification.
The blue line represents the left leg; the green line represents the right leg.

Appendix III: Cont.

Region: Walk Back



Typical stride from 135.19 to 136.52 seconds

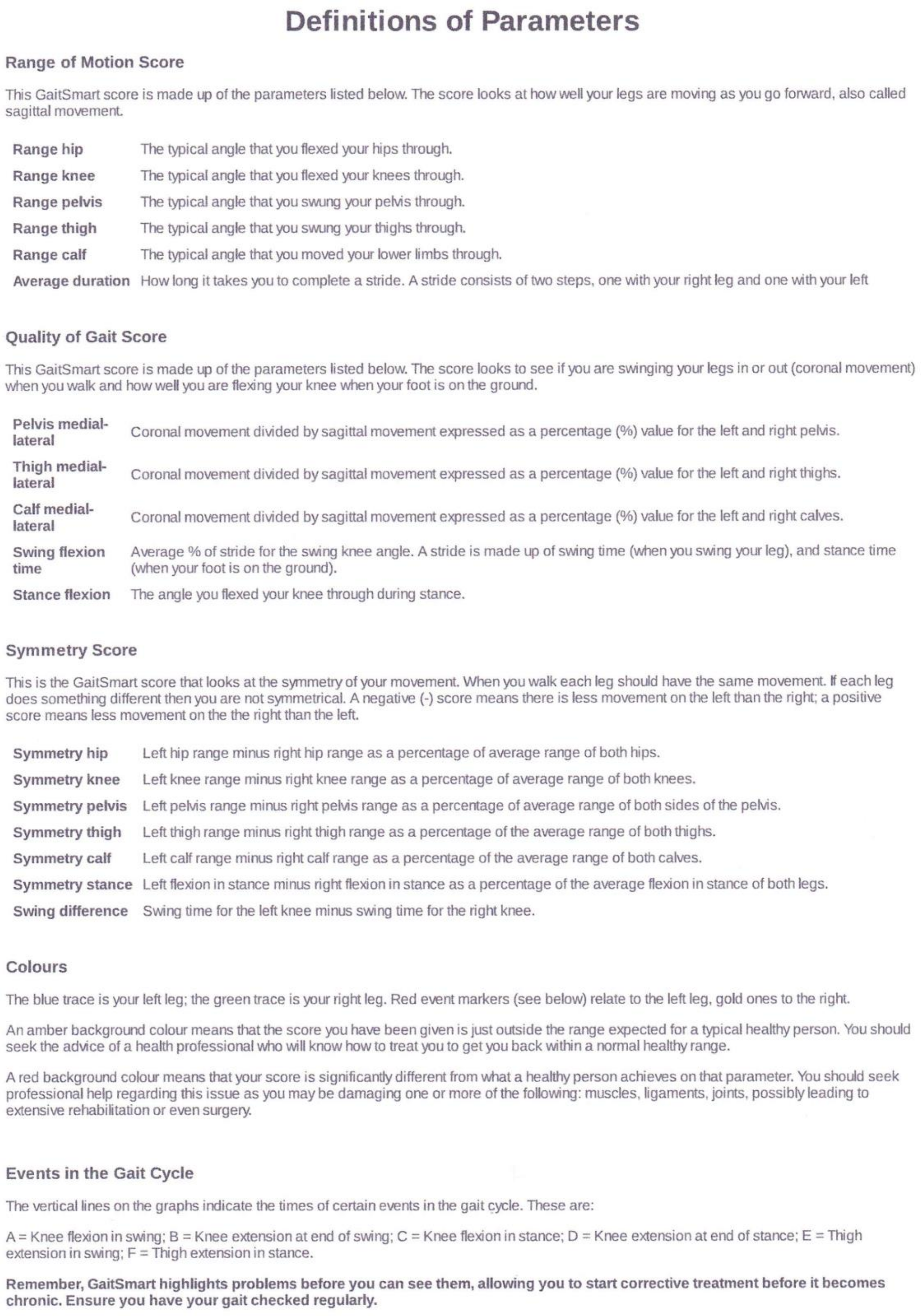
Range of Motion Score %		50.0
	Left	Right
Range hip (°)	25.71	31.00
Range knee (°)	51.38	54.41
Range pelvis (°)	5.14	3.89
Range thigh (°)	28.34	27.76
Range calf (°)	63.48	62.88
Average Duration (s)	1.39	
Quality of Gait Score %		**64.3**
Pelvis medial-lateral (°)	3.99	2.58
Thigh medial-lateral (%)	30.26	38.14
Calf medial-lateral (%)	22.50	21.54
Calf supination(+)/pronation(-) at end of swing (°)	1.32	-4.08
Calf supination(+)/pronation(-) at end of stance (°)	-10.71	-6.89
Swing flexion time (%)	48.00	46.00
Stance flexion (°)	10.76	10.26
Symmetry Score %		**86.4**
Hip (%)	-18.63	
Knee (%)	-5.73	
Pelvis (%)	27.80	
Thigh (%)	2.08	
Calf (%)	0.95	
Stance (%)	4.60	
Swing Difference (%)	2.00	

For symmetry scores negative values mean less movement on the left than the right; positive values mean less movement on the right than the left.

A score of 100% and no highlighted values means no concern.
Amber means caution and red means you should take action. Coloured borders indicate values approaching the next classification.
The blue line represents the left leg; the green line represents the right leg.

End of Report

Appendix III: Cont.



