Gait and postural control after total knee arthroplasty
Science never solves a problem without creating ten more.

George Bernard Shaw
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Abstract

The aim of the thesis was to investigate deficits and compensatory strategies after total knee arthroplasty (TKA) in different conditions during gait and quiet standing.

Although TKA is considered the gold standard treatment for end-stage knee osteoarthritis, it is associated with a number of implications. Reduced physical function after osteoarthritis is partly, but apparently not fully, remedied by surgery. The two most common deficits are reduced knee muscle strength and limited range of knee joint motion (ROM), partly due to mechanics of the prosthesis. Reduced postural control has also been shown shortly after surgery. In spite of sufficient passive knee joint ROM for normal ambulation, gait patterns are characterized by reduced knee flexion. Several factors such as reduced knee muscle strength, reduced proprioception, habitual strategies or fear of movement may be suggested as explanations for difficulties in gait and posture. As an effect, compensatory strategies may result.

In order to focus on the implications of TKA, participants had to be less than 65 years of age and healthy, TKA being the only factor different from controls. The same 23 individuals with unilateral TKA ~ 19 months post-operative and 23 controls participated in all studies. 3D whole body kinematics was used to assess gait and posture and electromyography was used to record muscle activity. Isokinetic measurements were used to determine dynamic knee muscle strength. Gait in the frontal and sagittal planes were assessed. The tasks included in the test protocol were negotiation up and down stairs, gait on hard and soft surface, quiet standing with sensory modulation (with and without vision and on soft surface), and single limb stance. Primary outcome variables addressed were: knee and hip joint kinematics in frontal and sagittal planes, upper body inclination, postural sway and relative knee muscle activity as an indicator of relative effort. Background factors used to explain group differences in the primary outcomes were derived from demographics, clinical examination, and questionnaires. Demographic factors were age, body mass index (BMI), and time since surgery. Clinical examinations were conducted for passive knee joint ROM, joint position sense, knee muscle strength, anterior knee joint laxity, and leg length. Questionnaires assessed fear of movement, pain, and knee related function and quality of life.

The results showed that knee flexion was reduced during stair descent in both the prosthetic and the contralateral knee in the TKA group compared to controls. Although reduced passive knee joint flexion in the TKA group was sufficient for normal stair descent, it was the only factor identified that explained reduced knee flexion in stair descent. As knee muscle strength was significantly reduced in the TKA group, it is reasonable to suggest that as a contributing factor. Furthermore, the TKA
group also displayed increased hip adduction during stair descent, which may indicate both a compensatory strategy as well as reduced hip muscle strength. In stair ascent, no significant group differences were found in relative knee muscle activity as expected due to knee muscle weakness. Nor were there any indications of compensatory forward inclination of the trunk to reduce knee joint moments. Instead, probably compensating for muscle weakness, the TKA group ascended stairs at a significantly slower speed. Surface modulation during level gait showed that reduced knee flexion in the prosthetic knee during the stance phase when walking on a hard surface was further decreased during gait on a soft surface. Knee and hip adduction at the stance phase were not affected by surface conditions. Nevertheless, the TKA group displayed increased knee adduction and hip adduction compared to controls, particularly in the prosthetic side. In addition, the TKA group displayed increased step width on the soft compared to hard surface. Single-limb stance for 20 seconds failed in 30% of the TKA group and in 4% of the control group. Those in the TKA group who were able to perform single-limb stance performed equally well as controls. During bilateral quiet standing, postural sway was similar in both groups, and inability to stand on one leg did not affect bilateral stance. Older age, higher BMI and reduced quadriceps strength are associated with the failure to maintain single-limb stance in the TKA group.

In conclusion, this thesis indicates that reduced knee muscle strength is a common denominator as part of the explanatory factors for reduced performance and compensatory strategies in individuals with TKA. Reduced speed during stair ascent as well as reduced knee flexion during stair descent may be compensations for reduced lower extremity strength. Increased hip adduction may compensate for reduced knee flexion in stair descent, but may also represent hip muscle weakness or reduced motor control as increased hip adduction is found also in level gait. The failure to maintain single-limb stance in the TKA group is also partly explained by reduced knee muscle strength. Muscle weakness may be an indicator for reduced physical capacity in general.
Svensk sammanfattning
Syftet med denna avhandling var att undersöka funktionsnedsättning och kompensatoriska strategier efter total knäartroplastik (TKA) under olika förhållanden, vid gång och i stående.


För att kunna fokusera på de implikationer som uppstår efter TKA inkluderades till studierna enbart friska personer, yngre än 65 år, med TKA samt kontrollpersoner, som inte opererats i knäleden. Samma personer deltog i samtliga studier; 23 deltagare med unilateral TKA ca 19 månader postoperativt och 23 kontroller. 3D helkropps-kinematik användes för att undersöka gång och postural kontroll och elektromyografi (EMG) registrerades för att mäta muskelaktivitet. Dynamisk styrka i knämusklaturen mättes i en isokinetisk dynamometer. Gångmönster undersöktes både i frontal- och sagittalplanet. De uppgifter som var inkluderade i testprotokollet var gång upp och ned i trappa, gång på hårt och mjukt underlag, stående med sensorisk modulering (med och utan syn och stående på mjukt underlag) och stående på ett ben. Primära utfallsvariabler var: knä- och höftkinematik i frontal- och sagittalplanet, överkroppens lutning, posturalt svaj och knämuskelaktivitet som indikator på relativ ansträngning. För att förklara utfallet i de primära variablerna togs ålder, kroppsmasseindex (BMI) och tid sedan operation i beaktande. Kliniska tester innefattade passiva test av rörelseomfång i knäleden, ledpositionssinne, knämuskelstyrka, anterior glidning i knäleden samt benlängd. Frågeformulären undersökte rörelserädda, smärta och knärelaterad funktion och livskvalitet.

Resultaten av studien visade att TKA-gruppen jämfört med kontroll hade nedsatt flexion både i protesknät och det kontralaterala knåtet när de gick nedför trappa. Trots att TKA-gruppen hade tillräckligt passivt rörelseomfång för att kunna gå nedför trappa på ett normalt sätt, så var nedsatt passiv rörelse i knåten den enda faktor som förklarade nedsatt knäflexion vid gång nedför trappa. Eftersom knämuskelstrykan var väsentligt lägre i TKA-gruppen föresläs att muskelsvaghet var en

Konklusionen av denna avhandling visar att reducerad knämuskelstyrka är en gemensam nämnare som bidrar till att förklara nedsatt förmåga och kompenserande strategier vid gång och trappgång hos personer med TKA. Reducerad gånghastighet uppför trappa såväl som reducerad knäflexion i gång nedför trappa indikerar nedsatt muskelstyrka i nedre extremteten. Ökad adduktion i höftleden kan kompensera för reducerad flexion i knät, men kan även indikera svaghet i höftmuskulaturen eller bristande motorisk kontroll eftersom ökad höftadduktion även uppvisades vid gång på plant golv. Även oförmåga att stå på ett ben i TKA-gruppen kan kopplas till muskelsvaghet. Muskelsvaghet kan således vara en indikator på generellt nedsatt fysisk kapacitet hos personer med TKA.
**Abbreviations**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tr>
<td>ACL</td>
<td>Anterior Cruciate Ligament</td>
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<tr>
<td>ADL</td>
<td>Activities of Daily Living</td>
</tr>
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<td>AKL</td>
<td>Anterior Knee Laxity</td>
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<tr>
<td>BMI</td>
<td>Body Mass Index</td>
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<tr>
<td>CoM</td>
<td>Center of Mass</td>
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<td>CPM</td>
<td>Continuous Passive Motion</td>
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<td>DLS</td>
<td>Double limb support</td>
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<td>EMG</td>
<td>Electromyography</td>
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<td>JPS</td>
<td>Joint Position Sense</td>
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<tr>
<td>KOOS</td>
<td>Knee injury and Osteoarthritis Outcome Score</td>
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<tr>
<td>KSS</td>
<td>Knee Society Score</td>
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<tr>
<td>MVCC</td>
<td>Maximal Voluntary Concentric Contraction</td>
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<td>NEMS</td>
<td>Neuromuscular Electrical Stimulation</td>
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<tr>
<td>NRS</td>
<td>Numeric Rating Scale</td>
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<tr>
<td>OA</td>
<td>Osteoarthritis</td>
</tr>
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<td>PCL</td>
<td>Posterior Cruciate Ligament</td>
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<td>PCR</td>
<td>Posterior Cruciate Retaining</td>
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<tr>
<td>PCS</td>
<td>Posterior Cruciate Sacrificing/Stabilizing</td>
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<tr>
<td>PPKF</td>
<td>Peak Passive Knee Flexion</td>
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<td>PKSD</td>
<td>Peak Knee Flexion During Stair Descent</td>
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<tr>
<td>QTM</td>
<td>Qualisys Track Manager</td>
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<tr>
<td>RMS</td>
<td>Root Mean Square</td>
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<td>ROM</td>
<td>Range of Motion</td>
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<td>SLS</td>
<td>Single limb support</td>
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<td>ST</td>
<td>Semitendinosus</td>
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<td>STA</td>
<td>Soft Tissue Artefact</td>
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<td>TKA</td>
<td>Total Knee Arthroplasty</td>
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<tr>
<td>TSK</td>
<td>Tampa Scale for Kinesiophobia</td>
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<tr>
<td>VL</td>
<td>Vastus Lateralis</td>
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Original papers

This thesis is based on the following papers, referred to by their roman numerals:


The original articles are reprinted in this thesis with kind permission from the respective publishers.
1 Introduction

Total knee arthroplasty (TKA), where damaged cartilage and diseased structures are replaced with new artificial parts, is considered the gold standard treatment for end-stage knee osteoarthritis (OA). During the past 45 years, knee joint replacements have undergone huge improvements. The joint replacements from the early 1970s were plagued by failure due to gross simplifications of the knee joint anatomy with a non-physiological articular surface loading that resulted due to excessive articular surface conformity (1). There was a lack of understanding of the asymmetrical nature of knee loading patterns during weight bearing (2). However, the modern TKA (Fig. 1) is considered a successful intervention with 90% of patients at long-term follow up reporting reduced pain and improved functional ability after the surgery and 85% of the individuals with TKA are satisfied with the outcome (3). Despite these improvements, patients continue to exhibit long-term functional deficits (2) and to report difficulties with lower limb function during activities of daily living (ADL) (4, 5).

Figure 1. NexGen TKA. Left: frontal plane. Right: sagittal plane. With kind permission from Professor K. G. Nilsson, Surgical & Perioperative Sciences, Umeå University Hospital.
1.1 Total knee arthroplasty

1.1.1 Prevalence of OA and TKA

Current estimates indicate that prevalence of osteoarthritis (OA) will be doubled by the year of 2020 and is predicted to be the single greatest cause of disability in the general population in 2030 (6, 7). A Norwegian population survey identified the overall prevalence of OA to be 12.8%, with a higher prevalence among women, older people, those with low financial income and unemployed, as well as those who are obese (8, 9).

The term osteoarthrosis and osteoarthritis are both commonly being used when describing joint degeneration. The “-itis” suffix indicates quantitatively variable inflammation present in each phase of the disease. However, as we are unable to proportionally quantify the inflammatory aspect and pathogenically-damaging agents, we are still not able to answer what term is better, arthrosis or arthritis. However, it should be mentioned that English-speaking countries, contrary to Norway and Germany at least, choose to call OA with the “itis” suffix even perhaps without inflammatory agents present (10). In this thesis, I will be using the term osteoarthritis, as it is a more common concept in the English language.

The Annual report of the Norwegian arthroplasty register (11) revealed that 4,526 knee prosthesis (all types) surgeries were performed in 2011 with an average patient age of 68.9 years. In Norway, there has been a gradual increase in the number of TKAs since 1994 when the registrations first took place. In comparison, there were 995 knee prosthesis surgeries in 1994. The national register for joint prostheses in Norway stated that 53.8% of all knee prosthesis surgeries were done on the right side and that 68.9% of all knee prosthesis surgeries were done on women. Interestingly, the numbers of surgeries performed for the age range 70-79 years has declined steadily since 1994 from around 50% to 35% of all surgeries in 2011, whereas the number of surgeries for the age range between 60-69 years has increased from 1994 from around 27% to 35% in 2008. The Swedish knee arthroplasty register reports the average patient age of knee prosthesis surgery to be 69 years in 2008, also a decline in age since 1994. This indicates that individuals with TKA are only getting younger. This dramatic increase cannot be fully explained by growth in population size or obesity epidemic, suggesting other factors as for instance a growing number of knee injuries and perhaps earlier doctor referral could account for this increase (12). The Norwegian arthroplasty register states the main reason for the primary surgeries of TKAs in Norway in 2011 was idiopathic arthritis with 3,613 surgeries, next comes sequela after meniscal injury (n=260), rheumatoid arthritis (n=160), sequela after ligament injury (n=133), and sequela after fracture (n=114) (11).
1.1.2 Implant systems

There are a number of different models and designs of knee prostheses available to surgeons. Each design varies slightly from the other and makes different claims regarding function and performance (13). There are mainly two different design characteristics that warrant special attention; one is related to mobility of the polyethylene tibial insert, and the other relates to whether the posterior cruciate ligament (PCL) is retained or sacrificed.

**Fixed bearing- vs. mobile-bearing tibial insert**

The main difference between these two designs attributes to the mobility of the polyethylene tibial tray between the femur- and tibial component. In the fixed-bearing design, the tray is fixated to the tibial plateau allowing no rotation, whereas in the mobile-bearing a certain degree of axial rotation is permitted. Initially, it was suggested that the mobile-bearing design would result in more normal knee kinematics (i.e. axial rotation of tibia during knee flexion/extension) (14). However, no difference in knee flexion (sagittal plane) range of motion (ROM) has been found. In addition, Knee Society Score (KSS) and pain were similar between these designs (15, 16).

**PCL retaining vs. PCL sacrificing**

In the posterior ligament sacrificing (PCS) design, there is a tibial spine that interacts with a femoral cam to provide anterior-posterior stability that initially was developed to provide a more normal femoral roll-back compared to the posterior ligament retaining (PCR) method (13). Joglekar et al. (17) found no difference between PCR and PCS in lower limb kinematics or kinetics during walking, stair ascent or descent. Another study found more forward displacement of the tibiofemoral contact area in flexion during stair negotiation in PCR compared to PCS. This was attributed to insufficiency of the posterior cruciate ligament (PCL) (18). The anterior cruciate ligament (ACL) and PCL are important structures in controlling knee joint laxity and restraining the tibia from anterior and posterior translation relative to the femur. The mean anterior laxity of healthy knees is reported to be 5.7 mm (19). The optimal anterior laxity in PCR TKAs is between 5-10 mm according to Jones et al. (20) in regard to function by Knee Society Score (KSS) (21). No studies have found a difference in the survivorship, patient’s perceived outcome or joint proprioception between these two designs (18, 22-24).

In addition to the two main different designs mentioned, there are also total knee prostheses with and without patella component (only cartilage replacement), and unicompartmental designs. The most commonly used type of knee prosthesis with 87.7% (n=4,281) surgeries in Norway in 2012 is the total knee prosthesis without a patella component (11). This is similar to statistics from the Swedish knee arthroplasty register (25). Unicompartmental
prosthesis is the second most common type (9.4%, 458 surgeries) in 2012 in Norway.

In Trondheim and the Mid-Norway Health District, the Duracon prosthesis from Stryker was primarily used around 2008 (annually 270 TKAs). This type of prosthesis with its features (PCL retaining, fixed bearing without a patella component) represents the most widely used TKA in Norway in 2012 according to The Annual report of the Norwegian arthroplasty register (11). The high prevalence of this type of design makes it clinically interesting on which to conduct research.