Definitions of Parameters

Range of Motion Score

This GaitSmart score is made up of the parameters listed below. The score looks at how well your legs are moving as you go forward, also called sagittal movement.

Range hip	The typical angle that you flexed your hips through.
Range knee	The typical angle that you flexed your knees through.
Range pelvis	The typical angle that you swung your pelvis through.
Range thigh	The typical angle that you swung your thighs through.
Range calf	The typical angle that you moved your lower limbs through.
Average duration	How long it takes you to complete a stride. A stride consists of two steps, one with your right leg and one with your left

Quality of Gait Score

This GaitSmart score is made up of the parameters listed below. The score looks to see if you are swinging your legs in or out (coronal movement) when you walk and how well you are flexing your knee when your foot is on the ground.

Pelvis medial-lateral	Coronal movement divided by sagittal movement expressed as a percentage (%) value for the left and right pelvis.
Thigh medial-lateral	Coronal movement divided by sagittal movement expressed as a percentage (%) value for the left and right thighs.
Calf medial-lateral	Coronal movement divided by sagittal movement expressed as a percentage (%) value for the left and right calves.
Swing flexion time	Average % of stride for the swing knee angle. A stride is made up of swing time (when you swing your leg), and stance time (when your foot is on the ground).
Stance flexion	The angle you flexed your knee through during stance.

Symmetry Score

This is the GaitSmart score that looks at the symmetry of your movement. When you walk each leg should have the same movement. If each leg does something different then you are not symmetrical. A negative (-) score means there is less movement on the left than the right; a positive score means less movement on the the right than the left.

Symmetry hip	Left hip range minus right hip range as a percentage of average range of both hips.
Symmetry knee	Left knee range minus right knee range as a percentage of average range of both knees.
Symmetry pelvis	Left pelvis range minus right pelvis range as a percentage of average range of both sides of the pelvis.
Symmetry thigh	Left thigh range minus right thigh range as a percentage of the average range of both thighs.
Symmetry calf	Left calf range minus right calf range as a percentage of the average range of both calves.
Symmetry stance	Left flexion in stance minus right flexion in stance as a percentage of the average flexion in stance of both legs.
Swing difference	Swing time for the left knee minus swing time for the right knee.

Colours

The blue trace is your left leg; the green trace is your right leg. Red event markers (see below) relate to the left leg, gold ones to the right.

An amber background colour means that the score you have been given is just outside the range expected for a typical healthy person. You should seek the advice of a health professional who will know how to treat you to get you back within a normal healthy range.

A red background colour means that your score is significantly different from what a healthy person achieves on that parameter. You should seek professional help regarding this issue as you may be damaging one or more of the following: muscles, ligaments, joints, possibly leading to extensive rehabilitation or even surgery.

Events in the Gait Cycle

The vertical lines on the graphs indicate the times of certain events in the gait cycle. These are:

A = Knee flexion in swing; B = Knee extension at end of swing; C = Knee flexion in stance; D = Knee extension at end of stance; E = Thigh extension in swing; F = Thigh extension in stance.

Remember, GaitSmart highlights problems before you can see them, allowing you to start corrective treatment before it becomes chronic. Ensure you have your gait checked regularly.

Appendix IV: Correlation matrix for the 23 gait variables

	Op Limb Knee flexion in stance (°)	Non-op/ op earlier limb KFS (°)	Op Limb Swing flexion time (%)	Non-op/ op earlier Limb SFT (%)	Op Limb Knee Sag ROM (°)	Non-op/ op earlier Limb Knee Sag ROM (°)	Op Limb Pelvis Sag ROM (°)	Non-op/ op earlier Limb Pelvis Sag ROM (°)	Op Limb Hip Sag ROM (°)	Non-op/ op earlier Limb Hip Sag ROM (°)	Op Limb Thigh Sag ROM (°)	Non-op/ op earlier Limb Thigh Sag ROM (°)	Op Limb Calf Sag ROM (°)	Non-op/ op earlier Limb Calf Sag ROM (°)	Op Limb Pelvis Cor ROM (°)	Non-op/ op earlier LimbPelvis Cor ROM (°)	Op Limb Thigh Cor ROM (°)	Non-op/ op earlier Limb Thigh Cor ROM (°)	Op Limb Calf Cor ROM (°)	Non-op/ op earlier Limb Calf Cor ROM (°)	Op limb Dif b/w 2 peaks of thigh sag angle (%)	Non-op/ op earlier LimbDif b/w 2 peaks of thigh sag angle (%)
Non-op/ op earlier limb KFS (°)	.459**																					
Op Limb Swing flexion time (%)	.018	.090																				
Non-op/ op earlier Limb SFT (%)	.078	-.090	.570**																			
Op Limb Knee Sag ROM (°)	.324**	.524**	.125	-.044																		
Non-op/ op earlier Limb Knee Sag ROM (°)	.355**	.593**	.043	.031	.793**																	
Op Limb Pelvis Sag ROM (°)	.192	.363**	.093	-.097	.310**	.373**																
Non-op/ op earlier Limb Pelvis Sag ROM (°)	.060	.297**	.189	.048	.351**	.432**	.662**															
Op Limb Hip Sag ROM (°)	.037	.305**	-.157	-.114	.408**	.351**	.052	.103														
Non-op/ op earlier Limb Hip Sag ROM (°)	.057	.387**	-.203	-.207	.366**	.365**	.199	.047	.793**													
Op Limb Thigh Sag ROM (°)	.065	.406**	-.141	-.142	.489**	.487**	.372**	.319**	.914**	.817**												
Non-op/ op earlier Limb Thigh Sag ROM (°)	.096	.463**	-.128	-.106	.472**	.521**	.397**	.369**	.776**	.910**	.889**											
Op Limb Calf Sag ROM (°)	.368**	.482**	.045	.041	.788**	.728**	.363**	.306**	.667**	.640**	.771**	.735**										
Non-op/ op earlier Limb Calf Sag ROM (°)	.389**	.651**	.039	.015	.719**	.824**	.442**	.383**	.628**	.652**	.774**	.778**	.913**									
Op Limb Pelvis Cor ROM (°)	-.118	.096	-.149	-.114	-.011	.055	.382**	.414**	.177	.224	.284*	.277*	.135	.160								
Non-op/ op earlier LimbPelvis Cor ROM (°)	-.028	.172	.001	.078	.112	.157	.374**	.480**	.206	.266*	.318**	.406**	.257*	.298**	.684**							
Op Limb Thigh Cor ROM (°)	.102	.241*	.009	.006	.111	.083	.081	.093	.186	.267*	.166	.219	.163	.206	.191	.200						
Non-op/ op earlier Limb Thigh Cor ROM (°)	.278*	-.031	.074	.151	-.066	-.095	.002	-.060	-.032	.022	-.058	-.001	.014	-.001	-.103	.053	.390**					
Op Limb Calf Cor ROM (°)	-.180	.186	.014	-.050	.085	.052	.008	.053	.136	.090	.089	.037	-.002	.047	.133	.078	.253*	.023	-			
Non-op/ op earlier Limb Calf Cor ROM (°)	.040	-.035	.086	-.036	.019	-.021	-.005	-.029	.241*	.127	.196	.073	.185	.064	.128	.100	.114	.246*	.120	-		
Op limb Dif b/w 2 peaks of thigh sag angle (%)	.354**	.286*	.203	.012	.510**	.348**	.009	.113	-.051	-.156	-.089	-.119	.137	.119	-.137	-.149	.001	-.019	.123	-.010	-	
Non-op/ op earlier LimbDif b/w 2 peaks of thigh sag angle (%)	.322**	.398**	-.088	.101	.528**	.641**	.244*	.309**	.115	.118	.168	.214	.416**	.423**	.114	.062	.139	-.003	-.030	-.005	.464**	-
Stride duration (sec)	-.321**	-.413**	-.298**	-.317**	-.413**	-.467**	-.070	-.188	-.354**	-.358**	-.388**	-.424**	-.471**	-.521**	.089	-.093	-.164	-.058	-.160	-.070	-.208	-.174

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

Appendix V: Statisticians Report

Statisticians Report

Full title: Can task-orientated rehabilitaion improve knee function in patients 12 months after knee replacement surgery for osteoarthritis?