Yong et al. (26) assessed the midterm outcome of the Duracon TKA, and found good clinical results with the absence of patello-femoral complaints. There were no revision surgeries 5 years after surgery. The mean range of passive knee flexion was $102^\circ \pm 13.4^\circ$ (26), which is expected, opposed to $144^\circ \pm 6.5^\circ$ in healthy knees (27). The mean tibiofemoral valgus angle in the operated limb in individuals with TKA (mixed genders) was $6^\circ \pm 3^\circ$ (26). In healthy men and women, the tibiofemoral valgus angle is found to be $9.2^\circ \pm 2.6^\circ$ and $10.9^\circ \pm 2.7^\circ$, respectively (28). There was no implant malposition or third body suggestive of polyethylene wear. Also, there was no aseptic loosening at minimum 5 years of follow-up, and compares favorably with others studies of modern TKAs (26). Infection rates were significantly lower in the Duracon than in any other brands after analysis of 29,946 TKAs without patellar button from 1993 to 2002 in Sweden (25).

1.1.3 Pain
It has been found that 94% of patients reported no or only mild pain with a mean 8.5 years after surgery (26). It is useful to divide the causes of the painful TKA in referred (often related to spinal pathologies), periarticular (IT-band irritation/inflammation, pes anserinus bursitis), and articular pain (abnormal patellar tracking, malpositioned tibial/femoral components) (29). Though most of these causes of pain are treated with physiotherapy, others need a surgical approach. As pain certainly will impose consequences for the TKA patient, it is however considered an unusual complication despite several reports on this challenging clinical issue (30). Bourne et al. (31) reported in a cross-sectional study that 72% of individuals with TKA were satisfied with their ability to negotiate stairs in regards to pain. Despite the low prevalence of pain after TKA, ambulation is often characterized by a pattern described in the literature as “quadriceps avoidance gait”; an adaptation developed pre-surgery due to pain with OA (32).

1.1.4 Postoperative rehabilitation
The treatment after TKA is conservative with respect to referral to physiotherapy, which involves various interventions based on seemingly sound theoretical rationale. These range from strength training,
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stretching, hydrotherapy, neuromuscular electrical stimulation (NEMS),
active and passive range of motion exercises, CPM (continuous passive
motion), and balance training (33-35). These treatments are used to
restore function, improve performance, increase mobility and strength,
and alleviate pain. A high frequency of treatment modalities without
evidence-based foundation has also been reported in a Dutch survey (36).
A review performed by Pozzi et al. (35) concluded that progressive
exercise is critical after TKA. They found that strengthening and intensive
functional exercises produced the most optimal results. Moreover,
 supervised or remotely supervised therapy was more effective than
studies without direct oversight from a physiotherapist. It is important
for physiotherapists to evaluate each TKA patient individually, as the
degree of physical function, fear of movement, time since surgery, pain,
strength, range of motion, age, and contralateral knee status differ across
this patient group. Hence, a thorough physical assessment in order to
identify which treatment modality and exercise regimen that should be
effectuated is important. Nevertheless, research agrees on improved post-
operative strength, function, and outcome expectations are followed by
improved pre-surgery status (37, 38). This emphasizes the importance of
an intensive exercise regimen in the time leading up to surgery.

There are no documented universally standardized guidelines or physical
restrictions for post-operative TKA rehabilitation and physiotherapy.
Even though research identifies the most common implications after TKA
to be decreased quadriceps strength and knee joint ROM (39), the whole
picture is not drawn as, for instance, when kinematic and kinetic aspects
of functional activities are performed.

The psychological aspect of the postoperative rehabilitation is rarely in in
focus. Sullivan et al. (40) did, in a 1-year follow-up, an assessment of
psychological determinants after TKA to see if there are correlations
between fear and physical function, and found pain-related fears of
movement by the Tampa Scale for Kinesiophobia (TSK) to predict post-
surgical functional difficulties following TKA. TSK was developed initially
to quantify movement-related anxiety in low back pain but has proved
valid in TKA studies as well (40). The use of task-oriented exercises,
together with the control of kinesiophobia, may be an innovative
approach to TKA rehabilitation in an attempt to overcome barriers to full
recovery. This may have added value over functional interventions. A
broader treatment perspective based on bio-psychosocial principles
should be suggested after discharge in order to address the patient’s
individual concerns (beliefs, fears, and worries) (41).

1.1.5 Social economy
Total knee arthroplasty has great impact on the social economy, and is a
considerable burden with lost days of work and early retirement (42). To
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identify patient function and working capacity, working status and sick leave was identified 2 years before and 2 years after primary knee arthroplasty in a Swedish study. More than 70% of the patients still working pre-surgery returned to work within 2 years after TKA surgery (42). Preoperative sick leave longer than 180 days was found to increase the risk of postoperative disability pension. In addition, progressive impairment in work motivation induced by the disability pension was suggested to be an important factor (42). Due to the large amount of individuality in age, type of work, overall fitness and physical capacity expressed within this group of patients, it is impossible to recommend a given period of sick leave (43). However, with the documented benefits obtained from physical activity, it is imperative from a public health perspective that patients are sufficiently active to maintain health following TKA. Physical activity is an efficient and cost-effective mechanism for improving health and reducing health care costs within this patient group (44). This suggests the importance of having great focus and intensity in the rehabilitation process the first 6 months after a TKA to help patients return to their preoperative working status.

1.2 Implications after TKA

When utilizing the "logical framework approach" (45) to structurally identify the implications of TKA, we first start with the focal problem which is the prosthesis itself. There are a number of causes to which such a surgery is necessary. It is often a direct consequence of pain and reduced function due to osteoarthritis (OA) (46). OA is caused by, amongst others, idiopathic reasons (11), meniscal injuries (47), old age (9, 48), poor diet and obesity (49, 50), genetic predisposition (51), and occupational reasons (52). After the surgery, a number of implications are also observed. Several of these are probably an effect of being exposed to OA for a longer period of time. These are asymmetrical gait patterns (32), pain (26, 31, 53), muscle weakness (54-57), ADL-limitations (58), mobility and range of motion problems (59), instability (60), poor balance and risk of falling (61, 62), fear of movement (40), limb length discrepancy (63, 64), obesity (65-67), and prosthetic loosening (68, 69). Eventually, the risk of contralateral OA (70) and ultimately contralateral TKA (71) appears as a consequence of the above mentioned implications. For the subjects’ own self-perceived outcomes after TKA, the questionnaire Knee injury and Osteoarthritis Outcome Score (KOOS) to assess pain, symptoms, activities of daily living, sport and recreation function, and knee-related quality of life, has reported decreased scores on all subscales in individuals with TKA (72, 73).

In this thesis, I chose to investigate how important functions such as gait and postural control are implicated after TKA, and this will be further elaborated on below.
1.2.1 Gait function

A number of asymmetries are observed in individuals with TKA. Kinematically, reduced peak knee flexion in level gait and stair negotiation, in both stance and swing phase, and increased knee adduction in the contralateral side compared to prosthetic side and to controls are well known (74-81) (Table 1). Some of these asymmetries, especially the reduced peak knee flexion observed during gait may likely be related to the reduced passive ROM following TKA, due to both the mechanics of the prosthesis and the pre-surgical condition with long periods of OA pain leading to flexion contractures (26, 82). Schiavone Panni et al. (83) reveals that there are both pre-operative and post-operative conditions limiting the passive ROM. Pre-surgical factors include pain and habitual gait patterns (79, 84). Post-operative factors also include pain and habitual gait patterns, and also infections, arthrofibrosis, heterotrophic ossifications, errors in soft-tissue balancing, component malpositioning, incorrect component sizing and incorrect rehabilitation protocol (85). As anterior knee laxity of the TKA-knee might differ amongst individuals with TKA, studies have assessed, and found no correlation between postoperative ROM and laxity or between the Knee Society Score (KSS) (20, 86, 87).

Normal ROM for a healthy knee ranges from 0° to 144°, while a knee ROM from 0° to 110° after TKA can be defined as a good result (27, 83), even if a lower ROM (5°–95°) is sufficient for daily activities (83). There is no difference in flexion before or after TKA between rheumatoid and osteoarthritic knees (59). Different studies have found that walking on level surface requires 45°–65° of flexion depending on gait speed (88, 89).

A paradox between gait and ROM appears when individuals with TKA who show more than adequate flexion properties for efficient and unrestricted walking still seem to show asymmetric flexion during gait. Milner (32) sums up the results in her review article with the conclusion that prosthetic knee flexion was restricted throughout all the 10 studies investigated. In contrast, there are also studies displaying symmetric and equal lower limb gait kinematics between individuals with TKA and healthy controls (90). As individuals with TKA are not a homogenous group, with ages ranging from the early 40s to late 80s, with different degrees of pain, and different pre-surgery physical states, it is no surprise that studies display different results. Milner (32) further explains the paradox of reduced prosthetic knee flexion during gait despite sufficient passive ROM by saying it may be a consequence of quadriceps avoidance gait, which is common in individuals with knee pain. Quadriceps avoidance gait, characterized by reduced knee flexion, may have been developed as a compensation to minimize pain in the affected knee due to OA. This pre-surgery pattern of walking may be retained as habitual and prevail after surgery even though the pain is reduced or gone. In a longitudinal pre- and post-surgery study, it was shown that pre-surgery
gait patterns were retained up to 18 months after surgery (53). Another study has shown that knee flexion at stance phase was still decreased after 46 months (79). Other studies hypothesized that compromised proprioception could be responsible for the decrease in ROM during level walking despite functional passive ROM (79, 84). The mechanisms behind the deviant walking patterns as such may be multi factorial and depend not only on reduced knee ROM, but also on factors such as habit, muscle weakness, kinesthesia and pain.

Not only the kinematics of the knee joint is altered after TKA, hip kinematics also seem to be affected due to proximal muscle weakness, reduced knee ROM or reduced motor control during gait. Studies have reported decreased hip extension and a tendency toward increased hip flexion in individuals with TKA in the stance phase compared to controls (91). Without full knee extension, they might need to reduce their hip extension to maintain balance (91). Hip kinematics in the frontal plane is however not assessed to our knowledge.

A systematic review (32) explains that abnormal gait patterns may predispose the individual to further joint degeneration, particularly in the contralateral knee. Alnahdi et al. (74) found increased knee adduction angle in the contralateral side and proposes this to be an important contributor to contralateral OA in individuals with unilateral TKA. This is reasoned due to increased medial side loading, and thus less compression force distribution to the lateral side. In fact, there is a 37.2% risk of a contralateral TKA in the next 10 years after primary TKA (70).

The spatiotemporal variables such as single-limb stance (SLS) time, double-limb stance (DLS) time, and speed during gait in individuals with TKA have also been found to be affected. SLS is when body weight has to be entirely supported by one limb while the other limb swings forward (92), and is considered a critical locomotor sub-phase where specific locomotor adaptations are used to compensate for residual impairments after the TKA surgery (93). Some studies have found shorter SLS time on the prosthetic side compared to the contralateral side (75, 78, 92), others found shorter SLS time in the prosthetic side compared to the control group (94). DLS when both feet are in ground contact is strongly related to speed, as increasing speed will lead to decreased DLS. Increased DLS and decreased speed (self-selected) has previously been found in individuals with TKA compared to controls (94, 95).

All known kinematic studies to assess gait in individuals with TKA have been performed on a hard surface. Natural conditions may however lead to different strategies. In an active life-style, people will encounter different surfaces, for instance when hiking off track. Reduced gait speed on a soft surface has been reported in healthy young and old people compared to a hard surface (92, 96).
Introduction

Gait function during stair negotiations also addresses some of the same issues as level gait for individuals with TKA. Scuderi (88) studied ROM in stair walking and found that 90° of flexion is required to descend stairs in healthy people. Others have stated that ascending or descending stairs require about 85° (89). However, the degree of knee flexion is dependent on leg length, as shorter subjects ascend stairs with greater peak knee flexion angles than taller subjects (97). This could explain some variability among different studies. Descending stairs has been shown to require larger knee flexion than ascending stairs (98). Knee flexion in stair decent has been shown to be decreased in individuals with TKA compared to the contralateral side and to healthy controls (77, 79-81). Although knee flexion is restricted due to the mechanics of the prosthesis (26), stair studies show that the ROM leaves a margin of 6-16°, theoretically permitting sufficient knee flexion for normal stair descent (77, 79, 99). Although the underlying mechanisms behind this paradox are uncertain in both level gait and stair negotiation, it would be possible to stress differences between the sides and groups more clearly in stair negotiation than level gait with increased demands on strength and ROM (100). A systematic review has synthesized the available evidence of factors that could possibly affect stair climbing ability in subjects with OA and TKA (101). Stronger lower limb muscles and less knee pain were related to greater stair-climbing ability in OA subjects, however, for the individuals with TKA, higher body weight was suggested as a factor influencing stair-climbing ability, yet the evidence related to strength and pain were scarce and more extensive research was suggested. Nevertheless, reduced quadriceps strength can be compensated for by leaning the upper body forward, thus reducing extension moments around the knee joint, which again makes stair climbing less demanding (102, 103). Furthermore, with varying degree of pain within individuals with TKA both pre- and post-surgery, it is therefore possible, indirectly or directly, that pain could affect the kinematic characteristics during both level gait and stair negotiation.
Table 1. Studies on gait function in subjects with TKA.

<table>
<thead>
<tr>
<th>Author</th>
<th>Main aim</th>
<th>TKA design</th>
<th>TKA/CTRL</th>
<th>Months post-surgery</th>
<th>Age TKA/CTRL</th>
<th>Pain assessed</th>
<th>BW TKA/CTRL</th>
<th>Results TKA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alnandi et al. (2011)</td>
<td>Gait</td>
<td>-</td>
<td>55/20</td>
<td>6-12</td>
<td>66/63</td>
<td>Yes</td>
<td>90/85</td>
<td>Increased knee adduction angle contralateral side. Reduced knee flexion stance and swing. Reduced knee flexion mid stance.</td>
</tr>
<tr>
<td>Benedetti et al. (2003)</td>
<td>Gait</td>
<td>PCR</td>
<td>9/10</td>
<td>6, 12 and 24</td>
<td>66,1</td>
<td>Yes</td>
<td>70,3/-</td>
<td>Reduced knee flexion stance and swing.</td>
</tr>
<tr>
<td>Fuchs et al. (2003)</td>
<td>Gait</td>
<td>PCR</td>
<td>12/-</td>
<td>16</td>
<td>68,6</td>
<td>Yes</td>
<td>-</td>
<td>Reduced knee ROM in gait and stair negotiation</td>
</tr>
<tr>
<td>Jevsevar et al. (1993)</td>
<td>Gait (level and stairs)</td>
<td>-</td>
<td>11/10</td>
<td>12-19</td>
<td>68,6/52,5</td>
<td>No</td>
<td>64/72</td>
<td>Reduced knee flexion in stair ascent.</td>
</tr>
<tr>
<td>Kramars-deQuervain et al. (1997)</td>
<td>Gait</td>
<td>-</td>
<td>5/-</td>
<td>24-60</td>
<td>75/-</td>
<td>Yes</td>
<td>88/-</td>
<td>Reduced knee ROM in gait.</td>
</tr>
<tr>
<td>Mandeville et al. (2006)</td>
<td>Gait (level and stairs)</td>
<td>PCR</td>
<td>21/21</td>
<td>6</td>
<td>63,7/62,8</td>
<td>No</td>
<td>88/75</td>
<td>Reduced knee flexion in stair ascent.</td>
</tr>
<tr>
<td>Wilson et al. (1998)</td>
<td>Gait (level and stairs)</td>
<td>PCS</td>
<td>16/16</td>
<td>46</td>
<td>69/68</td>
<td>No</td>
<td>82/72</td>
<td>Reduced knee flexion stance and swing.</td>
</tr>
</tbody>
</table>

TKA = total knee arthroplasty, CTRL = control group, BW = body weight, ROM = range of motion, PCR = posterior cruciate retaining, PCS = posterior cruciate sacrificing, DLS = double limb support, SLS = single limb support.
1.2.2 Muscle function

Several studies show there is a decrease in quadriceps and hamstring strength after TKA compared to the contralateral leg and compared to healthy controls (54, 55, 104) (Table 2). These strength deficits are attributed to neural activation problems and muscular atrophy, as well as biomechanical asymmetries (105-107), and appear already during OA due to inactivity with painful ambulation (108, 109). Positioning of the tibia relative to the femur also affects muscle function in degenerative arthritis (110, 111). Factors such as implant design, method of surgery, and anatomical alignment post-surgery may vary and give muscle groups more or less mechanical advantage than was available pre-surgery (100, 110, 112). Studies have found that quadriceps strength rarely ever reached the same level as in age-matched healthy individuals after surgery (54, 55). In fact, quadriceps and hamstring weakness is often persistent years after knee replacement surgery with a reduction of 40% and 35% respectively, compared to healthy age-matched groups (4).