Date: 9th September 2014

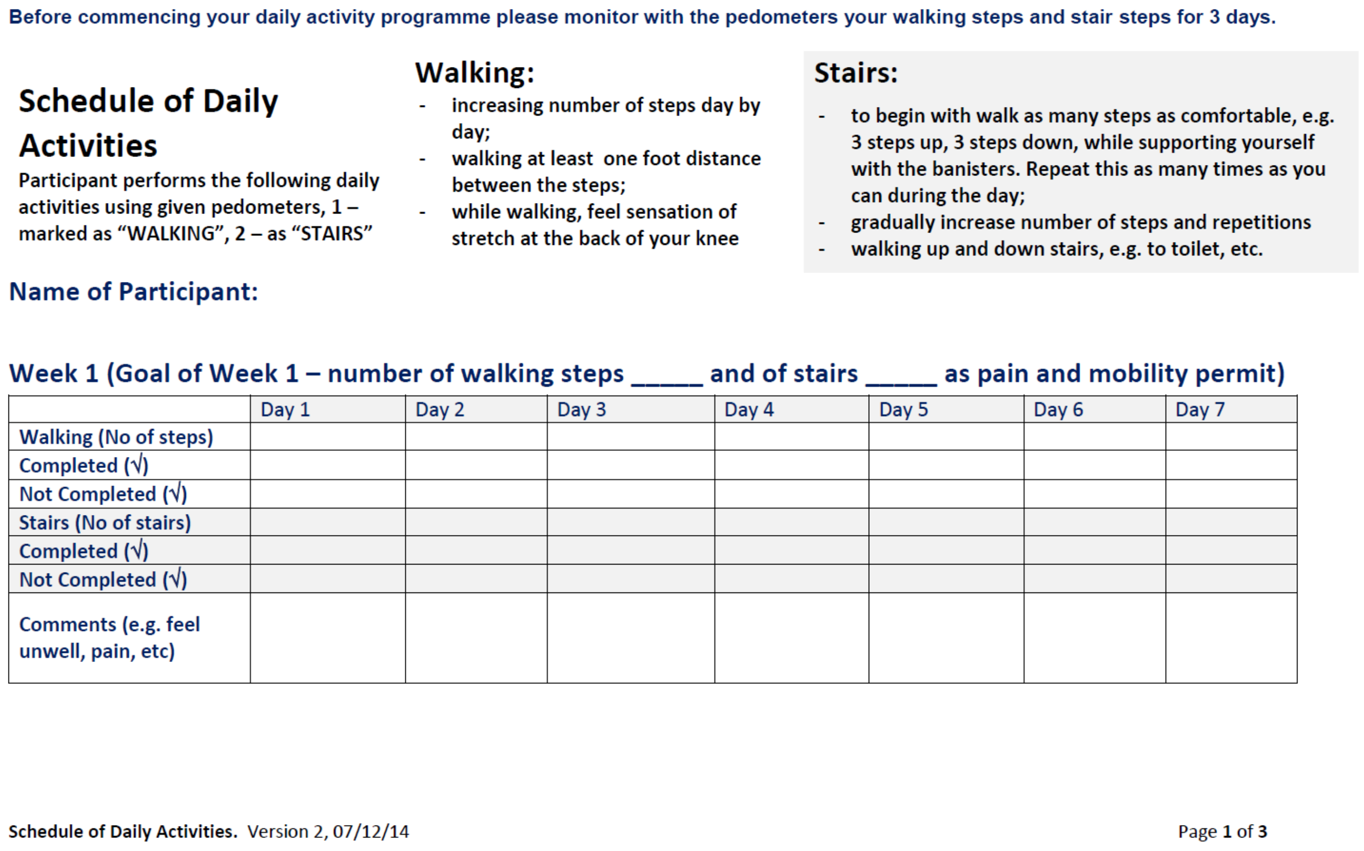
Sample Size

A sample size calculation was carried out based on existing data which suggests that the mean for controls is 19.8 (SD: +/- 4.9) and the mean for total knee replacement at 12 months is 8.4 (SD: +/-3.7). A total sample of 20 patients is needed based on 0.95% power, significance level of 0.05 (2 tailed) and a cohens d effect size of 0.7.

Dr Erica Cook

Statistician
MSc PhD CPsychol FRSPH AFBPsSCSc

Appendix VI: Schedule of Daily Activities



Before commencing your daily activity programme please monitor with the pedometers your walking steps and stair steps for 3 days.

Schedule of Daily Activities

Participant performs the following daily activities using given pedometers, 1 – marked as “WALKING”, 2 – as “STAIRS”

Walking:

- increasing number of steps day by day;
- walking at least one foot distance between the steps;
- while walking, feel sensation of stretch at the back of your knee

Stairs:

- to begin with walk as many steps as comfortable, e.g. 3 steps up, 3 steps down, while supporting yourself with the banisters. Repeat this as many times as you can during the day;
- gradually increase number of steps and repetitions
- walking up and down stairs, e.g. to toilet, etc.

Name of Participant:

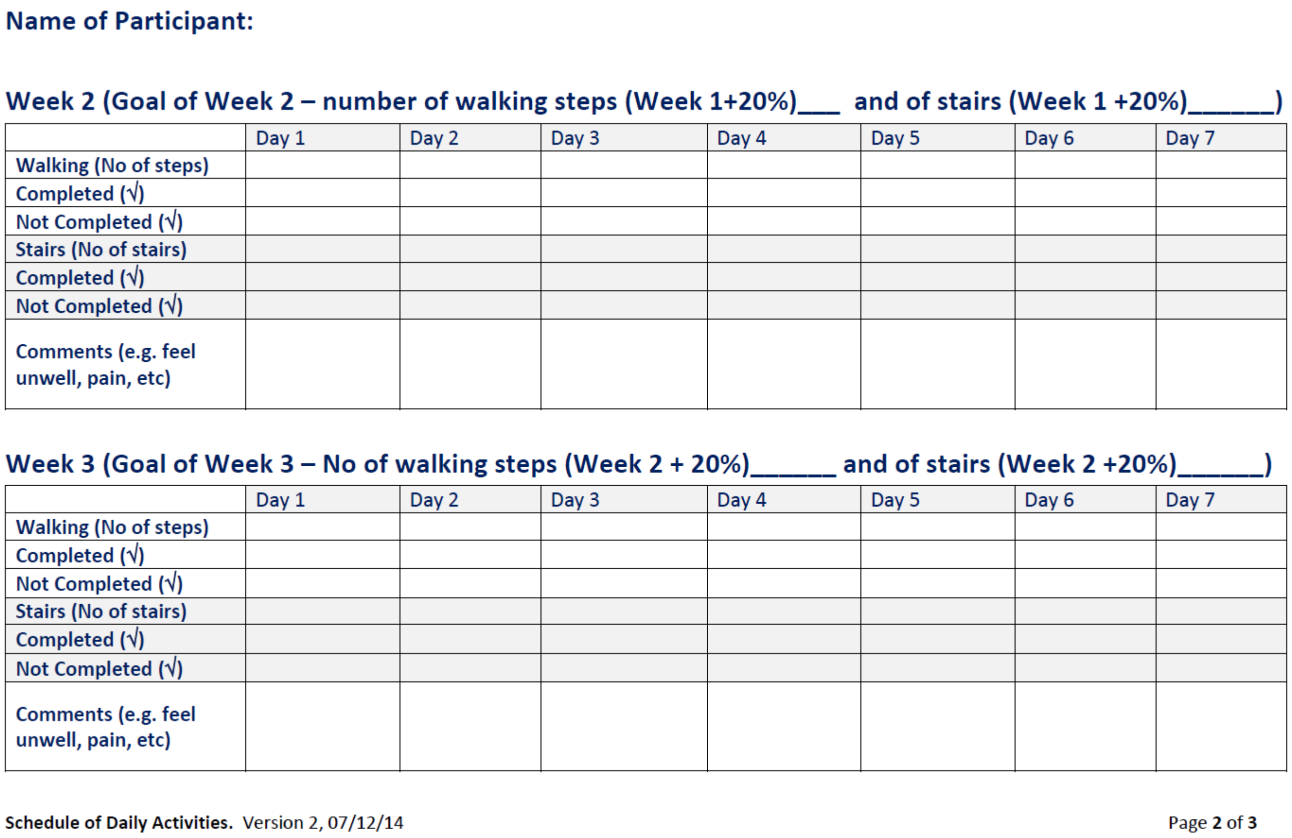
Week 1 (Goal of Week 1 – number of walking steps _____ and of stairs _____ as pain and mobility permit)

	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
Walking (No of steps)							
Completed (√)							
Not Completed (√)							
Stairs (No of stairs)							
Completed (√)							
Not Completed (√)							
Comments (e.g. feel unwell, pain, etc)							

Schedule of Daily Activities. Version 2, 07/12/14

Page **1** of **3**

Appendix VI: Cont.



Name of Participant:

Week 2 (Goal of Week 2 – number of walking steps (Week 1+20%)___ and of stairs (Week 1 +20%)______)

	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
Walking (No of steps)							
Completed (√)							
Not Completed (√)							
Stairs (No of stairs)							
Completed (√)							
Not Completed (√)							
Comments (e.g. feel unwell, pain, etc)							

Week 3 (Goal of Week 3 – No of walking steps (Week 2 + 20%)______ and of stairs (Week 2 +20%)______)

	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
Walking (No of steps)							
Completed (√)							
Not Completed (√)							
Stairs (No of stairs)							
Completed (√)							
Not Completed (√)							
Comments (e.g. feel unwell, pain, etc)							

Appendix VII: Patients' feedbacks

1. Female 77 years (e-mail from patient 28/12/2016)

Dear Yelena
I would like to thank you for giving me the opportunity to participate in your programme. I found that the instructions and advice you gave me were a tremendous incentive to improving the quality and range of my walking. In particular, the advice to lengthen my stride and increase the number of daily steps has resulted in pleasurable pain-free daily walks. A far cry from my pre-operative condition when walking was an ordeal. I have every intention of maintaining the good walking habits you have shown me and am most grateful for your excellent care and attention. With very best wishes for a successful osteopathic 2016 from a happy graduate on the 2015 class.

2. Female 63 years (e-mail from patient's daughter, 05/01/2016)

Hi Yelena,
Hope you are well,
Mum said she just wanted to say her knees have improved since working with you. She never used to sit on the floor as she was unable to stand up if she sat too low but now is able to sit on the floor, also lie down on the floor and do my exercises. Mum also climbed a ladder to clean the kitchen which she had been unable to do before.

3. Male 70 years (letter 08/02/2016)

To Alina
Thank you for letting me take part in gait analysis report. I have tried very hard to do the exercises which you explained to me the steps etc. My daughter bought me an exercise bike. Without your inspiration and helpful pushes I have been able to go the extra mile thank you.
When you asked me for my Participation in your study I was dubious to take part in your four week rehabilitation. Since meeting you and taking part in your knee replacement study I was very happy to be part of your study.
You have been very helpful and endeavour to help me to get the best treatment possible and to be motivated to get me full mobile. Since then my daughter has bought me an Exci-bike.
To Yelena know one in my whole life has motivated me to get my walking and I would like to thank you from the bottom on my heart.

4. Same male 70 years (letter from his wife 10/03/2016)

I would like to recommend Yelena Walters for the good job she does at the Royal National Orthopaedic Hospital in Stanmore. My husband had knee replacement on both his knees within three years and I was full time carer and wife and it was a struggle to see him go through the pain and Hospital Visits until December last year. We were in the waiting room when Yelena introduced herself to my husband and me and wanted to know if he would be interested in going forward with his card with the exercises etc which he agreed to. I his wife has seen a big difference in his confidence etc walking without his walking stick. I think she has *made a big difference to his aftercare. I would like to thank you Yelena for your help and support.*

5. Female 69 years (letter 12/02/2016)

Dear Yelena,
I would like to thank you for your help, encouragement and including me on this programme. As you know it is a year since my knee operation, I had eight sessions of physio plus a sheet of exercises to do, this was good but after four years of walking on a very painful leg one tends to develop a way of walking that causes less pain, my husband described it as resembling a 'Duck' so I was more than happy when you asked to check my gait, as I wasn't sure if my walk had improved or not as I still had pain when walking for any length of time plus my other knee was still seeming to take a lot of the strain.
The first thing you told me was to wear comfortable shoes or trainers, then when walking to take longer strides and to use the stairs to make me lift my legs. As I live on the top of a hill whichever way I go I am either walking up or down a hill, I wasn't really looking forward to it but I thought I'll give it a try. ! Started off slowly only going around the block as legs got tired and ached but gradually with taking longer strides and deeper breathes I can now walk a lot further for longer, previously I would stop three or four times coming up the hill now I only need to stop once to catch my breath, my walking is a lot better and I experience hardly any pain which is amazing seeing as its only been a couple of months.
I recently went into town to a show I wasn't looking forward to the underground and all the steps, these had always given me grief before but it was fine, a bit slow but this can only improve if I keep practising and it was already a big improvement on earlier trips.
I am still feel a little unsure putting all my weight on the new knee, but you have encouraged me to do simple exercises to increase my flexibility (squatting, stairs, walking, relaxing etc.) and if I do as you have advised I'm sure my confidence will only get better.
Thank you again for all your help I will continue the walking, It's hard to believe that simply by walking more and correctly can improve ones health so much, I do think if this could be introduced as another part of ones rehabilitation after the physiotherapy I'm sure it could help a lot of people to regain greater mobility.
Kind regards