As heavy demands are placed on the knee joint during stair negotiation, the work of surrounding muscle groups becomes much more important as opposed to gait on flat surface where knee ligaments are tauter and providing more of a stabilizing function. Consequently, hamstring and quadriceps must take primary responsibility for knee joint stabilization while still performing locomotor functions (113). During stair ascent, following the foot strike, the quadriceps contract concentrically in order to extend the knee. During the extension after the contralateral toe-off, the weight of the body must be raised up and over the stance foot with high levels of quadriceps activity (113, 114). In stair descent, the quadriceps are not battling gravity as in ascent, but rather contributing to progression. Therefore, the quadriceps’ primary task during stair descent is eccentrically to counteract flexion in the stance leg.

Yoshida et al. (56) found increased kinematic gait symmetry with increased quadriceps strength. To further reinforce the importance of good quadriceps strength, Mizner et al. (115) revealed that quadriceps strength prior to surgery is a strong predictor of functional performance one year after surgery. As many studies already are conclusive in relation to loss of strength of the prosthetic knee, it is important to include the pre-surgery status as an explaining factor for different outcome measures after TKA. As quadriceps strength asymmetries decrease in time after TKA, there are concomitant symmetrical improvements in kinematic, spatiotemporal and kinetic gait parameters. However, this is hypothesized to be attributed to a progressive decline in contralateral quadriceps strength (90), which again would lead to an overall reduction of physical function and performance. A quadriceps strength level and kinematic behavior more similar to that of healthy controls should set the standard of what to aim for after TKA.
Introduction

A number of studies show that muscle activity changes after TKA (Table 2). Increased quadriceps recruitment of the prosthetic side compared to the contralateral has been found during both stair climbing and level gait (116, 117), however, no interlimb hamstring recruitment difference was discovered (116). Greater relative quadriceps muscular effort in the prosthetic leg compared to the contralateral leg in individuals with TKA during level gait has been found by comparing average EMG activation values with maximal EMG activation values (118). Further explained; increased relative EMG activity equals increased utilization of total capacity. In a study comparing elderly and younger individuals without TKA (119), it was shown that bilaterally weakened quadriceps affected the ability to perform activities such as ascending stairs by requiring a substantially greater effort evidenced by higher relative EMG activity. The implications for older subjects may be slower execution times and higher risk of falling as they use more work relative to their maximal capacity (119). When there is a quadriceps weakness pronounced more to one side as in unilateral TKA, Mizner et al. (107) found not only that the prosthetic knee had lower peak torque production during strength assessment, but individuals with TKA performed the sit-to-stand task with relatively lower levels of quadriceps muscle recruitment in the prosthetic limb. Those individuals with weaker quadriceps used the contralateral limb in a compensatory fashion to complete functional tasks. It was hypothesized that less loading and lower muscle activity in the prosthetic side may be limiting the stress necessary to create enough stimuli for strength gain (120). Regarding knee muscle strength, there is more focus in the literature on quadriceps strength after a TKA rather than hamstring strength, as quadriceps are more vital in functional activities such as stair negotiation and walking shown by increased EMG amplitude (113).

As mentioned previously, individuals with TKA have been found to walk with a smaller range of knee-joint motion and hence a reduced knee extension moment during stance compared to healthy control subjects (121, 122). Li et al. (102) examined the mechanics behind this "quadriceps avoidance" gait pattern, and found that the vastii was contributing less to the extension moment developed about the knee during early stance. There was a decrease in the contribution of the vastii to the vertical acceleration and forward deceleration of the COM during early stance. The individuals with TKA compensated for this deficiency by leaning their trunks forward. The same distinctive compensatory pattern of movement to reduce the quadriceps demand during stair climbing in patients with osteoarthritis (OA) by increasing forward trunk lean as well as slower walking speed has been described previously (123).
Table 2. Studies on strength and muscle activation in subjects with TKA.

<table>
<thead>
<tr>
<th>Author</th>
<th>Main aim</th>
<th>TKA design</th>
<th>TKA/CTRL</th>
<th>Months post-surgery</th>
<th>Age TKA/CTRL</th>
<th>Pain assessed</th>
<th>BW TKA/CTRL</th>
<th>Results TKA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Berth et al. (2002)</td>
<td>Muscle activation</td>
<td>-</td>
<td>50/23</td>
<td>33</td>
<td>65.8/63.2</td>
<td>Yes</td>
<td>31/26 (BMI)</td>
<td>Decreased quadriceps muscle activation compared to healthy controls</td>
</tr>
<tr>
<td>Lester et al. (2013)</td>
<td>Muscle activation</td>
<td>PCR</td>
<td>7/-</td>
<td>24</td>
<td>73/-</td>
<td>No</td>
<td>33 (BMI)</td>
<td>Increased quadriceps demand in prosthetic side</td>
</tr>
<tr>
<td>Mizner et al. (2005)</td>
<td>Strength/ function</td>
<td>-</td>
<td>40/-</td>
<td>45</td>
<td>63/-</td>
<td>Yes</td>
<td>29 (BMI)</td>
<td>Preoperative quadriceps strength predicts 1-year stair climbing speed.</td>
</tr>
<tr>
<td>Stevens-Lapsley et al. (2009)</td>
<td>Strength</td>
<td>PCS</td>
<td>30/15</td>
<td>3 and 6</td>
<td>64/66</td>
<td>Yes</td>
<td>30/27 (BMI)</td>
<td>Decreased quadriceps and hamstring strength compared to contralat. and controls.</td>
</tr>
<tr>
<td>Yoshida et al. (2008)</td>
<td>Strength/ function</td>
<td>-</td>
<td>12/12</td>
<td>3 and 12</td>
<td>61/62</td>
<td>No</td>
<td>86/84</td>
<td>Increased symmetrical gait with increased quadriceps strength.</td>
</tr>
<tr>
<td>Yoshida et al. (2013)</td>
<td>Muscle activation/ strength</td>
<td>-</td>
<td>21/14</td>
<td>12</td>
<td>63/84</td>
<td>No</td>
<td>31/30 (BMI)</td>
<td>Decreased strength gives higher muscle activation.</td>
</tr>
</tbody>
</table>

TKA = total knee arthroplasty, CTRL = control group, BW = body weight, BMI = body mass index, PCR = posterior cruciate retaining, PCS = posterior cruciate sacrificing, DLS = double limb support, SLS = single limb support.
1.2.3 Postural control

Standing balance within 6 months after TKA is improved compared to pre-surgery status (24, 124), yet altered sensory output and motor functions are still persistent and decreased among individuals with TKA. Postural control has previously been examined in the literature (Table 3) and decreased static and dynamic postural control are found in subjects with both TKA and OA (78, 125). More specifically, postural sway has shown both increased medio-lateral amplitude and average velocity in individuals with TKA compared to controls (126). This increased frontal plane instability is also in accordance with other studies that have assessed aging and pathology (127, 128). Studies have found that decreased ability to maintain frontal plane stability is associated with increased fall risk (129). Furthermore, reorganization of equilibrium as a control strategy shows that voluntary laterally directed stepping is decreased in individuals with TKA (130), which again could lead to increased risk of falling. In addition, a history of falls prior to surgery is found to be a risk factor for similar accidents within 1 year after TKA (62).

When assessing postural control, most studies have only looked at postural sway bilaterally. Although single-limb stance and bilateral stance have been assessed in the same cohort after TKA surgery, single-limb stance was performed only on the operated limb and bilateral stance was assessed only before surgery (131). One study found that both the TKA side and the contralateral side demonstrated reduced quadriceps muscle activity and kinematic response to a perturbing platform compared to healthy age-matched individuals (132). In patients with anterior cruciate ligament injury, increased anterior knee laxity, poor proprioception and strength play a role in maintaining balance in single-limb stance (133). With bilateral tests, it is difficult (requires two force platforms) to quantify how each side contributes to maintain balance. It has been found that the majority of individuals with TKA put more weight on the prosthetic limb in bilateral stance, suggesting symptomatic OA development in the contralateral side. However, this study was conducted on older individuals with TKA with possibly increased OA development compared to a younger TKA population (134). One study has also found the opposite, with increased weight bearing on the contralateral side, however, this could presumably be explained by testing performed a very short time after the prosthetic surgery (1 week) (135). Again, other studies have not found such weight bearing differences between sides in individuals with unilateral TKA (124). As the populations with TKA are generally older (136) and often have higher BMI (137), postural control may be affected. However, other factors contributing to asymmetries in postural sway may be reduced muscle strength (56) and reduced joint position sense (JPS) in the prosthetic knee and contralateral knee. Thus, several factors alone or in combination may contribute to asymmetries in gait as well as single-limb stance or postural control during quiet standing. An understanding of the performance in single-limb balance in
individuals with TKA may be useful in assessing the risk of falling. In addition, if increased single-limb balance time is associated with increased single-limb support time during gait, it could help warrant single-limb balance training to achieve increased gait symmetry.

1.2.4 Kinesthesia
Joint position sense (JPS) as part of proprioception and kinesthesia has previously been examined in the literature (Table 3). Reduced JPS in the prosthetic knee and contralateral knee is also suggested to impact postural control (138). Barrett et al. (25) found JPS of the prosthetic side to be decreased compared to healthy controls. There are no differences in JPS between retaining (PCR) or sacrificing (PCS) the PCL (24), which suggest other structures are responsible for the decreased joint kinesthetics in individuals with TKA compared to healthy controls (139).

The anterior cruciate ligament (ACL), articular cartilage and menisci as well as other intra-articular structures of the knee joint, contain proprioception receptors (140, 141). However, during TKA many of these structures are resected as part of the surgery. Nevertheless, additional receptors are located outside the capsule and in soft tissue surrounding the joint (e.g. muscle spindles and golgi tendon organs). As these proprioceptive receptors are retained, they would partially compensate for the loss of proprioceptive capabilities found in the resected structures (142). Studies have also found age to have deleterious effects on JPS, although regular exercise can attenuate that age-related decline (139, 143).

For assessing proprioception by measuring threshold levels for the perception of passive knee ROM, Pap et al. (144) conducted a study that showed a marked loss of the perception of passive motion after a TKA, compared to the contralateral knees with early arthritis and compared to asymptomatic knees, by hypothesizing that the removal of intra-articular structures contribute to the loss of sense of movement. However, these changes apparently did not contribute to the loss of a good clinical outcome as the patients scored high in examinations yielded by good or excellent scores in amongst the Knee Society Score (KSS), which measures parameters as pain, ROM, varus/valgus alignment, antero-posterior/medio-lateral stability, as well as function concerning walking and stair climbing. In sum, there were no correlations between the KSS sub-scales and the ability to perceive passive motion. When evaluating differences in angle reproduction, Fuchs et al. (145) found reduced proprioceptive capabilities to be present after TKA in both the prosthetic and contralateral knee compared with healthy controls, especially in 60 degrees. This is considered a “loose-packed” position of the knee joint where the instability is at its greatest. The loss of muscle receptors, because of muscle deconditioning or an injury of the ligament receptors, might explain reduced proprioceptive capabilities.
Table 3. Studies on postural control and kinaesthesia in subjects with TKA.

<table>
<thead>
<tr>
<th>Author</th>
<th>Main aim</th>
<th>TKA design</th>
<th>TKA/CTRL</th>
<th>Months post-surgery</th>
<th>Age TKA/CTRL</th>
<th>Pain assessed</th>
<th>BW TKA/CTRL</th>
<th>Results TKA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bascuas et al. (2013)</td>
<td>Balance - 44/-</td>
<td>-</td>
<td>12</td>
<td>71.4/-</td>
<td>Yes</td>
<td>78.5/-</td>
<td>Balance improved after surgery.</td>
<td></td>
</tr>
<tr>
<td>Cho et al. (2013)</td>
<td>Single limb balance PCS 11/-</td>
<td>PCR</td>
<td>64</td>
<td>66/56</td>
<td>No</td>
<td>-</td>
<td>Improved single leg balance after surgery</td>
<td></td>
</tr>
<tr>
<td>Fuchs et al. (1999)</td>
<td>Joint position sense PCR 28/25</td>
<td>64</td>
<td>66/56</td>
<td>No</td>
<td></td>
<td>Reduced proprioception in TKA group.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gage et al. (2008)</td>
<td>Postural control - 8/9 &gt;6</td>
<td>PCR and PCS</td>
<td>15</td>
<td>74/-</td>
<td>Yes</td>
<td>26 (BMI)</td>
<td>Impaired single-limb and bilateral postural control compared to healthy controls.</td>
<td></td>
</tr>
<tr>
<td>Harato et al. (2010)</td>
<td>Standing weight-bearing - 10/-</td>
<td>-</td>
<td>55</td>
<td>60/-</td>
<td>No</td>
<td>-</td>
<td>Decreased knee extension in TKA leads to increased contralateral weight-bearing.</td>
<td></td>
</tr>
<tr>
<td>Pap et al. (2000)</td>
<td>Joint position sense - 15/-</td>
<td>-</td>
<td>8</td>
<td>63/-</td>
<td>No</td>
<td>-</td>
<td>Reduced threshold detection in TKA-side compared to contralateral side.</td>
<td></td>
</tr>
<tr>
<td>Stan et al. (2013)</td>
<td>Postural control PCS 10/-</td>
<td>-</td>
<td>2 days pre and 1 week post</td>
<td>63/-</td>
<td>Yes</td>
<td>74/-</td>
<td>Increased mediolateral displacement and velocity.</td>
<td></td>
</tr>
</tbody>
</table>

TKA = total knee arthroplasty, CTRL = control group, BW = body weight, PCR = posterior cruciate retaining, PCS = posterior cruciate sacrificing
1.3 Rationale for the thesis

A functional ambulation with symmetric gait and good balance, both on different surfaces and in stair negotiation is important for the function in daily activities for post-surgical TKA individuals. Although the TKA surgery is considered a successful intervention after painful OA, there is still reduced ROM, both in gait and stair negotiation. A reduction in quadriceps and hamstring strength is also common, along with reduced postural control. How these factors interact together is clearly an incentive for increased knowledge, and might create a broader picture of the limitations and implications individuals with TKA experience.

By determining which factors limit ROM during an important task such as stair negotiation, and how implications such as muscle weakness affects muscular demand in stair ascent along with compensatory movements, and how varying gait conditions such as a softer surface in line with natural conditions, affects these patients are of importance when designing rehabilitation protocols. If postural control differs in different conditions, to reveal which factors might explain this hypothesized difference could provide additional and valuable clinical information. A deeper knowledge concerning these topics will hopefully provide answers in how clinically to approach this patient group to achieve the best optimal results in important ADL-related encounters demanding gait, stair negotiation and balance. The outcome of the project is important for evaluation of post-surgical limitations after TKA, and the daily challenges these patients meet, their perceived level of knee function and thus quality of life. The results may also be of a socio-economic relevance in relation to costs of medical care and sick leave if a clinical rehabilitation addresses the post-surgery implications more effectively than that currently practiced.
Aims

Aims of the thesis

The overall purpose with this thesis was to investigate gait patterns and postural control, muscle function and compensatory strategies during different conditions in individuals with unilateral TKA ≥ one year to < three years post-surgery in comparison to contralateral side and knee-healthy controls.

Specific aims to investigate:

- Causes to reduced peak knee flexion during stair descent (PKSD) in individuals with TKA compared to healthy controls (Study I).
- If individuals with TKA use a higher percentage of their maximal muscular strength capacity during stair ascent than healthy controls (Study II).
- If individuals with TKA compensate muscle weakness by increased forward lean and slower gait speed during stair ascent compared to healthy controls (Study II).
- If postural sway is increased in both bilateral quiet standing and single-limb stance in individuals with TKA compared to healthy controls (Study III).
- Factors associated with the ability to maintain single-limb stance in the TKA group (Study III).
- If the existing kinematic characteristics and asymmetries in individuals with TKA amplify in gait on a soft surface compared to on a hard surface, and how it compares with healthy controls (Study IV).
2 Methods

All of the studies (I-IV) were executed at Sør-Trøndelag University College, Department of Physiotherapy (HiST) and Rosenborg Sports Clinic in Trondheim, Norway. The testing took place in the period of October to December 2010. Testing and logistics added up to approximately a 2-hour consultation.

The individuals with TKA were screened and recruited via the Norwegian National Center of Competence for Orthopedic Implants (NKSOI) at St. Olavs’ hospital in Trondheim. One hundred thirty-nine enquiries were sent to individuals with TKA who had surgery ≥ one year to < three years ago and were < 65 years of age (Fig. 2) with a cemented Duracon from Stryker Orthopedics (Howmedica, Rutherford, NJ); a posterior cruciate ligament-retaining prosthesis with fixed-bearing platform and without a patella component.

Seventy of the individuals with TKA did not respond to the inquiry to participate in the study. The non-responders were 58.0 ± 7.6 years of age and 50% of them lived outside Trondheim (more than 30 km). There were 69 individuals with TKA who responded. Seventeen of these responded themselves to be in violation of the inclusion criteria (more than one prosthesis; 15 subjects, other reasons; 2 subjects) and were thus excluded. Fifty-two individuals with TKA volunteered to participate. Twenty-nine of these were later excluded, as they did not reveal violation of exclusion criteria when responding (more than one prosthesis; 11 subjects, revision TKA; 4 subjects, diagnosed hip or knee OA; 4 subjects, other reasons; 10 subjects). In the end, 23 individuals with TKA filled the criteria and were included in the study.

A convenient sample of twenty-three age and gender matched control subjects without knee problems were recruited from HiST and hospital staff. For all participants, inclusion criteria were < 65 years of age to exclude age-related physical limitations (136), and no diagnosed neurological or orthopedic conditions (other than TKA). BMI was set to be < 35 to avoid implications with surface electrodes and limitations to range of motion (65, 146, 147).
2.1 Participants

<table>
<thead>
<tr>
<th>Variable</th>
<th>TKA group (N=23)</th>
<th>Control group (N=23)</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Male/female</td>
<td>11/12</td>
<td>10/13</td>
<td>.767</td>
</tr>
<tr>
<td>Age, (years)</td>
<td>57.6 ± 5.8</td>
<td>54.7 ± 7.4</td>
<td>.151</td>
</tr>
<tr>
<td>Body weight, (kg)</td>
<td>88.0 ± 15.1</td>
<td>74.3 ± 15.5</td>
<td>.004</td>
</tr>
<tr>
<td>Height, (cm)</td>
<td>172 ± 0.1</td>
<td>173 ± 0.1</td>
<td>.556</td>
</tr>
<tr>
<td>BMI, (kg/m²)</td>
<td>29.9 ± 5.0</td>
<td>24.5 ± 3.1</td>
<td>.000</td>
</tr>
</tbody>
</table>

*BMI = body mass index*

There were in total 46 participants in this cross-sectional study. As evident of the subject characteristics presented in Table 4, they were distributed to a TKA group and a healthy control group with an equal number of participants. The number of participants was chosen after power calculations with knee flexion in gait as the primary variable and ten was the least number of participants needed. Based upon the amount of variables included in the studies (I-IV) (Table 5), we chose to increase the number of participants to a number that was manageable both in the estimated testing time available to complete this project, as well as having enough assumed power in the other variables being tested.

We wanted to assess the gait and muscle function, and postural control after more than one year post-operative, and TKA participants with a post-operative time frame of 19.3 ± 8.2 months were included. TKA participants less than one year post-operative were excluded due to postsurgical recidivisms as acute pain and swelling, and to assure resolution.
of post-surgical symptoms that may interfere with gait (148). Andriacchi (148) found that 6 months may be insufficient postsurgical recovery time to allow for resolution of symptoms and attainment of control of gait velocity values. Milner (32) showed in a review that the follow-up periods were from 6-58 months, but most of the studies were from around 12-18 months post-operative. Thus, the upper time limit was selected to allow for increased compatibility with previous research and to get a more homogenous group in relation to the time of post-operative testing. Inclusion criteria were individuals with unilateral TKA below 65 years of age to exclude prominent age-related physical limitations (149). For a more thorough view of the exclusion criteria, see “studies I-IV.”

Table 5. An overview over the four papers regarding participants and outcomes variables.

<table>
<thead>
<tr>
<th>Outcome measures</th>
<th>Paper I</th>
<th>Paper II</th>
<th>Paper III</th>
<th>Paper IV</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>KINEMATICS</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PKSD</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Forward lean</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
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<tr>
<td>JPS</td>
<td>X</td>
<td>X</td>
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<tr>
<td>PPKF</td>
<td>X</td>
<td>X</td>
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<tr>
<td>PPKE</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
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<tr>
<td>Gait sagittal/frontal knee/hip</td>
<td></td>
<td>X</td>
<td></td>
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<tr>
<td>Postural sway</td>
<td>X</td>
<td>X</td>
<td></td>
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<tr>
<td><strong>SPATOTEMPORAL</strong></td>
<td></td>
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<tr>
<td>Speed</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SLS/DLS</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Step length/width</td>
<td>X</td>
<td>X</td>
<td></td>
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<tr>
<td><strong>KINETICS</strong></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Isokinetic strength</td>
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<td>X</td>
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</tr>
<tr>
<td><strong>ANTROPOMETRICS</strong></td>
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<tr>
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<tr>
<td>Leg length</td>
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</tr>
<tr>
<td>Muscular demand</td>
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<td>X</td>
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<tr>
<td>Age</td>
<td>X</td>
<td>X</td>
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<tr>
<td>BMI</td>
<td>X</td>
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<tr>
<td><strong>QUESTIONNAIRES</strong></td>
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<tr>
<td>TSK</td>
<td>X</td>
<td>X</td>
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<tr>
<td>Pain</td>
<td>X</td>
<td>X</td>
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<tr>
<td>KOOS</td>
<td>X</td>
<td>X</td>
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</tr>
</tbody>
</table>

PKSD = peak knee flexion during stair descent, JPS = joint position sense, PPKF = peak passive knee flexion, PPKE = peak passive knee extension, SLS/DLS = single and double limb stance, BMI = body mass index, TSK = Tampa Scale for Kinesiophobia, KOOS = Knee Osteoarthritis Outcome Score.

2.2 Ethics

All studies were performed according to the guidelines of the Helsinki declaration, and informed consent was obtained from all participants. The studies (I-IV) were performed in Trondheim and the participants were recruited from the local region. Ethics approval was granted by the Regional Ethical Review Board in the Mid-Norway Health District. Overall, the project was not considered to incorporate aspects of health
risk for the participants. The project was registered at the Umeå University, and all data storing/handling were performed according to their guidelines for privacy, anonymity and safety.

2.3 Test procedures

2.3.1 Gait assessment
In studies I, II, and IV, stair negotiation, as well as gait on hard and soft surface were assessed kinematically (see 2.5.1 Kinematic capture and 2.6.1 Kinematic analysis).

Stair negotiation
The subjects were asked to ascend and descend the stairs in a step-over-step pattern in one continuous effort with a total of six trials in a comfortable and normal paced tempo; the first three trials with the right foot on the first step and the three last trials with the left foot on the first step. The staircase model (Fig. 3) utilized in study I and II was designed with proportions according to standards for stairs. The height of the riser measured 18.5 cm, and the length of the tread was 26 cm. The length and the width of the entire staircase were 159 cm and 92.5 cm, respectively. The stairs design consisted of a total three steps up and three steps down without rails.

Figure 3. The stairs device.
Methods

**Gait on hard and soft surface**
For gait on soft surface (study IV), a soft surface walkway was utilized (Fig. 4). It was a rectangular wooden frame of 792 cm x 148 cm filled with 18 balance pads (Fig. 5) tightly compressed in a row allowing no space between each pad. The subjects were asked to walk across the floor on cushions in a self-selected and comfortable pace with a total of three trials. For gait on hard surface, the instructions were identical. All subjects were barefoot or had socks on. Silence was maintained during trials.

![Figure 4. Soft surface gait walkway.](image)

A balance pad (Airex balance pad, 495 x 406 x 63 mm) (Fig. 5) with enough viscous property to provide anterior/posterior and medial/lateral instability without having the feet sink to the underlying surface was utilized in study III as part of the postural control assessment and in study IV as parts of the soft surface walkway.

![Figure 5. Airex balance pad.](image)

**2.3.2 Postural control**
In study III, all postural control measures by centre of mass (CoM) and postural sway (bilateral quiet standing and single-limb stance) were assessed kinematically (see 2.5.1 Kinematic capture and 2.6.1 Kinematic analysis).

**Bilateral quiet standing**
Postural control was assessed with quiet standing during 3 min for each of three different test conditions; with vision standing on firm surface (VF), without vision standing on firm surface (NF), and with vision standing on a yielding surface (VY) (Airex balance pad, 495 x 406 x 63 mm) (Fig. 5). One minute’s rest was provided between trials where the subject could walk around or sit down to prevent stiffness and fatigue. Conditions were always presented in the same order to secure that
Methods

potential effects of order of presentation would be similar for all subjects (150). The subjects stood still and relaxed without talking in a modified Romberg position without shoes, feet parallel with 20 cm between the medial malleolus, and arms folded across the chest. A red cross 15x13 cm against a white background placed 4 m in front of the subject provided a set gaze fixation point (151). For the condition without vision, the subjects fixed the gaze on the red cross before closing their eyes. They were asked to tell the test leader if they happened to open their eyes. The subjects were closely but discretely observed and kinematics scanned for unwanted movements. If the stance protocol was violated, the test was cancelled and then repeated.

Single-limb stance
Single-limb stance was measured for 20 s for each leg starting with the contralateral side followed by the prosthetic side in the TKA group, and starting with the dominant leg in the control group. Stance was performed barefoot and with arms across the chest and the uplifted leg held apart from the stance leg. No other restrictions were issued. Subjects were given two trials for each leg to complete 20 s of uninterrupted stance. Number of trials and number of floor-supports with the contralateral foot were noted. Silence was maintained during trials.

2.3.3 Joint position sense
Joint position sense (JPS) (study I and III) was assessed and measured kinematically (see 2.5.1 Kinematic capture and 2.6.1 Kinematic analysis) according to the method of Ribeiro and Oliveria (143) with the subjects blindfolded and seated 90° at the hip at the edge of a therapy bench with feet hanging freely at a 90° knee angle. While the subjects relaxed their legs, the experimenter moved each leg to a stop at a random knee angle, which at that point was held actively by the subjects for 3 seconds without physical contact from the experimenter, and then returned back to the starting position by the subjects themselves. The subjects were then asked to try actively to reposition the leg into the same knee angle. There were 2 trials for each leg, and the relative mean absolute error of the reposition angular accuracy was obtained.

2.3.4 Peak torque
Maximal quadriceps and hamstring strength (studies I, II and III) was measured in an isokinetic dynamometer (Biodex®, System 2) at Rosenborg Sports Clinic following a low intensity 10 min warm-up period on a stationary bike. Three sub-maximal voluntary concentric contractions were performed for familiarization and to potentiate the muscle. To measure torque (Nm), maximal voluntary concentric contractions (MVCC) were performed in a standardized range of motion ranging from 0-90° at 60°/sec, with a total of 5 repetitions for each leg. The peak torque (Nm) for each leg, normalized to the patient’s body
weight, was used as a measure of relative strength. A physiotherapist with proper training and experience performed all muscle strength measurements. The experimenter provided verbal encouragement during the testing. Biodex dynamometers have proven highly reliable for measurement of quadriceps and hamstring strength values, provided proper calibration and subject positioning (152).

2.3.5 Peak passive knee flexion and extension
Peak passive knee flexion (PPKF) (studies I and III) and peak passive knee extension (PPKE) (study III) were measured kinematically (see 2.5.1 Kinematic capture and 2.6.1 Kinematic analysis), with the subjects resting relaxed in supine position on a therapy bench while the experimenter moved each knee toward flexion and extension, respectively, until a tight end feel.

2.3.6 Leg length
Leg length measurements (study I) were performed on a height adjustable therapy bench with the subjects in a supine position with both legs stretched out and relaxed. Measurements of both legs were performed with a regular tape measure from the center of the spina iliaca anterior superior (SIAS) to the top of the lateral malleolus.

2.3.7 Anterior knee joint laxity
The anterior knee laxity measurements was performed with a KT1000 arthrometer (MEDmetric©, San Diego, Ca, USA) in order to assess the anterior knee joint play (study I). In accordance with Daniel (19), we emphasized precision and accuracy to be able to reproduce the testing sequence in a satisfactory manner. Important points were; muscle relaxation, similar limb orientation, similar arthrometer placement on the leg with respect to the instrument marker at the joint line and instrument rotation in relation to the patella. Focus was also on consistent patella pad pressure technique and establishing the testing reference position. In addition, establishing the testing reference position and similar speed and vector of force application were considered important. Anterior tibial translation was expressed in millimeters (mm) and calculated as the mean test value for two trials.
2.4 Questionnaires

2.4.1 Tampa Scale for Kinesiophobia
The Tampa Scale for Kinesiophobia (TSK) was used to quantify fear of movement (study I). A Norwegian adjusted version to measure kinesiophobia was utilized. A version of 13, rather than 17 statements on subjective experience of injury and physical activity was used, which also has been shown to be internally reliable (coeff. alpha 0.77) (153, 154). Each statement is scored on a 4-point Likert scale with scores ranging from 1 "strongly disagree" to 4 "strongly agree." The total score ranges from 13 to 52, with a higher score indicating a higher degree of kinesiophobia.

2.4.2 Pain
A Numerical Rating Scale (NRS) ranging from 0 (no pain at all) to 10 (the worst imaginable pain) was utilized for assessing the TKA-participant’s level of discomfort/pain during the day of the testing procedure (155) (study I).

2.4.3 The Knee injury and Osteoarthritis Outcome Score
In studies III and IV, to gain insight into knee related functions, the concerns of the individuals with TKA were screened by the Knee injury and Osteoarthritis Outcome Score (KOOS) (156). KOOS assesses five subscales; pain, symptoms, ADL, sports/recreation, and quality of life. The maximum score in each subscale is 100, with lower scores indicating increasing self-perceived implications and problems. KOOS was chosen because of good psychometric properties, has been validated for use following TKA, and is commonly used internationally to assess patient-perceived health status following primary TKA (157, 158).

2.5 Data acquisition

2.5.1 Kinematic capture
Whole body kinematics was recorded at 100 Hz with an eight-camera system (Oqus, Qualisys, Sweden) and compiled into 3D animations (Qualisys Track Manager, 2.6 682, Qualisys, Sweden) in all studies (I-IV). The camera system was calibrated prior to each session and the global coordinate system was defined as medio-lateral X, antero-posterior Y, and vertical Z. System accuracy was measured with an average residual of ≈ 0.5 mm. The calibrated volume measured 1.3 * 3.5 * 2.00 m in the X, Y, and Z directions. This allowed capture of postural sway data and approximately five steps for level gait and full camera coverage of the reflex markers when the subjects were on top of the stairs.
Infrared light emitted from the cameras was reflected from spherical 19-mm markers attached to defined anatomical landmarks, denoting proximal and distal end of forearms, upper arms, thighs, shanks, feet, trunk and pelvic segments. Additional 4-marker clusters were placed on thighs and shanks. A static model was built for each individual consisting of 50 markers. For motion tracking, 34 markers were used (Fig. 6). All subjects wore tight clothing to ensure that the reflective markers were firmly secured to anatomical landmarks.