6. Female 47 years (e-mail 28/02/2016)

Dear Yelena,
So sorry that it has taken time for me to reply and complete some feedback for you. Life has been extremely busy both at work and home. I found taking part in the research extremely beneficial. Following my operation in November 2014 I had to request referral for physiotherapy. I had several physio sessions and was then discharged at the end of the programme. I often found it difficult to motivate myself to carry on the exercises at home. When you informed me that my walking gait was not as it should be I became concerned and this enabled me to become determined to remedy this. As I am relatively young and still working full time with a young child to care for I became more focused.
I work in the community visiting clients at home and I have been able to make

slight changes such as parking my car a distance away from the house and therefore walking more. Using the pedometer was a great boost as I could gauge my steps through the course of the day and look to improve the figure on a daily basis. Prior to the research study I often avoided stairs as it is still uncomfortable when going up and down stairs. Having the pedometer helped to change my view and fear of stairs and I have seen an improvement. Following Yelena's expert guidance and advice I began to look at taking longer strides and increasing my walking distance. Unfortunately due to my working hours and family commitments particularly in the week I was not often able to increase my walks. However when time allowed I did attempt to use the crosstrainer at home. I still continue to use this equipment as it helps to build the muscle strength and increase my activity levels. I have also followed the advice of the soft roller and stairs for exercises.

I feel I now enjoy walking much more than I used to and the encouragement by Yelena was amazing. The pain in my knee is decreasing and I believe this is due to the participation in Yelena's research. I have been able to reevaluate my recovery from the knee surgery which I found extremely painful and a traumatic process and become more focused and keen to improve my wellbeing.

I am so grateful for the wonderful advice, support and encouragement I received from Yelena.

Many thanks and Kindest Regards.

7. Female 75 years (letter 04/03/2016)

My feedback on the programme

During these 5 weeks I have thoroughly enjoyed participating in this programme. I found it much different from the course of physiotherapy which I had after both knee replacement.

Physiotherapy was very helpful, however I found that with this programme I was able to set daily targets for walking and going up and down stairs. Targets which were comfortable and achievable. Although I did not complete the targets some days, I had to make that extra effort towards my goal.

I learnt how to manage the stairs better. Now I am able to come down the stairs walking forward instead of backward. Going up the stairs I am now able to go up step by step instead of stepping up and standing before moving to the next step.

I have learnt how to make longer strides while walking also to wear footwear which are more comfortable for walking. I have less pain when walking. Although my thighs and calves get tired, and tight. The back of my knees get tight also especially at the end of the day.

I enjoy walking more and I find it easier to walk longer distances (to the shops) walking around the supermarket while doing the shopping.

Before I started the programme it was very difficult and uncomfortable to come down the stairs as I had to come down backward that easier for me. However since doing the programme I am able to come down forward.

My investigator has been very encouraging, her explanation of the programme and participating activities were clearly understood.

At the beginning I did not think that I would have been able to do much because of my other commitments. However I have done my best and although I did not complete some of the targets which I set I thoroughly enjoyed participating in this programme. I felt safe and self-confident to work on my own after the first *few days and it certainly helped to know that my investigator was at the other end of the phone if there was a problem.*

8. Male 70 years (letter 07/03/2016)

I had to do the physio on my own which I did every day after my initial meeting with you.
I have tried to do longer strides, I walk up steps and slopes but after a while it was slightly uncomfortable. I have made sure my footwear is more comfortable. The pain is slightly easier but still hurts after a longer distance. I cannot do anything new except to be mindful and take longer steps as advised.
The Investigator was so helpful. She has encouraged me to do so much. She has shown me lots of exercises which I do most days. She was always on the end of the phone if I had any problems. I felt very confident working on my own especially the walking.
I feel that this has been a very worthwhile programme for me and has really helped me.

9. Female 67 years (letter 09/03/2016)

Dear Mrs Walters,
I am writing to thank you for all the help and support you have given me over the last 5 weeks.
Before I started the programme I had a lot of pain on the right side of my right knee and could only bend it back half way. Since carrying out the exercises you gave me now I can bend it right back, kneel down and put pressure on the knee, get in and out of the bath a lot better.
Before the programme I was never informed that I was walking incorrectly but with your help I have definitely improved in my walking taking bigger steps able to walk longer distances, climb stairs slowly without holding on to the balustrades with little discomfort.
I now enjoy going out walking and taking my grandchildren out. When I was doing the programme with you I found great comfort because when you explained things to me they were very clear and direct. When I said something was hard for me to do you encouraged me to try and after a while I realised I could do it.
With your help I feel safe and self confident because your explanations were very clear and I knew that you were there to help me at any time because you are a very professional and caring person.
I just want to finish this letter thanking you for all your help.