Figure 6. Screenshot of kinematic capture of gait via Qualisys Track Manager. 2.6.682, Qualisys, Sweden. With permission from Qualisys, Sweden.

2.5.2 Electromyographic recording
Electromyographic recording was utilized in study II. During stair ascent and isokinetic testing, electromyography (EMG) was recorded with disposable Ag–AgCl surface electrodes (Ambu® Neuroline 720) bilaterally from vastus lateralis (VL) and semitendinosus (ST). Before the measurement, the skin area was shaved and cleaned with alcohol to reduce the skin-electrode impedance. The electrodes were attached in a bipolar arrangement along the direction of the muscle fibers with an inter-electrode distance of 20 mm, center to center, with adjoining reference electrode placed in recommendation following the SENIAM guidelines (159). EMG data were collected via an 8-channel portable device (Biomonitor ME6000® T16, Mega Electronics Ltd, Kuopio, Finland), which was strapped around the waist. For the stair ascent, EMG data were transferred telemetrically (WLAN) to QTM (Qualisys Track Manager, 2.6.682, Qualisys, Sweden) for recording and storage. For the isokinetic testing of maximal voluntary concentric contraction (MVCC), EMG data were transferred via a USB cable and stored in the Megawin 2.3-software (Mega Electronics Ltd, Kuopio, Finland). The recorded EMG signals were both in stair ascent and MVCC pre-amplified 305 times and band-pass filtered between 8 and 500 Hz before digitizing at a sample rate of 1000 Hz using 14-bits resolution.
2.6 Data analyses

2.6.1 Kinematic analysis
All kinematic data was acquired via Qualisys Track Manager (version 2.6 682, Qualisys, Sweden). In stair negotiation and gait on hard and soft surface, kinematics to assess knee and hip joint motion in the frontal and sagittal planes, as well as forward (sagittal) inclination of the trunk, were performed. PPKF and PPKE to assess passive knee flexion and extension ROM, and JPS to assess kinaesthesia by reposition accuracy, as well as kinematic capture of postural sway by CoM of quiet standing and single-limb stance were also performed.

The data were exported, analyzed and low-pass filtered with a Butterworth filter set at 6 Hz in Visual 3D Basic/RT software (version 5.00.34, C-Motion Maryland, USA) and Matlab (R2013a, 8.1.0.604, The MathWorks, Inc., Natick, MA, USA).

A rigid segment model was constructed where movement in six degrees of freedom for the local coordinate systems determined the Cardan/Euler angles (160). Each segment was given a local, mobile coordinate system, and angular displacement between two segments, that is, the joint angle, was defined as rotations of the coordinate axes of the distal segment relative to the proximal segment. This model consisted of 12 segments: pelvis, trunk and bilateral forearms, upper arms, feet, shanks and thighs (Fig. 7).

PKSD (study I) was measured between the thigh and shank segments in the sagittal plane around the x-axis in the swing phase, whereas peak knee flexion during gait on hard and soft surface (study IV) was measured in both the swing phase and stance phase. The adduction/abduction angle in the ipsilateral hip (studies I and IV) and ipsilateral knee (study IV) in the frontal plane around the y-axis at the moment of peak knee flexion was measured between the pelvic and thigh segments and the thigh and shank segment, respectively. The flexion angle of the ipsilateral...
In order to capture factors describing different aspects of postural sway, the following variables were derived from CoM data: 1) total displacement of sway, which is the total length of the trajectory described by CoM, 2) mean velocity of CoM in AP and ML directions, and 3) mean frequency for AP and ML. Data were low-pass filtered and detrended. The amplitudes were estimated with principal component analysis of the X and Y axes quantified by calculating the 95% confidence ellipse area (mm²) in the X-Y plane separately for each signal. The ellipse was defined using two axes, which were determined from the first two components of a principal components analysis of the CoM data. The two radii of the ellipses were defined by medio-lateral X and antero-posterior Y. Mean velocity was calculated from the first derivative of position. Mean
frequency was estimated by a Fourier-analysis of the characteristics of the power spectral density using the Welch’s periodogram method (162). While data collection of quiet standing was analyzed for the full 180 s, single-limb stance was cut at the first and last 2 s to avoid noise from starting and ending the test, thus 16 s was analyzed.

2.6.2 Electromyographic analysis
For the EMG data analysis in study II, the digitized EMG signals were later quantified via a Matlab (R2013a, 8.1.0.604, The MathWorks, Inc., Natick, MA, USA) script by using moving RMS with a window of 100ms. To calculate the normalized EMG activity, the peak root mean square (RMS) EMG signal of vastus lateralis (VL) and semitendinosus (ST) during stair ascent (six trials) was normalized as a percentage of the averaged median RMS EMG signal obtained during the MVCC (five repetitions) in knee extension and knee flexion. The median value of each full MVCC curve (from where the curve starts to rise to the point where the curve is back down and flattens out) was calculated, and all medians of the curves were then averaged to obtain the values used in the normalization.

2.7 Statistical analysis
Throughout all studies (I-IV), normal distribution of data was inferred by histograms, Q-Q-plots and Kolmogorov-Smirnov. In all studies, the level probability chosen as statistically significant was \( p < 0.05 \). Means ± SD are presented in tables. All statistics were performed using Statistical Package for the Social Sciences (SPSS Inc., Chicago, IL, USA), version 20.

Within and between group comparisons (studies I, II and IV) of subject demographics, kinematics, spatiotemporal values, peak torque values, and maximal, median, and normalized muscle activity were performed with one way ANOVA and paired sample t-test respectively. Group comparisons of KOOS, TSK and NRS were performed with one way ANOVA.

Within and between group comparisons of postural sway in study III was performed with repeated measures ANOVA. Sphericity was corrected when necessary (Huynh-Feldt). Post-hoc analyses of group differences in the three quiet standing conditions were analyzed with simple ANOVA. Post-hoc comparisons between the prosthetic and contralateral leg in the TKA group and the between the dominant and non-dominant leg in the control group in single-limb stance were performed with paired t-tests. For background factors (age, KOOS, BMI, muscular strength, JPS, and prosthetic fit, i.e., PPKE, PPKF), potentially affecting the ability to stand on one leg, univariate binary regressions were performed.
In study I, multiple regression analysis was used to explore factors (PPKF, JPS, anterior knee laxity, quadriceps peak torque, TSK, leg length, current pain (NRS), post-operative time, body mass index (BMI), and age) potentially explaining reduced PKSD in the TKA-leg. Correlations (Pearson) between PKSD, PPKF, JPS, leg-length and quadriceps peak torque (not normalized to amplify effect of peak torque) were made across and within groups and sides. Partial correlations controlled for leg-length were made for PKSD related to isokinetic quadriceps strength and to hip adduction at PKSD.
3 Results

3.1 Gait function
In study I, causes to reduced peak knee flexion during stair descent (PKSD) in individuals with TKA were explored. A significantly reduced PKSD in the prosthetic knee compared to the contralateral knee and controls was found (Table 7). Multiple regression analysis within the TKA-leg showed that only peak passive knee flexion (PPKF) explained (57%) the variance in PKSD ($\beta = .794$, $P = .001$).

The reduced quadriceps strength measured in the individuals with TKA could also contribute to PKSD. For more information on this, see 3.2 Muscle function.

At PKSD, hip adduction was significantly larger in the prosthetic side compared to the contralateral side and controls (Table 7). Hip adduction was positively correlated with PKSD across groups when corrected for leg-length ($R^2 = - .281$, $P = .011$). There were no within-group correlations between PKSD and hip adduction.

In study IV, we investigated if the existing kinematic characteristics and asymmetries observed in individuals with TKA were amplified in gait on soft surface compared to on hard surface, and how it compared with healthy controls. The effects of surface on gait kinematics and spatiotemporal values (Table 6), displayed the prosthetic knee with less flexion at stance on soft surface compared to on hard surface. Knee flexion increased in the swing phase on soft surface compared to on hard surface in both knees and groups. Both the TKA group and the control group displayed significantly increased DLS time and decreased gait speed on soft compared to hard surface (Table 6).

The group comparison of study IV (Table 7) revealed that the individuals with TKA displayed significantly less peak knee flexion and increased knee adduction in their prosthetic knee for both hard and soft surface at stance compared to the control group. The prosthetic side in the TKA group displayed significantly more hip adduction compared to the control group on hard surface at peak knee flexion at stance (Table 7). The TKA group displayed an increased step width on soft surface compared to the control group, 0.12 ± 0.02 vs. 0.10 ± 0.02 ($P = .009$).
Table 6. Comparison between hard and soft surface peak knee flexion kinematic values and spatiotemporal values (means and SD).

<table>
<thead>
<tr>
<th>Variables</th>
<th>Peak knee flexion, swing, HS</th>
<th>Peak knee flexion, swing, SS</th>
<th>Peak knee flexion, stance, HS</th>
<th>Peak knee flexion, stance, SS</th>
<th>Single limb support time, HS (s)</th>
<th>Single limb support time, SS (s)</th>
<th>Double limb support time, HS (s)</th>
<th>Double limb support time, SS (s)</th>
<th>Speed, HS (m/s)</th>
<th>Speed, SS (m/s)</th>
<th>p</th>
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<tbody>
<tr>
<td>Prosthesis</td>
<td>56.4 ± 6.7</td>
<td>73.9 ± 4.5</td>
<td>11.2 ± 8.1</td>
<td>9.4 ± 8.4</td>
<td>0.41 ± 0.02</td>
<td>0.42 ± 0.03</td>
<td>0.09 ± 0.02</td>
<td>0.16 ± 0.03</td>
<td>1.31 ± 0.14</td>
<td>1.13 ± 0.16</td>
<td>.000</td>
</tr>
<tr>
<td>Contralateral</td>
<td>59.2 ± 5.5</td>
<td>75.9 ± 8.2</td>
<td>15.4 ± 4.5</td>
<td>13.4 ± 8.7</td>
<td>0.42 ± 0.02</td>
<td>0.43 ± 0.03</td>
<td>0.09 ± 0.02</td>
<td>0.14 ± 0.02</td>
<td>1.35 ± 0.17</td>
<td>1.18 ± 0.18</td>
<td>.000</td>
</tr>
<tr>
<td>Control comb.</td>
<td>62.1 ± 5.9</td>
<td>77.0 ± 6.0</td>
<td>16.9 ± 6.4</td>
<td>16.6 ± 7.4</td>
<td>0.42 ± 0.02</td>
<td>0.43 ± 0.02</td>
<td>0.09 ± 0.02</td>
<td>0.14 ± 0.02</td>
<td>1.35 ± 0.17</td>
<td>1.18 ± 0.18</td>
<td>.000</td>
</tr>
</tbody>
</table>

 HS = hard surface, SS = soft surface, step length is normalized to leg length.  
 P = Surface-to-surface differences (paired t-test)
Table 7. Kinematic comparison between sides and groups of knee and hip at PKSD and peak knee flexion at stance phase in gait on hard and soft surface (means and SD).

<table>
<thead>
<tr>
<th>Joint angles, (degrees)</th>
<th>TKA group (N =23)</th>
<th>Control group (N=23)</th>
<th>Prosthesis vs. ctrl. (both legs comb.)</th>
<th>Contralateral vs. ctrl. (both legs comb.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PKSD x (°)</td>
<td>Prosthesis</td>
<td>Contralateral</td>
<td>Both legs comb.</td>
<td>P&lt;sup&gt;2&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>88.9 ± 4.8</td>
<td>96.0 ± 6.1</td>
<td>101.0 ± 6.3</td>
<td>0.000**</td>
</tr>
<tr>
<td></td>
<td>110.5 ± 13.0</td>
<td>138.0± 13.9</td>
<td>147.8 ± 9.7</td>
<td>0.000**</td>
</tr>
<tr>
<td>PPKF, x (°)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hip y at PKSD</td>
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<tr>
<td>(adduction) (°)</td>
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<td>Peak knee flexion,</td>
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<tr>
<td>swing, HS</td>
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<tr>
<td>Peak knee flexion,</td>
<td></td>
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<tr>
<td>swing, SS</td>
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<tr>
<td>Peak knee flexion,</td>
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</tr>
<tr>
<td>stance, HS</td>
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<td></td>
<td></td>
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<tr>
<td>Peak knee flexion,</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>stance, SS</td>
<td></td>
<td></td>
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<tr>
<td>Knee abduction/adduction, HS</td>
<td>4.7 ± 4.2</td>
<td>4.4 ± 5.1</td>
<td>1.7 ± 4.0</td>
<td>0.021*</td>
</tr>
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<td>Knee abduction/adduction, SS</td>
<td>5.3 ± 3.6</td>
<td>4.9 ± 5.3</td>
<td>2.7 ± 4.5</td>
<td>0.045*</td>
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<tr>
<td>Hip flexion, HS</td>
<td>16.8 ± 9.6</td>
<td>16.6 ± 9.6</td>
<td>18.1 ± 10.3</td>
<td>0.703</td>
</tr>
<tr>
<td>Hip flexion, SS</td>
<td>18.9 ± 12.0</td>
<td>18.8 ± 7.7</td>
<td>19.1 ± 10.0</td>
<td>0.857</td>
</tr>
<tr>
<td>Hip abduction/adduction, HS</td>
<td>-10.8 ± 6.1</td>
<td>-8.6 ± 5.0</td>
<td>-6.7 ± 4.1</td>
<td>0.018*</td>
</tr>
<tr>
<td>Hip abduction/adduction, SS</td>
<td>-9.1 ± 5.1</td>
<td>-9.8 ± 5.1</td>
<td>-6.7 ± 4.1</td>
<td>0.078</td>
</tr>
</tbody>
</table>

P < .05, **P < .01, PKSD = peak knee angle descending stairs, PPKF = peak passive knee flexion HS = hard surface, SS = soft surface. Side-to-side differences (paired t-test), P<sup>2</sup> = Group differences (ANOVA). Knee sagittal plane: + towards flexion, Knee frontal plane: + towards adduction, Hip sagittal plane: + towards flexion, Hip frontal plane: - towards adduction.
### 3.2 Muscle function

In study II, the main aim was to investigate if individuals with TKA use a higher percentage of their maximal muscular strength capacity during stair ascent than do healthy controls. As evident by Table 8, individuals with TKA did not utilize a higher percentage of their maximal muscular strength capacity during stair ascent compared to healthy controls. This is shown by equal normalized EMG RMS for vastus lateralis (VL) and semitendinosus (ST) across groups. In the TKA group, no side-to-side differences were found in normalized EMG RMS for VL or ST, however, in the control group, a significantly lower value was found for VL in the non-dominant side compared to the dominant side.

Furthermore, we also wanted to investigate if individuals with TKA compensate muscle weakness by increased forward lean and slower gait speed during stair ascent compared to healthy controls. As evident by Table 8, the individuals with TKA ascended the stairs in a slower speed than did healthy controls. There was no group difference in forward lean of the trunk during stair ascent.

In study I, the TKA group displayed decreased quadriceps peak torque and decreased PKSD (Table 7 and 8) compared to healthy controls and compared to the contralateral side, and correlations were performed to analyze the relationships between these factors. Smaller PKSD correlated with higher quadriceps peak torque within the control group ($R^2 = -.647$, $P = .002$), whereas higher quadriceps peak torque correlated with larger PKSD across groups ($R^2 = .229$, $P = .040$). There were no leg length differences between groups, however smaller PKSD correlated with longer legs across groups ($R^2 = -.219$, $P = .049$) and within the control group ($R^2 = -.634$, $P = .002$). When controlled for leg-length, PKSD and quadriceps torque correlated only across groups ($R^2 = .279$, $P = .012$). None of these factors correlated within the TKA group.