10. Female 73 years (letter 14/04/2016 and additional comments e-mail 24/04/2016)

The physiotherapy I received after the operation was in the gym at RNOH, for 1 hour, with a group of people (max8) all who had had TKR. This physio was offered for up to 8 weekly sessions. There were several ways to exercise the knee and written instructions around the gym told you what to do and for how long. An instructor was available to give advice but there was no 1:1 physio or checking that you were doing it properly. At the end of each session the leg was

examined for knee bend etc. I do not recall advice about how good walking would be, just advice on keeping up the knee bend exercises.
I had not thought about lengthening my stride which I tried to do for this exercise but sometimes I had to concentrate on the uneven pathways which was sometimes challenging.
Some days I found the walking tiring, particularly if I increased the distance and on one occasion when I increased the pace my leg was aching.
I do feel safe and confident when walking but do look out for uneven surfaces as my balance has changed but I had clear instructions from the Researcher on the programme and reason for the research she was undertaking.
What I did find was that as I had to record my daily walking it gave me an incentive to go walking every day and walk up and down stairs more often. So I shall now buy a FitBit and do my own recordings.

Dear Yelena - thank you for your prompt reply and confirming my own observations being a non-professional of these things. I will continue to take your advice and little by little there will be improvement. It would have been very useful advice at physio stage after the operations, all they seem to be interested in is bending the knees.
Kindest regards.

11. Male 67 years (letter 04/05/2016)

Dear Yelena, I found very useful during these 5 weeks. First of all I made it a habit to walk every day round the block. Since the operation, I still have problems with my right knee. Still I have got a pain. Of course I learn something ie making longer strides. I have got no problem walking, but still I have got pain. It does not make any different the pain is there. I do enjoy walking, I am able to walk longer distances. When I am walking I am fine (no pain) after I have got the pain.
Also with the physiotherapy It helps me to bend my leg more. Of course you help and encourage me and the explanations are very clear. Yes, I am feel self-confident working on the programme on my own. Thank-you very much.

12. Female 74 years (letter 15/05/2016)

Mixed emotions.
At the beginning of the project I felt apprehensive, enthusiasm and positive.
2nd week – walked long distance at a steady pace without getting breathless or wanting to sit down. Much better week.
It was during the 1st and 2nd that I got to know all the benches in Bushey.
I cannot remember what I was taught by the Physiotherapist post replacement. I tried to take longer strides when walking. Strides are slow when going uphill, stop at the top, and come down very quickly. I enjoy coming down from downhill and stairs.
SHOES What I wear now are very comfortable. My trainers were uncomfortable. I intend to get a new pair.
On good days when the weather is good and I am painfree I really enjoy the walks.

I feel self-conscious when I am working on programme because I used to drive everywhere. I try to avoid lonely places when I am on my own.
Yesterday I walked from home to the Harlequin Centre and returned without stopping and taking even breath only. No more SILENT PANTING.
The weather is not good for me.
I used to suffer from sleepless nights or insomnia, now I don't.

13. Female 51 years (e-mail 25/06/2016)

Dear Yelena,
Thank you for inviting me to take part on the 5week gait program.
As you are aware I have had both knees full replacement in approx two half years.
After my first replacement I had intensive physiotherapy a six week group physio and one to one physio for six months then self continued physiotherapy at home and water aerobics. With problems continuing in tight shortening hamstrings.
My left knee only had a six week group physio once a week.
I have a lot of pain in the area above and below my knees also pain in my right hip and arthritis in my feet and ankles that swell with fluid.
When you explained to me about wearing correct footwear I was slightly apprehensive but on purchasing my Asiacs running shoes, I was so surprised how light, comfortable and supportive they are. Shame about the colour but no choice.
Very happy to invest £150. Money well spent!
Since wearing them both feet haven't swelled or been inflamed. Still slightly painful but I understand that is the arthritis.
I feel it has change how I walk which of course helps my knees.
Gosh again I was happy to try and follow your walking and striding advice (swing my legs) heel to toe which I already know how I walked and placed my feet.
Actually I found it has change many things like strengthening my inner core and giving me more confidence walking. I found I can walk faster and further.
Stairs.... As I explained I was avoiding stairs at all cost to the point I have moved my bedroom down to the ground floor.
I felt going up and down stairs was so uncomfortable and painful.
You have encouraged me to conquer them and build up doing them daily.
Still painful and don't feel comfortable or graceful climbing them.
But I will continue with this task.
Overall pain is less and walking is slightly more comfortable. But very stiff after sitting, I find low seating almost impossible to get up from gracefully!
During this programme I have addressed my eating habits and found I have some weight loss and my body shape has changed.
I do walk more and didn't realise as I have never had a pedometer the distance I did do and now do daily.
I didn't reach my goals you set each week. But overall I have increased my distances that I now walk. I plan to carry on and increase my steps and distance.
Yelena I found your explanations and advice very clear and felt your support was individual to my needs. I appreciate your contact and flexibility to

appointments and communication. I also found that guidance in stretching at the last appointment very beneficial.
With regards to pain I'm still taking nearly my full complement of medication.
With extra voltarol in the night rubbed in the knee and ankle area!
I think this is due to the increase of walking I'm doing and stairs!!!
Long car journeys are still uncomfortable and I still drive with my seat as far back as possible so my legs are straight! I drive a automatic car and find it very beneficial just like the wide opening doors and a high height vehicle.
I find wearing tight and heavy fabric trousers or jeans very drawing on my legs!
As my legs are different sizes it's not always possible to find the right shape for me in the best fabric.
Sleeping at night hasn't changed I still move my legs a lot and occasional get cramp where I have to get out of the bed for the cramp to go. So I rarely sleep through the night. I tend to go to bed by 9.30 -10 most evening as I am a early riser this is habit and work commitments.
Thank you once again Yelena, I look forward to you 2nd report and its findings and how the comparisons compare.
See you at the beginning of September, I will keep up the good work for me that you have shown me and put me on a new road to my recovery.
If you need to contact me before please feel free or if I can support your hard work in another way just ask.
Kind regards.