In study III, 30% of the TKA group, opposed to 4% of the control group, failed to maintain balance in the 20 s single-limb stance test. This failure was explained amongst others by reduced contralateral quadriceps strength in the TKA group by a regression analysis (for more information, see 3.3 Postural control).
Table 8. EMG (RMS) of vastus lateralis and semitendinosus during isokinetic MVCC/stair ascent, and forward lean thorax and time up stairs (means and SD).

<table>
<thead>
<tr>
<th>Variable</th>
<th>TKA group (N=23)</th>
<th>Control group (N=23)</th>
<th>Prosth. vs ctrl. (both legs)</th>
<th>Contralat. vs. ctrl. (both legs)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Prosthesis</td>
<td>Contralateral</td>
<td>P1</td>
<td>P2</td>
</tr>
<tr>
<td>Quadriceps peak torque (Nm/bw)</td>
<td>1.24 ± 0.40</td>
<td>1.67 ± 0.43</td>
<td>.000</td>
<td></td>
</tr>
<tr>
<td>Hamstring peak torque (Nm/bw)</td>
<td>0.92 ± 0.29</td>
<td>0.96 ± 0.32</td>
<td>.121</td>
<td></td>
</tr>
<tr>
<td>MVCC, vast lateralis, (µV)</td>
<td>199.1 ± 108.0</td>
<td>220.9 ± 107.5</td>
<td>.114</td>
<td></td>
</tr>
<tr>
<td>MVCC, semitendinosus, (µV)</td>
<td>223.2 ± 131.6</td>
<td>258.3 ± 110.7</td>
<td>.124</td>
<td></td>
</tr>
<tr>
<td>Stair ascent, vast lateralis (µV)</td>
<td>111.2 ± 54.4</td>
<td>132.9 ± 48.4</td>
<td>.034</td>
<td></td>
</tr>
<tr>
<td>Stair ascent, semitendinosus, (µV)</td>
<td>101.0 ± 61.6</td>
<td>108.1 ± 63.8</td>
<td>.758</td>
<td></td>
</tr>
<tr>
<td>Normalized, vast lateralis, (%)</td>
<td>68 ± 43</td>
<td>69 ± 31</td>
<td>.873</td>
<td></td>
</tr>
<tr>
<td>Normalized, semitendinosus, (%)</td>
<td>56 ± 36</td>
<td>46 ± 26</td>
<td>.109</td>
<td></td>
</tr>
<tr>
<td>Forward lean thorax during stair ascent (°)</td>
<td>13.3 ± 4.3</td>
<td>16.3 ± 6.8</td>
<td>.087</td>
<td></td>
</tr>
<tr>
<td>Time up stairs (s)</td>
<td>2.6 ± 0.5</td>
<td>2.3 ± 0.3</td>
<td>.013</td>
<td></td>
</tr>
</tbody>
</table>

MVCC = maximal voluntary concentric contraction, Nm/bw = newton meter/body weight, µV = micro volt, P1 = Side-to-side differences (t-test), P2 = Group differences (ANOVA)
3.3 Postural control

Table 10 shows that 7/23 were unable to maintain single-limb stance on any leg without contralateral support for 20 s in the TKA group, whereas 1/23 in the control-group was unable to maintain single-limb stance on any leg and 1/23 was unable to stand on the non-dominant leg without contralateral support. This group difference was statistically significant (p=.027). For individuals with TKA who were able to maintain single-limb stance without contralateral floor supports, mean velocity in the ML direction was higher in the prosthetic side, however, negligible with a very small effect size (Cohen’s d: 0.66, r=0.31). No other differences were found for postural sway between legs in any group (Table 9).

No between subjects effects in any of the sway parameters were found for quiet standing or for single-limb stance. Post-hoc analyses did not show any differences in any conditions of quiet standing between individuals with TKA who were able and those unable to maintain single-limb stance without contralateral floor supports or between individuals with TKA unable to maintain single limb stance and controls able to stand on one leg (Table 10).

In order to find which factors were associated with the failure to maintain single limb stance in the TKA group, binary logistic regressions showed that older age (R²=.4; p=.001), higher BMI (R²=.3; p=.011), and reduced contralateral quadriceps strength (R²=.2; p=.041) each were significant factors.
Table 9. Sway parameters for single-limb stance in subjects who maintained 20 s without floor supports with the contralateral leg, separate for the TKA and control groups (means and SD).

<table>
<thead>
<tr>
<th>Variables</th>
<th>TKA (N=16)&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Control (N=21)&lt;sup&gt;b&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Prosthetic</td>
<td>Contralateral</td>
</tr>
<tr>
<td>Mean amplitude AP</td>
<td>0.030 ±0.013</td>
<td>0.027 ±0.009</td>
</tr>
<tr>
<td>Mean amplitude ML</td>
<td>0.027 ±0.009</td>
<td>0.022 ±0.006</td>
</tr>
<tr>
<td>Mean velocity AP</td>
<td>0.008 ±0.003</td>
<td>0.007 ±0.010</td>
</tr>
<tr>
<td>Mean velocity ML</td>
<td>0.009 ±0.004&lt;sup&gt;*&lt;/sup&gt;</td>
<td>0.007 ±0.002&lt;sup&gt;*&lt;/sup&gt;</td>
</tr>
<tr>
<td>Mean frequency AP</td>
<td>0.231 ±0.050</td>
<td>0.208 ±0.052</td>
</tr>
<tr>
<td>Mean Frequency ML</td>
<td>0.249 ±0.120</td>
<td>0.243 ±0.070</td>
</tr>
</tbody>
</table>

<sup>a</sup>TKA: 16 out of 23  
<sup>b</sup>Control: 21 out of 23  
AP: antero-posterior  
ML: medio-lateral  
<sup>*</sup>p<.05 (repeated measures ANOVA: between subjects effects; TKA and control, and within subjects effects for the leg; prosthetic / contralateral and non-dominant / dominant in TKA and control respectively)
Table 10. Quiet standing with vision, without vision, and on yielding surface with vision

<table>
<thead>
<tr>
<th>Variable</th>
<th>Group</th>
<th>TKA (N=7)</th>
<th>TKA (N=16)</th>
<th>Control (N=21)²</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mean amplitude AP</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vision</td>
<td></td>
<td>0.033 ± 0.006</td>
<td>0.034 ± 0.016</td>
<td>0.033 ± 0.015</td>
</tr>
<tr>
<td>No vision</td>
<td></td>
<td>0.036 ± 0.008</td>
<td>0.032 ± 0.008</td>
<td>0.031 ± 0.012</td>
</tr>
<tr>
<td>***Vision, yielding</td>
<td></td>
<td>0.048 ± 0.017</td>
<td>0.045 ± 0.010</td>
<td>0.045 ± 0.010</td>
</tr>
<tr>
<td><strong>Mean amplitude ML</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vision</td>
<td></td>
<td>0.021 ± 0.013</td>
<td>0.019 ± 0.009</td>
<td>0.019 ± 0.008</td>
</tr>
<tr>
<td>No vision</td>
<td></td>
<td>0.026 ± 0.010</td>
<td>0.021 ± 0.007</td>
<td>0.018 ± 0.006</td>
</tr>
<tr>
<td>***Vision, yielding</td>
<td></td>
<td>0.046 ± 0.018</td>
<td>0.038 ± 0.012</td>
<td>0.040 ± 0.016</td>
</tr>
<tr>
<td><strong>Mean velocity AP</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vision</td>
<td></td>
<td>0.004 ± 0.001</td>
<td>0.004 ± 0.002</td>
<td>0.003 ± 0.010</td>
</tr>
<tr>
<td>No vision</td>
<td></td>
<td>0.005 ± 0.001</td>
<td>0.004 ± 0.001</td>
<td>0.004 ± 0.002</td>
</tr>
<tr>
<td>***Vision, yielding</td>
<td></td>
<td>0.008 ± 0.003</td>
<td>0.007 ± 0.003</td>
<td>0.007 ± 0.002</td>
</tr>
<tr>
<td><strong>Mean velocity ML</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vision</td>
<td></td>
<td>0.002 ± 0.001</td>
<td>0.002 ± 0.001</td>
<td>0.002 ± 0.001</td>
</tr>
<tr>
<td>***No vision</td>
<td></td>
<td>0.003 ± 0.001</td>
<td>0.002 ± 0.001</td>
<td>0.002 ± 0.001</td>
</tr>
<tr>
<td>***Vision, yielding</td>
<td></td>
<td>0.007 ± 0.002</td>
<td>0.006 ± 0.002</td>
<td>0.006 ± 0.001</td>
</tr>
<tr>
<td><strong>Mean frequency AP</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vision</td>
<td></td>
<td>0.112 ± 0.031</td>
<td>0.095 ± 0.034</td>
<td>0.094 ± 0.034</td>
</tr>
<tr>
<td>*No vision</td>
<td></td>
<td>0.109 ± 0.022</td>
<td>0.102 ± 0.030</td>
<td>0.112 ± 0.031</td>
</tr>
<tr>
<td>***Vision, yielding</td>
<td></td>
<td>0.152 ± 0.020</td>
<td>0.127 ± 0.040</td>
<td>0.126 ± 0.040</td>
</tr>
<tr>
<td>Mean Frequency ML</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vision</td>
<td></td>
<td>0.108 ± 0.026</td>
<td>0.088 ± 0.043</td>
<td>0.094 ± 0.034</td>
</tr>
<tr>
<td>***No vision</td>
<td></td>
<td>0.114 ± 0.032</td>
<td>0.095 ± 0.035</td>
<td>0.108 ± 0.040</td>
</tr>
<tr>
<td>***Vision, yielding</td>
<td></td>
<td>0.152 ± 0.015</td>
<td>0.144 ± 0.032</td>
<td>0.146 ± 0.039</td>
</tr>
</tbody>
</table>

¹ Unable to maintain single-limb stance for 20 s
² Able to maintain single-limb stance for 20 s
³ The two control subjects unable to maintain single-limb stance for 20 s are not presented in this table.

AP: antero-posterior, ML: medio-lateral
* denotes significance relative to the condition above (repeated measures ANOVA: within subjects effects of factors vision and no vision, and between no vision and yielding surface;) *<.05; **<.01; ***<.001
3.4 Kinaesthesia
Joint position sense (JPS) assessed in studies I and III did not contribute to explain the variances of PKSD in study I or to explain the failure to maintain 20 s single-limb stance in study III. No within or between group differences were found for JPS.

3.5 The Knee Injury and Osteoarthritis Score
The TKA group scored significantly worse than the control group on all sub-categories of the Knee injury and Osteoarthritis Score (KOOS) assessed in studies III and IV (Table 11). None of the KOOS-scores were associated with the failure to maintain balance in the single-limb stance in the TKA group in study III.

<table>
<thead>
<tr>
<th>KOOS</th>
<th>TKA group (N=23)</th>
<th>Control group (N=21)</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pain</td>
<td>66.7 ± 23.4</td>
<td>96.2 ± 7.6</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Symptoms</td>
<td>67.7 ± 17.5</td>
<td>95.2 ± 10.6</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>ADL</td>
<td>75.9 ± 24.4</td>
<td>99.5 ± 1.3</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Sport/recreation</td>
<td>40.0 ± 28.2</td>
<td>95.7 ± 9.3</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Quality of life</td>
<td>52.7 ± 27.9</td>
<td>92.0 ± 12.8</td>
<td>&lt;.001</td>
</tr>
</tbody>
</table>

KOOS = Knee Injury and Osteoarthritis Score (0-100). Higher scores reflect better outcomes for all subscales. ADL = Activities of Daily Living.
4 Discussion

Overall, this thesis found reduced lower limb strength to be held accountable for the asymmetry during gait and stair negotiation as well as reduced physical performance and balance. More specifically, reduced quadriceps strength affected peak knee flexion during stair descent (PKSD) and may lead to reduced stair-climbing speed. In stair descent, increased hip adduction may compensate for reduced PKSD. Reduced PKSD may in turn compensate for reduced quadriceps strength in order to reduce knee joint moments. Increased hip adduction was also found in level gait and points to reduced strength or motor control in the hip abductors. The failure to maintain single-limb stance in the TKA group is partly explained by reduced contralateral quadriceps strength, suggesting general deconditioning.

This thesis found that reduced PKSD in the TKA group was associated with reduced peak passive knee flexion (PPKF) and strength across groups (study I). Individuals with TKA did not use a higher percentage of their muscular maximal capacity during stair ascent than did healthy controls. Individuals with TKA presumably compensated for muscle weakness by slower gait speed during stair ascent compared to healthy controls. Increased forward lean, initially suggested as a possible compensation for muscle weakness in the TKA group, was similar between groups (study II). In the TKA group, reduced knee flexion in the prosthetic knee during gait on hard surface was further reduced on soft surface. Ipsilateral knee and hip adduction at stance were not affected by surface conditions; nevertheless, there was a difference between groups, in particular regarding the prosthetic side, showing greater knee and hip adduction than in the control group. In addition, step width increased on soft surface compared to on hard surface in individuals with TKA (study IV). About 30% (7/23) of the TKA group was unable to maintain single-limb stance on any leg without contralateral support, whereas 4% in the control group was unable to maintain single-limb stance (1/23 on any leg, and 1/23 was unable to stand on the non-dominant leg without contralateral support). Those able to perform 20 s single-limb stance in the TKA group displayed equal postural sway in single-limb stance and bilateral quiet standing as did the control group (study III). The prosthesis performed as expected concerning flexion and extension, anterior knee laxity and joint position sense.

4.1 Gait function

Stair negotiation
The results from study I displayed reduced peak knee flexion during stair descent (PKSD) in the TKA-side compared to contralateral side and healthy controls. This is in coherence with other studies (77, 79, 99, 100).
Peak passive knee flexion (PPKF) was the only factor that explained the variance of PKSD in the TKA-leg (study I) by the regression analysis. In contrast, authors have previously proposed that the mechanisms behind the reduced PKSD in individuals with TKA may be multi-factorial (79).

PPKF of 110.5° ± 13.0° is an expected ROM after TKA, and similar to other studies (83). This leaves a good margin for stair negotiation, which requires from 85°-90° of flexion (88, 89). The individuals with TKA walked with smaller PKSD than did the controls, although PPKF was sufficient in both the prosthetic knee and in the contralateral knee to descend stairs with similar knee flexion as controls. This suggests that retained patterns of abnormal gait prior to the surgery could be responsible for the reduced PKSD (79, 84).

The reason for the reduced PKSD in the contralateral knee in study I could be due to influence of the limited PKSD in the prosthetic knee. A further utilization of flexion in the contralateral knee would lead to a very asymmetrical and dysfunctional gait. An alternative explanation to the reduced contralateral PKSD could be an existing asymptomatic knee OA limiting PKSD and PPKF, as well as contralateral quadriceps strength. Although the present study did not have access to x-rays of the contralateral knees, it could still be proposed that there exists asymptomatic arthritis limiting knee flexion (163).

The reduced quadriceps strength found in the TKA group could lead to the asymmetric gait patterns observed in both stair negotiation and gait on soft and hard surface (studies I and IV). Studies show that quadriceps strength increases with time after TKA surgery, and there is evidence of strength reaching a threshold where gait symmetry no longer is affected (56). Reduced quadriceps strength might also contribute to other compensations affecting stair negotiation for individuals with TKA, such as slower self-selected speed in stair ascent compared to healthy controls as evident in study II. Although slower stair climbing speed is in line with other studies assessing the effects of reduced strength (4), it might also be caused by a heavier body weight in individuals with TKA compared to healthy controls (164), which also was found in study II. Another known compensation affecting gait kinematics during stair ascent could be forward leaning of the upper body to reduce the demand on the quadriceps (102, 103). This was however not revealed while assessing kinematics during stair ascent in study II (more information regarding this topic, see 4.2 Muscle function).