14. Female 74 years (telephone conversation 05/07/2016)

Your advice how to walk correctly was helpful, and encouraging. The programme motivated me to walk more, I can push myself more now and not be frightened that it will make my knees worse.
My knee feels alright now, but I would like it to bend more.
Walking up and down stairs is better now, and I can alternate my legs, which I couldn’t do before.

15. Female 70 years (e-mail 08/09/2016)

Hi Yelena.
First of all, I must thank you for giving me the opportunity to take part in your research programme; I found it extremely interesting.
When you learn to walk as a toddler you are not shown the correct way to walk, unless there is a problem which is picked up in childhood.
You therefore develop a way of walking which is comfortable for you, but which may not be conducive to good posture and may not be the most efficient and healthy way of walking.
Taking part in your programme enabled me to examine how I was walking after my two knee replacements, something that I had not considered before.
Just being able to walk without pain after years of suffering seemed to be enough for me and was a great relief. Obviously over the years, as my arthritis set in, I developed my own way of walking to limit the pain.
Now that I can walk without pain, it was a good exercise to examine how I walk and try to improve it. Your programme gave me that opportunity.

I am now more aware of the walking technique of bending my knees and taking longer strides. I am walking more quickly and for longer distances. I find that walking is more pleasurable now.

Although the physiotherapy I received post ops was very good, it concentrated mostly on bending and achieving a good degree of bend, and also on leg strength. I know that physiotherapy time is limited but perhaps it could include an element of walking technique.

I found you very helpful and enthusiastic to work with and you thoroughly explained the programme to me.

All in all it was a pleasurable experience and I am grateful to have had this opportunity. Thank you again.

Am I due to receive feedback from you with the results you obtained?

I wish you well with your continued research.

16. Female 50 years (e-mail 14/09/2016)

Physio exercises after knee replacement were just to do as and when they fitted into your day, the walking programme was easy to include all day every day. I learnt to walk with longer strides and found that I was walking with more confidence, I am walking much further than I have for the last few years. I have now got a Fitbit so I can continue to improve the distance that I walk, Yelena was so encouraging with me, giving me the confidence to walk more, the pain in both knees is significantly improved and I don't feel as though I need to have quiet times to get over a busy day because of pain.

17. Male 64 years (letter 19/09/2016)

Dear Yelena,

Firstly I would like to say it was a pleasure to assist you in this very focused and important work, which brings very positive benefits not only to patients, but to the surgeons that carry out the knee replacement operations.

1. *I found the 5-week assessment very useful because, before I started the trial I had a problem walking up stairs and I did not feel confident in doing that particular exercise when necessary – however, when I committed to the programme I started to feel more confident and my left knee became stronger and a lot of the pain I felt became less the stronger my left quad and calf got.*
2. *Following the schedule I was given made me stronger more confident in walking both on the flat and when walking up inclines.*
3. *I also noticed that my left knee became less painful, during the trial it was also pointed out to me that my Gait needed to be lengthened, because I was swinging my leg from the hip which resulted in hip pain. I am glad to say that this now gone.*
4. *This type Physiotherapy differs from other Physiotherapy, because all geared to strengthening the Quad muscles, which in turn takes a lot of pressure off of the knee, and it lessens the pain in the knee joint.*
5. *I also learned how to walk correctly and to make sure I did not walk swinging from my hip.*

6. *One important thing I also learned was that comfortable footwear is imperative.*
7. *I now have less pain in my knee in fact it feels normal.*
8. *I also have NO pain in walking longer distances.*
9. *Yes before being involved in the programme I wasn't able to stretch my left hamstring because it was very tight and stiff this has also become very subtle (supple!).*
10. *I found Yelena very encouraging and helpful and very approachable.*
11. *I also gained additional information in understanding the overall working of my knee and hip joint.*
12. *Yes I feel very confident and I am able to train and work the programme on my own.*
13. *This programme only gives you great results if you commit 100% to it.*

Best wishes.

18. Male 72 years (e-mail 23/09/2016)

Hi,
As regards feedback :
I am walking with my head up and taking slightly longer strides, this is becoming easier as I am getting more used to it.
I am combining walking up hills on the flat and upstairs, some days I do a lot more than others, time permitting .I have reached 1& half hours now but a more average walk for me is 40/50 minutes .
I did not have much Physio as I was walking well and I had good bending movement I just maintained the exercises and tapered them off after 3 months.
I quite enjoy walking and feel good about it and I feel safe and confident in my abilities.
I definitely feel that I am benefiting from this programme and will try to extend my distances which at the moment on a long days walk I have got up to 3.4 miles.
I am just about to go on this mornings walk.

19. Male 60 years (e-mail 27/09/2016)

hi yelena a few words on my 5 week programme. i did enjoy the extra walking that came with trying to do abit moore each day i did feel the real benefit for me was the extra stairs and walking uphill as also good for my lungs and building some strength in my thighs . i did find that my knee diid get a bit sore at the end of the day but not painful there did not seem to be any improvement in that even today if i do some extra walking