Increased hip adduction (i.e. pelvic drop) in the prosthetic side at PKSD compared to the contralateral side during stair descent suggests that greater hip adduction compensated for reduced PKSD, or possibly that increased hip adduction depends on weakness of the hip abductors as shown by Piva et al. (57). There were however no correlations between
PKSD and hip adduction within groups. The effect may have been attenuated, at least in part, due to leg-length, as the correlation becomes stronger when controlled for leg length, with smaller PKSD correlating with longer legs across groups and within the control group (see Muscle function 3.2). There was, however, no leg length difference between the groups, thus normalization of PKSD to leg length was deemed unnecessary. In stair descent, hip adduction may compensate for short legs when normal knee flexion does not suffice.

In daily life, it is important to realize that individuals with TKA probably are more inclined to use rails when available for support to minimize pain and to compensate for decreased quadriceps strength when negotiating stairs compared to healthy counterparts. As the stairs device utilized in studies I and II was without rails, stair negotiation could perhaps lead to a more challenging task for the individuals with TKA.

**Hard and soft surface gait**

In study IV, we investigated if the existing kinematic and spatiotemporal characteristics and asymmetries observed within individuals with TKA amplify in gait on soft surface compared to on hard surface. Similar to previous studies (107), however, only 3 months post-operatively, reduced flexion in the prosthetic knee was found during the stance phase on hard surface compared to the contralateral side. Another study found symmetric knee flexion in the stance phase 28 months after surgery (165), with a tendency to decreased prosthetic knee flexion, hypothesizing that the contralateral side is tending towards the prosthetic side over time to reduce the interlimb asymmetry after TKA. Study IV revealed that flexion during the stance phase in the prosthetic knee was further decreased on soft compared to hard surface. This may be attributed to insecurity toward the soft surface at initial contact in early stance. Knee flexion in the swing phase increased on soft compared to hard surface in both knees and groups. Although the speed difference between hard and soft surface was quite small, with faster gait on hard surface, decreased speed usually is followed by reduced knee flexion in the swing phase (166). Thus, quite the opposite was observed in study IV. This leads to the conclusion that presumably the yielding effects of the cushions demanded more flexion in mid-swing in order to reach enough clearance off the floor. Gait on hard and soft surface, respectively, displayed no within group differences apart from reduced prosthetic knee flexion at stance on hard surface with a strong trend (p=0.053) on soft surface as well. This asymmetry is comparable to other studies on hard surface (53, 75, 79, 80, 167, 168).

Spatiotemporal variables were also affected when comparing soft and hard surface. Double-limb stance (DLS) was prolonged on soft surface compared to on hard surface. Contralateral single-limb stance (SLS) time was prolonged on soft surface compared to contralateral SLS time on hard surface. A prolonged SLS time on soft surface also means longer
DLS time and is a logic consequence of reduced walking speed and longer time delay at toe-off (169). Despite a statistical significance between surfaces in SLS for the contralateral side, the tiny difference was considered of virtually no clinical relevance. Reduced gait speed as a general effect when walking on soft surface is in coherence with findings in other studies (96, 169). In study IV, self-selected gait speed was similar between groups regardless of surface. Other studies have found similar results (56, 79, 167), whereas some report reduced gait speed (94, 170) in the TKA group, which may be due to less time since surgery, as well as older participants. In addition, step width increased on soft surface in individuals with TKA, which we suggest could be due to reduced dynamic balance compared to controls (see 4.3 Postural control).

When assessing group differences on each of the two surfaces, reduced knee flexion in stance in the prosthetic knee as well as the strong trend of reduced flexion in the prosthetic knee during swing compared to controls on both surfaces was in accordance with other studies conducted on hard surface only (75, 79, 167). Milner (32) suggested this reduction to be because of pain, however comparable studies (75, 79, 167) did not report any significant pain, but rather reduced gait speed in the TKA group, which might explain the reduced knee flexion observed in the stance phase. However, in study IV, this rather suggests that the pre-surgery habitual gait pattern presumably caused by previous OA pain, could explain the reduced knee flexion in the stance phase as gait speed was similar across groups.

Furthermore, study IV showed that knee and hip adduction angle at stance were not affected by surface conditions; nevertheless, there was a difference between groups, in particular regarding the prosthetic side. Knee adduction angle at stance in the prosthetic side was increased compared to the control group both on hard and soft surface. In contrast, earlier gait studies on hard surface report increased knee adduction instead in the contralateral side in individuals with TKA compared to controls (74). However, a trend (p = .057) towards increased adduction also in the contralateral knee compared to the control group (on hard surface only) may suggest development of OA, as severity of OA is commonly characterized by increased knee adduction angle and moment (171-173). Studies that corroborate the present results (74) propose increased contralateral knee adduction angle to be an important contributor to OA in individuals with unilateral TKA, and claim this is due to increased and excessive medial condylar loading, and thus less compression force distribution to the lateral side of the knee. Ultimately contralateral TKA (71) appears as a consequence of the increased contralateral knee adduction angle. As previously mentioned, there is a 37.2% risk of a contralateral TKA in the next 10 years after primary TKA (70). Although knee adduction was increased in the control group on soft surface, it was still significantly smaller than in the TKA group.
Increased hip adduction was found at stance at the time of peak knee flexion in the prosthetic side compared to the control group, however only on hard surface. It could be proposed that this increased hip adduction potentially explains the increased prosthetic knee adduction. Chang et al. (174) found that hip abductor muscle weakness leads to pelvic drop towards the swing limb and will thus increase knee adduction angle at stance. In level gait, no compensation for reduced PKSD as described in stair descent (study I) is needed, and increased hip adduction may in this case suggest reduced strength or motor control in the hip abductors. This emphasizes the importance of sufficient proximal strength and control (175).

4.2 Muscle function
The reduced quadriceps peak torque in the prosthetic side compared to the contralateral side and to controls expressed in studies I-III, which is in coherence with other studies (54, 55, 104), may also contribute to explain the reduced PKSD in individuals with TKA in study I. In the control group, smaller PKSD correlated with longer legs as well as with greater quadriceps torque. This shows that although individuals with longer legs were stronger, they were also able to descend stairs with less knee flexion, as shown when controlled for leg-length, the negative correlation between PKSD and quadriceps peak torque disappeared. In the TKA group, there were no correlations between PKSD and leg length, between PKSD and quadriceps strength, and PKSD and quadriceps strength controlled for leg length, indicating that other factors such as reduced PPKF had greater impact on PKSD. Results across groups, however, indicate that quadriceps peak torque may be an important factor for normal stair descent. A combination of reduced PPKF and quadriceps peak torque may affect the length-tension relationship in the muscle with considerable weakness close to full flexion and explain why individuals with TKA did not use their available knee ROM expressed by PPKF to descend stairs without compensation. Reduced PPKF is followed by reduced muscle length, and optimal myofibril cross binding is likely reduced to a smaller part of ROM. This is based on the fact that PPKF is larger in healthy knees. Thus healthy knees will exhibit a higher force generating capacity especially near PKSD due to a more optimal length-tension relationship (176). Reduced PPKF and strength might also be a factor explaining reduced flexion in the TKA group in study IV on level surface as well, however, that has not been assessed in this thesis.

Studies on elderly have shown that stair negotiation require knee extensor moments in excess of the maximum isometric muscle strength available and that stair decent exceeded maximal isometric capacity (177). No comparable studies have explored the relationship between strength and kinematics of stair negotiation in individuals with TKA, but findings for gait on flat surface show correlations between asymmetric peak knee
Discussion

flexion and quadriceps strength three months after surgery (56, 105). Gait asymmetry seem to disappear over time, while strength asymmetry still persists, suggesting there may be a strength threshold when gait symmetry is no longer affected (56).

With the evidence of reduced quadriceps and hamstring strength, we assessed the relative muscular effort to map out the resource capacity of these muscle groups (study II). Despite significantly lower quadriceps and hamstring strength in the TKA group, which already mentioned is in line with other studies (54, 55, 104), the relative muscular effort in the prosthetic side during stair ascent was similar to the contralateral side and the control group (Table 8). This is in contrast to other studies assessing differences in level gait for individuals with TKA and comparing older and younger individuals (118, 119). However, the study of Lester et al. (118) did not use EMG normalized to maximal effort for each leg, but compared absolute values between legs during gait only. In study II, the control group displayed significantly higher proportion of the maximal capacity in the stronger and dominant side during stair ascent. This asymmetry may be explained by limb dominance, suggesting that the dominant side is more active during gait (178, 179).

Similar relative muscular effort in both groups in study II could perhaps be explained by a difference in stair climbing speed, as the TKA group ascended stairs at a slower self-selected speed than healthy controls. This is in coherence with others studies (4). EMG activity is positively correlated with gait speed (180, 181). Reduced gait speed may indicate reduced knee extension moment and therefore reduced activity in VL, the net effect resulting in similar effort relative to MVCC in both groups. Similarly, Milot et al. (182), showed that by slowing gait speed, utilization of maximal capacity was reduced. Past studies have shown that hamstring strength is correlated with flat gait speed by finding that the percentage of time spent in stance was negatively correlated with concentric hamstring strength (183). This suggests that if hamstring strength increases, the percentage of time in stance decreases with increased gait speed. In addition to decreased strength, a heavier body weight, which was displayed in the TKA group compared to the control group (Table 4 and Table 8), might be argued to be a reason for a slower execution time ascending stairs in the TKA group (164). Others have shown reduced knee extension moments and significantly lower force in the vastii and rectus femoris in individuals with TKA compared to controls during level gait was compensated by increased back joint extension moments (102). Similar studies have found that individuals with TKA reduce quadriceps demand during level gait and stair ascent by leaning forward (102, 103). Thus, different strategies may be adopted to compensate for muscle weakness and reduce the relative effort. However, kinematics did not reveal increased forward lean of the trunk in the TKA group as a compensation for muscle weakness during stair ascent. We believe the
lack of coherence with these studies can be explained by less pain, a relatively young TKA group, as well as a longer post-operative time from surgery to testing in the present study as opposed to the other studies.

Reduced quadriceps strength, particularly in the contralateral limb, contributed with other factors to explain the failure of 30% of the TKA group to maintain single limb stance for 20 seconds (study III). The strength deficiency in the contralateral quadriceps indicates that inability to stand on one leg may be explained by low physical fitness rather than the isolated effects of a prosthetic knee (for more on this topic, see 4.3 Postural control).

4.3 Postural control

Study III showed that 30% of the TKA group and 4% of the control group were not able to perform the 20-second single-limb stance test. The rest of the individuals with TKA who were able to maintain balance throughout the single-limb stance test exhibited increased mean velocity in the ML direction in the prosthetic side compared to the contralateral side, however with such a small effect size that the deficit was considered negligible. Initially, it could be proposed that decreased single-limb balance time would be associated with increased SLS time during gait, as decreased static balance would probably lead to decreased dynamic balance (184). Although this is information we possess, however not analyzed, it still remains to be determined whether those unable to complete the single-limb balance test in fact displayed slower gait speed or increased SLS time. Even though the SLS time of the prosthetic side in study IV was by definition shorter, both on hard and soft surface compared to the than the contralateral side, which presumably was due to weaker quadriceps strength, the difference was considered so small that there was virtually no clinical relevance.

No other differences were found between the groups in single-limb stance. In quiet standing, individuals with TKA, both able and not able to maintain single-limb stance, performed equally to that of the control group. Although other studies have found impaired postural control closer to the time of surgery (132), our results suggests that function improves with time, at least in bilateral stance, and is comparable to controls for those able to maintain single-limb stance.

The individuals with TKA not able to maintain single-limb stance exhibited reduced bilateral quadriceps strength, higher age and increased BMI. Old age and increased BMI, associated with lower level of physical performance, is detrimental to the ability to maintain single-limb balance (136, 146). This suggests that the prosthesis itself cannot be attributed to the failure to maintain single-limb balance.

Discussion
During level gait (study IV), step width was influenced by the surface, as the TKA group walked with greater step width than did controls on soft surface with similar gait speed. On hard surface, there was no difference between the groups. This suggests that individuals with TKA need a larger base of support to cope with modulation of the surface and to easier maintain dynamic stability. Comparisons to healthy subjects have demonstrated that TKA does not fully restore static or dynamic postural control (185), and that greater postural sway is still present six months after surgery, not only in the prosthetic side but also in the contralateral side (132).

4.4 Kinaesthesia

We suggest the reason joint position sense (JPS) as a factor in the regression analysis did not predict the variance in PKSD in study I, and the ability to maintain balance in the single-limb stance in study III, is because the accuracy of JPS was equal between legs and groups. The relationship between JPS and postural control has previously been established with evidence of improved postural control with better JPS (186). This also confirms the lack of group differences found in JPS and quiet standing of postural control. The failure to maintain single-limb balance rather is attributed to other factors as previously explained.

The lack of group differences is in coherence with another study that displayed equal JPS between individuals with TKA and healthy controls (187). In contrast, others found JPS of the prosthetic side in posterior cruciate ligament retaining designs (PCR) to be decreased compared to healthy controls (145), however, a significantly older TKA group compared to the control group might account for this difference. Initially, it could be suggested that there would be lack of afferent proprioceptive information in PCL sacrificing designs (PCS) compared to retaining designs (PCR) as used in studies I and III, and thus a decrease in JPS. However, no significant improvement of JPS by retaining compared to sacrificing the PCL has been found (188, 189), which suggest proprioceptive capabilities in the surrounding structures are able to compensate for loss of the PCL. JPS is reported to be improved following TKA compared with the pre-operative state (61). The reason for this might be less influence from pain post-operatively.
4.5 Questionnaires

4.5.1 Knee injury and Osteoarthritis Outcome Score

The Knee injury and Osteoarthritis Outcome Score (KOOS) was primarily used in study III as a background factor potentially to find factors associated with the ability to stand on one leg. In study IV, it was used as part of subject demographics to get a general overview of the self-perceived knee status. The results of KOOS were in accordance with other studies that have reported decreased scores on all subscales in individuals with TKA (72, 73). The control group displayed KOOS scores within the range of what was considered normal knee function (85-100) (190). The reason the results of the KOOS did not contribute to explain the ability to maintain balance in the single-limb stance in the TKA group in study III might be due to problems with construct validity of the questionnaire, or maybe rather that the magnitude of balance is not addressed properly with KOOS. When examining the items of the subscales (Likert scale 0-4 with increasing number corresponding to greater difficulties or pain) closer it should be mentioned that the TKA group scored 1.4 ± 1.3 on stair descent (KOOS A1) and 1.1 ± 1.1 on stair ascent (KOOS A2) in terms of degree of difficulties. To walk on flat surface (KOOS A6) scored 0.9 in terms of difficulties. Concerning pain, the TKA group scored 0.9 for straightening (KOOS P3) and 1.8 for bending the knee (KOOS P4) and 1.8 ± 1.3 for stair negotiation (KOOS P6). These items, which are more specifically related to the items of this thesis, reveals little (score 1) to some (score 2) degree of difficulty or pain, suggesting the TKA group is well conditioned and has little to no problems with their prosthesis. Even though the numeric rating scale (NRS) for pain was used in the regression analysis in study I, an alternative analysis was used, substituting NRS with item P6 (pain in stair negotiation), and found as expected similar results with regard to the lack of contribution of pain on PKSD with low degree of pain in both items (KOOS P6: 1.8 ± 1.3 of 4 versus NRS: 1.4 ± 1.8 of 10).

4.5.2 Numeric Rating Scale

NRS scoring from 1-10, with 10 as the worst conceivable pain ever experienced or imagined, was primarily used in study I as part of identifying factors responsible for reduced PKSD in the TKA group, as well as part of subject demographics in studies II-IV to demonstrate the general level of pain. With a score on the NRS as mentioned of 1.4 ± 1.8 in the TKA group, this thesis is in coherence with other studies reporting a low degree of pain (26, 30, 31). To recruit a TKA group at least 12 months after surgery with a low degree to no pain was an important aim of this thesis, as it would be easier to identify the biomechanical implications during gait if pain was not a factor of influence. Thus, the low degree of pain made no contribution to identify factors responsible for reduced PKSD in the TKA group in the regression analysis performed in study I.
4.5.3 Tampa Scale for Kinesiophobia

A Norwegian adjusted Tampa Scale for Kinesiophobia (TSK) that ranged from 13-52 was assessed in study I, amongst several other items to identify factors responsible for reduced PKSD in the TKA group. The TSK displayed a value of 28, which indicated a medium degree of fear of movement in the TKA group. This value is identical to the study of Sullivan et al. (40) assessing individuals with TKA only 6 weeks post-operative, suggesting that kinesiophobia does not change much throughout the course of time following TKA. Although this value is considered a medium degree of kinesiophobia, the impact was probably not large enough to contribute to being a factor in the regression analysis to identify the reduced PKSD in study I. The study of Sullivan et al. (40) found fears of movement by TSK to predict post-surgical function assessed by using a questionnaire (The Western Ontario and McMaster Universities Arthritis Index (WOMAC)) (191). However, WOMAC, subjected to issues of patient subjectivity in post-surgical function, is a quite different measure as opposed to an objective and specific measure as the kinematic variables assessed in study I. Hence, the predictors in study I and in the study of Sullivan et al. (40) are impossible to compare.

4.6 Methodological considerations

4.6.1 Kinematics

In accordance with recommendations by Qualisys (Qualisys, Gothenburg, Sweden), markers were placed on designated anatomical positions on the skin or on tight clothing with the same set-up throughout all studies (I-IV). Accurate measurement of kinematics during functional activities suffers mainly from soft tissue artifacts (STA). As with all motion capture systems with body worn markers or sensors, STA is always a consideration. The skin or clothing will slide over the underlying structures. As such, surface markers may not accurately represent the underlying skeletal motion during dynamic activity (192, 193). STA may increase with higher BMI as a thicker subcutaneous adipose layer would lead to more distance between the designated anatomical position and the reflective markers (194). Thus, kinematic accuracy may be affected also by obesity (see further, 4.6.4 Subjects). Although the use of marker clusters on the thighs and shanks would partly solve the problem of sliding of markers relative to each other, it could however not entirely be ensured that the entire cluster would not drift to some extent during gait. Benoit et al. (193) described the average standard error of estimate of the tibio-femoral kinematics from skin-marker derived kinematics during walking. The study found knee flexion to be 2.5° and knee adduction/abduction to be 3.6°. It was thus concluded that kinematic observations below these standard errors must be dealt with, with great precaution, which applies to studies I, II and IV.
Although the use of three-dimensional kinematic measures to assess gait and stair negotiation are routinely used in clinical gait analysis, it is however not as common of a method as when measuring postural sway by CoM. Even though force platforms would be a better choice when assessing postural control, we had to utilize kinematic measurements as the two force platforms that originally were part of study III had major technical problems.

4.6.2 Peak torque

In all studies (I-IV), peak torques of quadriceps and hamstring were measured to assess muscular strength. The testers made sure the instructions and feedback intensity were identical to make the subjects perform equally optimally. Although such measures were taken, it is still difficult to determine to what degree an individual is able voluntarily to contract their muscles. The psychological threshold for maximal performance is individual and largely based on previous training background, pain, and fear of movement (109, 195). Even though the individuals with TKA reported very little pain (NRS of 1.4 of 10), it could still be proposed that the maximal effort produced during an MVCC feels rather extreme and might trigger some degree of pain that is not felt in ADL. Nevertheless, it should be noted that none of individuals with TKA or in the control group reported any pain during or after the MVCC.

With the older version of Biodex® System 2, in addition to the experience of the engaged experimenters at Rosenborg Sports Clinic (they were only trained to perform the concentric protocol), we were unfortunately not able focus on the eccentric phase or identify peak torque values at the same angles as PKSD in order to create conditions isokinetically equivalent to the eccentric movement occurring in stair descent in study I. With later versions of the Biodex®, it is possible to identify torques at different parts of the knee ROM. With information concerning the length-tension relationship of the quadriceps and hamstring, we could achieve a deeper understanding of the knee kinetics as the strength varies dependent of the myofibril overlapping and lengthening/shortening of the muscle.

4.6.3 Electromyography

In study II, electromyography (EMG) was utilized for assessing muscular demand during stair ascent. When applying EMG, some considerations need to be addressed. As cross talk with adjacent muscles might disturb the signal when using surface electrodes, considerable measures were taken in order to achieve accurate electrode placement. The recommendations of the SENIAM guidelines (159) were followed to minimize the potential of signal interference and other errors, such as for instance problems with instability with signal quality with EMG.
Discussion

placement on or close to motor points. In addition, as the EMG activity was normalized, the inter-individual variances were equalized, thus making the group comparisons possible. In addition, the same experimenter applied all electrodes.

To reduce the impedance, the skin was shaved and cleaned with alcohol. Prior to the testing, all muscles with surface electrodes were individually tested to ensure that the EMG signal responded in concert with dynamic contractions, but also to observe that the baseline was consistent and without interference, e.g. crosstalk or noise from other sources.

Individual shapes and sizes of the test subjects is a challenge when using EMG (147). The upper BMI limit of study inclusion was set to be 35 to avoid EMG issues with too much adipose tissue interfering with the signal. However, more adipose tissue would also make muscle palpations difficult and lead to inaccurate electrode placement.

In study II, we were unable to use the peak RMS EMG of MVCC, as problems with spikes were not resolved with filtering. Instead, the median value of each full MVCC curve (from where curve starts to rise to where curve flattens out) was calculated and all medians of the curves were then averaged to obtain the values used in the normalization. Median RMS EMG is a more robust measure of MVCC than peak RMS EMG, as peak values are sensitive to inconsistent “spikes”. EMG-data from dynamic contractions are very much susceptible to motion artifacts (196), thus the peak values could therefore be less trustworthy than median values taken this into account. Nevertheless, peak RMS EMG of stair ascent exhibited excellent signal quality opposed to peak RMS EMG of MVCC.

4.6.4 Subjects
The same TKA group (n=23, 11 males and 12 females) and control group (n=23, 10 males and 13 females) participated throughout all studies. Despite a small surplus of females, it could however be argued that population surveys of individuals with TKA also contain a small surplus of females (11), and thus provide a correct estimation of reality. The height and age was identical among the groups. However, the body weight was considerably increased in the TKA group, as also shown in other studies (94, 104). This may however lead the body weight difference to be a factor when comparing the two groups, especially related to stair ascent. A study found that BMI less than 40 kg/m² has no influence on strength or functional performance after TKA (197). However, we believe it is plausible to suggest, in coherence with another study, that a heavier body weight would decrease stair-climbing speed, especially when the heavier group exhibits decreased strength (164). To compensate for body weight difference, the strength assessment in study II was normalized to
body weight. Furthermore, a heavier patient group could also be proposed to be more inactive (198). A lower BMI as an inclusion criterion could perhaps have equalized body weight among groups, however, it would probably have resulted in too few individuals with TKA. Although we set the limit of BMI to be less than $35 \text{m/m}^2$, two of the included individuals with TKA were mistakenly not filtered through this exclusion and displayed a higher BMI than 35, i.e. 42 and 41. They could however have been removed before the statistical analysis, but in accordance with the study of Stevens-Lapsley et al. (197) stating that BMI less than 40 exhibits no influence on strength and functional performance, we decided to include these two patients nonetheless as they complied with the rest of the inclusion criteria. In hindsight, it might be proposed that they should have been excluded anyway due to possible issues with fatty tissue limiting knee flexion ROM (possibly giving too small an estimate of PPKF) and signal quality of EMG, as well as problems with locating correct anatomical structures for reflective marker and electrode placement (65, 147).

Pain measured by NRS was assessed at the day of testing, and not on each testing exercise. This could lead to an inaccurate assessment of pain, especially in study I where pain was not associated with PKSD. Nevertheless, the pain assessed (1.4 of 10 on NRS) was very low at the day of testing, which leads us to believe that the TKA group was not subject to pain during stair negotiation. Furthermore, pain measured by KOOS during stair negotiation (item P6) was accounted for in the regression analysis and scored similar to NRS and did not contribute to explain reduced PKSD in the TKA group either (more information located in 4.5.1 Knee injury and Osteoarthritis Outcome Score). Nevertheless, assessment of pain on the specific day of testing could prove to be a more valid measure.

### 4.6.5 Statistics

A weakness of the multiple paired t-tests is occurrence of type 1-errors. To decrease the possibility of type 1-errors in studies I, II, and IV, it was suggested that another type of statistics should be introduced. A linear mixed effects model (LMM) would however probably overestimate the data with such a small sample of subjects (199). Repeated measured would provide a good alternative to paired t-tests, however, that demands no missing values or at least random missing values (200). As the present study contains clustered missing (missing not at random = MNAR) kinematic values especially related to x- and y-plane of the hip in stair negotiation (in total 18 missing values from both legs and both groups), imputations would be a wrong choice. Missing value imputation is commonly performed when some random observations in a long line of data are missing, but performing imputations on such a low number of subjects and with MNAR characteristics would be incorrect (201). To
reduce occurrence of type 2-errors, an alpha of <.05 was selected as well as power calculations to set the least necessary sample size.

4.7 Clinical implications
The results of stair ascent and single limb postural control suggest individuals with TKA should utilize a training regime to increase quadriceps strength and single-limb balance skills, as well as increased general activity to address obesity. The quadriceps strength deficit should be addressed with closed chain weight-bearing training methods mimicking the motion of stair negotiation in line with the principle of specificity (202). Closed chain exercises such as step up/down exercises, squats and lunges may prove more functional and effective concerning specificity than open chain exercises such as seated quadriceps exercises where the legs are isolated in a specific knee flexion and extension movement pattern often used in rehabilitation protocols (203). Pre-rehabilitation quadriceps training does increase quadriceps strength and walking speed before TKA surgery, but does not impart lasting benefits to patients 12 weeks after surgery. Analysis of the results suggests that quadriceps strength alone may not drive functional improvements after surgery (204). In addition, reduced activity secondary to OA and the TKA surgery may impair the function of the contralateral side as well, and reduce the general physical capacity with increased BMI and reduced physical performance. Thus, carefully chosen single-limb balance exercises for both the prosthetic and the contralateral side in addition to quadriceps strengthening both pre- and post-surgery may prove beneficial for individuals with TKA in terms of increased stair negotiation speed, increased kinematic symmetry during gait and in single-limb balance performance. Added to the quadriceps strength-training regime already suggested, exercises aiming to decrease BMI and enhance general physical fitness might also prove beneficial to increase stair negotiation speed and single-limb balance performance.

As long as asymmetries are not amplified, gait on soft surface may be recommended for dynamic balance training. In daily life-related activities (ADL), people will in an active life-style encounter different surfaces, for instance when hiking off track. The intention in the present study was to simulate such an environment by assessing gait on a soft surface floor. Furthermore, low impact activities reduce reaction forces across the joint (205). The clinical implications following soft surface point toward problems with proximal control and stability in the kinetic chain, and should be recognized and amended with strength training and coordinative exercises consisting of gait training on hard and soft surfaces, surface-to-surface transfer training, and standing dynamic balance training (206).
Individuals with TKA should emphasize working on increasing knee flexion ROM (limited to soft tissue contractures and not prosthetic flexion limitation), hip abduction and quadriceps strength to achieve increased lower limb symmetry in various gait- and balance-related tasks. Even though the TKA group in this thesis displayed satisfactory post-operative results in knee ROM, and the potential for increasing ROM of the prosthetic knee is limited, there is reason to believe a certain progression can be achieved with specific approaches such as continuous passive motion (CPM) and manipulation under anesthesia in the early post-operative phase (< 1 year) (207, 208). Increased passive knee ROM, expressed in this thesis as PPKF, may also increase PKSD due to the strong correlation with each other, thus achieving increased knee flexion symmetry in stair negotiation.

4.8 Future research
Based on the results in this thesis, we suggest that future research should involve kinetic measurements with force platforms as part of both postural sway and gait/stair negotiation assessment in order to achieve a wider understanding, as kinematics only measures motion and not force. Force platforms integrated in the walkway to measure forces acting on the knee joint during gait in study IV could provide additional clinical recommendations, as soft surface probably would display lower compression forces as the stance leg hits the soft surface compared to hard surface.

To investigate the length-tension curve during MVCC regarding identifying and matching the torque angles produced to the specific angle of flexion to that of PKSD would provide the regression analysis a stronger validity between strength at a critical angle in knee ROM and PKSD.

To investigate pre-surgery status would also be beneficial to have a point of reference to the variables being tested.

A beneficial addition to the gait and stair assessments could be to study the kinematic and kinetic patterns during timed-up-and-go. This will assess how individuals with TKA deal with chair raise and especially turning 180° around the cranio-caudal axis. This turning will provide rotational forces around lower limb joints, which might disclose abnormal kinematic and kinetic patterns.

It could also be of future interest to conduct an intervention study describing the effects of strength and/or mobility training on the kinematic gait and stair negotiation pattern, as well as on postural control. Especially when this thesis has showed reduced bilateral lower limb quadriceps strength and indications (not measured) of reduced hip
abductor strength as a common denominator throughout all studies (I-IV), indicating that the general physical fitness within the TKA group is reduced compared to the control group.

4.9 External validity
The extent to which the results of studies I-IV can be generalized to other individuals with TKA is not without consideration. Although the type of prosthesis used and surgery technique performed are quite representative for the general TKA population, at least in Norway (11), the individuals with TKA tested in this thesis are younger (57.6 ± 5.8 years) than the average TKA population (68.9 years) (11) and most likely healthier regarding comorbidity, as the subjects were carefully screened through the extensive inclusion criteria (see 2 Methods). The reason such criteria were chosen was to isolate the effects of the TKA from other factors (especially regarding age, neurological and orthopedic diagnoses other than unilateral TKA), which could have caused unknown implications on gait patterns, muscular function and postural sway, and thus added confounders to the analyses (in particular regression analysis) and raise doubts on the validity of our results.
5 Conclusions

The overall purpose of this thesis was to investigate gait patterns and postural control during different conditions, muscle function and compensatory strategies among relatively young and healthy individuals with unilateral TKA and compare the prosthetic side with the contralateral side and with knee-healthy controls.

In conclusion, this thesis points to a common denominator of reduced lower limb strength, with the strength reduction affecting peak knee flexion during stairs descent (PKSD) and during stair ascent compensated for by reduced stair climbing speed. In stair descent, increased hip adduction may compensate for reduced PKSD. Reduced PKSD may in turn compensate for reduced quadriceps strength in order to reduce knee joint moments. Increased hip adduction in level gait points to reduced strength or motor control in the hip abductors. The failure to maintain single-limb stance in the TKA group is partly explained by reduced contralateral quadriceps strength, suggesting general deconditioning. Where differences exist, these can be attributed to decreased strength in the TKA group. Thus, this thesis confirms a review (35) that concluded that progressive strengthening and intensive functional exercises is critical after almost 2 years after TKA.

- Peak passive knee flexion (PPKF) correlated with reduced peak knee flexion during stair descent (PkSD) in individuals with TKA.
- Reduced quadriceps peak torque may contribute to reduce PKSD, as PKSD within the TKA group correlated with strength across groups.
- Individuals with TKA did not use a higher percentage of their maximal muscular capacity during stair ascent compared to healthy controls.
- Individuals with TKA compensated muscle weakness by slower gait speed during stair ascent compared to healthy controls; however, increased forward lean was similar between groups.
- In the TKA group, 30% were not able to perform 20 s single-limb stance, opposed to 4% in the control group.
- There was equal postural sway between the TKA group and healthy controls in bilateral quiet standing, as well as single-limb stance in those able to maintain balance for 20 s.
Conclusions

- Older age, higher BMI and reduced contralateral quadriceps strength were associated with the failure to maintain single limb stance in the TKA group.

- Gait on soft surface did not amplify existing kinematic asymmetries found in hard surface in the TKA group.

- The kinematic values of knee flexion at swing, speed and double-limb support (DLS) time were amplified in soft surface compared to hard surface.
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